Laser Shaping:
A method for controlling the elastic behaviour of stretch fabrics for a targeted and graduated compressive effect on the body

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TWI

Copyright statement

Abstract

This research was commissioned and funded by The Welding Institute (TWI). The Welding Institute are a global research and development facility specialising in the joining of materials for industrial applications. The purpose of this research was to develop capability in textiles joining, particularly ultrasonic and laser welding technologies, which is relatively new to TWI.

The appointed researcher adopted a 'multi-strategy' (Cresswell 2009) approach to the research; encompassing methods that were both familiar and unfamiliar to those usually adopted by TWI employees and researchers, whom mostly come from engineering and scientific backgrounds. The research was primarily undertaken with the adoption of a 'craft-design' approach that uses material investigation to explore and uncover interesting leads for investigation, which was the familiar approach of the researcher coming from a background in textile design. Material studies were carried out inquisitively without the formation of a particular hypothesis and insights were discussed with industry to identify potential commercial and functional application opportunities. Following the identification of an interest in welding stretchy fabrics Speedo agreed to become the main industry partner for the research, providing materials, access to testing equipment and validation of commercial opportunities for material samples relative to their application.

The main hypothesis for the research *Laser melted patterns can be used to control the elastic behaviour of stretchy textiles to have a targeted and variable compressive effect on the body* developed through discussion with Speedo in response to material samples produced using transmission laser welding equipment. A predominant scientific approach was adopted during the second phase of the research to quantify and control this effect: to demonstrate repeatability and test it both on fabric and the body. Methods that were unfamiliar to the researcher prior to this research such as mechanical testing and microscopic analysis were employed. Selection of either a 'craft design' or 'scientific' approach was made pragmatically in response to the research as it developed. Through a retrospective analysis of applied methods throughout the research trajectory it has been possible to define this particular 'multi-strategy' project as a 'sequential exploratory' design (Cresswell 2009), whereby periods of subjective investigation are followed by empirical testing.

The main process that has been developed by this research is a decorative method of controlling the elastic behaviour of stretchy fabrics using transmission laser welding equipment for a controlled and variable compressive effect on the body. Compression

fabrics are used widely within the medical, lingerie and sportswear fields to apply pressure to the body either for an aesthetic or functional advantage. In swimwear, compression fabrics are applied to streamline the silhouette and minimise drag resistance.

The technique developed by this research makes a contribution to knowledge within the field of laser processing of textiles, specifically within the field of transmission laser welding, and within the field of compression apparel. In the field of transmission laser welding a new functional capability for all-over surface patterns has been demonstrated. In the field of compression apparel a new decorative method for achieving an increasingly variable compressive effect for a smoother transition between different zones of stretch has been achieved.

N.B. All redacted information throughout this thesis is confidential to Speedo.

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Preface

An opportunity to undertake this research project followed the completion of an MA in Textiles at the Royal College of Art in 2011. Professor Clare Johnston, the programme leader for Textiles, initiated an introduction to TWI during the final year of study.

Having identified an interest in constructed textiles whilst studying for a BA qualification, a specialism in knitted textiles for fashion had been defined and continued to be the area of investigation for MA. Throughout the course of MA study, textile samples developed became increasingly mixed media in their approach as new opportunities were sought through unlikely and opposing material combinations.

A project brief set by the trend forecasting agency WGSN required innovative textile samples to be produced as inspiration for the upcoming season. Students were each assigned a particular theme to work to, which was defined by WGSN. Working under the theme of ‘ceramic’ there was a heavy influence on the work from the Anish Kapoor show that was being exhibited at the Royal Academy of Art at the time. There was a fascination with Kapoor’s use of wax material, which sets into a solid form, yet retains an appearance as though in a state of flux. Both ceramic and wax materials have an ability to change states from liquid to solid, and this particular material behaviour influenced the development of samples for the WGSN brief. Polyfilla was used to coat knitted textile swatches, which were pulled and distorted manually once the Polyfilla had been applied. A variety of surface effects were achieved by varying the construction of the knitted fabric and the length of time that the Polyfilla had been applied for before the sample was distorted. Methods of recreating this effect using commercially viable textile processes were explored during the final year of work for the MA qualification. A method of screen printing knitted surfaces with puff binder and manipulating them before the binder was activated with heat was developed.

Through this investigation it was found that the heavily printed surfaces developed could not be joined using traditional knitwear processes such as over-locking or linking as they had become too thick and stiff. It was therefore necessary to explore alternative joining solutions and this is how an introduction to TWI was initiated. It was not long after completing the MA that an opportunity to continue working with TWI on this PhD project brief arose.

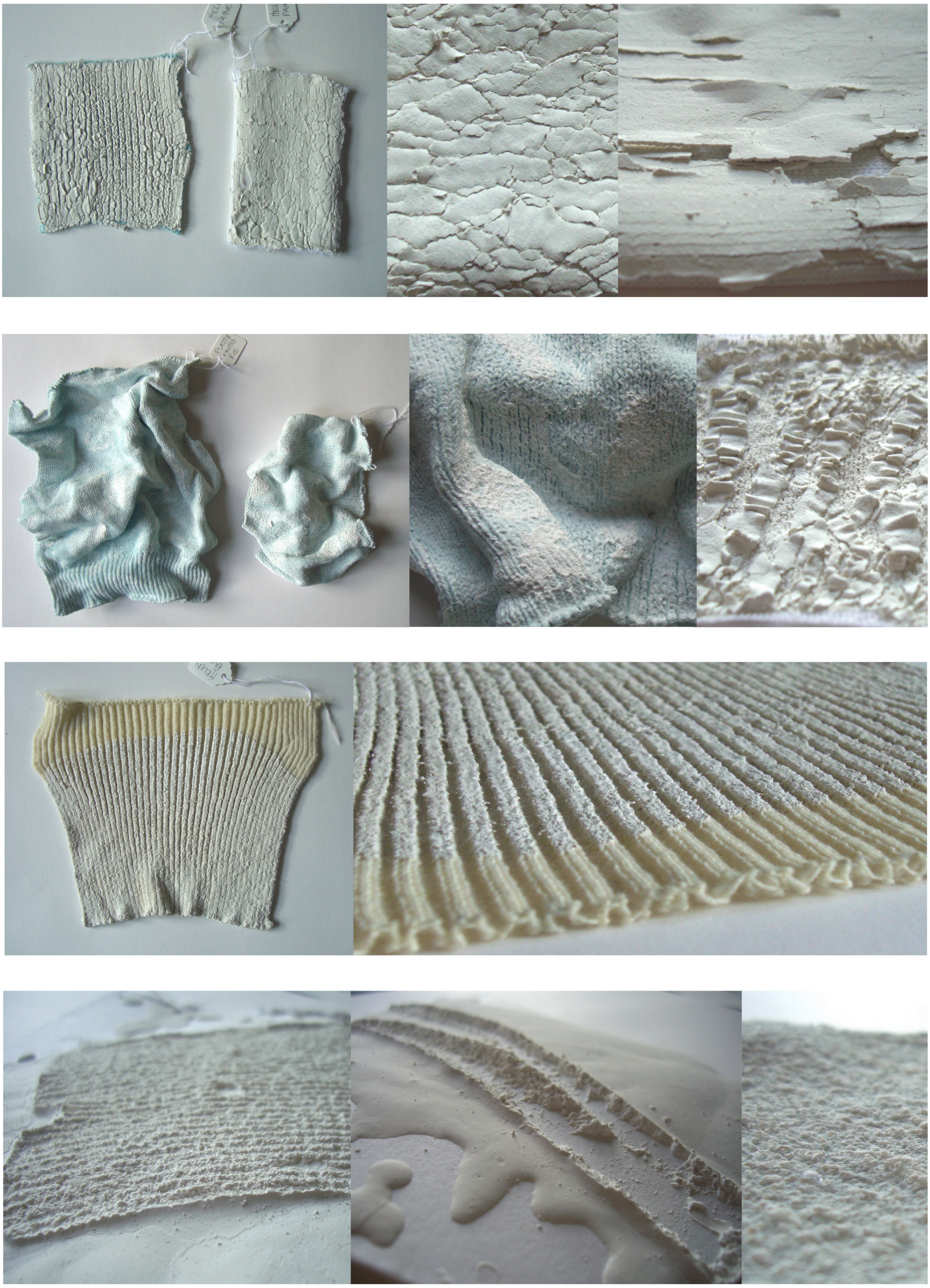


Figure i) Samples created for WGSN 'Ceramic' brief by Helen Paine (Paine 2009)

Figure ii) Garments from final MA collection of Helen Paine, 2011 (Photography by Hitomi Kai Yoda, 2011)

Acknowledgements

First and foremost I would like to express my special appreciation and thanks to my primary supervisor Professor Sharon Baurley, who has been a tremendous mentor to me. Your continued support and encouragement of the project has been hugely significant in influencing the direction of the work. I would also like to thank you for your impeccable feedback on my writing, which has been invaluable in drafting this thesis.

I would like to extend my gratitude to my secondary supervisor Dr. Kate Goldsworthy. You have been so generous with your time and knowledge throughout this process. Through your acquaintance I have been able to broaden my knowledge and connections within the field of design research, which has been an indispensible benefit to this project. I have really valued your positivity and enthusiasm through our discussions and shared experience working at TWI as textile design researchers; and I hope that our relationship will continue long after the PhD is complete.

I would like to thank TWI for their financial and technical contributions to the work. My special thanks go to Ian Jones, my industrial supervisor, for sharing his technical knowledge and expertise; and Roger Wise, who I understand was responsible for my appointment. This opportunity has enabled me to extend my boundaries as a textile designer and make connections with industry and academia that would not have otherwise been possible, and for that I am extremely grateful.

I would also like to thank Speedo for their contributions. In particular I would like to thank Ben Hardman, Rachel Webley and Jannette Tarnai for their time, ongoing enthusiasm, and brilliant suggestions that have influenced the development of the work. It has been a fantastic opportunity to validate the research through this connection with industry, and I could not have wished for a better more energetic team to work alongside.

Last but by no means least I would like to thank my family and friends for their support. I would especially like to thank my mother, Lesley Paine, for her relentless support of my academic endeavours; and my mother-in-law, Maria Presswell, for her calming influence. Thanks also to my father, Graham Paine, for his final proof reading of the thesis. I would also like to thank all of my friends who supported me in writing, and incented me to strive towards my goal. Finally, I would like to express my appreciation to my beloved Husband, Ollie Presswell, for his unyielding support and affection. I could not have done this without you.

Author's declaration

During the period of registered study in which this thesis was prepared the author has not been registered for any other academic award of qualification. The material included in this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted.

1 Introduction

This research makes contributions to knowledge both in the fields of transmission laser welding and compression apparel.

The contribution to knowledge that has been made within the field of transmission laser welding is:

a new application opportunity to use the equipment to create all-over surface patterns that have a controlled effect on the elastic behaviour of stretchy fabrics.

The contribution to knowledge that has been made within the field of compression apparel is:

a method of creating a graduated targeted compressive effect across the surface of a single fabric layer without the addition of any extra material.

1.1 Objectives of the brief

TWI is a world leader in the field of materials joining and mostly specialises in the joining of metals and plastics for industrial applications. TWI has acquired expertise more recently in the field of textiles joining and the main aim of this research was to develop this knowledge further, enhancing technical understanding and developing novel techniques. The funding for the research was awarded through TWI's Core Research Programme. The Core Research Programme is a three year rolling programme funded by the annual fee paid by TWI's industrial member companies. Projects can vary between one and three years in length and are designed to develop skills and knowledge in materials joining specific to the needs of TWI's member companies. Results from projects funded via the Core Research Programme are published in TWI's industrial member reports that are only available to member companies.

Due to the industrial funding route for this research there was a requirement that the outcomes should be of value to industry, and specifically TWI's member companies. It was encouraged during the first year of study that industrial case studies should be sought to provide validation and support for the research and it was during this time Speedo was introduced to the research and became the main industry partner (2.1.1).

A brief for the research had been written prior to the researcher's appointment as part of an internal proposal at TWI for the Core Research funding (See Appendix 8.2). The original objectives of the brief evolved with the progression of the research; however, there were a number of overarching requirements of the research that were established through discussion with employees and the industrial supervisor for the project at TWI. A summary of the overarching objectives that were applied to the research is provided below:

• Develop capability for current textile welding technologies, specifically ultrasonic and transmission laser welding (TLW) equipment

• Assess the performance of developed techniques using mechanical testing equipment

• Define process parameters for repeatability in industry applications

• Develop case studies with industry to validate research and develop TWI's existing network

Having come from a background in textile design and worked with industrial equipment in the field of knit and print, the researcher was confident in her ability to develop novel techniques that would extend capability in the field of advanced methods for joining textiles. It was evident, however, from the objectives of this brief supplied by TWI that an increasingly scientific approach would need to be adopted for this research. A number of industrial design briefs had been undertaken by the researcher during and subsequently to her MA qualification, which included projects set by Umbro, Anthropologie and Rowan. The main deliverables for these briefs were typically a collection of knitted material swatches and garment design ideas in the form of illustrations and prototypes. The requirements of this brief provided by TWI, specifically relating to performance analysis and process guidelines, were increasingly technical and had an impact on the methodological approach adopted. The next section of this chapter provides an overview of the methodological approach adopted by this research.

1.2 Overview of methodological approach

This research followed a 'multi-strategy' framework of inquiry encompassing both 'craft-design' and 'scientific' approaches. A multi-strategy methodology utilises more than one approach within its design. The term 'craft-design' has been used by this thesis to describe an approach that bridges between the disciplines of craft and design and was the familiar approach of the researcher coming from a background in textile design. Hands-on methods of material investigation organised within a systematic reflective framework of inquiry that acknowledges the implicit knowledge of the researcher characterise this approach, which is commonly referred to as 'practice-led.' Throughout the researcher's BA and MA qualifications novel aesthetic opportunities for knitted textiles had been identified through material investigation and developed by practical means. A novel technique for creating double layer knitted fabrics using a combination of knit and print processes was developed during the researcher's MA qualification (see Preface p.11). Implicit knowledge relating to the behaviour of textile materials, particularly knit and print processes, gained from the researcher's prior experience assisted in identifying interesting leads for investigation.

A scientific approach, in contrast, suspends the personal know-how of the investigator in the pursuit of absolute objective knowledge and uses quantifiable methods to provide measurable evidence. The researcher would have employed a scientific approach during project work prior to this research, for instance when establishing optimum conditions for a particular print process; however, enhanced transparency was now required to ensure industry repeatability and diligent recording of parameters and results became essential. Knowledge of analytical methods such as microscopic evaluation and mechanical testing was completely new to the researcher and had to be developed.

Methods of inquiry that oscillated between a craft-design and scientific approach were selected pragmatically as the research progressed. A craft-design approach that encompassed discussions with industry was adopted primarily at the beginning of the research to identify interesting leads for investigation. TWI provided introductions to potential industry partners and opportunities for collaboration were explored during this primary phase, which has retrospectively been called 'project scoping' (Chapter 3). Following the identification of an interest in welding stretchy fabrics Speedo was identified as a suitable industry partner and became the project's main collaborator; providing feedback on material samples and access to testing facilities at their head office in Nottingham. A scientific approach was adopted predominantly during the latter studies 'surface modification I' and 'surface modification II' to test the main hypothesis for the investigation, which had been identified during the 'project scoping' phase and developed by the Literature Review (Chapter 4).

An introduction to the project background that was understood following an initial literature review upon commencement of the research is provided below.

1.3 Project Background

The main aim of the research was to develop capability in the field of advanced technologies for textiles joining. This covers a broad range of technologies, specifically ultrasonic, dielectric, laser, hot air, hot wedge and adhesive hot melt films; however, there was a particular interest to explore ultrasonic and laser welding methods.

Advanced methods of joining textile seams were first implemented for the construction of waterproof clothing. Sewing creates holes in the surface of the textile that are susceptible to water penetration. This problem is avoided using advanced methods of construction. Charles Macintosh produced the first waterproof coat in 1823 by joining the seams together with a rubber adhesive (Di Rienzo 2011). High performance clothing for the military and outdoor workers continued to push the development of new joining technologies, and outerwear-clothing brands such as Berghaus and Barbour were born as a result of these product innovations (Di Rienzo 2011).

Implementation of advanced joining methods has spread as the inclusion of textiles has grown into industrial product sectors. Initially it was the waterproof capability of the techniques that attracted clothing manufacturers, however, the potential to reduce reliance on manual labour within the manufacturing of textile products, increasing automation and reducing costs, is now drawing wider market interest (Jones, Wise 2005). A European collaborative project 'Leapfrog' completed in 2009 demonstrated the potential for laser welding equipment to be integrated with an automated system for clothing production.

1.3.1 Ultrasonic welding

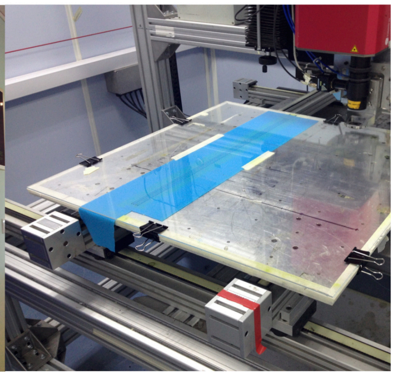
Ultrasonic welding is widely used across industry sectors, specifically the automotive, electrical and packaging industries, to join textile and other polymeric film materials (Devine 1998). Continuous ultrasonic welding equipment is set up similarly to a sewing machine; with the operator feeding material samples through the machine manually, from the front to the back. As the materials pass through the machine mechanical energy is supplied via a sonotrode or horn that creates frictional heating and melts the material to form a weld (Devine 1998).

Figure 1.1 Pfaff continuous ultrasonic welding equipment at TWI (TWI 2012)

1.3.2 Development of transmission laser welding

TWI developed transmission laser welding technology (TLW) for textiles during the mid 1990s. The process utilises the application of an infrared laser absorbing dye, which is placed at the interface of two thermoplastic textile materials. Upon irradiation from the laser the dye is activated and causes heating in between the material layers to form a weld, which has an almost seamless appearance (Jones, Patil 2013). A broad range of product applications such as waterproof clothing (Hilton, Jones 2000), car airbags, medical chair covers and inflatable airships have been demonstrated (Rooks 2004).

Despite suitability being demonstrated across numerous product sectors there has yet to be any large scale implementation of TLW in the textiles sector (Jones, Patil 2013). The main identified drawback of the technology, which could be responsible for its lack of uptake in industry, is limited material compatibility (Grewell, Rooney et al. 2004). Materials for all textile welding processes must be thermoplastic so that they melt and reform once cooled. For TLW, however, there is an additional requirement that the top layer in the material configuration is transparent to the infrared wavelength of the laser (Figure 1.4). This is so that the laser can travel through the top substrate to reach the site of the weld at the material interface. Many textile materials contain additives and/or pigments that absorb the infrared wavelength of the laser and prevent sufficient transmittance to form a weld. Carbon black is a well-known infra-red absorbing pigment often used to dye black coloured textile materials.



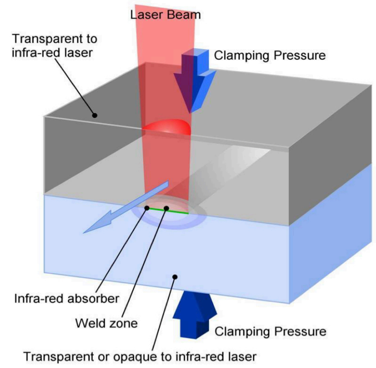


Figure 1.2 (Left) Researcher operating laser welding equipment from outside lab at TWI (TWI 2012)
Figure 1.3 (Centre) Sample set up on x-y table for laser welding at TWI (Paine 2013)
Figure 1.4 (Right) Material configuration for transmission laser welding (Image courtesy of TWI)

1.3.2.1 A new application

The recently completed doctoral research of Kate Goldsworthy has demonstrated a new application for TLW using it as a tool to create mono-material finishing effects for polyester fabrics. Goldsworthy's research centred on developing new decorative finishing techniques for textiles that maintained the virgin quality of the material to enable repeat recycling within a closed loop system. Material limitations that are applicable to the welding process are less relevant with the objective of marking textile surfaces to create decorative effects (Goldsworthy 2012). An extended discussion of Goldsworthy's work relative to other academic researchers in the field of laser processing of textiles is provided in the Literature Review chapter of this thesis (4.2)

Figure 1.5 Examples of 'Laser-Finished' textile samples from Kate Goldsworthy's PhD research (Images courtesy of Kate Goldsworthy)

An introduction to the research hypotheses that drove the investigation is provided in the following chapter section.

1.4 Introduction to research hypotheses

The initial 'project scoping' phase can be divided into two distinct studies: 'preliminary ultrasonic study' (3.2) and 'stretch seaming and surfaces investigation' (3.3). Two initial hypotheses were developed during the 'preliminary ultrasonic study' and investigated by the 'stretch seaming and surfaces investigation.'
These two initial hypotheses were:

• Weld pattern can be used to enhance the elasticity of welded textile seams

• The welding process can be used to shape the stretchy textiles for the construction of three dimensional products

The main technique for investigation, specifically a method for controlling the elastic behaviour of stretchy fabrics, was identified during the 'stretch seaming and surfaces investigation' (3.3) and developed in discussion with Speedo (See chapter section 3.3.4). It was identified that laser marked patterns on stretchy fabrics could be used to have a compressive effect on the body. The main hypothesis for investigation, specifically relating to a targeted and variable compressive effect, was developed through a subsequent review of methods for shaping the body. (See chapter sections 4.3 and 4.4)

The main hypothesis that has been investigated by this research is:

Laser melted patterns can be used to control the elastic behaviour of stretch textiles to have a targeted and variable compressive effect on the body

The final section of this chapter provides a chapter-by-chapter overview of the thesis structure.

1.5 Thesis Structure

This thesis has been structured chronologically to demonstrate the iterative nature of the work. An overview of the contents of each chapter is provided below:

Chapter 1 introduces the project with the overarching objectives that were stipulated in the original brief, drafted by the funding company for the research: TWI. An overview of the methodological approach describes how a 'multi-strategy' framework has been used that encompasses both craft-design and scientific approaches; an introduction to the project background, research hypotheses and summary of the thesis structure is provided.

Chapter 2 describes in more detail the 'multi-strategy' methodological framework adopted by the research. This chapter is split into two sections: Methodology (2.2) and Methods (2.3). The Methodology section describes the overall approach to the research, which combines both 'craft-design' and 'scientific' approaches. The Methods section provides descriptions of the individual methods that characterise the separate craft-design and scientific approaches employed.

Chapter 3 reports on the key studies carried out and insights gained during the 'project scoping' phase of this research. During this phase a research gap was sought through the adoption of a predominant 'craft-design' approach. Speedo was established as the main industry partner for the research and provided validation for the first research gap within the field of TLW; to control the elastic behaviour of stretchy fabrics using laser melted patterns. Through discussion with Speedo it was understood that this effect could be used to have a targeted and variable compressive effect on the body.

Chapter 4 provides an overview of academic research in the field of laser processing for textiles and a review of historical and contemporary methods for shaping the body through the critical lens of ability to produce a targeted and variable compressive effect on the body. There is a focus on the technical aspects of garment and fabric construction for both shapewear and sportswear applications that contribute to achieving a targeted and variable compressive effect. The chapter culminates in the identification of a gap in knowledge within the field of compression apparel; namely, to create a variable compressive effect across a single fabric layer; and the main hypothesis for the investigation: *Laser melted patterns can be used to control the elastic behaviour of stretch textiles to have a targeted and variable compressive effect on the body*

Chapter 5 reports on a study to explore the precise control of laser melting to create a variable compressive effect, which was identified in the review of the literature as a key objective for contemporary compression technologies. The first half of the study examines how the proportion of melting can be controlled using precise programmable machine settings that can be simply implemented in industry, and the second half of the study measures the effect on the elastic behaviour of the fabric by employing mechanical testing equipment. Results show that the level of melting is proportional to the effect on the elastic properties of the fabric and can be controlled accurately both through the depth and across the surface of stretchy materials to have a precise and repeatable effect. Other insights gained were that melt pattern orientation can be used to control the elastic behaviour of stretch textiles and that melted surfaces deteriorate the tensile strength of the parent material.

Chapter 6 tests new insights signposted in chapter 5. The second half of the chapter demonstrates how laser melted surfaces can be applied to create a targeted compressive effect on the body; developing processes for targeting the laser to specific areas of the fabric and using testing methods, specifically 3D body scanning and pressure testing, made available to the research by Speedo, to validate the compressive effect on the body.

Chapter 7 discusses the results that have been generated in the research in relation to the main hypothesis, arising from the gaps in knowledge. Conclusions from the research are drawn to identify novel aspects that define the contributions to knowledge. Conclusions are drawn on the main findings in relation to the requirements of the original brief by TWI to develop capability in the field of advanced methods for joining textiles. Contributions to knowledge that have been made by the research are stated and opportunities for further work are identified.

2 Methodology: Transcending boundaries as a craft-designer

2.1 Introduction

This methodology chapter describes the framework and individual approaches that have been used to carry out the research. The chapter begins with an expanded description of the cross-disciplinary context for the research and the impact this had on the adopted approach. The first half of the chapter explains the ‘multi-strategy’ framework that was adopted, which oscillated between a ‘craft-design’ and ‘scientific’ approach. The sequence in which a ‘craft-design’ and ‘scientific’ approach were applied throughout the research trajectory is mapped to gain further insight. The second half of the chapter describes the individual methods that were applied.

2.1.1 Research context

The context for this academic research was unusual in that the researcher was situated at the head offices of their funding company TWI in Cambridge and the brief for the research had been written by them. The majority of employees and researchers at TWI are from engineering or scientific fields. This was an unfamiliar environment for the researcher coming from a background in textile design.

The main bulk of the investigation was carried out during the first two years of study when the researcher was situated at TWI on a full-time basis and had open access to the laser and ultrasonic welding equipment to be developed. During this period the researcher was able to access some technical assistance from employees at TWI and introductions to unfamiliar processes and equipment were provided.

One of the requirements of the brief for the first year of study was to find an industrial case study for the research. Routing the PhD firmly within an industrial context was of clear benefit to TWI, ensuring that the work had industrial validity.

Working at TWI’s offices in Cambridge introductions with various companies were made possible. TWI is a members-based organisation, and companies pay a fee for access to their expertise. Before companies come into membership it is sometimes possible to do some small-scale testing of their materials to demonstrate initial feasibility, which could be used to form the basis of a larger future project. By providing technical assistance on these small-scale studies it was possible to identify companies that were interested in advanced technologies for joining textiles and could, potentially, be approached as case studies for the research.

Speedo was introduced to the work during the first year of the project and became a consistent thread providing industrial validity throughout the research. Discussions with employees at Speedo were undertaken periodically to reflect on the progression of material samples and validate the research through the suggestion of suitable application opportunities. Speedo also provided access to testing and manufacturing equipment for the production and analysis of garment prototypes during the latter phases of the research.


Figure 2.1 (Left) TWI head office, Cambridge (Image supplied by TWI)
Figure 2.2 (Right) Industry discussion with Speedo at their head office in Nottingham (Paine 2014)

2.1.2 Modification of the expected scientific approach

There was an expectation from TWI that a scientific approach would be adopted to carry out the research, which was indicated by the wider objectives of the brief; specifically, that mechanical testing methods should be used and process parameters should be defined (see Appendix 8.2). A scientific approach requires that the researcher take an objective non-interactive position. Insights are deduced or suggested from the collection of observable evidence relating to a specific objective or hypothesis (Crouch, Pearce 2012).

Coming from a background in textile design the researcher had become accustomed to following an alternative approach to research that uses material investigation and a practical understanding of materials to discover solutions. This is an emerging approach within the academic field and has been termed as a 'craft-design' approach by this thesis. A full description of a 'craft-design' approach is provided in chapter section 2.2.2. In summary, a 'craft-design' approach uses hands-on methods of investigation to develop understanding and seek novel opportunities for investigation through a visual assessment of material samples. In this process the researcher is actively engaged with the research and 'subjectivity, involvement, reflexivity is acknowledged' (Gray, Malins 2004).

During the researcher's MA qualification an investigation of new aesthetic effects for knitted fashion fabrics was undertaken through a hands-on practical investigation of stitch and printed surface combinations and new discoveries had been realised through the process of making (See Preface, p.11). Building on this prior experience it was the belief of the researcher that an approach that integrated familiar 'craft-design' methods within the expected 'scientific' approach would be advantageous when applied to the TWI brief to come up with novel solutions in the fields of TLW and ultrasonic welding. As such a 'multi-strategy' framework adopting multiple approaches that oscillated between a 'craft-design' and 'scientific' approach was taken that fulfilled the requirements of the brief and utilised hands-on methods of investigation that were already familiar to the researcher.

Suitable methods were selected in response to the research problem as it progressed through the accumulation of new insights. During the preliminary phase there was an interest in exploring opportunities suggested through the production and evaluation of new aesthetic effects. This required a 'craft-design' approach that acknowledges implicit knowledge from prior experience to make judgments on the novelty of specific effects. As the research progressed functional opportunities for these effects were tested using scientific methods, such as mechanical testing, that provide quantifiable objective evidence. Material investigation or methods relating to a 'craft-design' approach were returned to when new opportunities were being sought or an extended knowledge of particular process needed to be developed.

A diagram of how this 'multi-strategy' methodology was split, and the individual methods used within each approach, is provided in Figure 2.3. An extended discussion of how the methodology oscillated between a 'craft-design' and 'scientific' approach throughout the research trajectory can be found in chapter section 2.2.3.2.

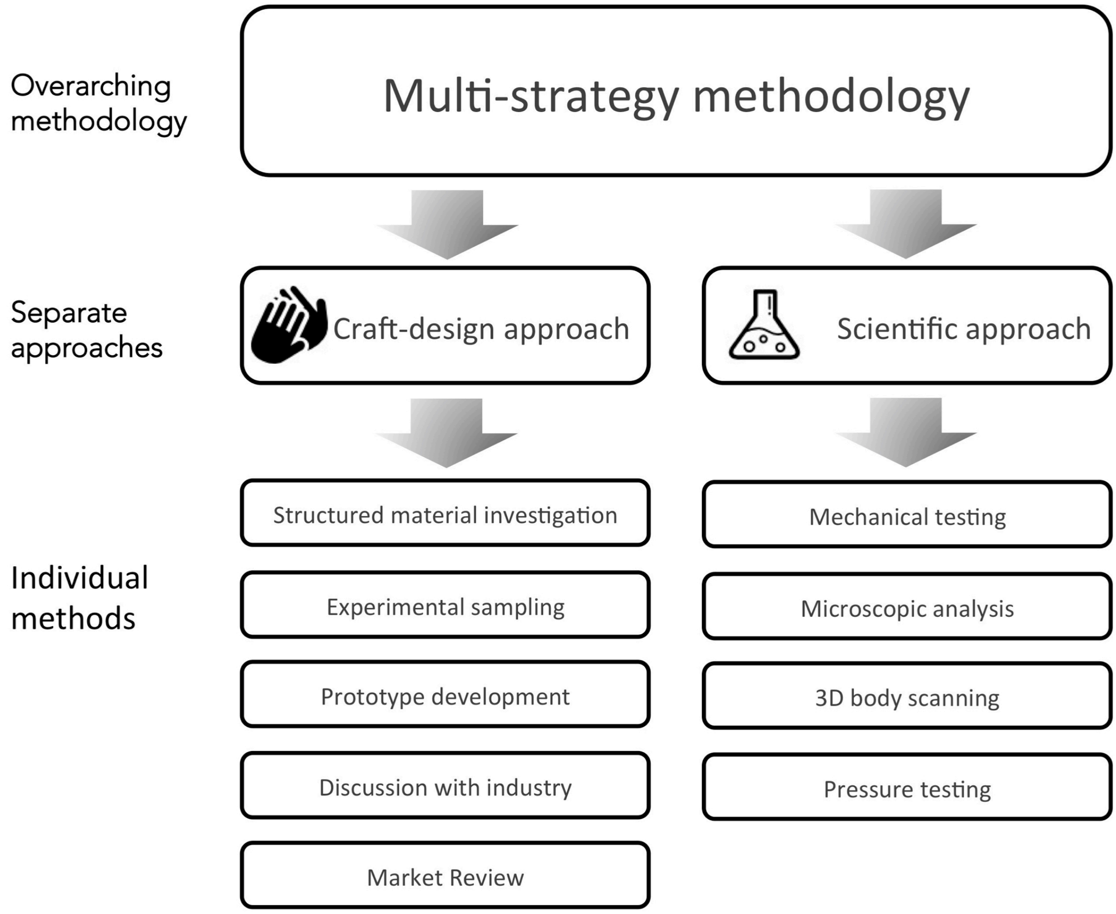


Figure 2.3 Illustration of multi-strategy methodological framework, separate approaches and individual methods adopted by this research (author's own)

The following Methodology section of this chapter (2.2) provides descriptions of the individual 'scientific' (2.2.1) and 'craft-design' (2.2.2) approaches and 'multi-strategy' framework (2.2.3) that were applied by the research.

2.2 Methodology

2.2.1 A scientific approach

A scientific approach is the traditionally accepted form of academic research and follows a positivist paradigm of inquiry. A research paradigm defines 'the basic set of beliefs that guide action' (Cresswell 2009). Following a scientific approach the researcher must suspend any personal know-how in the pursuit of absolute knowledge. The post-positivist paradigm of inquiry is contemporarily the more widely accepted variation on this approach; acknowledging that complete objectivity free from bias is rarely achieved (Gray, Malins 2004).

An understanding of a scientific approach was gained by observing other researchers working at TWI from engineering and scientific backgrounds: material studies have a pre-defined structure that is set up to investigate the validity of a particular hypothesis, which is developed through a review of the relevant technical literature.

The expected scientific approach was adopted when embarking on initial material experiments for this research. Working in this structured scientific way it was observed that there was limited opportunity for the development of new ideas. Results that do not support the general pattern emerging are treated as anomalies and are either repeated or discarded so that an overarching conclusion can be drawn.

A scientific approach was utilised to provide quantifiable and objective evidence on lines of enquiry revealed through a craft-design approach. An extended description of methods employed whilst following this approach is provided in the 'Methods' section of this chapter (See chapter section 3.1).

2.2.2 A craft-design approach

A craft approach is an emerging approach to research in the academic design field, however definitions are evolving with a growing body of published works (Philpott 2011, Kane 2007, Goldsworthy 2012). This approach may be referred to by other names such as 'reflective-craft approach'. Hands-on material investigation or practice-led methods of inquiry that are typical of a craftsperson characterise this approach and are situated within a systematic framework of reflective inquiry.

A craft approach or similar practice-led design approach follows a constructivist paradigm of inquiry. A constructivist paradigm, in contrast to a positivist paradigm, acknowledges the existing knowledge of the inquirer (Gray, Malins 2004). This was considered an advantage by the researcher when approaching the TWI brief as know-how developed through prior experience working with textile materials could be called upon to assist in the development of increasingly novel concepts for investigation. Some of the features of the particular approach adopted by this research can be more closely associated with design than a traditional idea of craft (Wilson 2000): machines have been used throughout the investigation; and industry, specifically Speedo, was invited to give opinions on the material samples that were produced and assist with the development of ideas for industrial applications. Traditional definitions of craft are evolving to recognise inter and cross-disciplinary practices (Niedderer, Townsend 2010), however, for the purposes of this research the approach has been termed as 'craft-design' to indicate the use of methods that bridge between traditional distinctions made between the two disciplines.

The following subsections of this chapter section introduce the concepts of tacit knowledge and reflective practice that are fundamental to a craft-design approach. As has already been touched upon in chapter section 2.1.2 a crafts-person has an embedded knowledge of their specific materials and discipline developed through practical experience. This type of practical know-how can also be called implicit or tacit knowledge and assists in guiding the crafts-person's ongoing material investigations. Reflective practice is a method employed by practice-led researchers, including those from craft-design backgrounds, to add rigour and structure to their investigations for academic validity.

2.2.2.1 Tacit knowledge

Tacit knowledge is developed through experience and has been explored in the works of Michael Polanyi. Polanyi began his investigation of human knowledge starting from the statement 'we know more than we can tell.' He compared this type of knowledge to the recognition of a face in a crowd; we can recognise a face but are unable to tell 'how' we recognise it (Polanyi 1966).

Polanyi advocates that it is tacit knowledge that comes to the fore in the application of a skill. He writes that tacit knowledge can be divided into two terms: the proximal and the distal. The distal term is the symptom of the knowledge; the part that we can know and describe. The proximal term precedes the distal, however, this is the part that is difficult to describe. Despite this, we are aware of its existence, as it is through our 'awareness' of it that the action is triggered (Polanyi 1966). Relating this to the application of a practical skill, particularly to the manipulation of materials, the proximal term can be understood as the hunch, conceived from prior experience, which guides the decisions or physical actions of the maker.

Tacit knowledge of textile materials held by the researcher was acquired whilst studying textile design at BA and MA level and specifically relates to the manipulation of stretchy materials using industrial knit and screen-printing technologies (See Preface, p.11). Existing knowledge of textile materials has been developed not through reading about their properties, but through physically working with them and manipulating them by hand. Through experience of working with textile materials by hand it has become possible to predict, in certain situations, how the materials will be behave; or at least, have a hunch about how they might behave. This prior knowledge and sensibility to textile materials has proved invaluable, opening up increasingly interesting leads for investigation. Implicit knowledge informed some of the early decisions that were made during the 'project scoping' phase of this research and, specifically made it possible to identify the unique behaviour of stretchy fabrics when treated with ultrasonic welding equipment (See chapter section 3.2.2.2).

Tacit knowledge developed through hands-on interaction with materials has been recognised within the literature as an asset of the craftsperson that is advantageous when interacting with new technologies.

> 'It is not craft as handcraft that defines contemporary craftsmanship: it is craft as knowledge that empowers a maker to take charge of technology' (Dormer 1997a, p.140).

2.2.2.1.1 Tacit knowledge in a research context

Tacit knowledge has only in recent decades been recognised within the field of academic research. Following the merging of traditional redbrick universities with polytechnic institutions in 1992 there was a call for practice-led methods, that acknowledge tacit knowledge in their approach, to be more widely recognised (Press 2007).

The often intuitive nature of the practice-led design process can be difficult to articulate and communicate. However, a prerequisite for academic research is that methods must be made explicit, so that the research can be fully understood and, if necessary, repeated by others. Following this call for increased acceptance of practice-led methods, there has been much discussion, and some disagreement, within the academic sphere over how to make this research more widely accessible (Biggs, Buchler 2007, Scrivener 2002).

It has been suggested that there should be a reconsideration of research requirements specifically related to practice-led design research and outcomes, as the insights gained cannot be compared with absolute knowledge obtained using traditional scientific methods (Scrivener 2002). However, there has also been the suggestion that if practice-led design research outcomes are to be valued equally to those produced in other subjects then they should be judged against the same criteria (Biggs, Buchler 2007). If practice-led design research is to be considered of equal value to the research produced in other areas, such as the sciences, it has been suggested that the methodological approach taken needs to become more rigorous (Biggs, Buchler 2007). However, there has been some criticism of this; as, if rigour is taken to refer to a rigid and inflexible framework, this would be in direct conflict with the iterative opportunistic stance that is typical of the design process (Scrivener 2002).

The following sub-section of this chapter will describe the strategy of reflective practice that provides a flexible structured approach for practice-led researchers.

2.2.2.2 Reflective practice

Donald Schon believed that practice-led research should be valued equally to research carried out in traditional academic fields and developed the concept of reflective-practice as a strategy for practice-led researchers to enhance the academic rigour of their inquiries.

In Schon's book 'The Reflective Practitioner' an analogy of an architectural student in conversation with their tutor is used as an illustration specifically relating to the design process. Ideas are developed through conversation and mapped out through a system of drawing. Schon advocates that reflection of action in the design process should take place both 'in' and 'on' action:

> 'If they are good designers, they will reflect in action on the situations back-talk, shifting stance as they do from 'what if?' to recognition of implications, from involvement in the unit to consideration of the total, and from exploration to commitment' (Schon 1983, p103).

Working in this way, thoroughly integrating reflection both during and after practice, Schon advocates a generative design approach that develops like a conversation; where the situation or problem to be solved becomes increasingly clear over time (Schon 1983). Reflective-practice is widely employed by practice-led researchers within the design field:

> 'If the maker scrutinizes and assess their actions as they make this can advance the practice as they can respond rapidly to insights gained

whilst making and amend their actions as necessary' (Philpott 2013, p.9).

Action research was first developed in the UK in the 1950's as a framework for the teaching profession, and was unique in the way that it placed practice as the generator of new theory. Crouch and Pearce describe the principles of the Action research framework in their book 'Doing Research in Design': reflection is implemented to reframe situations and present new ways of moving forward. This action inspiring method of reflection is referred to as reflexivity (Crouch, Pearce 2012). The methodology is split into a five stage repeating cycle of: observe, reflect, act, evaluate and modify. The cyclical nature of the framework, although not originally intended for use by designers, has much in common with the design process (McNiff, Whiteread 2005).

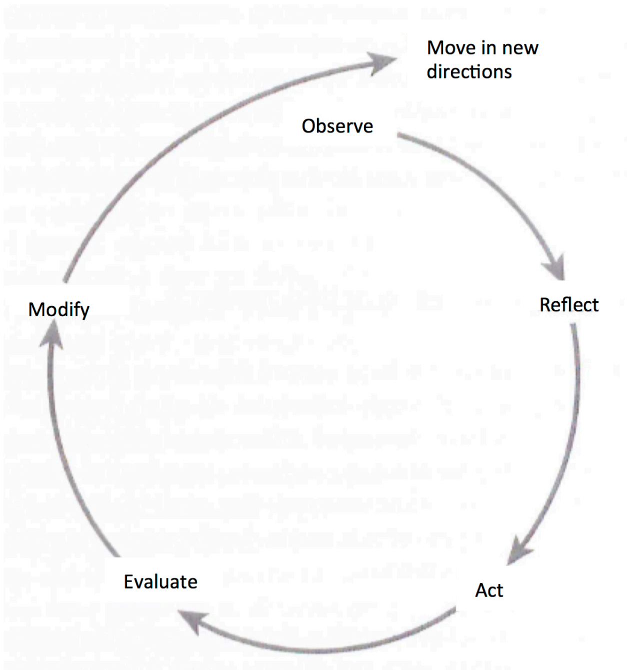


Figure 2.4 Illustration of an action-reflection cycle (McNiff, Whiteread 2005, p 9)

A hypothesis for investigation is not drawn up in advance following an Action research approach. The research is undertaken in response to a particular problem and a solution is sought through repeating cycles of action and reflection. This methodological approach can appear to lack structure as research methods are selected as and when they are appropriate. McNiff has referred to this approach as a 'spiral' of research as there is no pre-defined point of closure and research cycles follow on from one another in a spiral-like generative fashion with the acquisition of new insights (McNiff, Whiteread 2005).

Knowledge generated following this approach is called a 'living theory' and must be reported systematically to enhance wider academic understanding. It is encouraged that practice-led design researchers find methods to record and visualise their research processes to enhance comprehension and academic validity (Gray, Malins 2004).

> 'The representation of problems and solutions in words and sketches (sometimes using quite sophisticated visualisation techniques) is important because it allows the designer to develop their ideas in conversation with their representation' (Dorst 2010, p.133).

Specific methods for recording practice have been utilised within this research whist adopting a 'craft-design' approach. Taking a systemic approach, plans of action have been drawn out in advance and intermitted with periods of reflection. Methods were employed to keep track of reflective insights during practice: spec-sheets were pre-prepared so that observations for each sample could be recorded; and photographs were taken, documenting practical developments as they occurred. These physical records of practice, along with the material samples, were reflected upon after action both individually and through discussions with Speedo and with academic and industrial supervisors to assist in defining subsequent stages of research.

Figure 2.5 Sketchbook page showing laser welded sample with accompanying spec sheet (Paine 2014)

Alongside the development and interpretation of structured research strategies for practice-led design researchers, there has been a growing interest in the advantage of integrating tacit knowledge within scientific contexts, which is particularly relevant to this research.

2.2.2.3 Creative leaps in knowledge

The way designers think has been explored by Cross and Pearce in their book 'Research in Design' (Crouch, Pearce 2012). It is the designer's tendency to think abductively that allows them to come up with inventive ideas (Crouch, Pearce 2012). Abductive thinking can be more familiarly understood as intuition. Crouch and Pearce describe tacit knowledge as 'the engine that drives abductive reasoning' and suggest that it is the designer's ability to bridge between practical and intellectual thoughts that enables them to come up with inventive solutions (Crouch, Pearce 2012, p37). A paper by Chris Rust, considers the advantage of embedded tacit knowledge held by designers in the development of new scientific inventions:

> 'If the gap between our existing situation and the new world which we wish to inhabit is made wider by our inability to conceive of what the world is like, that, I suggest, is where designers can help' (Rust 2004, p77).

This contributes to an understanding that a practical understanding of materials and an acknowledgement of tacit knowledge can be advantageous in seeking increasingly novel outcomes; and supports the integration of a 'craft-design' approach within this research methodology.

A description of the separate 'craft-design' and 'scientific' approaches employed by this methodology has been provided. The following chapter section will describe the 'multi-strategy' framework that encompassed both approaches.

2.2.3 Multi-strategy methodologies

Multi-strategy approaches can be referred to in numerous ways and are listed in John Cresswell's book as 'integrating, synthesis, quantitative and qualitative methods, multi-method, and mixed methodology' (Cresswell 2009). The first comprehensive handbook of multi-strategy approaches was published in 2003 (Tashakkori, Teddlie 2003).

Multi-strategy methodologies use both quantitative and qualitative research methods. Quantitative research methods typically rely on the collection of numerical data. The analytical methods employed within a 'scientific' approach are typically quantitative. Qualitative research methods typically rely on the collection of non-numerical data such as words. The analytical methods employed within a 'craft-design' approach, which follows a constructivist paradigm of research, are typically qualitative. Historically these two approaches have been applied separately, however there is now a growing body of research that adopts both quantitative and qualitative methods within the same methodological framework (Gray, Malins 2004).

Multi-strategy approaches are often necessitated by the nature and questions of the research; for instance, when either a qualitative or quantitative approach would not generate sufficient information or data to answer the research questions. Colin Robson notes that this type of research is often carried out in the real world where the nature of research problems is complex and the main objective is not to extend an academic discipline (Robson 2011). Following a multi-strategy approach researchers are able to be increasingly flexible in their approach, allowing it to evolve in response to the research as it progresses (Robson 2011). The flexible nature of a multi-strategy approach is summmarised in the below quote:

> 'In these designs you don't have to foreclose on options about methods. Ideas for changing your approach may arise from your involvement and early data collection. Or, as you change or clarify the research questions, different means of data collection may be called for. Similarly, your sampling of who, where and what does not have to be decided in advance. Again, you need to start somewhere but the

> sampling strategy can and should evolve with other aspects of the design.' (Robson 2011, p133)

Multi-strategy approaches stem from a pragmatic research paradigm. Pragmatism is concerned with developing solutions and responding to actions. Methods are adopted in response to particular problems as the research progresses.

A pragmatic paradigm of inquiry was adopted for this research, whereby either a 'craft-design' or 'scientific' approach was adopted in response to new insights. The literature on 'multi-strategy' approaches has mostly targeted researchers in the field of humanities. However, these approaches are widely implemented by researchers in the field of design (Gray, Malins 2004).

2.2.3.1 Multi-strategy approach to design research

The use of two or more methods is widely referred to as 'triangulation' in the field of practice-led design research (Gray, Malins 2004). Research outcomes realised using triangulated methods can be considered to be more rigorous as they have been analysed from multiple perspectives. This is supported by the below quote from Gray and Malin's book Visualising Research:

> 'the more information we have from varying perspectives, the more able we are to test our ideas. The different views either corroborate or refute our original proposition or hunch, thus making our research more rigorous and robust. Using several complementary methods is more likely to yield a more significant, critical and holistic view than any single method alone.' (Gray, Malins 2004, p.31)

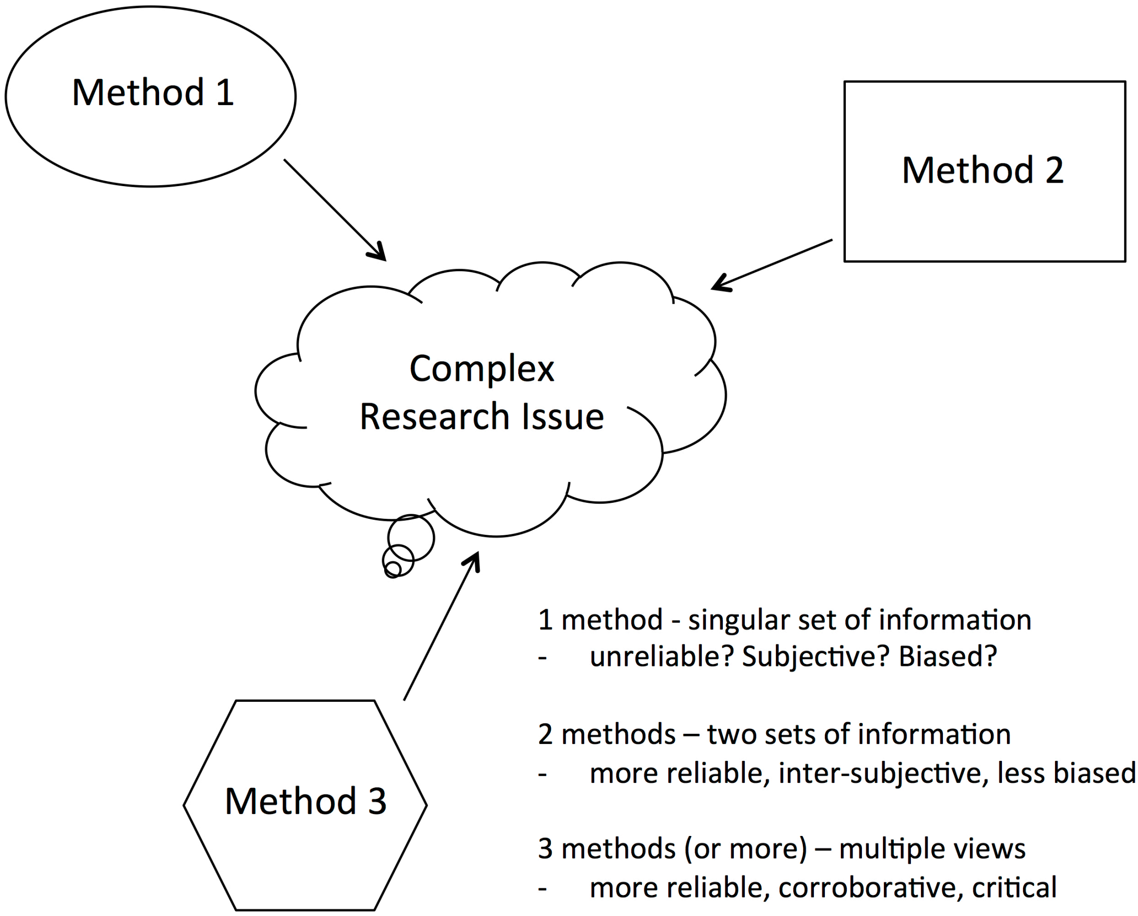


Figure 2.6 Illustration of 'triangulation' (Gray, Malins 2004, p 31)

Since the industrial revolution the role of the craftsperson has been under threat as hand-made methods of production were replaced by machine. In an increasingly digital age there continues to be concern surrounding the future of craft skill and knowledge. However, Mike Press has written about the evolving role of craft-knowledge when integrated within cross-disciplinary frameworks of research. Press writes:

> 'Their outcomes may not be "craft" in the conventional sense, but the processes they apply in solving the very diverse problems and contexts they are working within derive from the knowledge, methods and philosophies of craft' (Press 2007, p261).

Craft practitioners, it has been recognised, can often have quite an insular way of working, however, this 'inwardlookingness' is increasingly being challenged when craft practices are integrated within more formal cross-disciplinary frameworks of research (Rees 1997). With reference to research specifically relating to textiles, the recently completed doctoral projects by Faith Kane (2007), Rachel Philpott (2011) and Kate Goldsworthy (2012) have all contributed to this growing body of cross-disciplinary research.

2.2.3.2 A sequential exploratory strategy

Cresswell and colleagues have defined six different types of multi-strategy approach by analysing four distinguishing features: timing, weighting, mixing, and theorizing or transforming perspectives. 'Timing' refers to the order in which qualitative and quantitative methods are generally applied or whether they are used concurrently throughout the research. 'Weighting' is used to indicate whether precedence is given to a particular methodological approach, either quantitative or qualitative. 'Mixing' refers to the way that data sets are combined from the two approaches. For instance, 'mixing' is described as 'connected' if either a qualitative or quantitative research method leads to a subsequent study using the opposite approach. Theorizing relates to the application of a broader theoretical perspective that could influence the research (Cresswell 2009).

Timing	*Weighting*	*Mixing*	*Theorizing*
No sequence Concurrent	Equal	Integrating	Explicit
Sequential Qualitative first	Qualitative	Connecting	
Sequential Quantitative first	Quantitative	Embedding	Implicit

Figure 2.7 Table showing varying aspects of a 'multi-strategy' research approach (Cresswell 2009, p.207)

Since the completion of the research a project map has been drawn. This map demonstrates when during the research trajectory either a 'craft-design' (qualitative) or 'scientific' (quantitative) approach was applied and provides insight that has helped to further define the overarching 'multi-strategy' methodology. The map lists the three main practical studies in the left hand column. Each study is divided into two sub-studies and the approach for each applied method (either 'craft-design' or 'scientific') is indicated in the sequence that they occurred. Qualitative methods relating to a 'craft-design' approach were: structured material investigation; market review; experimental sampling; discussion with industry and prototype development. Quantitative methods employed whilst using a 'scientific' approach were: microscopic analysis; mechanical testing; 3D body scanning and pressure testing. Full descriptions of each of these methods and specific examples of where they were employed by the research can be found in chapter section 2.3.

Study	Sub-study	Methods	
Project scoping 3	Preliminary ultrasonic study (3.2)	Structured material investigation (3.2.2)	
		Microscopic analysis (3.2.2.2.1)	
		Market review (3.2.3)	
		Experimental sampling (3.2.4)	
	Stretch seaming and surface investigation (3.3)	Experimental sampling (3.3.2 & 3.3.3)	2 Initial Hypotheses
		Discussion with industry (3.3.4)	
		Mechanical testing (3.3.5)	
4 Literature Review			Research Gap 1
Surface modification I 5	Methods of controlling the level of melted material (5.2)	Structured material investigation (5.2)	Research Gap 2 Main Hypothesis
	Testing the mechanical effects of melted material (5.3)	Mechanical testing (5.3)	
Surface modification II 6	Testing insights identified during Surface modification I (6.2)	Mechanical testing (6.2.1 & 6.2.2)	
		Microscopic analysis (6.2.2.3)	
	Compression validation (6.3)	Prototype development (6.3.2)	
		Discussion with industry (6.3.2.2)	
		3D body scanning (6.3.3.1)	
		Pressure testing (6.3.3.2)	

Key

(green)	Scientific approach (quantitative methods)
(pink)	Craft-design approach (qualitative methods)

Figure 2.8 Project map showing breakdown of studies; sub-studies; methods and approaches with key milestones (author's own)

On review of the project map it is possible to see how the research oscillated between a 'craft-design' and 'scientific' approach; indicated by the alternating colours in the methods column. During the 'project scoping' phase (3) leads for investigation were mostly sought through the adoption of a 'craft-design' approach using qualitative methods, specifically experimental and structured material investigation were used to generate ideas and reflection on material samples was applied to make judgments on opportunities for development. An interest in joining stretchy fabrics developed following the identification of a unique aesthetic effect on the fabric (3.2.2) and a market review of methods for joining stretchy fabrics in the sportswear sector where stretchy fabrics are widely applied was carried out (3.2.3). On reflection of material samples and insights from the market review, 2 initial hypotheses were identified at the end of the 'preliminary ultrasonic study' (3.2). These 2 initial hypotheses were developed through further experimental sampling (3.3.2 and 3.3.3) and interest from industry in techniques developed using laser welding equipment was identified through a discussion with Speedo (3.3.4).

A 'scientific' approach using quantitative methods was applied during the 'project scoping' phase in an exploratory way by the researcher, as the advantages of such an approach were largely unfamiliar during this early stage of the investigation (2.1.2). Microscopic analysis was used to analyse the effect of welding on stretchy fabrics at the fibre level (3.2.2.2.1). Mechanical testing was used to compare the strength of laser welded seams in comparison to existing industry applied techniques (3.3.5). The strength of laser welded seams was not comparable to existing methods applied by Speedo, which terminated this particular line of enquiry. However, a new opportunity to use TLW equipment to create all-over surface patterns to control the elastic behaviour of stretchy textiles for a compressive effect on the body had been identified through the earlier discussion with Speedo (3.3.4). From this insight Research Gap 1 was identified at the end of the 'project scoping' phase in the field of TLW: to use the equipment as a method of controlling the elastic behaviour of stretchy fabrics for a compressive effect on the body. A subsequent Literature review (4.3 and 4.4) on methods for shaping the body assisted in identifying Research Gap 2 in the field of compression apparel: to create a variable compressive effect to the body across a single layer of fabric. The main hypothesis for the research **Laser melted patterns can be used to control the elastic behaviour of stretch textiles to have a targeted and variable compressive effect on the body** was developed as a result of these cumulative insights from the fields of TLW and compression apparel.

The main bulk of the investigation following the identification of the main hypothesis (indicated in grey on the project map) applied a predominant 'scientific' approach. 'Surface modification I' (5) began with a period of structured material investigation (5.2) used to define process parameters that could be used to control the level of melting to the fabric. Subsequent methods were mostly quantitative, collecting data to measure the effect of the level of melting on the elastic behaviour of the fabric and compression of the body (5.3; 6.2.1; 6.2.2; 6.2.2.3; 6.3.3.1; 6.3.3.2). A 'craft-design' approach was only returned to for the development and production of prototypes for testing (6.3.3 and 6.3.2.2).

Through an analysis of the project map it has been possible to identify that the research can be broadly segregated into two distinct phases: 'project scoping' and 'surface modification I and II'. A 'craft-design' approach (qualitative) was predominant during the 'project scoping' phase, which is indicated on the project map by a purple colour fill on the methods applied. A 'scientific' approach (quantitative) was predominant during 'surface modification I and II', which is indicated on the project map by a green colour fill on the methods applied. Interesting leads for investigation that had been identified during the 'project scoping' phase using a 'craft-design' approach were tested using quantitative methods during 'surface modification I and II'. In this way quantitative methods were used to provide objective evidence for insights gained following a 'craft-design' approach. Although contributions of the research were proven using quantitative evidence, more weight has been placed in the first qualitative phases of the research that enabled their original identification.

On a review of the project map (Figure 2.8) in relation to Cresswell's six multi-strategy approaches (2.2.3.2) it has been possible to define the approach adopted by this research as a 'Sequential Exploratory Design'. An illustration of the three types of sequential research design as outlined by Cresswell is shown in Figure 2.9. The distinguishing features of a 'Sequential Exploratory Design' are:

- A first phase of qualitative data collection is followed by a quantitative phase
- The quantitative phase of research builds on the insights gained during the qualitative stage
- More weight is generally placed on the first phase of research (qualitative)
- Data are mixed through being connected between the qualitative data analysis and quantitative data collection
- The design may or may not be implemented within an explicit theoretical perspective

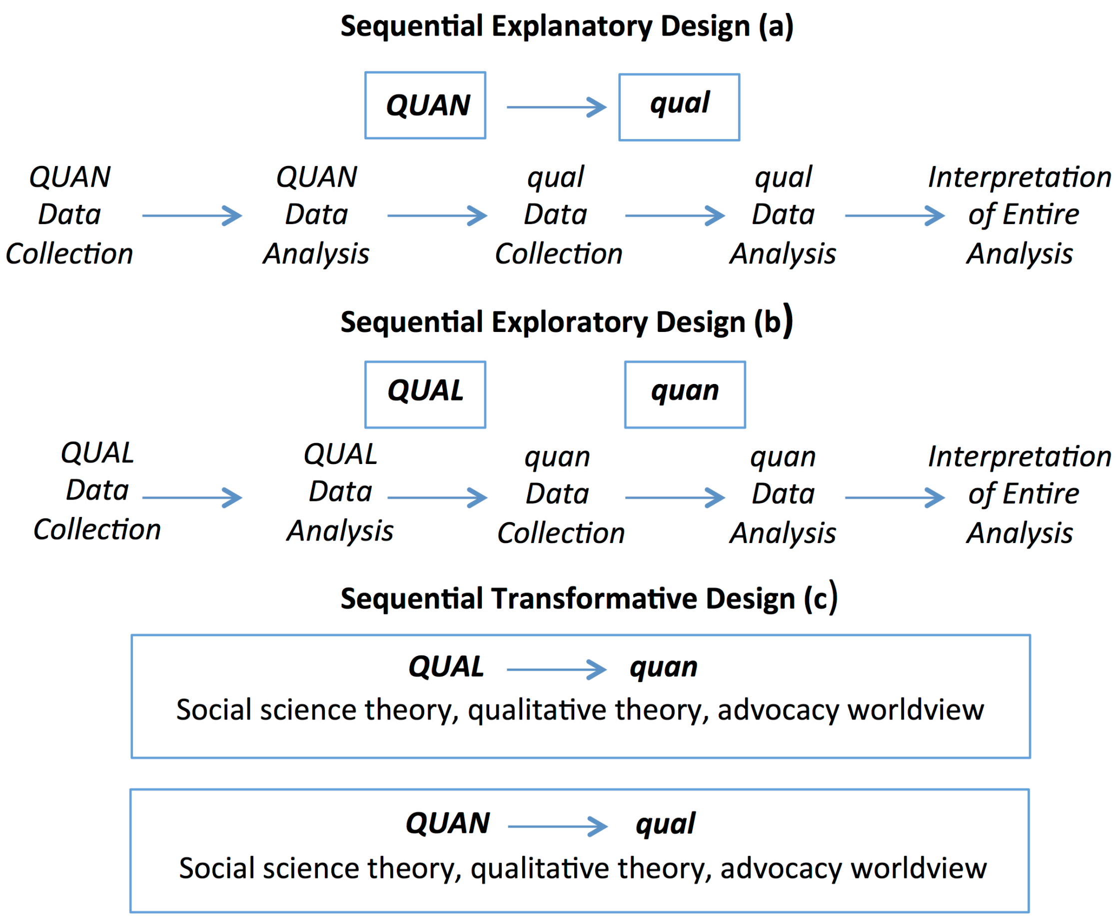


Figure 2.9 Illustration of possible three sequential multi-strategy designs as outlined by Cresswell (Cresswell 2009,p.209)

2.3 Methods

The preceding sections of this methodology chapter have focused on describing the overarching multi-strategy framework (Figure 2.3) and separate 'craft-design' and 'scientific' approaches that were adopted to tackle the research. This section focuses on describing the individual methods that were used within the separate approaches. A description of each method is provided with an example of how and where it was applied in the research. Refer back to the project map (Figure 2.8) for an overview of the sequence of approaches and methods applied throughout the research trajectory.

2.3.1 Scientific methods

As was established in chapter section 2.2.3.2, scientific methods were used throughout the research to gain quantifiable evidence for hypotheses developed whilst following a 'craft-design' approach. An understanding of this methodological pattern was gained in retrospect of the project work. During the investigation, research methods were selected pragmatically in response to new insights (2.2.3). This section provides a description and example from the research of each method that was employed whilst adopting a 'scientific' approach.

Mechanical testing

This method tested the tensile strength and/or elastic behaviour of textile samples and/or seams. Material samples for testing were prepared in advance. From each material sample to be tested three smaller samples were cut to specific dimensions stipulated by the relevant industry standard. Samples were placed in between metal grips and pulled at a controlled speed and force. Each of the three smaller samples was tested in succession and an average result was calculated.

The researcher prior to this investigation had not carried out mechanical testing of material samples. An understanding of mechanical testing was gained whilst working amongst employees and researchers at TWI from engineering and scientific fields. Material investigation undertaken using this method required enhanced structure and discipline compared to the more intuitive approach that was familiar to the researcher; and the benefit of such a structured approach was not clear at first. However, it soon became evident whilst using this method that hypotheses developed through a craft-design approach could be tested and proved empirically. Functional possibilities for material samples made during the researcher's MA and BA investigations had been imagined; however, mechanical testing presented the opportunity to develop concepts further and prove them empirically.

Example from research:

Mechanical testing was used to measure the effect of different process variables on the elastic behaviour of stretchy fabric during the second half of 'surface modification I' (See chapter section 5.3). This followed a period of structured material investigation utilising a 'craft-design' approach that had identified suitable process variables to test.

Microscopic analysis

Microscopic analysis involves the inspection of material samples at the micro level. Small sections of material samples were examined under a microscope and images were produced for further evaluation. SEM and stereograph microscopic equipment were used at different stages of the investigation with technical assistance from experts at TWI.

Microscopic equipment had not been introduced to the researcher whilst studying textile design at art and design institutions and the benefit of this approach was unknown prior to undertaking this investigation. Practical experience working with microscopic equipment at TWI revealed that mechanical defects to the fabric as a result of the welding process could be identified at the fibre level.

Example from research:

SEM equipment was used during the 'preliminary ultrasonic study' to investigate the wavy-three dimensional effect of ultrasonic welding equipment on stretchy fabrics (See chapter section 3.2.2.2.1). A stiffening effect to the fabric caused by the welding process was identified during a period of structured material investigation. Microscopic analysis revealed this was caused due to melting of material fibres.

3D body scanning

3D body scanning generates a scaled 3D image of the body. The person to be scanned must stand still for a period of time in a booth whilst the image is generated. Exact dimensions from multiple areas of the body were dissected from the images produced.

This method of analysis was introduced to the researcher by Speedo to measure the compressive effect of laser treated fabrics on the body. At this stage in the investigation the effect of the laser on the elastic behaviour of stretchy fabrics had been proved at a material level using mechanical testing. Further analysis using 3D body scanning equipment enabled an application for the technique to be demonstrated, specifically a method to apply controlled levels of compression to the body.

Example from research:

This method was used to test prototype swimsuits and quantify the compressive effect of laser treated textiles on the body (See chapter section 6.3.3.1).

Pressure testing

Pressure testing is a method of measuring the pressure exerted on the body by a garment. The equipment used is called a [redacted]

This method was introduced to the researcher by Speedo. It also enabled the collection of quantifiable evidence to test the compressive effect of the laser treated fabrics on the body.

Example from research:

Pressure testing was used to quantify the compressive effect of laser treated fabrics on the body during ‘surface modification II’ (See chapter section 6.3.3.2).

2.3.2 Craft-design methods

This research was undertaken with the adoption of a ‘craft-design’ approach (2.2.2). Adoption of a ‘craft-design’ approach conflicted with the original TWI brief that implied a scientific approach to the research should be taken. However, it was the belief of the researcher, having come from a background in textile design, that a practical exploration of the technologies that acknowledges the researcher's implicit knowledge of textile materials and processes would lead to increasingly insightful development opportunities (2.1.2). Through retrospective analysis of methods applied throughout the research trajectory it has been identified that a 'craft-design' approach was adopted predominantly at the beginning of the research (2.2.3.2) to develop hypotheses for investigation. This section provides a description and example from the research of each method that was employed whilst adopting a 'craft-design' approach.

Structured material investigation

This method was applied typically to develop further understanding of an insight that had been gained during a period of experimental sampling. An initial hypothesis had usually been conceived that needed further evidence in the form of material investigation. Using this method a detailed plan of the work to be carried was defined in advance, and specification sheets were drawn up to record variable settings and insights gained 'in action' (Schon 1983). Material samples were attached to their accompanying specification sheets and stored chronologically either in a sketchbook or ring binder. Insights gained were summarised in a list form and stored with the material samples.

The researcher prior to this investigation had used this method of working during their BA and MA qualifications to develop novel textile processes. During this research there was an enhanced necessity to make physical records of practice increasingly visible and understandable to others for the purpose of repeatability.

Example from research:

This method was applied during the first study of 'surface modification I' (See chapter section 5.2). The insight that laser melting had an effect on the elastic behaviour of stretchy textiles was identified during the 'project scoping' phase, however a period of structured material investigation was carried out to understand further the effect of individual process variables.

Experimental sampling

This is a method of 'playful' material investigation. The objective of this method was to discover interesting leads for further more structured research. Experimental sampling was carried out without the formation of a hypothesis. New insights were recorded as they occurred in a notebook. Material samples were stored in a sketchbook and typically grouped by aesthetic 'type'. Illustrative 'maps' were used to articulate the insights gained and share the research findings with others. Figure 2.10 is a map of techniques that was drafted during the 'project scoping' phase. A time frame for investigation, materials and equipment to be used were typically defined in advance of using this method.

Example from the research:

Experimental sampling was used during the 'preliminary ultrasonic study' to uncover opportunities for further more structured investigation (See chapter section 3.2.4). It was during this period of increasingly 'free' investigation that the opportunity to create all-over surface effects using equipment for seaming applications was first identified.

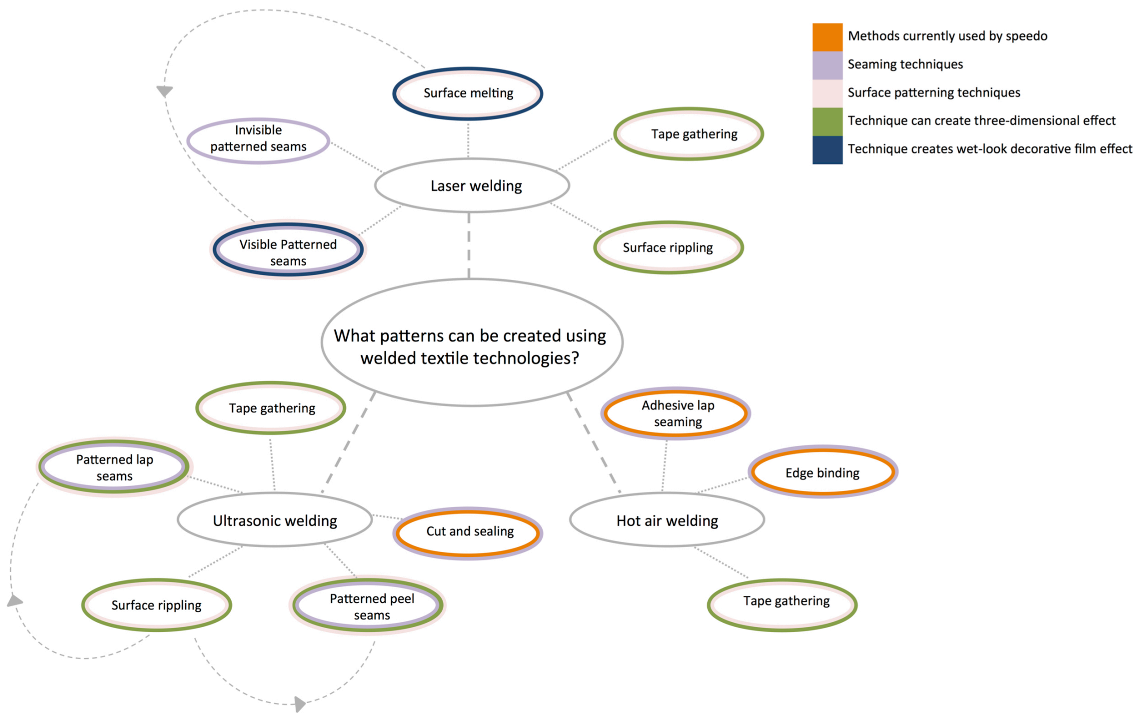


Figure 2.10 Illustrative map of techniques developed during 'project-scoping' phase (author's own)

Prototype development

This method was applied after a material solution or technique had been developed and an idea for a suitable application had been defined. The objective of the method was to test the suitability of a developed technique ‘in situ’ with a defined application. This method required collaboration with product manufacturers so that material samples were produced with reference to the required specifications, and manufacturing equipment/skills that were outside of the researcher’s areas of expertise could be accessed.

This prototyping method is widely used in the field of textile design to demonstrate potential applications for developed techniques and was familiar to the researcher prior to embarking on this investigation.

Example from research:

Prototype development was used to create a laser treated swimsuit during the ‘compression validation’ phase of the research (See chapter section 6.3.2).

Discussion with industry

‘Discussion with industry’ was a method used to critically reflect on material samples produced and identify possible areas for application. The objective of this method was to validate the research as it progressed ensuring that the work was of industrial interest. Discussions were recorded in notebooks and reflected upon before subsequent stages of action were taken.

This method of concept development can be compared to a design discussion with a university tutor, which was a familiar process to the researcher coming from a background in textile design. Material samples are reflected upon and ideas for their development and application are explored and tested collectively; often through lively discussion.

Example from research:

A discussion with Speedo during the ‘project scooping’ phase was used to analyse the material samples that had been developed using ultrasonic and laser technologies (See chapter section 3.3.4). It was during this discussion that the opportunity to apply all-over surface effects to control the elastic behaviour of stretchy fabrics for a compressive effect on the body was identified.

Market review

A market review, or 'comp shop' as it is often called in the clothing industry, is an assessment of similar products that currently exist in the market place. This activity can be carried out online but often involves visiting retail outlets for a closer inspection of products. The objective of this activity is to create awareness of contemporary trends to inform the subsequent phases of research. Using this method insights were recorded by taking photographs and making notes on site.

Example from research:

A market review of contemporary methods for joining stretchy fabrics was carried out during the 'project scoping' phase of the research (See chapter section 3.2.3). An opportunity to explore methods of welding that maintain material flexibility in the weld region was identified by this review.

2.4 Summary

This chapter has described the particular methodological approach applied to the research in response to a brief that had been written by TWI. <u>**The main points**</u> that characterise the adopted methodological approach are summarised below:

• A 'multi-strategy' framework that encompasses both 'scientific' and 'craft-design' approaches was applied to the research

• A 'craft-design' approach acknowledges the implicit knowledge of the researcher and uses practice-led methods of inquiry, which was considered beneficial when combined with the expected 'scientific' approach to develop increasingly inventive solutions and enhance capability in the field of textiles joining

• A pragmatic paradigm of inquiry was adopted for this research, whereby either a 'craft-design' or 'scientific' approach was adopted in response to new insights

• The broad sequence of methods applied throughout the research trajectory fits Cresswell's description of an 'exploratory sequential design' strategy, whereby quantitative methods are used to test insights gained through a preliminary qualitative phase

3 Project scoping

3.1 Introduction

The preliminary phase of investigation for this PhD research, which accounts for approximately the first 18 months of work, has retrospectively been called 'project scoping.' During this phase a research gap was sought primarily through the adoption of a craft-design approach although scientific methods were used occasionally. Industry was widely consulted throughout this 'project scoping' phase to assist in developing understanding of prior art (1.3 and 4.2); to gain an understanding of possible application opportunities for the techniques developed; and, to seek out an industry partner for the research.

For the purpose of summarising and articulating the insights gained from this phase the research has been divided into two broad umbrella studies, specifically 'preliminary ultrasonic study' and 'stretch seaming and surface investigation', which consist of a number of smaller investigative studies. Cumulative insights gained as a result of the 'preliminary ultrasonic study' led to the development of two initial hypotheses, which were addressed in the subsequent 'stretch seaming and surfaces investigation'. At the end of the 'stretch seaming and surfaces investigation' the main technique for investigation by the research had been discovered, specifically a method of controlling the elastic behaviour of stretch textiles using laser melted patterns. It was understood through a discussion with Speedo that this technique could be used to have a compressive effect on the body and streamline the silhouette for sportswear applications.

3.2 Preliminary ultrasonic study

This study groups together three smaller investigative studies, specifically a material compatibility study, a sportswear market review of methods for joining stretchy textiles, and a practice-led investigative study. A summary of the research carried out for each of these small investigative studies and the key insights gained leading to the formation of two initial hypotheses that are addressed by the subsequent 'stretch seaming and surfaces investigation' are provided by the following subsections of this chapter.

3.2.1 Equipment

A PFAFF 8304-081 continuous ultrasonic welding machine and a LEO 1550 field emission gun scanning electron microscope were used for this investigation. Both pieces of equipment were accessed from TWI's premises.

3.2.2 Compatibility investigation

It was understood from the TWI brief that there was an interest in exploring the compatibility of different textile materials using a range of joining technologies. A preliminary study was set up to explore the compatibility of 15 different textile materials constructed from various structures, including knitted, woven and non-woven; and fibre types, including natural and synthetic. The majority of textile materials selected contained a high proportion of synthetic fibres, which are thermoplastic and have an ability to melt and reform upon cooling: a characteristic that is essential for the welding process.

An understanding of how to structure this empirical experiment was gained from an industry report that tested the compatibility of various rigid polymers (Devine 1998). Rectangular samples approximately the size of an A6 piece of paper, of each textile material, were cut and joined together using a PFAFF 8304-082 continuous ultrasonic welding machine. Machine parameters were explored for each material combination so that a weld could be formed. Parameter settings were not recorded at this early stage of investigation when seeking novel opportunities for investigation. A more rigorous approach to recording machine parameters was adopted when exploring specific techniques as the research progressed. Material compatibility was assessed manually by applying a moderate level of force. Each sample was categorised depending on the strength of the weld produced. Blue was used to denote a high level of compatibility for welds that showed good resistance to the manual test; red indicated a moderate level of compatibility; and pink indicated that it was not possible to form a weld. The colour awarded for each material combination was plotted in a table (Table 3.1)

Material	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 PE	High	Poor	Poor	Moderate	High	Poor	High	Poor	High	Poor	Poor	Poor	Poor	Poor	High
2 Cotton | nylon | PU		High	High	High	Moderate	High	High	Moderate	High	High	Moderate	Moderate	Poor	Moderate	High
3 PVC | latex			High	High	Moderate	Moderate	High	Moderate	Moderate	Moderate	Moderate	Moderate	Poor	High	High
4 PVC | cotton				High	High	Moderate	High	Moderate	Moderate	Moderate	Moderate	Moderate	High	High	High
5 Polyester | viscose | elastane					High	Moderate	High	High	High	High	High	High	High	High	High
6 Nylon | elastane						High	Moderate	Moderate	Moderate	High	Moderate	Moderate	Poor	Moderate	Poor
7 Nylon							High	High	High	High	Moderate	High	High	High	High
8 Linen | PU								High	High	High	Moderate	High	High	Moderate	High
9 Polyester | elastane									High	High	Poor	High	High	Moderate	High
10 Polyester | nylon | cotton | elastane										High	Moderate	High	High	Moderate	High
11 Nylon tulle											High	High	Moderate	Moderate	Moderate
12 Polyester | nylon | elastane												High	High	Moderate	High
13 Woven polyester													High	Moderate	High
14 PVC | polyester														High	High
15 Fleece polyester															High

Table 3.1 Table showing level of material compatibility for a variety of textile materials joined using continuous ultrasonic welding equipment

Key

- (light blue) High compatibility
- (red) Moderate compatibility
- (pink) Poor compatibility

At this early stage of the research a scientific approach was adopted to fulfill the industry driven requirements of the TWI brief; however, interesting or unusual aesthetic effects identified by the researcher were logged for further investigation.

3.2.2.1 Insights gained through a scientific approach relating to material compatibility

Knowledge relating to material compatibility had first been gauged through a review of the technical literature on textiles welding and was reaffirmed through this practical investigation. The main insights were:

- Like materials form stronger bonds than dissimilar materials

- Materials with a smooth surface finish form stronger bonds than materials with a rough surface finish

- Materials containing a mixture of different fibre types generally form weaker bonds than materials made from single thermoplastic fibre types

3.2.2.2 Insights gained through a craft-design approach relating to unique aesthetic effects

Through the concurrent adoption of a craft-design approach increasingly novel insights were made that had not been identified through a review of the technical literature on textiles welding. The researcher made an intuitive evaluation of the physical appearance and handle of welded samples as unique opportunities for investigation were sought, calling upon tacit knowledge developed from previous practical experience working with textiles. A stiffening effect was noted for most material types following the welding process. This effect was particularly intriguing when applied to stretchy fabrics, as the elastic properties of the fabric were restricted in the weld region. Through consultation with industry experts at TWI it was understood that stretchy fabrics are largely unsuitable for welding due to the detrimental effect on the elastic properties of the fabric; however, this unusual change of behaviour indicated to the researcher a unique opportunity for investigation. There was also an interest from the researcher in the visual appearance of the welded region of the stretchy fabric. It was observed that stretchy fabrics assume a wavy three-dimensional surface aesthetic once welded, which was unlike any effect achieved using known seaming or surfacing techniques for textiles. (See Figure 3.7)

Through a reflective analysis of the samples as they were welded it was possible to call upon tacit knowledge developed from previous practical experience working with textiles to identify this novel opportunity for investigation. A scientific approach using scanning electron microscopy equipment to investigate this unusual effect of the welding process on stretchy fabrics was suggested by TWI.

3.2.2.2.1 SEM investigation

An investigation of the wavy three-dimensional effect recognised during the compatibility study was carried out with assistance from technical experts at TWI. This empirical investigation was carried out speculatively without any previous experience working with microscopic equipment.

A non-welded textile sample was examined and compared with two welded samples: one produced at a high speed, and one produced at a low speed. The examined textile material was made from 87% nylon and 13% Lycra. The images reveal that only the nylon fibres are melted as a result of the welding process and the amount of melted material increases at a reduced welding speed. Further to this, the structure of the nylon fibres is completely destroyed. Individual fibres are melted together to form a pool of molten material that has an appearance similar to a polymer film (See Figures 3.1 to 3.3). An understanding of the restrictive effect the welding process has on the elastic properties of stretchy fabrics was gained from reflecting on the change in the handle of the material, however further insight into the locking effect on the material at a fibre level was understood through this empirical microscopic investigation.

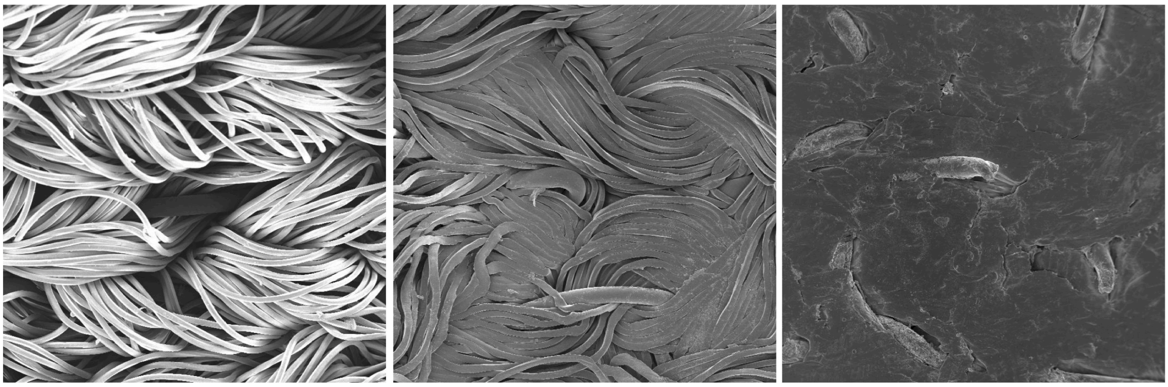


Figure 3.1 (Left) SEM image of an unwelded sample of stretchy jersey fabric (TWI 2012)
Figure 3.2 (Centre) SEM image of a sample of stretchy jersey fabric welded at high speed (TWI 2012)
Figure 3.3 (Right) SEM image of a sample of stretchy jersey fabric welded at slow speed (TWI 2012)

Throughout the 'project scoping' phase a suitable industry partner was sought in response to the requirement for industrial validation that was stipulated by the TWI brief. The sportswear industry was identified as a suitable target market for the research, having identified an interest in welding stretchy jersey fabrics that are commonly used for the construction of sports clothing. In anticipation of positioning the research within the sportswear sector, a review of commercially applied methods of joining stretchy sportswear garments was carried out.

3.2.3 Review of methods for joining stretchy fabrics

In order to gain an understanding of existing methods used for joining stretchy fabrics in the sportswear sector a review of the technical literature and consultation with industry experts in textiles joining was supported by a market review carried out by visiting a range of sports retailers across market levels. This practical method of investigation allowed the researcher to gain a tactile understanding of existing techniques, which was considered advantageous to a review of the literature alone in developing a personal connection with the work that might assist in the development of increasingly insightful solution concepts.

Through this review it was understood that either traditional stitched or advanced adhesive methods are used to join stretchy fabrics. Over-locking and flat-locking are multiple loop stitch types that have been developed specifically for joining stretchy fabrics (Hayes, Mcloughlin 2013). These stitch types are formed with longer lengths of loose thread that enable the seam to stretch with the fabric (Mukhopadhyay, Midha 2013), which prevents mechanical locking observed as a result of the welding process. Adhesives used for advanced methods of joining have also been specially developed to stretch with the fabric so that the elastic properties are minimally affected across the seam region to prevent premature breakage. Fabric tapes that are backed with adhesive are applied across welded or stitched seams for reinforcement; or double sided adhesive tapes can be used to join fabrics in a lap joint configuration.

Through this sportswear market review an understanding of opportunities for development was also gained. There is an interest in the sportswear industry to reduce the number of processing steps in the manufacture of stretch textile seams joined using adhesives. Current methods frequently consist of two or more processing steps, which increase manufacturing time and cost. This demand for a reduction in processing steps supports further investigation into welding technologies, which could offer a one step alternative to existing adhesive methods. There is also a growing prominence of seamless manufacturing methods used for the production of sports apparel. Garments are knitted in one piece and shaping can be incorporated within the structure of the fabric, using specialist moulding or knitting technologies.

Practice-led investigation on the ultrasonic welding machine was ongoing throughout the preliminary stage of the 'project scoping' phase. This next chapter section will explain how insights from the 'compatibility study' (3.2.2) and review of methods for joining stretchy fabrics (3.2.3) influenced concurrent practice-led investigations and report on the insights gained.

Figure 3.4 (Top) Sportswear garment seams joined using traditional stitched methods (Paine 2013)
Figure 3.5 (Middle) Examples of sportswear items manufactured using seamless methods (Paine 2013)
Figure 3.6 (Bottom) Sportswear garment seams joined using advanced adhesive methods (Paine 2013)

3.2.4 Insights gained through practice-led investigation

An understanding that the welding process restricts the elastic properties of stretchy fabrics had been gained through the compatibility study (3.2.2); and commercial methods of joining and shaping stretchy fabrics, specifically looped stitch types and stretchy adhesives, which avoid mechanical locking had been identified through the sportswear market review (3.2.3). Concurrent practice-led investigations on the ultrasonic welding machine were influenced by these insights to develop new solutions for joining and shaping stretchy fabrics.

A technique was developed for creating stretchy seams by applying patterns in the weld area that break up the continuity of the weld-line. In continuous ultrasonic welding equipment the anvil is made from metal, and pulls the material through the machine applying pressure to assist in the formation of a weld. The anvil can be plain or engraved with a pattern to create a decorative effect. Anvils engraved with a pattern were applied to stretchy fabrics to break up the continuity of the weld line, thus retaining stretchy portions of fabrics that would reduce the effect of material locking in the weld region. It was found that the effect on the elastic properties of the fabric varied depending on the density of the engraving on the anvil's surface. Anvils with a higher density of engraving produced welds of increased elasticity as a reduced proportion of the fabric in the weld region is locked together by material melting.

A method of shaping stretchy fabrics from the two-dimensional lay-up of flat pieces was also developed that was influenced by techniques identified in the review of methods for joining stretchy fabrics (3.2.3), specifically moulding and seamless knitting technologies; and built on the insight gained from the compatibility study (3.2.2) that stretchy fabrics take on a wavy three-dimensional effect when welded. It was found that by applying the anvil repeatedly to the surface of a stretchy fabric in a linear motion an all-over surface rippled effect could be created, which demonstrated potential for the development of other three-dimensional effects.

The closing chapter section of this 'preliminary ultrasonic study' will summarise the insights that have been gained through the 'compatibility study' (3.2.2), 'review of methods for joining stretchy fabrics' (3.2.3) and practice-led investigation (3.2.4) that influenced the development of two initial hypotheses, which are addressed by the subsequent 'stretch seaming and surfaces investigation.'

Figure 3.7 Sketchbook pages from practice-led investigation using ultrasonic welding equipment (Paine 2013)

3.2.5 Hypotheses developed through cumulative insights for further investigation

<u>The main insights</u> gained throughout this 'preliminary ultrasonic study' are summarised below:

• Stretchy fabrics take on a wavy-three dimensional effect when welded using continuous ultrasonic welding equipment

• The elastic properties of stretchy fabrics are reduced by the welding process

• Commercial methods of joining stretchy fabrics in the sportswear sector have been developed to accommodate fabric stretch and avoid premature seam failure

• There is a desire to reduce processing steps for advanced adhesive methods of joining stretchy fabrics in the sportswear industry, which could reduce manufacturing time and cost

• New seamless technologies of manufacturing stretchy fabrics are being applied commercially, which are reducing the need for seams altogether

• Stretchy seams can be produced using continuous ultrasonic welding equipment by using a patterned anvil

• The elastic properties of the seam vary depending on the density of the patterned engraving on the anvil

• Three-dimensional surface effects can be achieved by welding across the surface of stretchy fabrics using continuous ultrasonic welding equipment

In review of these insights **two initial hypotheses** were developed:

• Weld pattern can be used to enhance the elasticity of welded textile seams

And

• The welding process can be used to shape stretchy textiles for the construction of three-dimensional products

These two initial hypotheses are investigated by the subsequent 'stretch seaming and surfaces investigation.'

3.3 Stretch seaming and surfaces investigation

This study set out to investigate two initial hypotheses identified by the 'preliminary ultrasonic study', specifically that *weld pattern can be used to enhance the elasticity of welded textile seams* and that *the welding process can be used to shape stretchy textiles for the construction of three-dimensional products*; with the aim of narrowing the project scope and building a hypothesis that would sustain the main bulk of the research. The primary phase of this study adopted a craft-design approach to extend opportunities for creating patterned seams and three-dimensional surfaces using ultrasonic and laser welding technologies. Discussion with industry and mechanical testing, were integrated during the latter stages of the study to narrow the scope of the investigation and develop the main hypothesis for the research. Following reflection on cumulative insights at the end of this study, the focus for the research shifted and a gap *to explore the effect of laser melted patterns on the elastic behaviour of stretchy textile materials* was identified, which is addressed by the main bulk of this PhD investigation.

3.3.1 Equipment and materials

A selection of nine commonly used swimwear fabrics supplied by Speedo, was included in the investigation. Details of each of the fabrics are provided in Table 3.2. Each of the materials was trialed for their compatibility with the technologies by creating preliminary welds, which were tested for strength by applying a moderate level of manual force.

A Pfaff 8310-042 continuous ultrasonic welding machine, made available to the research by Triumph Needle; and, a Laserline 150W diode laser made available to the research by TWI, was used for this study. A Tinius Olsen HK5-T UTM bench top-testing machine was made available by Speedo.

Fabric	Speedo range	Colour	Construction	Composition
A	Racing	blue	woven	80% nylon 20% elastane
B	Racing	black	woven	80% nylon 20% elastane
C	Lady's shaping	black	knitted	80% nylon 20% *Xlife Lycra*
D	Competitive	black	knitted	80% nylon 20% *Xlife Lycra*
E	Racing	black	woven	65% nylon 35% elastane
F	Competitive	black	knitted	100% polyester
G	Lady's shaping	black	knitted	73% nylon 27% *Xlife Lycra*
H	Racing	black	woven	70% Nylon 30% elastane
I	Lady's shaping	black	knitted	80% Nylon 20% *Xlife Lycra*

Table 3.2 Materials included in investigation

3.3.2 Investigation of ultrasonic welding equipment

During the primary phase of this investigation opportunities for creating patterned seams and three-dimensional surfaces were explored through the application of a craft-design approach. A description of the insights gained using continuous ultrasonic welding equipment relating to material compatibility and opportunities for creating patterned seams and three-dimensional surfaces are provided herein.

3.3.2.1 Insights relating to material compatibility

It was understood following the 'preliminary ultrasonic study' that most textile materials made from a high proportion of thermoplastic content are suitable for ultrasonic welding. All nine of the fabrics included in this investigation contained either a high proportion of nylon or polyester, which are both thermoplastic polymers. Each of the materials was joined to themselves and all of the welds created showed a reasonable level of resistance to a moderate degree of manual force. All nine fabrics were included in further investigations.

3.3.2.2 Identified opportunities for creating patterned seams

Having identified a method of creating patterned seams using ultrasonic welding equipment during the 'preliminary ultrasonic study', using differently patterned anvils to emboss the surface of the fabric; the methodological approach applied to this investigation was increasingly structured in its approach. Seven differently patterned anvils (Figure 3.10) were used to create welds on each of the nine selected swimwear fabrics. Welds were made in a lap and peel joint configuration. Fabrics joined in a lap joint configuration had an almost seamless appearance as the rippled surface effect disguised the overlap of the two separate layers (Figure 3.8). Fabrics joined in a peel joint configuration created a ruffled frill on the exterior of the fabric (Figure 3.9).

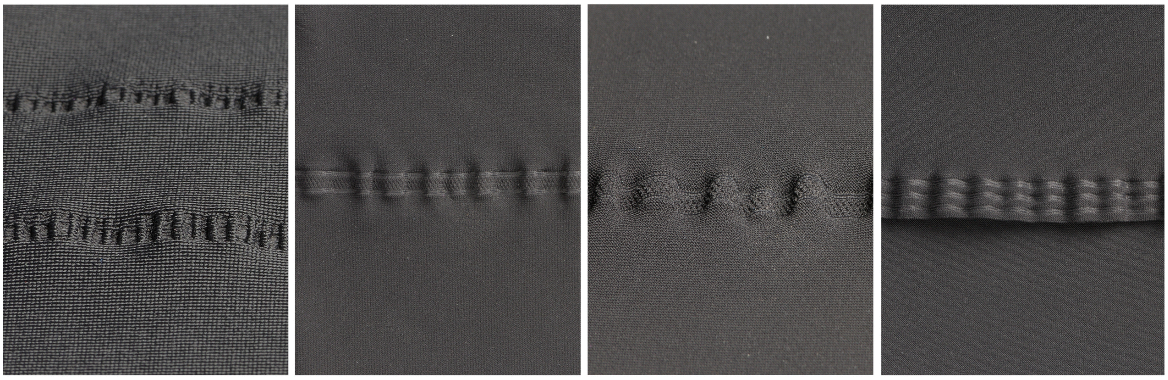


Figure 3.8 (Left, Centre Left and Centre Right) Examples of ultrasonic seams joined in a lap configuration using continuous ultrasonic welding equipment (Paine 2013)

Figure 3.9 (Right) Example of ultrasonic seam joined in a peel joint configuration using continuous ultrasonic welding equipment (Paine 2013)

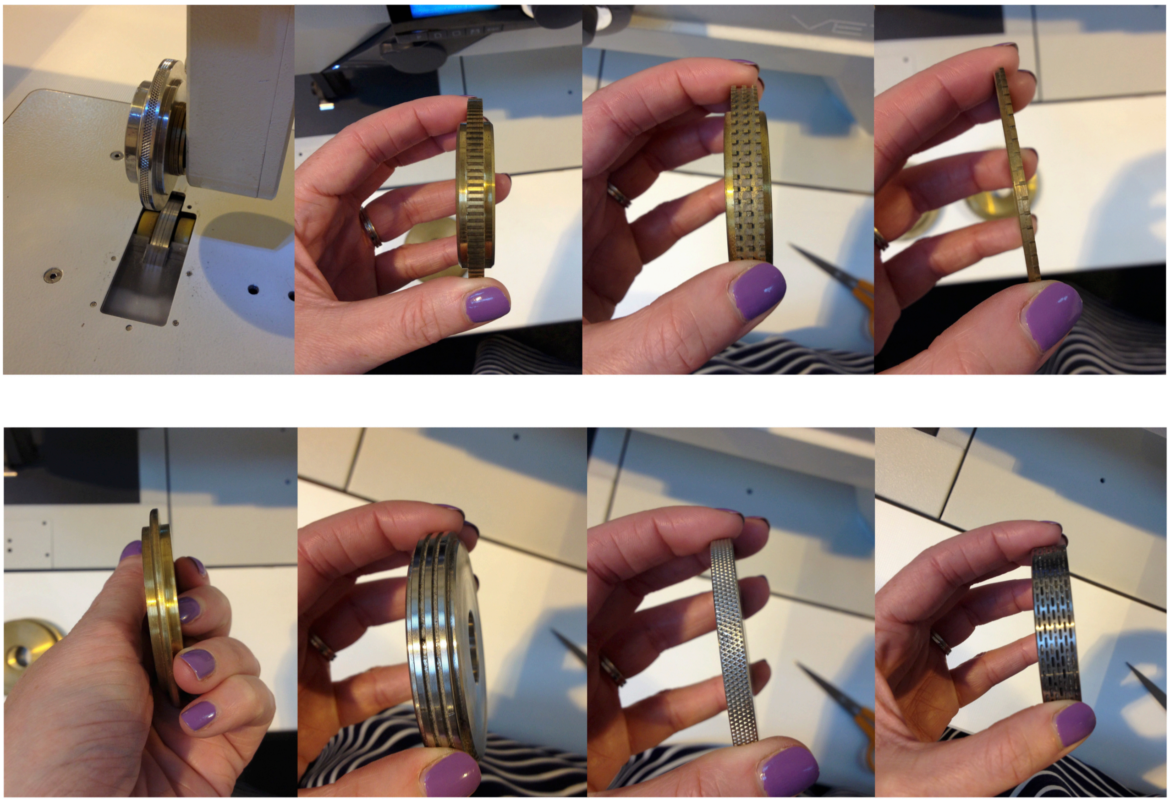


Figure 3.10 Patterned anvils from continuous ultrasonic welding machine used for seaming investigation (Paine 2013)

3.3.2.3 Identified opportunities for creating three-dimensional surfaces

An opportunity to create three-dimensional surface effects was first identified during the 'preliminary ultrasonic study'. It had been discovered that stretchy fabrics take on a wavy-three dimensional appearance when welded and that a rippled all-over surface effect could be created by repeatedly welding across the fabric in a linear motion. This effect can be applied to the surface of a single fabric layer or can be used to join two fabrics together and create a double-layered laminate (Figure 3.11). A further insight was gained during this study that engraving on the anvil can be used to vary the appearance of the weld produced by imprinting different patterns onto the surface of the fabric.

Polyurethane tape can also be used to create a three-dimensional surface effect. The tape is commercially known as Framillon and is widely used for the manufacture of straps in the apparel and lingerie industries. The tape is tensioned by hand as it is welded to a layer of fabric. Once the tension is released, after welding, the tape returns to its original dimensions and causes the fabric to gather on the surface and create an effect akin to ruching (Figure 3.12). This ruched effect retains its stretchiness after welding and can be repeatedly extended and released without breaking.

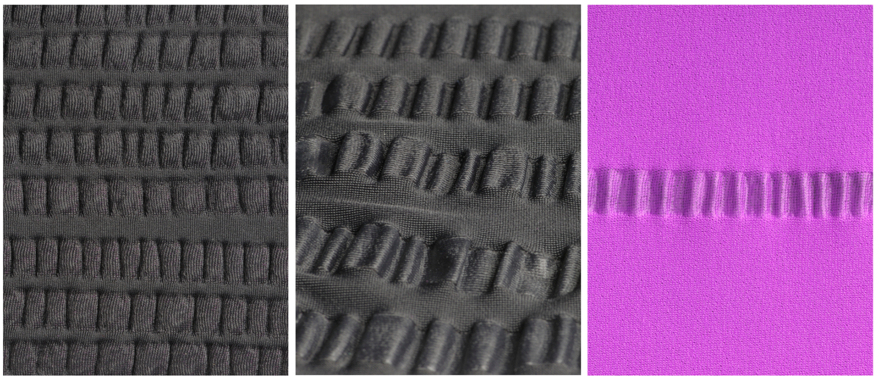


Figure 3.11 (Left, Centre Left, Centre Right) Fabric samples demonstrating all-over rippled surface effect created using ultrasonic welding equipment (Paine 2013)
Figure 3.12 (Right) Fabric sample demonstrating ruched effect created using polyurethane tape and ultrasonic welding equipment (Paine 2013)

3.3.3 Investigation of TLW equipment

Although some experience working with TLW equipment had been gained working on client work for TWI, it had not yet been investigated for this research. The methodological approach taken to explore this technology was comparatively opportunistic as an understanding of the potential novel effects was developed. A description of the insights gained relating to material compatibility; opportunities for creating patterned seams and three-dimensional surfaces are provided herein.

3.3.3.1 Insights relating to material compatibility

Material requirements for TLW are more complex than ultrasonic welding. As has already been explained materials must have a high thermoplastic content for welding so that they have an ability to melt and reform upon cooling; however materials used as the top layer for TLW must also be transparent to the near-infrared wavelength of the laser (Jones, Patil 2013). Various pigments and additives within the manufacture of a textile material affect its transparency to the laser and it is impossible to understand a material's compatibility with the process through handling alone. An empirical method for testing the transparency of materials was introduced at TWI using an energy meter. It is recommended that at least 20% of the laser energy needs to pass through the material for welding. This was true for two of the materials supplied by Speedo: a blue woven nylon/Lycra fabric (A), and a black knitted polyester fabric (F) (Table 3.3). All the other fabrics supplied by Speedo absorbed over 80% of the laser energy and were unsuitable as the top layer in the weld configuration.

Fabric	Colour	Proportion of energy transmitted (%)
A	blue	41.9
B	black	18
C	black	0
D	black	11.4
E	black	7.7
F	black	28.6
G	black	0
H	black	13.4
I	black	8.8

Table 3.3 Transmission levels of various fabrics supplied by Speedo

3.3.3.2 Identified opportunities for creating patterned seams

The recommended material lay-up for TLW is: two transparent layers with a laser absorbing dye applied discretely, by a spray application, at the interface (Jones, Patil 2013). This maintains the melt region at the interface of the joint so that the weld appears near to invisible from the exterior. This innovative process is called Clearweld and was developed by TWI (Jones, Patil 2013). Prior to the development of the Clearweld process TLW relied on the presence of conventional laser absorbing materials such as carbon black; however, the dark colour of the carbon black pigment limited opportunities for application (Jones, Patil 2013). The potential for the Clearweld process to replace existing methods for joining textile materials has been demonstrated across various products including general and waterproof clothing (Jones 2007) curtain airbags; balloon air ships (Rooks 2004) and vascular stent grafts (Jones, Patil 2013).

For this investigation there was an interest in exploring methods for creating patterned seams and exposing the weld line on the surface of the fabric. It was found that by varying the position of the laser absorbing dye, and also by combining absorbent fabrics within the material configuration, a variety of decorative effects could be achieved (See Figure 3.14).

Having identified methods for exposing the weld line on the surface of the fabric the next stage in the investigation was to develop seam patterns with the aim of breaking up the continuity of the weld line for enhanced elasticity. A practice-led approach was applied to develop systems for visualising the path of the laser beam, specifically attaching a pen to the laser head and placing carbon paper beneath the laser beam operated on a low power setting; to gain an understanding of the computer coding used to manipulate the moving x-y table beneath the laser head. This visual and practical way of developing understanding was preferential to the researcher over reading the manual on how to operate the system, so that a personal knowledge could be developed that might influence further practice-led investigation. Through this practical process of discovery an understanding of the system's software was gained that enabled a variety of patterned seam designs to be developed.

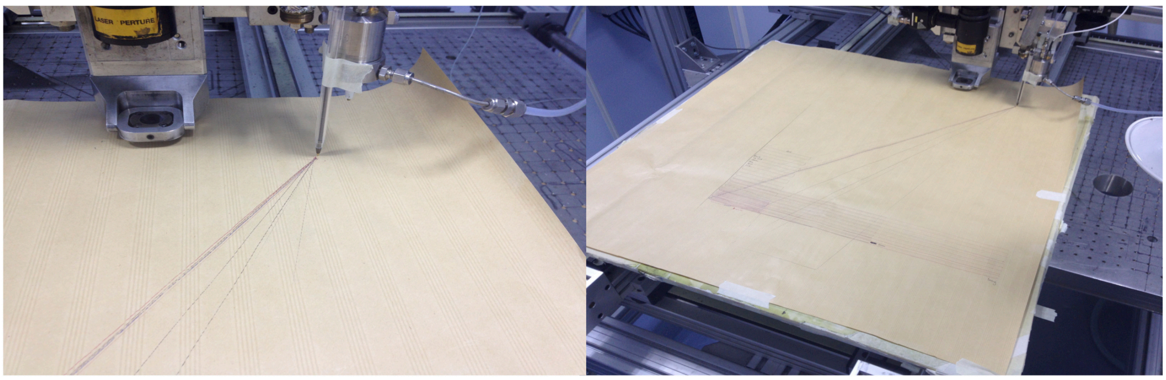


Figure 3.13 Pen attachment to TLW equipment at TWI used to assist in translating the code that moves the x-y table beneath the laser head (Paine 2013)

An additional method of creating a dashed seam design was also identified using the laser control pad. The laser can be operated using either a pulsed or continuous beam. Using a pulsed setting the laser blinks on and off during operation and a dashed effect is created on the fabric. The patterned seams developed included curved, linear and zig-zag designs and were inspired by those created using ultrasonic welding equipment so that a comparison between the two techniques could be made. The visual effect on the surface of the fabric was varied by altering material configuration.

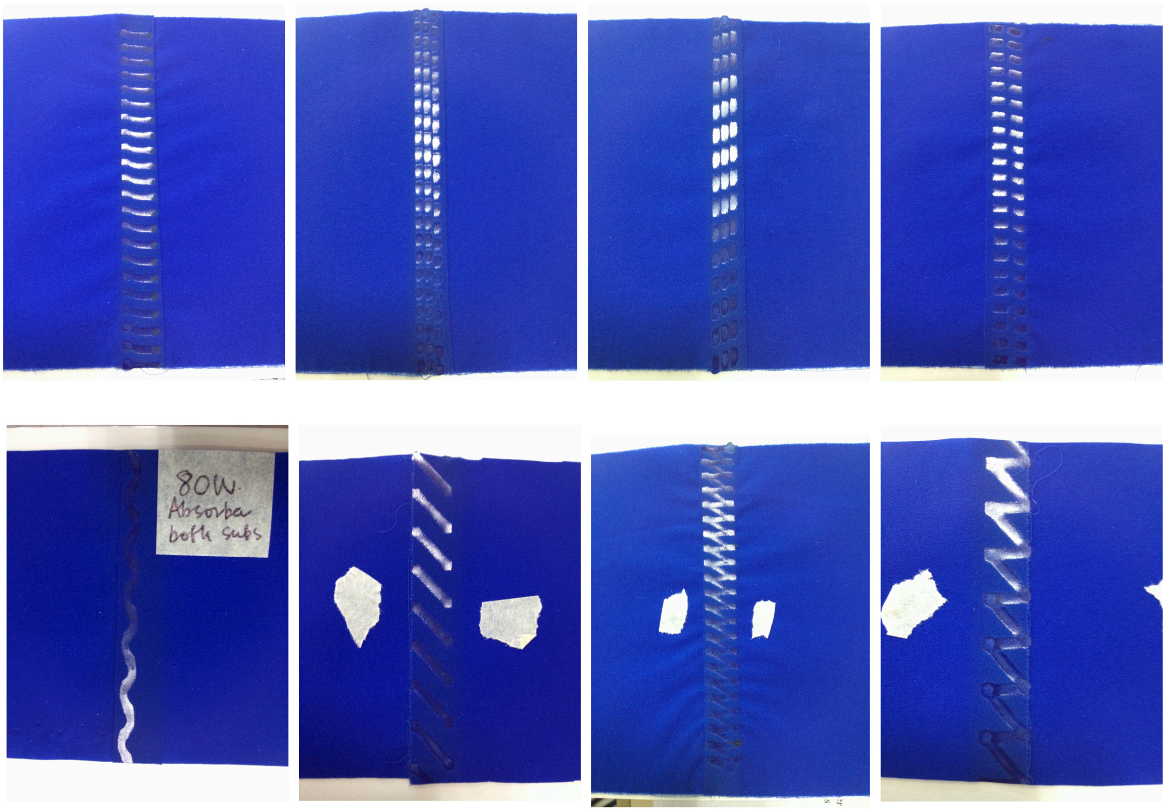


Figure 3.14 Fabric samples showing a variety of decorative patterned laser welded seams (Paine 2013)

Although the research at this stage was mainly concerned with developing patterned seam designs, there remained to be an opportunistic element to the researcher's approach, especially when investigating effects using TLW equipment, which had yet to be thoroughly explored. Whilst developing patterned welded seams using the TLW equipment an opportunity to create all-over decorative surface effects was identified. The co-ordinates of patterned programmes originally developed for seaming were adjusted to cover the whole surface of the fabric. It was found that the laser could be applied to either a single layer of absorbing fabric or double layer material configurations to create a variety of decorative effects.

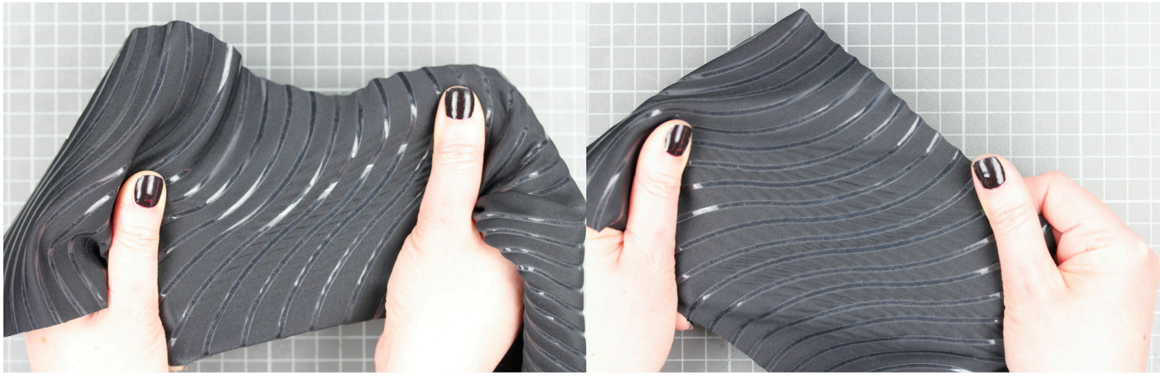


Figure 3.15 Sample demonstrating the effect of laser surface melting across the full width of a fabric sample (Paine 2013)

Kate Goldsworthy, also a textile designer, is the only other person prior to this research to use the laser welding equipment to create decorative surface effects (See chapter sections 1.3.2.1 and 4.2). The objective of Goldsworthy's doctoral research was to create surface finishing effects for polyester fabrics that maintain the virgin quality of the material for re-cycling within a closed-loop system (Goldsworthy 2012).

Identified opportunities for creating three-dimensional effects using TLW equipment are explained in the following chapter subsection.

3.3.3.3 Identified opportunities for creating three-dimensional surfaces

Seams produced using stretchy fabrics do not take on a wavy three-dimensional appearance, as they do with ultrasonic welding, using TLW equipment. It was identified that the set up of the equipment could be responsible for this difference in the appearance of the welds produced. Materials are kept in a flat stationary position for TLW, whereas, materials are manually guided through the ultrasonic welding equipment and pulled forwards by a metal anvil. Three-dimensional surface effects created using ultrasonic welding equipment have been emulated using TLW equipment by holding the material samples under tension during the welding process.

Using a medium sized embroidery hoop single layers of stretchy fabric were held under tension throughout welding. The heat produced by the laser melts thermoplastic material fibres and re-sets them into a new elongated position. Upon removal from the embroidery hoop, in response to the pull from surrounding untreated fabric areas, the welded surface collapses inwards to create a wavy three-dimensional surface appearance (Figure 3.17).

An embroidery hoop was also used to hold materials under tension for the attachment of polyurethane tape to an underlying layer of stretch fabric. The polyurethane tape is held under tension in an embroidery hoop above a layer of stretchy fabric that is absorptive to the laser; and is attached to the fabric following exposure to the laser. Upon release from the embroidery hoop, the fabric gathers inwards to create a ruched surface effect (Figure 3.16). This technique, developed by the researcher, serves as an example of how tacit knowledge gained from prior experience working with textile equipment has been used to inform and develop novel opportunities for the research.

Figure 3.16 (Centre Right, Right,) Fabric samples demonstrating ruched effect created using polyurethane tape and laser welding equipment (Paine 2013)
Figure 3.17 (Left, Centre Left) Fabric samples demonstrating all-over surface rippling effect created using laser welding equipment (Paine 2013)

Following this initial period of practice-led research developing patterned seams and three-dimensional surface effects using ultrasonic and TLW equipment, consultation was sought from Speedo, who had now become an industry partner for the research, on possible application opportunities for the techniques developed; to narrow the project scope and validate the subsequent stages of the research. It has already been described in the methodology chapter (2) how anchoring the research within an industrial context was of interest to TWI who was looking to expand their existing network within the textiles industry.

Figure 3.18 Sketchbook pages from 'stretch seaming and surfaces investigation' (Paine 2013)

3.3.4 Industry consultation with Speedo to narrow project scope

[redacted] were the researcher's main contacts at Speedo and provided feedback on the research as it progressed. Their opinion on material samples was sought typically after a period of experimental sampling (2.3.2) to gauge interest for a swim application and define possible functional opportunities for further investigation. [redacted] Speedo [redacted]. Material samples developed during the 'stretch seaming and surface investigation' were presented to [redacted]. **Insights gained from consultation with Speedo are summarised below:**

• Adhesive methods currently employed by Speedo have a stiff handle and appearance 'driven by the manufacturing process' as described by [redacted]. Welding techniques created using ultrasonic and laser welding techniques demonstrate an improved appearance and handle by removing the need for adhesive

• The three-dimensional appearance of seams and surfaces created using ultrasonic welding equipment has a feminine decorative appeal that could be used to create areas of detail or shaping within Speedo's [redacted] range of swimwear, [redacted]

• Seams and flat surface finishes developed using the laser welding equipment have an appearance that 'looks fast' according to [redacted], and would suit consumers of their competitive range who are interested in enhancing their performance

• The shiny surface aesthetic of seams and surfaces developed using laser welding could improve athletic performance by improving swimmer confidence and, potentially, reducing resistance to drag in the water

• Laser treated patterns on the surface of the fabric could be used to control the elastic behaviour of the material; creating areas of resistance that compress the body into a more streamlined silhouette for enhanced athletic performance

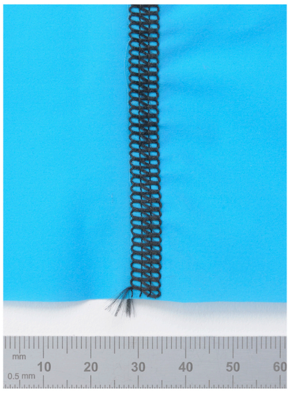
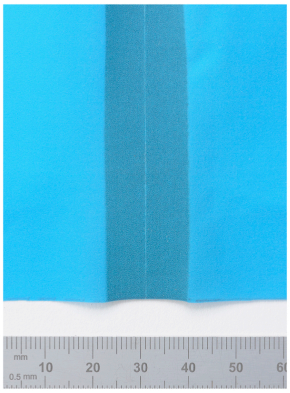
Techniques developed using laser welding equipment were of most interest to Speedo. TLW is an emerging technology and there was an interest in the novel opportunities that could be gained through its development. This influenced the decision to develop the laser welding work further in the next stage of the investigation.

3.3.5 Tensile testing of seams against industry benchmark

The primary stage of this 'stretch seaming and surfaces investigation' had adopted a craft-design approach to develop methods for creating patterned seams and surfaces using ultrasonic and TLW equipment. Having identified an interest in the techniques developed using laser welding equipment through consultation with Speedo, this scientific study used mechanical testing equipment, made available to the research by Speedo, to measure the strength of laser welded patterned seams in comparison to existing seaming methods used by Speedo. The initial hypothesis relating to the development of patterned seams had proposed that *weld pattern can be used to enhance the elasticity of welded textile seams* by creating gaps in the weld-line; however it was necessary to test the strength of the laser welded seams in comparison to existing techniques to validate this further stage of the research.

3.3.5.1 Method and preparation of seams

Seams were prepared in accordance with the in-house standard for testing seam strength used by Speedo (British Standard BS 4674 Tensile Tenacity Test). Four seam types commercially applied by Speedo, using both traditional stitch and advanced adhesive methods of construction; and nine differently patterned laser welded seams were selected for testing. Three samples for each seam type were tested to obtain an average breaking force.

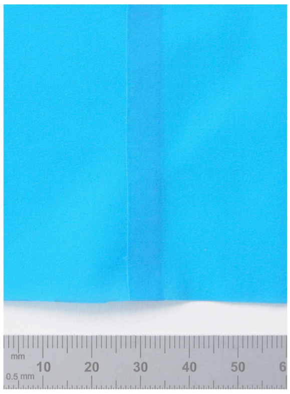


Figure 3.19 (Left) Flat-locked seam (Paine 2014)
Figure 3.20 (Centre left) Adhesive taped seam (Paine 2014)
Figure 3.21 (Centre right) Over-locked seam (Paine 2014)
Figure 3.22 (Right) Adhesive lap seam (Paine 2014)

Each sample was clamped into the equipment as shown in Figure 3.23 and was pulled at a constant rate of extension until a point of failure was reached. Extension vs. force was plotted on a chart recorder at an accompanying workstation.

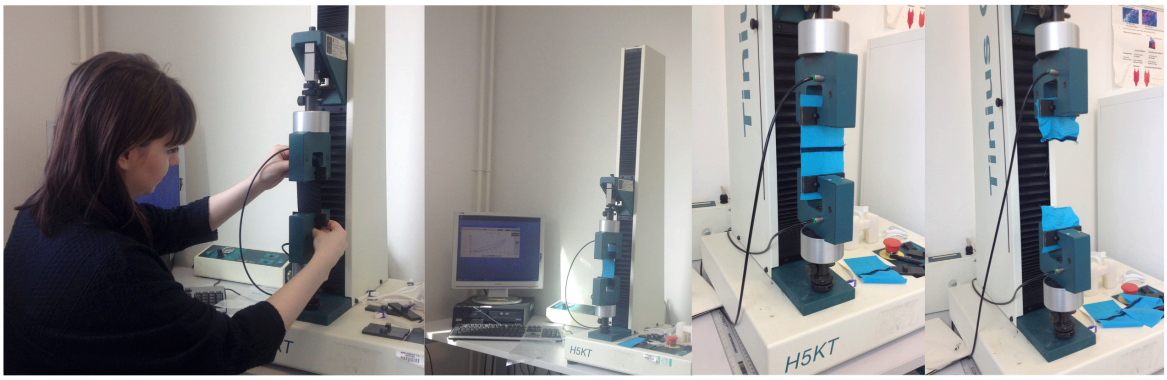


Figure 3.23 Mechanical testing of seams at Speedo (Paine 2014)

3.3.5.2 Results

All four seam types used for the construction of Speedo's swimsuits broke at an approximate force of 400N, which is very close to the strength of the parent material. Adhesive methods were only mildly stronger than stitched methods overall.

Seam type	Average force at break (N)
Flat-locked	397.5
Over-locked	360.5
Adhesive taped	408
Adhesive lap	417.2

Table 3.4 Tensile testing results for Speedo seams

All nine patterned laser welded seams broke at approximately 50-60N. Seams produced using the recommended material configuration for TLW, with the laser absorbing dye placed at the interface of two transparent materials, were slightly stronger than other seam types, however there was no significant improvement with welds still breaking at approximately 60N. See Table 3.5 for full details of results and Figure 3.25 for images. Image numbers correspond with sample numbers in the table.

Sample number	Lower substrate	Upper substrate	Laser absorbing dye	Weld pattern	Average force at break (N)
1	Transparent	Absorbent	Top of lower substrate	Trep of 150ms with Tpuls of 75ms at 5m/min	60
2	Transparent	Absorbent	Top of lower substrate	Trep of 200ms with Tpuls of 75ms at 5m/min	Initial break at 60N (approx.)
3	Transparent	Absorbent	Top of lower substrate	Trep of 250ms with Tpuls of 75ms at 5m/min	61
4	Transparent	Transparent	Top of lower substrate	4 line continuous	57.1
5	Transparent	Transparent	Top of lower substrate	6 line continuous	63.7
6	Transparent	Transparent	Top of lower substrate	8 line continuous	61.8
7	Transparent	Absorbent	No	4 line continuous	54.5
8	Transparent	Transparent	Top of both substrates	4 line continuous	51.2
9	Transparent	Transparent	Top of lower substrate	4 line continuous	58.1

Table 3.5 Tensile testing results of patterned laser welded seams

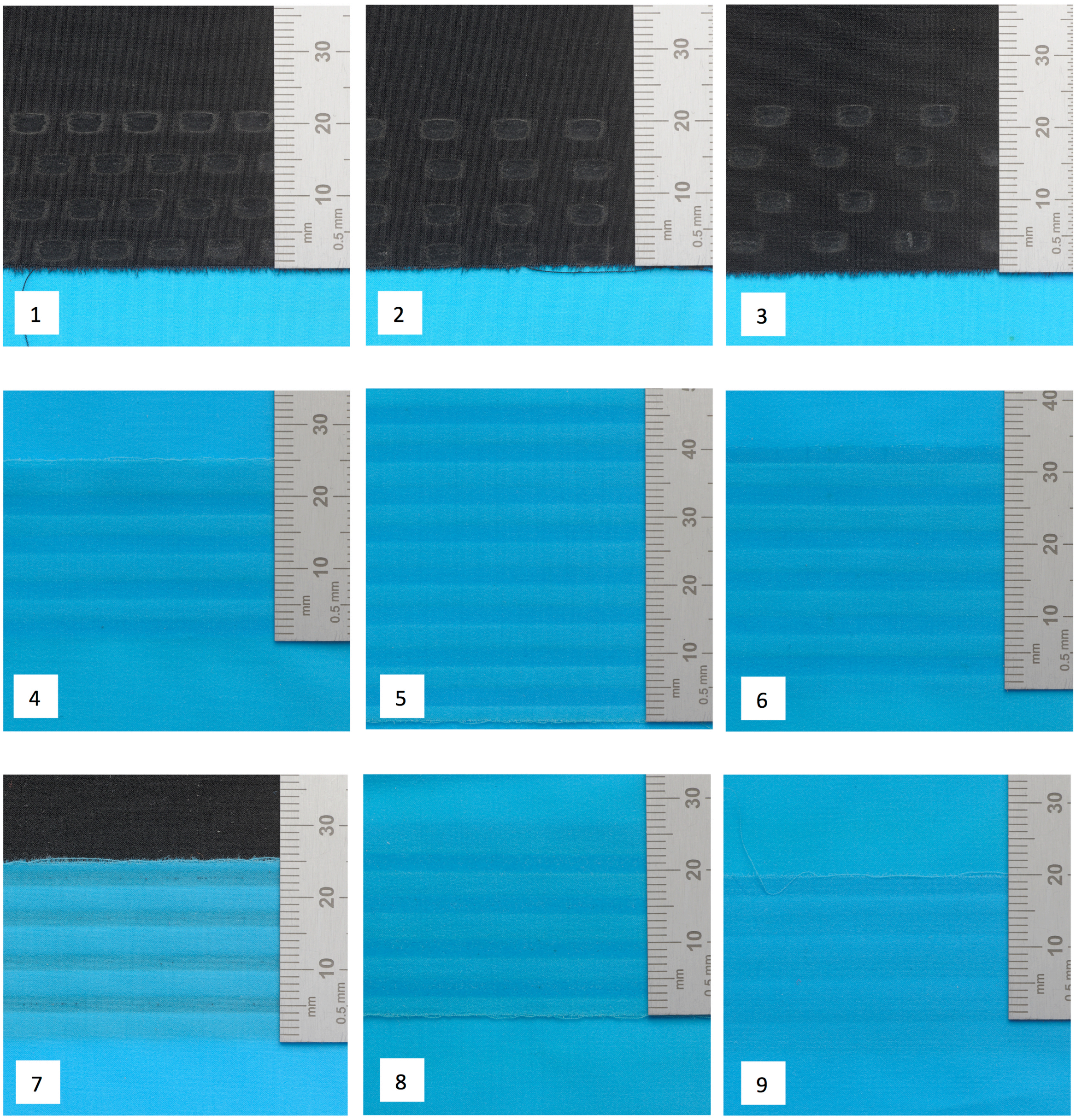


Figure 3.24 9 patterned laser welded seams included in the investigation (Paine 2014)

3.4 Summary and identification of route forwards

A summary of insights for the first stage of this investigation 'preliminary ultrasonic study' is provided in the chapter subsection 3.2.5.

Insights accumulated from the 'preliminary ultrasonic study' (3.2) contributed to the formation of two initial hypotheses, specifically that *weld pattern can be used to enhance the elasticity of welded textile seams* and *the welding process can be used to shape stretchy textiles for the construction of three-dimensional products (3.2.5)*. These initial hypotheses were addressed by the subsequent 'stretch seaming and surfaces investigation' (3.3).

<u>The main insights</u> from this second stage of the investigation are summarized below:

• Patterned seam designs and three dimensional surfaces created using ultrasonic welding equipment can be emulated using TLW equipment

• An additional opportunity to create all-over surface decorative effects by exploring different material lay-ups was identified using TLW equipment

• Speedo was most interested in developing seaming and surfacing ideas using laser welding equipment for their application due to the novel effects that could be achieved working with this emerging technology

• Patterned laser welded seam strengths were not comparable to those already implemented by Speedo

The next stage of research with reference to the initial hypothesis *weld pattern can be used to enhance the elasticity of welded textile seams*, would have been to compare the elastic properties of the seams; however a reconsideration of the research focus was required following the insight that the strength of patterned laser welded seams was not comparable to seaming methods commercially applied by Speedo.

A potential application for laser treated surfaces to control the elastic behaviour of stretchy fabric and create areas of variable graduated compression on the body to streamline the silhouette for a performance enhancing effect, had been identified through consultation with Speedo during the 'stretch seaming and surface investigation' (3.3.4). The researcher had also been introduced to a method of measuring the elastic properties of fabrics using mechanical testing equipment whilst testing seam strengths at Speedo, which contributed to the identification of a **new focus for the research: to explore the effect of laser melted surfaces on the elastic behaviour of stretchy textiles.**

TLW equipment has been used previously to create decorative effects on the surface of textile materials (1.3.2.1); however this was the first time these decorative effects have been used in combination with stretchy fabrics to change their elastic behaviour.

The **gap in knowledge** that has been identified is within the field of TLW: **to control the elastic behaviour of stretchy fabrics using laser melted patterns for a variable compressive effect on the body.**

4 Literature Review

4.1 Introduction

Through the 'project scoping' phase of this investigation a gap for investigation to use TLW equipment as a tool to control the elastic behaviour of stretch fabrics; to have a variable compressive effect on the body; and streamline the silhouette for an athletic advantage, was identified.

This chapter begins with an overview of design research in the fields of ultrasonic and lasers processing for textiles to demonstrate the position of the work within its wider academic context. The main focus of this overview is in the field of laser processing, as this is where the research makes its contribution to knowledge. This introductory section is followed by a review of historical and contemporary methods for shaping the body, which was carried out specifically to identify a gap in the field of compression apparel that could be addressed by the laser melting technique developed during the 'project scoping' phase (3). A review of the literature has been supported through consultation with industry, specifically discussions with members of the innovation team at Speedo, and a market review of contemporary compression methods at the sportswear industry tradeshow ISPO.

4.2 Overview of academic research in the fields of ultrasonic and laser processing of textiles

It has been established in the Introduction to this thesis that ultrasonic welding is widely employed by the packaging and automotive industries to join polymeric textile film materials (1.3.1). Ultrasonic welding equipment is also used in industry as a stitch-replacement technology to create all-over surface quilted effects for the manufacture of quilts and decorative padded upholstery (Jones 2013). Textile designers and researchers, such as Janet Stoyel (Wilson 2011); Janet Emmanuel (Emmanuel 2001); Jacob Schlaepfer (Huddleston, Whittaker 2009); and Eugene van Veldhoven, have demonstrated enhanced capability for ultrasonic equipment to create a variety of surface effects, for instance embossing; laminating; initiating colour change; creating three-dimensional surface effects; and transferring coloured pigments from paper to create decorative surface patterns.

CO_2 lasers are widely used in industry for cutting and marking textile materials. Complex decorative surface effects are achievable at high speeds using lasers that are driven by CAD software. Synthetic fabric edges are sealed when cut by a laser eliminating the need for time consuming labour-intensive finishing work. The development of laser technology is a broadening area of investigation amongst textile design researchers as they seek alternative applications and opportunities. An overview of the research in this field is provided below.

Lasers were first applied to textiles in the academic field as a dry ecologically superior alternative to commercially applied wet finishing methods such as dyeing and printing. Janet Stoyel was the first researcher to apply laser technology to textile materials. Her PhD research at the Royal College of Art investigated novel felting and dyeing techniques, however it was not until witnessing these processes in Japan on an industrial scale that she became aware of their harmful impact on the environment, specifically relating to the waste and pollution of water. Stoyel met with a company that manufactures lenses and vibratory elements that can be used to treat the surface of textiles without using water at the industry tradeshow Techtextil, and this inspired her investigation of alternative dry-processing methods, specifically laser and ultrasound technologies. Her first laser was developed in collaboration with the MOD and installed within the grounds of her home. Stoyel used a process of trial and error to develop a range of unique decorative effects and set up her company the 'Cloth Clinic' in 2004 specialising in the design and manufacture of decorative eco materials (Wilson 2011).

Numerous PhD projects with a focus on applying laser technology to textiles have been carried out at Loughborough University over the past decade. The first of these projects was carried out by Savithri Bartlett and completed in 2006. Her research investigated the effect of lasers on dye uptake in synthetic fabrics. The research is split into two parts. The first part employs an experimental scientific design method to compare the effect of various lasers. The second part of the research uses a qualitative research method to analyse a collaborative venture between an haute couture design team and a manufacturer of laser equipment in the development of laser-etched denim (Bartlett 2006).

Figure 4.1 Laser etched denim garments by Savithri Bartlett in collaboration with an haute couture designer (Bartlett 2006, p.240 and p.244)

The doctoral research of Kerri Akiwowo of Loughborough University completed in 2015 builds on Bartlett's research to demonstrate how CO_2 lasers can be used to achieve an increasingly gradual and variable colourful effect on the surface of the fabric by employing the laser as a dots per inch tool, mimicking the tonal capacity of the digital printing process. Akiwowo has also enhanced the industry applicability of her research by integrating quantitative methods within her approach that require accurate recording and dissemination of experiment variables for repeatability (Akiwowo 2015a).

Figure 4.2 Laser treated fabrics by Kerri Akiwowo (Akiwowo 2015a, p.131)

Janette Matthews completed her PhD at Loughborough University in 2011. Her research centred on the development of novel processes for creating three-dimensional textile surfaces using laser technology. Three separate methods for achieving three-dimensional surfaces in textile substrates were developed. These were laser assisted template pleating; laser pre-processing of cashmere cloth and laser sintering.

'Laser assisted template pleating' employs a CO_2 laser to cut the fabric and create origami inspired card templates that are used to clamp the fabric when being steamed. Using this method over commercially applied techniques increasingly novel and complex pleated designs can be achieved.

'Laser pre-processing of cashmere cloth' is a method of laser cutting cashmere cloth prior to washing and felting to create variable controllable three-dimensional surface effects. The 'careful selection of fabric construction, hole size, shape and position and yarn colour allows a variety of three dimensional patterned surfaces to be determined' (Matthews 2011, p234).

'Laser sintering' is a method of fusing small particles of polymer, metal or ceramic powder to form three-dimensional objects. Matthews demonstrated through her research that a number of different polymer powders could be sintered onto the surface of both natural and synthetic woven textile surfaces to create three-dimensional effects (Matthews 2011).

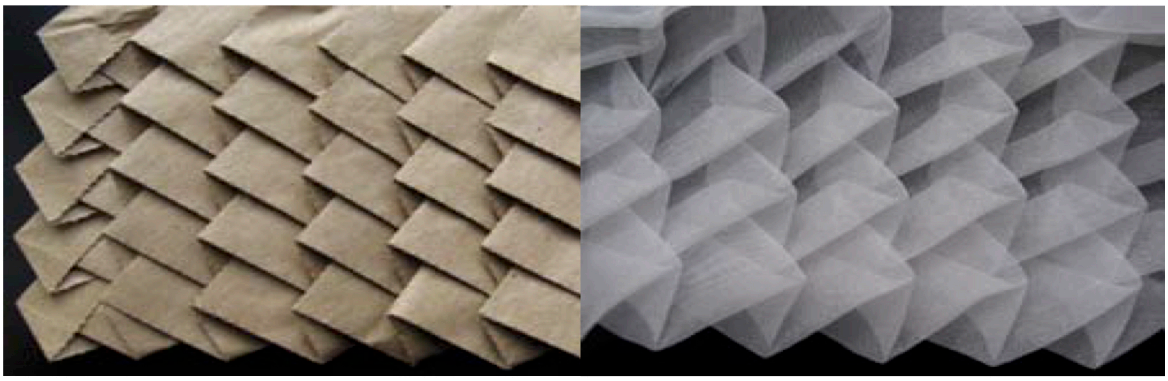


Figure 4.3 (Left) Paper template for laser assisted template pleating by Janette Matthews(Matthews 2011, p.181 and182)
Figure 4.4 (Right) Fabric sample of pleated silk organza by Janette Matthews made using template in Figure 4.3(Matthews 2011, p.182)

The 'Cutting Edge: Lasers and Creativity Symposium' held at Loughborough University in 2009 brought together practice-led academic design researchers working with laser technology. Kate Goldsworthy, Faith Kane and Sara Robertson presented their textile-based research. Kane's PhD research completed in 2007 had focused on the design of non-woven textile materials. This conference presentation outlined research relating to the construction of non-wovens specifically for laser processing to create unique decorative effects. Kane reported that laser marking could be used to reveal contrasting fibre layers and embedded materials to achieve unique surface pattern effects. An ability to create subtle relief and translucent effects on the fabrics was also reported (Kane 2009).

Figure 4.5 Selection of laser-treated non-woven fabrics by Faith Kane(Kane 2009)

Robertson's PhD was awarded in 2011 by Heriot Watt University and investigated the design potential of thermochromatic textiles used with electronic heat profiling circuitry. The work presented at the Cutting Edge Symposium in 2009 demonstrated how a CO_2 laser can be used to create linear surface patterns before coating the textile with liquid crystal dye systems. The laser-etched lines create a lighter colour of the same hue on the surface of the fabric and enhance the variety in the aesthetic effects achieved (Robertson 2009).

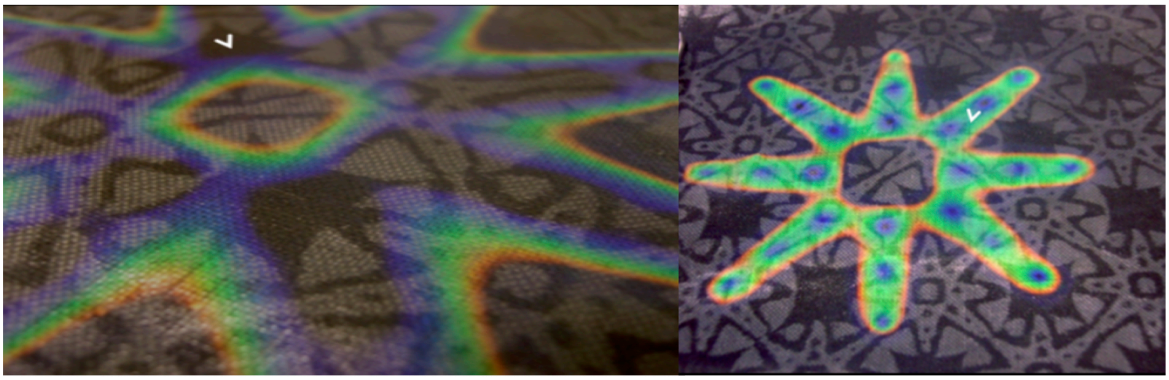


Figure 4.6 Samples of laser etched fabric by Sara Robertson(Robertson 2009)

Kate Goldsworthy's PhD research was introduced during the Introduction chapter of this thesis (1.3.2.1). Goldsworthy's PhD research used laser technologies to create novel all-over decorative effects on polyester fabrics, but was unique in its proposition to use laser technology as a finishing tool to maintain material purity over multiple product life cycles in a closed loop system of recycling. Her initial investigations used CO_2 laser equipment, which is widely accessible within most university design departments for cutting applications and is the type of laser adopted by most other textile-researchers in the field. Goldsworthy was also able through her research to gain access to the diode laser at TWI. Working with the diode laser Goldsworthy observed that the laser beam interacted differently with the fabric enabling a greater variety of visual effects to be achieved. In total Goldsworthy was able to demonstrate over 20 different visual surface effects, some of which emulated traditional textile processing methods, such as flocking, quilting and devoré; and others, which demonstrated more unique effects, such as 3D surface lamination and internal bond decoration (Goldsworthy 2009, Goldsworthy 2012). For images refer to 1.3.2.1.

This research can be aligned to Goldsworthy's as it too centres on the use of a diode laser to create all-over surface effects. However, there is a fundamental difference between the aims of the two projects. Goldsworthy's research sought to uncover methods for decorating polyester fabrics whilst maintaining material purity, which led her to discover the laser. Her research was concerned with demonstrating a breadth of aesthetic opportunities for further development. The brief for this research was written by TWI (8.2) and necessitated the adoption of a scientific approach so that developed techniques could be replicated in industry. The 'multi-strategy' approach adopted by this research (See chapter 2) can be most closely aligned to the recently completed doctoral research of Akiwowo who also integrated quantitative methods to enhance repeatability and industry applicability (Akiwowo 2015a). The integration of a scientific approach within this research has also enabled the development of functional opportunities, specifically a method of controlling the elastic behaviour of stretchy fabrics.

The following section of this chapter reviews both historical and contemporary methods for shaping the body to identify a gap in the field of body shaping apparel that can be addressed by the laser melting technique developed during the 'project scoping' phase.

4.3 Historical methods of shaping the body

The oldest form of body shaping garment is the corset, which dates back to the 16th Century (Lim, Yu et al. 2006). The corset predates the invention of stretchy knitted fabrics that cling to the body and relies on complex pattern cutting techniques to achieve three-dimensional form and a close body-hugging fit when worn. The dimensions of the various panels are cut to fit and accentuate the curves of the female form, splaying outwards across wider parts of the body, such as the hips and chest, and reducing inwards across narrower parts of the body, such as the waist (Lynn 2014).

Strips of rigid material such as metal or whalebone, known as bones or stays, are inserted into fabric channels to create a solid framework, which pushes downwards on the surface of the body and assists in manipulating its shape. The density of bones can be varied to influence the degree of pressure that is applied. Corsets often have a concentration of boned sections across the abdomen to achieve a flattening effect. Whalebone stays are curved and set with a hot iron to assist in moulding the shape of the figure. The direction of the bones is crucial in manipulating the shape of the silhouette, which are often squeezed inwards across the abdomen and splayed outwards over the hips to accentuate a thinning effect at the waist. Interlinings and embroidery techniques can be applied in targeted areas on the corset such as the diaphragm and abdomen to enhance the rigidity of the fabric and provide support to specific areas of the body such as the bust (Lynn

2014). The degree of pressure exerted on different parts of the torso can be controlled by a lace-up fastening technique, known as tight-lacing, which cinches the garment inwards (Steele 2001). See Figures 4.7 and 4.8


Figure 4.7 (Left and Centre Left) Boned corset showing close-up of fabric channels and metal bone insertions (Images courtesy of Victoria and Albert Museum)
Figure 4.8 (Centre Right and Right) Corset with supportive embroidered panels ca. 1825 (Images courtesy of Victoria and Albert Museum)
© Victoria and Albert Museum, London

From the 1820s onwards many companies and inventors had been exploring methods for producing elastic materials that would enhance comfort for corset wearers by providing greater ease of movement. However, it was not until the 1930s that these elastic materials became commercially available and had an effect on the design of body shaping apparel. Elastex, a type of stretchy elastic fabric, was developed in 1941 especially for the manufacture of all-in-one body shapers (Lim, Yu et al. 2006). Elastic fabrics have an ability to cling to the body and were incorporated as panels in the construction of shape wear garments during the 1940s, specifically girdles that focused on compressing the abdomen, hips and thighs. See Figure 4.9

Dupont, now Invista, developed Lycra in 1958. Lycra is an elastic filament that produces fabrics that are highly extendable with good recovery characteristics. This new type of elastic yarn was three times more powerful than previous inventions and offered twice the recovery power, which enabled it a unique ability to cling to the body, applying pressure to achieve a body hugging fit without the need for complex paneling. The 'Little X' girdle widely available in the 1960s was one of the first garments to incorporate Lycra and used a single layer of fabric that wrapped around the waist in an 'X' shape to cover the hips, buttocks and upper thighs (Lynn 2014). See Figure 4.10

Manufacturing time was reduced with a reduction in the manual work required to construct garments made from stretchy Lycra fabrics; however there was less flexibility and control over the variable degrees of compression that could be applied to different areas of the body. Contemporary methods employ various techniques, namely 'cut and sew', 'seamless' and 'surface application', to create variable degrees of compression across the surface of a garment and have an increasingly controlled effect on the manipulation of the figure. The following subsections of this chapter provide a description of each of these techniques.

Figure 4.9 (Left and Centre Left) 1940's girdle made from stretchy panels of fabric (Images courtesy of Victoria and Albert Museum)
Figure 4.10 (Centre Right and Right) Lycra undergarments ca.1960-1970 (Images courtesy of Victoria and Albert Museum)
© Victoria and Albert Museum, London

4.4 Contemporary methods of shaping the body

Contemporary compressionwear technologies are implemented both within the field of shapewear and sportswear. An application opportunity within the sportswear sector was identified following an extensive study on the effect of compression garments on athletic performance carried out at Penn State University from 1991 to 1995 (Voyce, Dafniotis et al. 2005). The results of this study revealed that wearing compression clothing supports muscles preventing them from vibrating and assists blood flow, which enhances stamina; and improves recovery post exercise by assisting the swift removal of lactic acids that can cause delayed onset muscle soreness (Voyce, Dafniotis et al. 2005). Small proportions of Lycra were integrated within the manufacture of sportswear fabrics from the 1970s onwards allowing tight-fitting clothes to be worn during exercise without restricting freedom of movement. Compression fabrics with high proportions of Lycra, of up to 30%, were integrated within the collections of numerous sportswear brands from the turn of the 21st century; and were notably adopted over more traditional loose fitting shirts by the Italian football team in 2002 (Kappa) and the England Rugby squad in 2003 (Adidas).

Through consultation with Speedo, an understanding that a variable compressive effect across the surface of a swimsuit is advantageous in streamlining the silhouette for an improved athletic performance was gained. In Speedo's FS3 swimsuit high levels of compression are targeted at the hips and chest to assist in streamlining the shape of the silhouette and improving resistance to drag that could impede athletic performance. Methods of achieving a variable targeted compressive effect using contemporary stretchy fabrics, most of which are applied in both sportswear and shapewear applications, are described herein.

4.4.1 Cut and sew

The majority of compression garments, especially for shapewear applications remain to be cut and sewn together. Shapewear industry experts have praised the cut and sewn method of construction over more contemporary seamless methods, as the effect on the silhouette can be engineered using pattern cutting techniques to accentuate a curvaceous silhouette (Usigan 2011). This is due to the precise placement of panels that are engineered to nip and tuck the figure into the desired silhouette. See Figure 4.11

The first undergarments produced using Lycra had a uni-directional line of stretch that caused them to roll up the body when worn (Lynn 2014). Stitching stretchy pieces of fabric together at different orientations corresponding with the body's movements helped to overcome this problem (Lynn 2014). A US patent published in 1985 describes the design for a multipanel foundation garment where unidirectional stretch panels are sewn together at orientations that correspond with movements from the body, thus improving comfort for wearer by decreasing resistance to movement (Pundyk 1985). The patent describes the design of a panty girdle that is comprised of 6 panels. The central panel that covers the abdomen is positioned so that the line of stretch is in the longitudinal direction and is surrounded by 2 side panels that stretch outwards from one another in a bias direction; two back panels stretch across the body in a transverse direction. The 6th panel covers the crotch and the line of stretch is in the longitudinal direction, which corresponds with the centre front panel covering the abdomen. Joining panels of the same fabric together at different orientations achieves a targeted compressive effect that remains in position whilst the body is moving. See Figure 4.12

A paneled construction method has also been implemented within sportswear applications. Wacoal Sports Science developed a range of compression clothing that created targeted zones of compression using bi-stretch Coolmax® Lycra. The patented technology called Conditioning Web uses engineered panels of fabric that are joined together in structures influenced by kinesiology taping mechanisms (CW-X 2015). Kinesiology taping is applied to parts of the body in specific patterns to provide support that prevents and heals muscular injuries. These panels of fabric are sewn inside the garment to apply moderate pressure to prevent muscle oscillation, which protects against pain caused by existing injuries, particularly around the knee, and improves athletic performance. Studies have shown that wearing CW-X performance conditioning wear reduces muscle pulse frequencies, which is an indicator of fatigue, post exercise (Voyce, Dafniotis et al. 2005).

Nike's Project Swifts uses panels of different fabrics joined together using an adhesive taping method, to create all-in-one suits that help maximize performance by compressing the body into a more aerodynamic shape. Panels of stretch fabric, with varying levels of firmness, are stitched together at different orientations to create variable control across the surface of a garment. The Swift Suit was originally released for the 2000 Sydney Olympic games, developed for track and field events. Nike tested over 50 fabrics for the development of the Swift Skin used for speed skiing, which was released in 2002. Fabrics were tested for wind resistance, elasticity, warmth and breathability. 6 different fabrics were selected for the construction of the suit; which were a coated stretch fabric, textured stretch fabric, stretch-vent fabric, textured mesh fabric, stretch tricot fabric and silver speed fabric. The different fabrics provide variable degrees of compression to shape the body to create the most aerodynamic silhouette. Optimum placement of the different fabrics was designed using Nike Zoned Aerodynamic Technology, which is an advanced form of body mapping, that scientifically determines where to place different fabrics for maximum benefit (Voyce, Dafniotis et al. 2005).

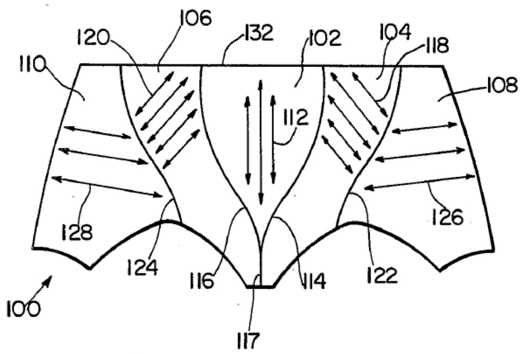


Figure 4.11 (Left and Centre) La Perla cut and sewn body undergarment, 2011 (Images courtesy of Victoria and Albert Museum) © Victoria and Albert Museum, London
Figure 4.12 (Right) Illustration of foundation garment demonstrating arrangement of panels with uni-directional lines of stretch (Pundyk 1985, p.2)

4.4.2 Seamless

Seamless manufacturing methods have been implemented in both shapewear and sportswear applications; however the effect on the body has been described as 'flattening' rather than accentuating; and may be preferred for sportswear applications where the aim is to streamline the shape of the body to improve athletic performance. Seams in paneled compression apparel can create an uneven modulus across the surface of the garment (Pascual 1998), which is particularly undesirable in sportswear applications where gradual compression is applied functionally to enhance athletic performance. The presence of lumpy seams on shapewear garments can also have an undesirable aesthetic effect when worn under tight fitting clothing.

Circular weft knitting is widely used for the manufacture of seamless compression garments that are created in one piece, or tubes of fabric can be made that are joined together (De Araujo, Fangueiro 2011). Circular weft knitting is also used for the manufacture of knitted tubes with small diameters for medical implants, such as esophagus stents etc. (De Araujo, Fangueiro 2011). The removal of seams enhances comfort for the wearer as excess fabric or adhesive tapes are no longer present inside the garment that could cause irritation to the skin.

A number of patents have been published more recently that explore the potential to integrate varied zones of compression seamlessly, so that the targeting capability of the cut and sew technique can be achieved without the need to sew different fabrics together. A US patent published in 2001 describes the design for a 'seamless torso-controlling garment' that is constructed from a circular weft knitted fabric with elastomeric yarn included on selected courses. A selected front portion of the tubular panel is knitted using a different stitch pattern to the rest of the fabric that increases the modulus by up to 8%, creating a targeted zone of compression that covers the abdomen when worn. (Browder 2001). See Figure 4.13

A US patent published in 1999 describes a design for a swimsuit and body support system (Balit 1999). The torso-controlling garment is seamlessly manufactured using circular knitting technology. A variety of different stitch types are used to create varied degrees of compression across the body that target specific areas. The patent describes 6 different stitch types that can be used on different portions of the garment to enable varied levels of support and compression. Each stitch type has been tested to determine its power characteristics and suitability for use on different areas of the body. The three main stiches that offer different levels of support and compression are: the maximum support stich, medium support stitch and soft selection area stitch. A maximum support stitch is used in areas that require maximum fabric stiffness for support such as under the bust, mid-section and anchor points around the buttocks and hips. A medium support stitch is used where moderate levels of support are required such as at the waist, rear portions and around the legs. A soft selection area stitch is used to cover areas that require the least support such as across the bust, buttocks and crotch area. The selection of stitches across the surface of the body can be used to sculpt the silhouette as desired. A variety of seamless control garments knitted using different stitch types were exhibited at the Industry trade fair ISPO (2015). See Figures 4.14 and 4.15

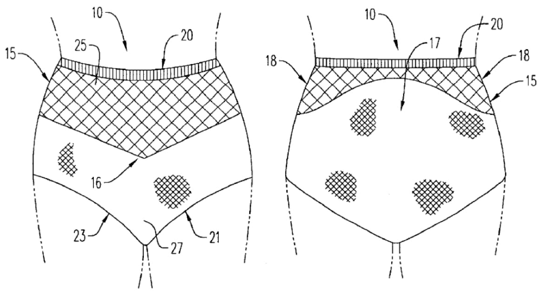


FIG. 1 FIG. 2

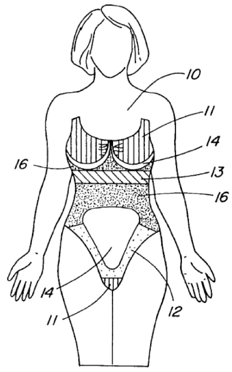


Figure 4.13 (Left) Illustration of seamless torso controlling garment (Browder 2001, p.2)
Figure 4.14 (Centre) Example of seamless control garment shown at ISPO, 2015 (Paine 2015)
Figure 4.15 (Right) Illustration of swimsuit and body support system(Balit 1999, p.1)

An alternative method of creating differential zones of compression across a single layer of fabric is to vary the proportion of Lycra. A US patent published in 2007 describes the manufacturing process for an elastic fabric that has varied zones of compression (Shannon 2007). Elastane threads of various densities are incorporated within the fabric to provide a gradual transition between different zones of compression. This technique can be incorporated within either knitted or fabric woven constructions. Non-elastic and elastic threads can be incorporated in both the weft and warp directions to provide fabrics with a two-way stretch; however, it is preferable that elastic threads are only incorporated in one direction.

FIG. 2

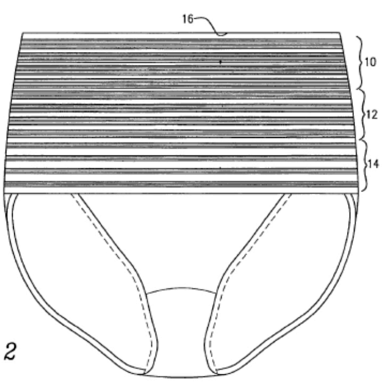


FIG. 3

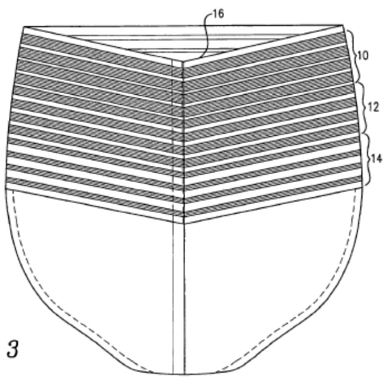


Figure 4.16 Example of application for elastic fabric with varied zones of compression (Shannon 2007, pp.2-3)

Speedo's FS3 swimsuit used widely throughout the London Olympic games in 2012 used a technology that has been referred to as a 'body stability web' (Martin 2012). A warp knitted fabric with variable zones of compression, achieved by varying the density of Lycra across its surface, forms the main body of the suit. The fabric has been cut and positioned in different orientations; combined with different fabrics to create a paneled construction.

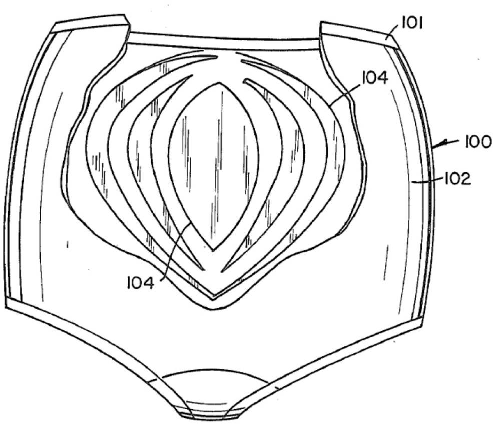
4.4.3 Surface application

The main identified methods of affecting fabric modulus and achieving a compressive effect is by varying the density of elastic yarn and/or stitch type across the fabric's surface. Surface treatments of the textile, using finishing techniques such as printing and laminating, have also been used to change the modulus of stretchy fabrics and provide increased resistance to selected portions (Bell 1987).

A US patent published in 1987 describes a method of attaching an extra layer of fabric using a printed thermoplastic adhesive to provide support across the abdomen of a lady's control garment (Bell 1987). A hot melt powdered thermoplastic adhesive is applied to the surface of the stretch fabric in a pre-determined patterned through a silk screen. The adhesive is left to cure in a drying oven and a cover panel is attached to the adhesive layer using heat and pressure. It has been found that the pattern of the adhesive on the surface of the fabric has a direct effect on the degree of control of the stretch fabric. A dot pattern, for instance, provides less control than a bar shaped pattern; and a block pattern offers further increased resistance. The adhesive can be applied in such a way the level of control is varied across the surface of the fabric, and an attractive aesthetic appearance with a range of patterned features is simultaneously achieved as a result. See Figure 4.17

Speedo currently uses a method of creating zones of compression by attaching additional panels of material inside the garment, which are positioned to target protruding areas and assist in streamlining the shape of the silhouette to improve resistance to drag and enhance athletic performance. Areas of the body that are covered by a double layer of fabric experience higher degrees of pressure and are flattened as a result of this effect.

A US patent published in 1999 describes a method of controlling the elongation of a two layer laminate material, using an interfacing patterned adhesive layer. The adhesive is printed as a series of dots that offer resistance to the elongation of the laminate and can be used on selected areas of a garment to add reinforcement and control stretch (Girard 1999). The adhesive is applied in a regularly repeating pattern that is designed to increase the resistance of the laminate fabric when distorted. The resistance to elongation offered by the fabric is controlled by the pattern and orientation of the individual adhesive elements in combination with the stretch characteristics of the fabrics. A thermoplastic adhesive is used which adheres to the underlying fabric layer when exposed to a suitable temperature. The adhesive is applied by a hollow cylinder with a patterned circumferential screen that controls the amount of adhesive deposited to restrict full saturation of the fabric, which can result in unwanted stiffness to the fabric. See Figure 4.18



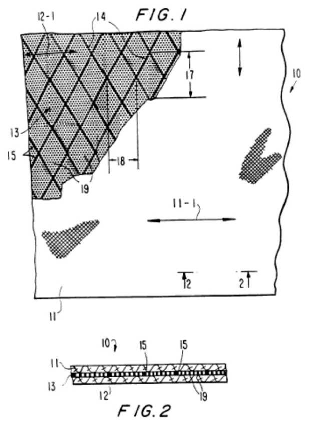


Figure 4.17 (Left) Illustration of undergarment with laminate adhesive panel across abdomen (Bell 1987, p.1)
Figure 4.18 (Right) Illustration of two layer laminate material with patterned adhesive layer (Girard 1999, p.2)

A clear advantage of controlling the elastic behaviour of stretch fabrics using a printed laminating technique is the aesthetic appearance of the end product. The first patent describes a decorative surface application that can be seen from the exterior of the product. The second patent describes a method of using adhesive applied in a pattern to join two materials together, however, it is mentioned that the top layer of fabric can be selected so as to reveal the printed adhesive under layer through the top surface for decorative effect. It is also possible to gain power control of thin stretchy fabrics using this method. Other techniques using high Lycra quantities or dense stitch types are likely to have a heavier quality that could cause discomfort to the wearer.

A control fabric exhibited at ISPO developed by Seiren, a Japanese fabric manufacturer, uses a technique called 'Viscomagic' to create a single layer of fabric with varying degrees of compression. The fabric is made from what appears to be panels of two different materials joined together like a patchwork to create a decorative pattern; however, the transition between zones of the pattern is seamless. A diagram of the technique provided by Seiren reveals that the method uses a fabric constructed from both nylon and polyester fibres. After the 'Viscomagic' treatment the polyester fibres are removed in selected areas to reveal a thinner mesh-like fabric; which, Seiren claims, offers different power control compared to untreated regions of the fabric. The amount of polyester fibres removed and the density of the pattern used could control this effect; creating different powered regions within the same fabric. The effect has a similar appearance to devoré; a textile finishing method that uses chemicals applied through a silk screen to dissolve selected portions of cellulose fibres from a mixed-material fabric.


Figure 4.19 (Left) Display garment demonstrating 'Viscomagic' technique shown at ISPO, 2015 (Paine 2015)
Figure 4.20 (Centre Left, Centre Right, Right) Examples of garments with decorative patterned laminated surfaces on display at ISPO, 2015 (Paine 2015)

4.5 Summary

A gap within the field of laser processing of textiles, specifically relating to the use of TLW equipment, to control the elastic behaviour of stretchy fabrics was identified at the end of the 'project scoping' phase (3.4). Prior art in the field of TLW field was discussed in the Introduction to this thesis (1.3.2).

An overview of ultrasonic and laser processing in the field of academic research was provided at the beginning of this chapter (4.2), to assist in positioning the research within its wider academic context. This research builds on prior research in the field by adopting a multi-strategy framework that utilises a 'scientific' approach to demonstrate functionality. Prior to this research TLW equipment had been used by Kate Goldsworthy to create decorative all-over surface effects. This research demonstrates a new opportunity for these effects when applied to stretchy fabrics, specifically to control their elastic behaviour for a compressive effect on the body.

From a review of both historical and contemporary methods of shaping the body (4.3 and 4.4) an understanding of the technical aspects of compression fabric and garment manufacture has been gained that has highlighted a gap for the research within the field of compression apparel.

<u>A summary of the main insights</u> leading to the identification of the second gap and the main hypothesis for the research is provided below:

• Corsets use complex pattern cutting techniques, rigid frameworks, fabric reinforcement techniques, and a tight-lacing fastening mechanism to achieve a targeted and variable compressive effect on the body

• The invention of Lycra enabled the manufacture of close-fitting garments and compression apparel without the need for complex pattern cutting techniques

• There is a desire in both sportswear and shapewear applications to create a variable compressive effect that can target specific areas of the body to tailor the shape of the silhouette

• Contemporary processes, specifically 'seamless' and 'surface application' methods, demonstrate an ability to achieve a variable compressive effect across a single fabric layer

The gap in knowledge that has been identified is: **to create a variable compressive effect across a single fabric layer.**

The main hypothesis for this investigation is:

Laser melted patterns can be used to control the elastic behaviour of stretch textiles to have a targeted and variable compressive effect on the body.

5 Surface modification I

5.1 Introduction

This study set out to explore the effect of laser melted patterns on the elastic behaviour of stretchy textile material and, particularly, if variable levels of flexibility could be achieved. Through a review of methods for shaping the body and consultation with Speedo it was understood that the latest compression technologies offer variable degrees of compression across a single layer of fabric. This is achieved by manipulating the flexibility of the fabric; achieved by varying stitch type, density of Lycra (4.4.2) or applying a laminated surface effect (4.4.3). An understanding that laser melted surfaces could be used to change the elastic behaviour of stretch fabrics had developed during the 'project scoping' phase of the research (3.3.4); however, precise control of this effect to create fabrics with variable degrees of flexibility had yet to be demonstrated.

There are two stages to this study. The first stage explores methods of controlling the level of melting to the material using assessment by eye only. A broad understanding that fabric extensibility decreases proportionately to the amount of surface melting had been gained through handling material samples, however, a more in depth evaluation of the technique was required to understand the individual elements of the process that could be used for precise control of the effect. The second stage used mechanical testing to quantify the effect on the elastic behaviour of the fabric. Elements of the procedure identified through the first phase of the study were tested mechanically at incremental settings to measure their exact effect on the elastic behaviour of the fabric.

5.2 Methods of controlling the level of melted material

This preliminary phase of the study explored methods of controlling the level of material across the surface of the fabric.

5.2.1 Materials and equipment

Laser equipment used during the 'project scoping' phase of the research was used for this study (3.3.1).

Laser melted surfaces can be created on single layers of fabric that are transparent or absorbent to the infrared wavelength of the laser beam. The proportion of laser energy that can be transmitted by each of the materials supplied by Speedo for the research was measured during the 'project scoping' phase of the research (Table 3.3). Only absorbent fabrics were included for this stage of the study as this avoided the necessity of applying laser absorbing dye, which lengthens the production process. All of the fabrics were black in colour and were made using either a knitted or woven construction. In total six materials were tested.

Fabric	Construction	Composition	Proportion of laser energy transmitted (%)
B	Woven	80% nylon 20% elastane	18
C	Knitted	80% nylon 20% *Xlife Lycra*	0
D	Knitted	80% nylon 20% *Xlife Lycra*	11.4
E	Woven	65% nylon 35% elastane	7.7
H	Woven	70% nylon 30% elastane	13.4
I	Knitted	80% nylon 20% *Xlife Lycra*	8.8

Table 5.1 Selection of materials for surface modification I: stage I

5.2.2 Method

A preliminary material investigation was carried out to identify individual variables within the process of laser melting that could be used to control the level of melted material produced. Variables were tested sequentially at incremental settings across the surface of the fabric using a simple striped all-over pattern; surface effects were evaluated through manual and optical assessment. Increased levels of surface melting were demonstrated by enhanced fabric stiffness and a wet-looking appearance on the surface of the fabric.

Through this investigation two main methods for controlling the proportion of melted material were identified. The first method controlled heating of the material at the point of interaction with the laser; and the second method varied the proportion of surface coverage with the laser. Both methods controlled the amount of melting on the top surface of the fabric using programmable process variables.

The next stage of the study used mechanical testing to quantify the effect of variables, identified through the first stage of the investigation, on the elastic behaviour of the fabric.

5.2.3 Controlling heating of material at the point of interaction with the laser

The first identified method of controlling material melting was by using machine processing conditions to affect heating at the point of interaction with the laser. It was understood from previous experience using the laser to weld materials together that weld quality could be optimised by careful selection of machine processing conditions. This signified that the level of melted material was being affected, influencing the quality of the weld produced. It was considered that this same method could be used to control the amount of melted material on the surface of the fabric. This belief was reaffirmed by preliminary practical investigations: samples demonstrated a visual and mechanical change to the fabric when the laser was applied at different settings. The main adjustable machine processing conditions are power, speed and laser spot size.

5.2.3.1 Power

Laser power was tested from 10-70W at 10W increments for each of the 6 selected materials. Speed was set to 5m/min and the laser spot size was approximately 4mm wide. There were some general insights that could be drawn across all fabric types, and some particular insights relating to knitted and woven fabrics. Marking to the top surface of all the fabrics began to show at 20W; increasing in width and gaining a wetter looking appearance as power increased, which suggested an increased level of melted material. This incremental change to the appearance of the melt region can be seen in Figures 5.1 to 5.3. Knitted fabrics started to show signs of deterioration at 60W with splits occurring to the surface of the material in welded regions (Figure 5.3). Woven fabrics showed signs of deterioration at much lower powers from 20W upwards and tore under minimal force applied by hand. Woven fabrics were eliminated from further investigation at this stage due to the damage caused to the strength of the parent material.

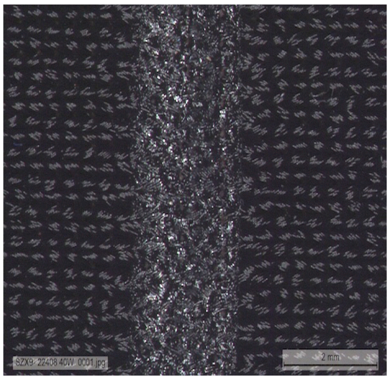
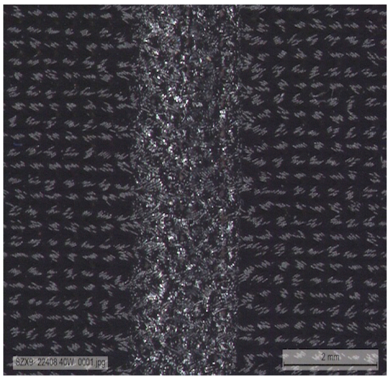
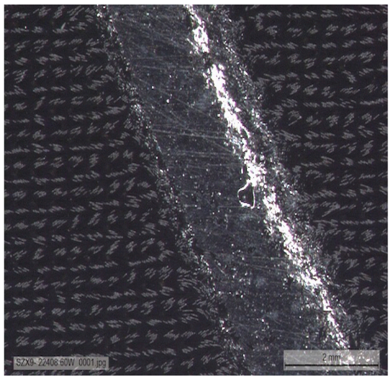
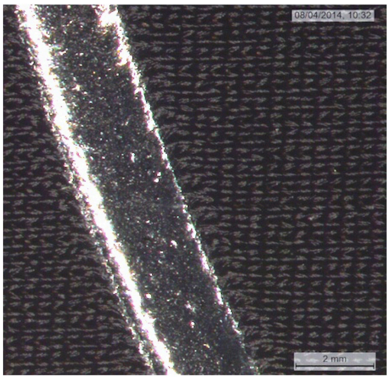
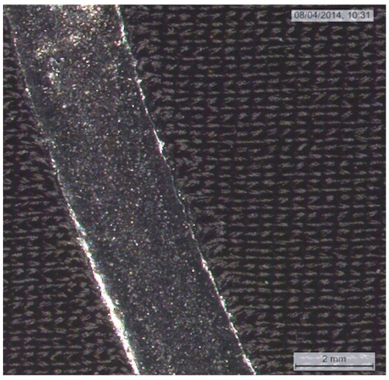




Figure 5.1 (Left) Fabric sample showing laser surface melting created using a power setting of 40W (Paine 2014)
Figure 5.2 (Centre) Fabric sample showing laser surface melting created using a power setting of 50W (Paine 2014)
Figure 5.3 (Right) Fabric sample showing laser surface melting created using a power setting of 60W (Paine 2014)

5.2.3.2 Speed

The laser is static above a moving x-y table, upon which material samples are placed (see Figure 1.3). Equipment speed refers to the speed that the table is moving. The table can operate at speeds of up to 10m/min. Speed was tested from 1-10m/min at 1m/min increments. Laser power was held at a constant level of 50W and laser spot size was maintained at approximately 4mm. The effect of varying speed on the surface of the fabric is shown in figures 5.4 to 5.6. Figure 5.6 shows the effect of the laser at the slowest speed tested of 1m/min. The melted region has a wet-looking appearance and is beginning to show some signs of degradation, as there is some cracking to the top surface of the fabric in the melted region. As speed increased it was found that the width of laser melted regions decreased and so did the wet-look appearance on the surface of the fabric. At 10m/min the appearance of the melted region was barely visible.





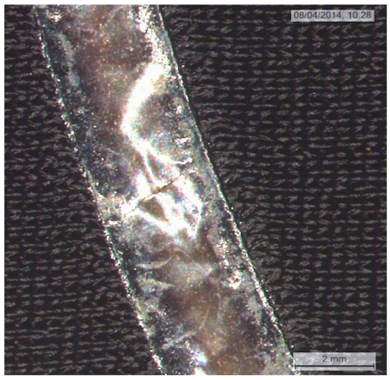


Figure 5.4 (Left) Fabric sample showing laser surface melting created using a speed setting of 3m/min (Paine 2014)
Figure 5.5 (Centre) Fabric sample showing laser surface melting created using a speed setting of 2m/min (Paine 2014)
Figure 5.6 (Right) Fabric sample showing laser surface melting created using a speed setting of 1m/min (Paine 2014)

5.2.3.3 Laser spot size

For welding applications laser spot size is generally kept at a width of 2-3mm so that there is sufficient melted material to form a strong weld without causing a detrimental effect to the appearance of the joint on the surface of the fabric. For this investigation, varying laser spot size presented an alternative method of controlling the level of material melting on the surface of the fabric. Raising or lowering the height of the laser above the x-y table adjusts the size of the laser spot. A pilot light that indicates the width of the beam or the height in between the x-y table and the laser head can be measured and recorded for repeatability. The distance in between the x-y table and the laser head was measured for this part of the investigation. Distances of 55-70mm were tested at increments of 5mm. Speed was kept at a constant level of 5m/min and laser power was maintained at 150W. The effect on the appearance of the melt line when the laser is positioned at incremental levels above the surface of the x-y table is shown in figures 5.7

to 5.9. As the laser head is raised further above the x-y table the width of the melted region on the surface of the fabric increases. Although melt width increased with spot size, heating of the material appeared to reduce, which is indicated by a reduction in colour change and the wet-looking appearance on the surface of the fabric.

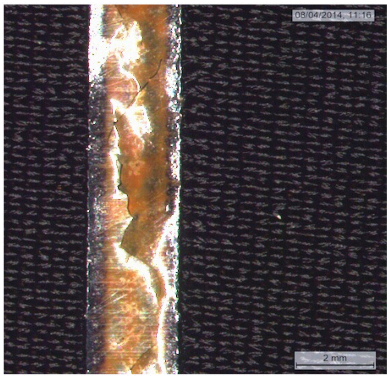
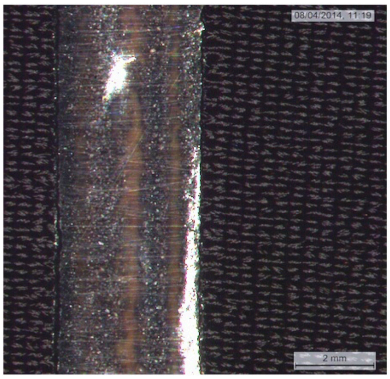
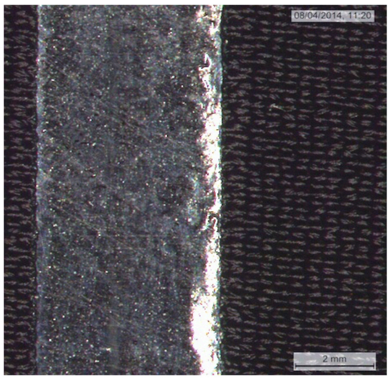




Figure 5.7 (Left) Fabric sample showing laser surface melting created with a laser height of 55mm between x-y table and laser head (Paine 2014)
Figure 5.8 (Centre) Fabric sample showing laser surface melting created with a laser height of 60mm between x-y table and laser head (Paine 2014)
Figure 5.9 (Right) Fabric sample showing laser surface melting created with a laser height of 65mm between x-y table and laser head (Paine 2014)

5.2.4 Controlling surface coverage with the laser

The first identified method used to control the proportion of melted material on the surface of the fabric used machine processing variables to affect heating of the material at the point of interaction with the laser. The second identified method of controlling the proportion of melted material was to control surface coverage of the laser on the fabric. This method of varying the level of melted material was closely related to the decorative pattern on the surface of the fabric. It was considered that dense melt patterns would have an increased effect on the elastic behaviour of the fabric compared to sparser weld patterns. This belief was reaffirmed by manual assessment of samples produced during preliminary material investigations. Fabrics with denser weld patterns demonstrated an increased resistance to force compared to fabrics with sparser weld patterns.

Having identified that melt pattern density could be used to affect the elastic behaviour of stretch fabrics, it was necessary to identify variables that could be used to control the effect on the fabric so that samples could be produced at incremental levels for mechanical testing. Following preliminary material investigations two variables were identified that could be used to control surface coverage with the laser, specifically the distance in between melt lines and the density of the pulse when the laser is applied on a pulsed beam setting.

5.2.4.1 Distance in between melt lines

The first identified method of controlling the density of the melted pattern on the surface of the fabric was by manipulating the path of the x-y table beneath the static laser head, upon which the material sample is placed. Some knowledge of the motion control software had been gained through the 'project scoping' phase of the investigation to create patterned seam designs. For this study a simple linear pattern was used that traveled backwards and forwards across the sample, moving sequentially across after each line in the programme to cover the whole surface of the fabric. A simple method of varying the coverage of the laser by changing the distance in between the lines in the programme was identified. This allowed surfaces to be created that demonstrated incremental levels of surface coverage with the laser. Figures 5.10 to 5.12 show samples with distances of 5, 10 and 15mm in between melt lines.

5.2.4.2 Applying a pulsed beam setting

An alternative variable was identified that could be used to control the density of melt pattern on the surface of the fabric. The laser beam can be irradiated as either a pulsed or continuous wave. For most welding applications a continuous wave is used to create strong sealed seams. A familiarity with this particular setting had developed during the 'project scoping' phase exploring methods for creating stretchy seams (3.3.3.2). It had been proposed that gaps in the weld line could be used to improve seam elasticity: the larger the gaps the greater the seam would be able to extend. A more thorough material investigation of this setting was explored for this study exploring all-over surface effects.

The length of the pulse on the surface of the fabric and the length of the gap in between each pulse are controlled by two separate settings: Tpuls and Trep. Each setting is measured in milliseconds and so the effect on the surface of the fabric is dependent on the speed at which the x-y table is travelling. Through material investigations it was understood that the Tpuls setting controlled the length of time that the laser was activated for each pulse. The Trep setting controlled the length of time in between the beginning of each of pulse. Increasing the length of time in between the Tpuls and Trep setting created a sparse weld pattern; whereas, setting the Tpuls and Trep close together created a dense weld pattern. Figures 5.13 to 5.15 show the effect of changing the Tpuls setting on the surface of a single fabric layer.

5.2.5 Summary

An understanding of programmable machine variables that could be used to control the degree of melting both across the surface and through the depth of the fabric was gained through this preliminary stage of investigation.

A summary of **the main insights** is provided below:

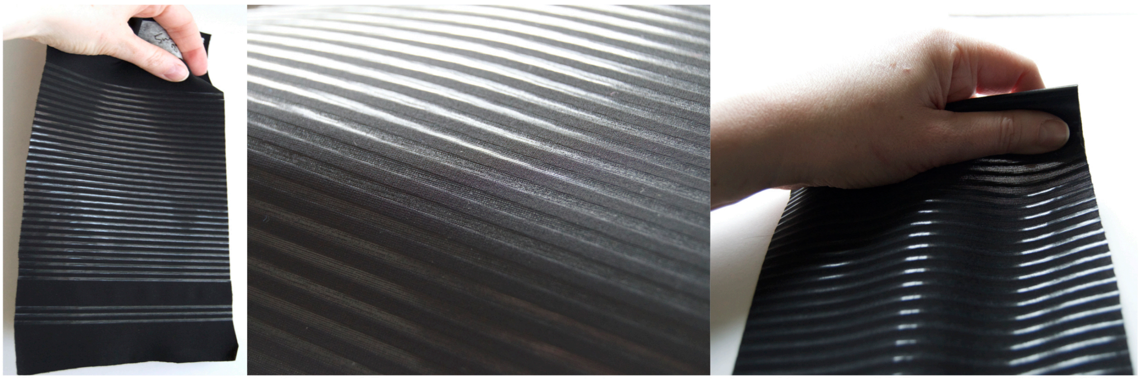
• Power and speed settings demonstrated a controlled effect on the surface of the fabric when implemented at incremental settings. Surface melting increased at slower speeds and higher powers

• Laser spot size did not have a clear effect on the amount of melted material produced

• A greater laser spot size increased the width of the melted region, whilst heating of the material at the point of interaction with the laser decreased

• Varying the distance in between melted lines is a simple way to control the proportion of melting on the surface of the fabric

• A pulsed laser setting can also be applied to control the proportion of melted material



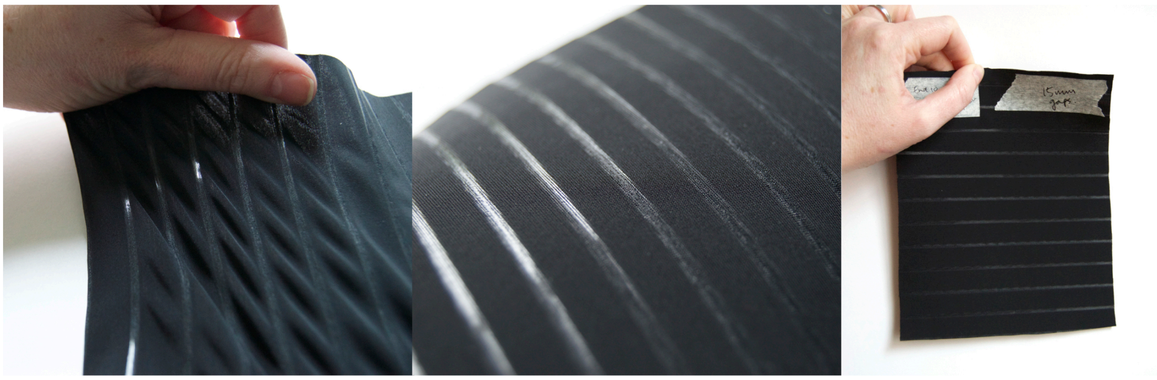
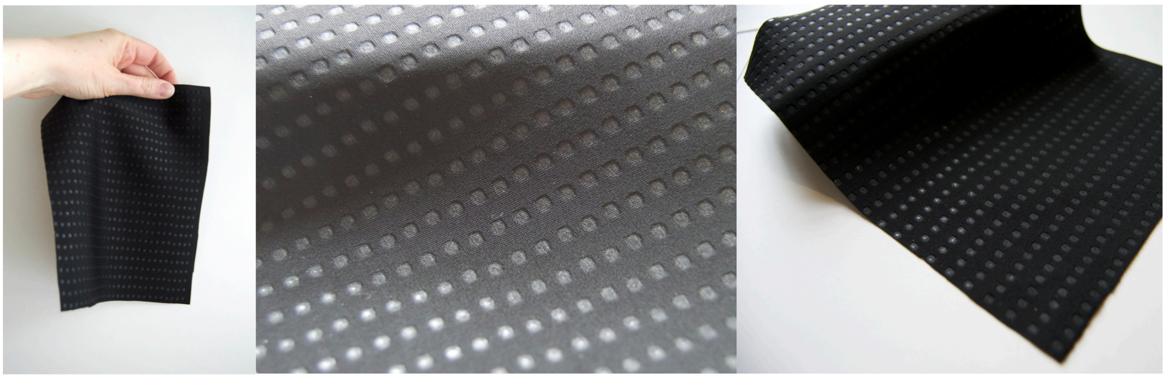
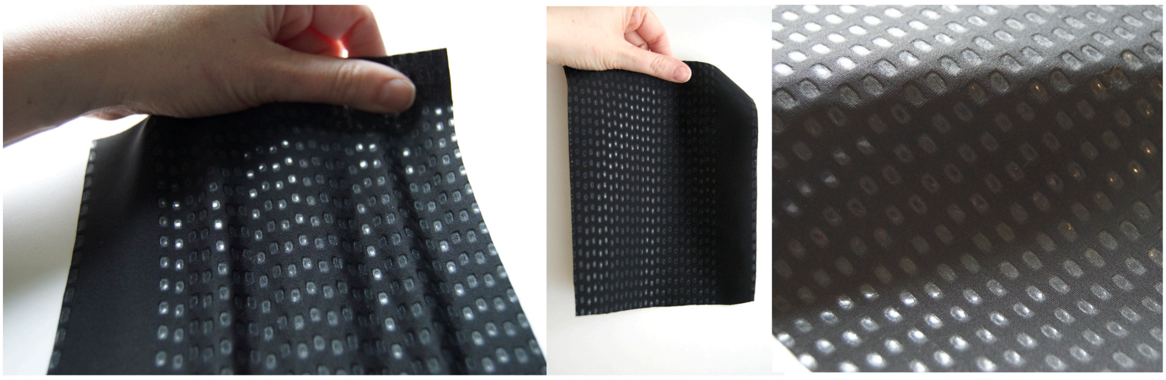


Figure 5.10 (Top) Fabric sample with laser melted lines, 5mm apart (Paine 2014)
Figure 5.11 (Middle) Fabric sample with laser melted lines, 10mm apart (Paine 2014)
Figure 5.12 (Bottom) Fabric sample with laser melted lines, 15mm apart (Paine 2014)





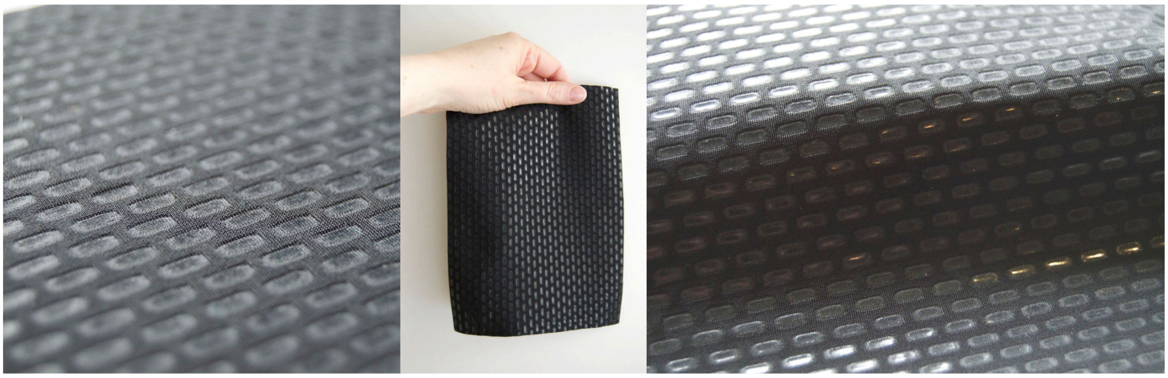


Figure 5.13 (Top) Fabric sample with laser melted spots, Tpuls 30 ms, Trep 100ms (Paine 2014)
Figure 5.14 (Middle) Fabric sample with laser melted spots, Tpuls 50 ms, Trep 100ms (Paine 2014)
Figure 5.15 (Bottom) Fabric sample with laser melted spots, Tpuls 70 ms, Trep 100ms (Paine 2014)

5.3 Testing the mechanical effects of melted material on the fabric

The first stage of this study explored methods of controlling the amount of melted material on the top surface of the fabric using assessment by eye only. The second stage of this study set out to measure the effect of melted surfaces on the elastic behaviour of the fabric using mechanical testing equipment. Three variables that had demonstrated a significant and controllable effect from the first stage of the study were selected for investigation. These were laser power; distance between melt lines and pulse density.

5.3.1 Materials and equipment

The investigation continued to use the diode laser made available to the research by TWI and testing equipment made available by Speedo (3.3.1).

Only single layers of fabric that were absorbent to the infrared wavelength of the laser beam were included in the first stage of the investigation (5.2.1). Most of the fabrics that had been supplied by Speedo were black in colour, which suggested they contained carbon pigment, and were absorbent to the near-infrared wavelength of the laser beam. Woven absorbent fabrics had been eliminated due to their reaction to the laser, which had significantly reduced the parent strength of the materials (5.2.3.1).

For this second stage of the investigation double layer material configurations were reintroduced. It had been discovered through 'the stretch seaming and surfaces investigation' during the 'project scoping' phase of the research that joining a dark absorbent fabric to an upper lighter coloured transparent layer could create a decorative surface pattern (3.3.3.2). The melted material from the underlying dark fabric layer was revealed through the surface of the upper transparent layer creating a decorative surface effect. The visual appearance of this technique on the surface of the fabric was enhanced when large panels of fabric were joined together. Methods of varying the level of melting were the same for double layer material configurations as they were for single layer materials. The main difference in double layer material configurations was that the melted region is maintained at the interface of the joint and not on the surface of the fabric.

A potential application area for double layer material configurations was identified through consultation with Speedo. Speedo's [redacted] range of competitive swimsuits uses lining panels on the inside of the garment, providing an extra layer to cover private areas of the body [redacted] It was considered that laser welding could be used as an alternative method of joining these panels to the inside of the swimsuit. Laser welded patterns across the surface of the fabric could be used to add variable zones of compression to selected areas [redacted].

Fabric D, a knitted black fabric that is absorbent to the laser beam, was selected for the single layer material samples developed through this second stage of the study. Fabric A (woven) was used in combination with Fabric C (knitted) for double layer material configurations.

Fabric	Colour	Construction	Composition	Proportion of laser energy transmitted (%)
A	Blue	woven	80% nylon 20% elastane	41.9
C	Black	knitted	80% nylon 20% Xlife Lycra	0
D	Black	knitted	80% Nylon 20% Xlife Lycra	11.4

Table 5.2 Selection of materials for surface modification I: stage II

5.3.2 Method

Using material investigation a base set of parameters for both single and double layer material configurations was established. Power and speed, which are the main programmable machine parameters, were tested sequentially whilst all other settings were held at a constant level. Surface quality was assessed optically.

Once a suitable set of machine parameters had been established for both single and double layer material configurations, samples exploring each of the three main variables that had been identified to affect the level of melted material were produced separately at three incremental levels.

Three samples were cut for each variable level so that an average reading could be calculated during mechanical testing. Samples measuring 50 x 140mm were cut in accordance with the British Standard; 1992 2.1 & 2.2 Elastic Fabrics Extension and Modulus, used by Speedo. The same testing equipment that was used to measure seam strength during the 'project scoping' phase of the research was used for this study (3.3.1). The fabric sample is pulled and released three times at a constant rate of 500mm/min to obtain an average reading during a single test cycle. A force vs. extension graph is plotted at a workstation situated next to the mechanical testing equipment. Measurements are extracted from the graph at 40% extension and 36N. Fabrics were tested in the warp direction. According to the specification for Fabric D provided by Speedo, Force in the warp direction at 40% extension is 0.7 to 1.2 N; and extension at 36N is 175 to 235%. It is not relevant to provide information regarding the specified extension/modulus for the double material configuration as two fabrics of different elastic behaviours were combined together.

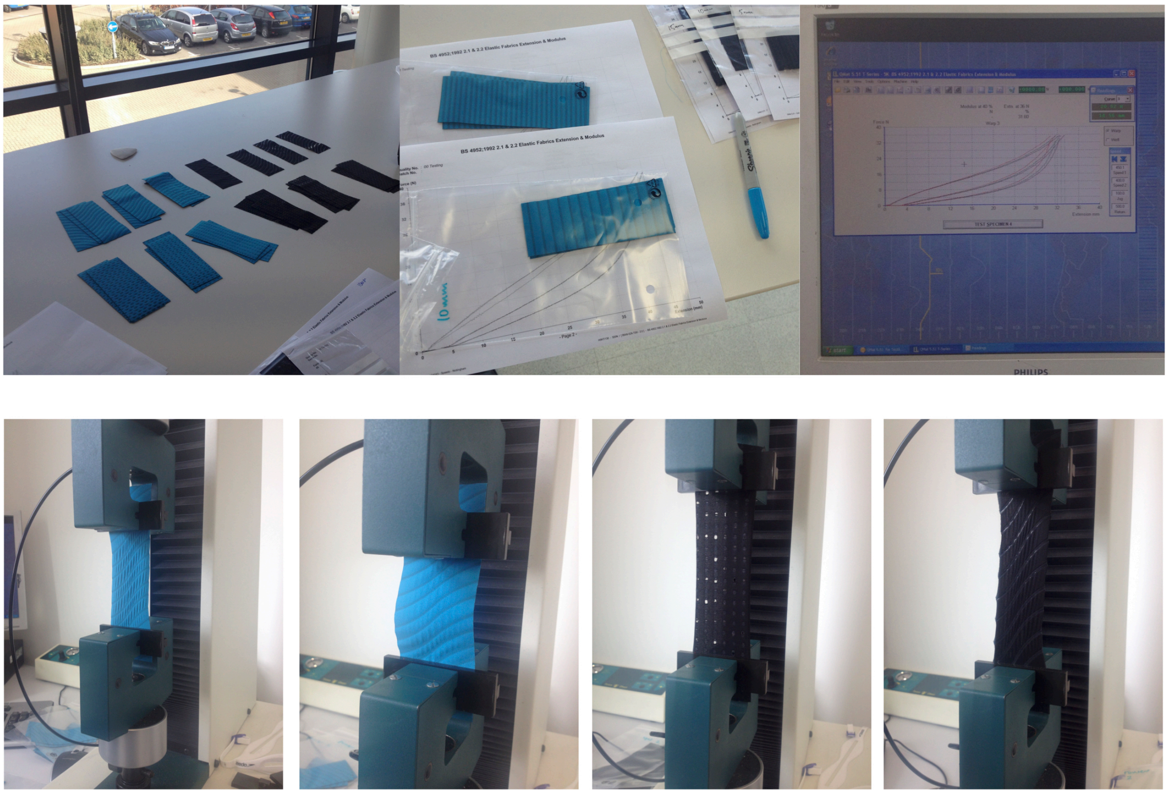


Figure 5.16 Mechanical testing of all-over surface effects at Speedo (Paine 2014)

5.3.3 Results

For each variable setting a measurement of force, at an extension of 40%, and extension, at a force of 36N, was extracted by the testing software. The results revealed for all 3 variables tested that fabric extension reduced and the force taken to extend the fabric increased with an increase in surface melting. Results for each variable are provided in the following part of this chapter section.

5.3.3.1 Power

Test results for both single and double layer material configurations showed that the force required to pull the fabric increased and fabric extension decreased with an increase in weld power.

Sample number (For images refer to 8.5)	Power (W)	Average force at 40% extension (N)	Average extension at 36N (%)
POWER S 30	30	2.56	105.07
POWER S 40	40	3.29	92.63
POWER S 50	50	3.52	83.93

Table 5.3 Single layer mechanical testing results for power (Fabric D)

Sample number (For images refer to 8.5)	Power (W)	Average force at 40% extension (N)	Average extension at 36N (%)
POWER D 70	70	16.52	51.27
POWER D 90	90	19.81	47.53
POWER D 110	110	21.27	46.27

Table 5.4 Double layer mechanical testing results for power (Fabric A, Fabric C)

5.3.3.2 Distance in between melt lines

Test results for both single and double layer material configurations showed that the force required to pull the fabric increased and fabric extension decreased the closer the distance in between melt lines.

A force measurement was not recorded for a double layer material configuration with a distance in between melt lines of 5mm, as the sample did not reach 40% extension.

Sample number (For images refer to 8.5)	Distance in between melt lines (mm)	Average force at 40% extension (N)	Average extension at 36N (%)
DISTANCE S 5	5	8.6	57.6
DISTANCE S 10	10	4.36	82.2
DISTANCE S 15	15	3.12	96.9

Table 5.5 Single layer mechanical testing results for distance in between melt lines (Fabric D)

Sample number (For images refer to 8.5)	Distance in between melt lines (mm)	Average force at 40% extension (N)	Average extension at 36N (%)
DISTANCE D 5	5	No reading	29.79
DISTANCE D 10	10	24.2	44.87
DISTANCE D 15	15	16.93	51.1

Table 5.6 Double layer mechanical testing results for distance in between melt lines (Fabric A, Fabric C)

5.3.3.3 Pulse density

Testing results for a single layer material showed that the force required to pull the fabric increased and fabric extension decreased the longer the length of the laser pulse (Table 5.7).

Force measurements were not recorded for double layer material configurations, as samples did not reach 40% extension. Fabric extension decreased the longer the length of the laser pulse, following the same pattern as a single material layer (Table 5.8).

Sample number (For images refer to 8.5)	Length of pulse (ms)	Average force at 40% extension (N)	Average extension at 36N (%)
PULSE S 30	30	3.69	90.1
PULSE S 50	50	6.52	63.8
PULSE S 70	70	10.6	54.6

Table 5.7 Single layer mechanical testing results for length of pulse (Fabric D)

Sample number (For images refer to 8.5)	Length of pulse (ms)	Average force at 40% extension (N)	Average extension at 36N (%)
PULSE D 30	30	No reading	39.09
PULSE D 50	50	No reading	32.57
PULSE D 70	70	No reading	27.16

Table 5.8 Double layer mechanical testing results for length of pulse (Fabric A, Fabric C)

Figure 5.17 shows the negative effect the proportion of material melting controlled by altering pulse density has on the extension of the fabric at a force of 36N. As the pulse density increases a downward trend in fabric extension is revealed for both single and double layer material configurations.

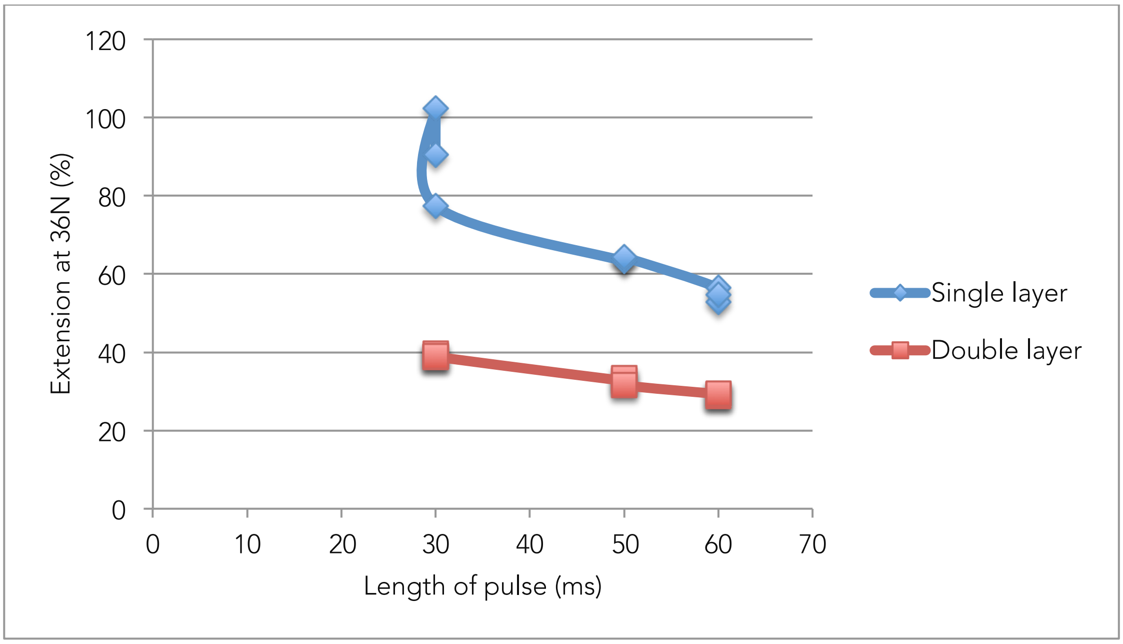


Figure 5.17 Graph showing the effect of pulse density on fabric extension

Figure 5.18 shows the positive effect the proportion of material melting controlled by altering pulse density has on the resistance of the fabric at an extension of 40%. As the pulse density increases an upward trend in force at 40% extension is revealed.

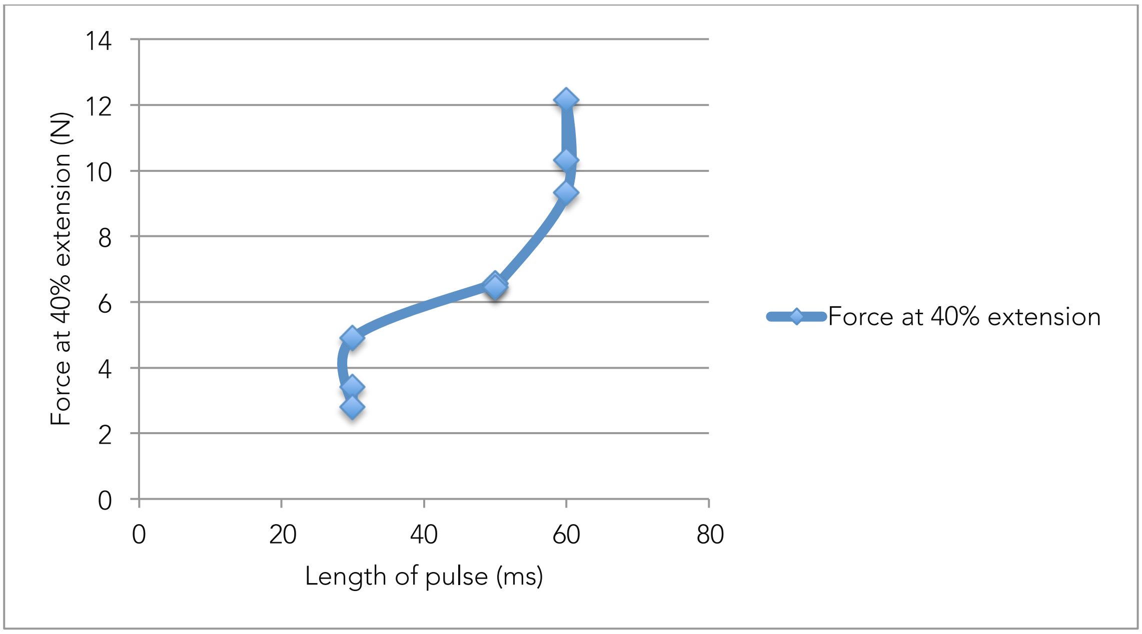


Figure 5.18 Graph showing the effect of pulse density on fabric resistance

5.3.4 Opportunities for investigation presented by anomalous results

The results presented demonstrate a linear causal relationship between the amount of melted material and the effect on the elastic behaviour of the fabric. The effect of individual variables at incremental settings has been demonstrated on both single and double layer material configurations.

The results that have been presented were obtained over two rounds of testing. During the first round of testing a wavy surface pattern had been applied to the samples exploring different power settings. This was true for both double and single layer samples. The effect of the wavy pattern on the results of the mechanical testing had not been considered, however, the researcher was alerted after obtaining some anomalous results. Single layer materials prepared at 60W tore during testing as they were being pulled. There was also an exception to the pattern of results. For all the samples tested, fabric extension had decreased with an increase in surface melting. This was not true for the double layer material configuration exploring different weld powers. Extension decreased from 70W to 90W, and then increased again at 110W. This highlighted to the researcher the effect of the wavy surface pattern, which had not been used for any of the other samples tested. Samples exploring power were prepared and tested again using a straight line pattern, which provided the results that have been presented.

The anomalous results obtained through the first round of testing had highlighted effects of the laser melting process that had not been known prior to the study. For this study it was necessary to eliminate any factor that could cause inconsistencies within the results; however, new opportunities to explore the effect of melt pattern orientation on fabric extension and laser power on the tensile strength of the fabric were suggested as a result of these insights.

5.4 Summary

This study has been carried out to explore the effects of laser melted patterns on stretch textile materials. An understanding that laser melted patterns could be used to control the elastic behaviour of stretch fabrics had been gained through the 'project scoping' phase, and a belief that this effect could be used to compress the body for athletic advantage had developed through consultation with Speedo (3.3.4). The main objective of the study was to develop methods for controlling the amount of melted material to create fabrics of variable flexibility using precise and repeatable methods.

The study was carried out in two parts: the first part explored the effect of a range of variables on the surface melting of a single layer of stretch fabric. Assessment of the effects of this material investigation was carried out by eye only and three variables were selected for mechanical testing during the second stage of the study to quantify their effect on the elastic behaviour of the fabric.

During the first stage of the investigation laser power and speed had been identified as individual variables that could be used to control the amount of melting on the surface of the fabric (5.2.3). This was indicated by the quality of the melt region on the surface of the fabric, and specifically the wet-looking appearance, which increased with enhanced melting. Slow speeds and high powers increased the amount of melting. It was found that the precise programming of these variables could control the amount of melting, indicated by the appearance on the surface of the fabric. The effect of laser spot size was less conclusive and as such was eliminated from further investigation (5.2.3.3). It was also identified that surface coverage with the laser could be used as a method of controlling the amount of melting across a given surface area (5.2.4). By either affecting the path of the x-y table beneath the laser head or applying the laser on a pulsed setting it was found that surface coverage could be controlled precisely.

The second half of this study (5.3) has tested the mechanical effects of controlled melting on the elastic behaviour of the fabric. The effect of weld power, the distance in between weld lines and the pulse density of the laser were the three variables selected for further investigation. Samples prepared for mechanical testing explored effects created using both single and double layer material configurations. The main insights from this second stage of the investigation are:

• There is a direct relationship between the amount of melting and the elastic behaviour of the fabric

• Fabric extension decreases and the force required to extend the fabric increases with an increase in melting

• This controlled effect on the elastic properties of the fabric was true for each of the three variables tested

• This study has demonstrated that laser melted patterns can be used to control the elastic behaviour of stretch fabrics to create variable predictable effects

Other insights leading to further stages of investigation are that the orientation of the melted pattern has an effect on the extension of the fabric and surface melting could reduce the tensile strength of the fabric when used to treat a single fabric layer.

6 Surface modification II

6.1 Introduction

The final body of work for this research project forms the basis of this study 'surface modification II', which has been split into two parts. The first part of the study explores new opportunities for investigation, which were identified following insights gained through mechanical testing during 'surface modification I', namely the effect of melt orientation on the elastic behaviour of the fabrics and the effect of surface melting on the tensile strength of the fabric. The second part of the study seeks to validate the compressive effect of the fabric by testing prototype garments using 3D body scanning equipment and a pressure measurement system.

6.2 Testing of insights identified during Surface modification I

6.2.1 Effect of melt pattern orientation on elastic behaviour

A straight line all-over surface pattern that travels backwards and forwards across the surface of the fabric had been used to produce samples for mechanical testing during 'surface modification I'. However, during a preliminary round of testing a wavy surface pattern had been used that had revealed an unexpected effect on the results (5.3.4). Samples were cut across the wavy surface design and orientation of the melt lines varied depending on the section of the wavy surface design they had been cut from (Figures 6.1 to 6.3). Using a straight line pattern it was revealed that fabric extension decreased with an increase in surface melting. This was not true for the samples cut across the wavy surface design, which produced an anomalous result. This alerted the researcher to the fact that melt pattern orientation could be an unexplored process variable, which could have a controllable effect on the elastic behaviour of the fabric. Samples that had been produced using a wavy surface design were retested during 'surface modification I' using a straight line surface design and the anomaly was omitted from the results, which supported further the belief that melt pattern orientation has an effect on the elastic behaviour of the fabric.

Through consultation with Speedo it was understood that this effect of melt pattern orientation on the elastic behaviour of the fabric could be used to manipulate movement of the body during athletic activity, providing resistance to targeted muscle groups; and could even be used to improve body positioning for optimum performance, providing targeted resistance that is tailored to an individual's stroke pattern. This insight provided validation to explore the effect of melt-pattern orientation further and gather evidence to quantify the effect.

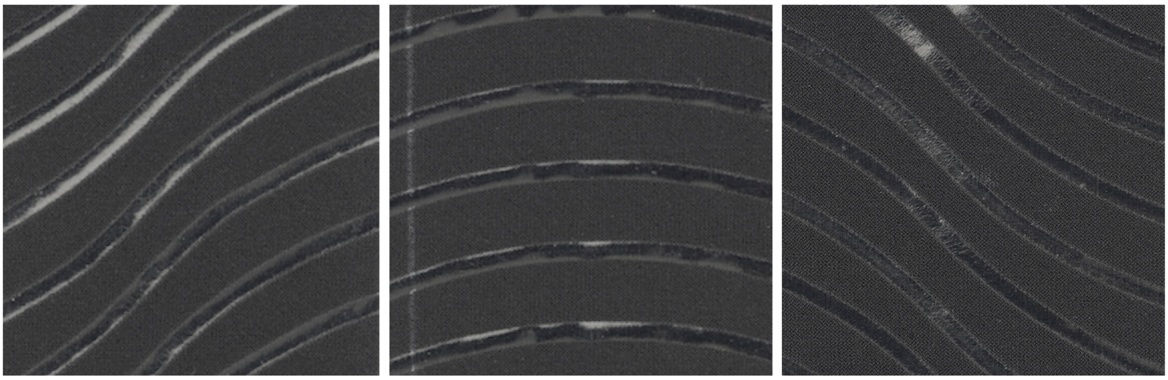


Figure 6.1 (Left) Fabric sample showing left side of curved laser melted pattern (Paine 2014)
Figure 6.2 (Centre) Fabric sample showing middle section of curved laser melted pattern (Paine 2014)
Figure 6.3 (Right) Fabric sample showing right side of curved laser melted pattern (Paine 2014)

6.2.1.1 Selection of materials

It had been identified during 'surface modification I' that knitted fabric supplied by Speedo were more suitable for surface melting by the laser than woven fabrics (5.3.1). The tensile strength of woven fabrics had been significantly reduced by the process; tearing under minimal force applied by hand. Fabric C, a knitted fabric that had shown a high level of absorbency to the laser and compatibility with the laser melting process, was selected for this investigation.

6.2.1.2 Method and equipment

The investigation continued to use the diode laser made available to the research by TWI and mechanical testing equipment made available by Speedo (3.3.1). Microscopic analysis of samples was carried out using an Olympus SZX9 stereomicroscope made available at TWI.

The parameter settings for treating Fabric C had been established during 'surface modification I'. All parameter settings were held at a constant level and the wavy melt pattern was applied to the surface of the fabric using the laser. Samples for mechanical testing were cut from three areas across the width of the fabric; each capturing a different orientated section from a singular curve of the wavy surface pattern (Figures 6.1 to 6.3). Three samples for each differently orientated section were cut so that an average result for each section could be calculated. Samples were prepared to the same dimensions and tested as before during 'surface modification I' using the industry testing method for fabric extension used by Speedo. A force vs. extension graph was plotted for each of the samples tested and an average extension at 36N and force at 40% extension was calculated for each differently orientated section by the system's software. Samples were tested in the warp direction, and, according to the specification for Fabric C provided by Speedo, force in the warp direction at 40% extension is 2.7N ±25%; and extension at 36N is 100% ±15%.

6.2.1.3 Results

The specification of the parent material used for this investigation has a defined modulus and extension range. The modulus, as referred to by Speedo, defines the force required to pull the material to 40% extension. The extension defines the percentage the fabric stretches under a force of 36N. Untreated Fabric C has a specified range of extension of 100% ±15% and a modulus of 2.7N ±25%. The results obtained for the middle curve section (Figure 6.2) do not reveal any significant effect on the extension/modulus of the fabric as they fall within the range for the untreated fabric defined by the specification. The laser melting process at the outer edges of the curved surface design (Figures 6.1 and 6.3) demonstrate a more notable effect as fabric extension is reduced to approximately 75%, which is 10% below the lower value in the specified range for the untreated fabric; and modulus is increased to over 4N, which is above the upper value of the specified range for the untreated fabric.

Weld orientation	Average force at 40% extension (N)	Average extension at 36N (%)
Outer edge of curve (right)	4.37	73.53
Outer edge of curve (left)	4.13	75.3
Middle curve	2.56	92.1

Table 6.1 Mechanical testing results for the effect of surface pattern orientation (Fabric C)

6.2.2 Effect of surface melting on the tensile strength of the fabric

During the preliminary round of mechanical testing for 'surface modification I' testing the effect of different process variables on the extension and modulus of the fabric a sample had torn under moderate force (5.3.4). The testing procedure stretches the fabric three times to obtain data regarding the elastic behaviour of the fabric and fabric samples should be retained in one piece. This premature failure of the fabric alerted the researcher to the fact that the process of laser melting could impair the tensile strength of the parent material. Laser melting had been demonstrated as a method to control the elastic behaviour of stretch textiles that could be used to compress the body for sportswear applications; however, the effect of the process on the tensile strength of the fabric had been identified as a possible drawback of the technique that required further investigation. Two variables were selected for further investigation. Laser power and pulse density had both demonstrated a controllable effect on the elastic behaviour of the fabric when tested during 'surface modification I' and were selected for further investigation. Fabric C was used for the preparation of samples.

6.2.2.1 Method

Using the diode laser equipment at TWI (3.3.1) an all-over straight line pattern was used to cover the surface of the fabric. Two large fabric samples, which were cut into smaller samples for testing, were produced. The first sample explored different power settings across the width of the fabric ranging from 30-60W at 10W increments. Bands of laser melted pattern that were approximately 20cm wide were produced for each power setting across the width of the fabric sample. Equipment speed was maintained at 5m/min. The laser was operated on a pulsed setting at three incremental settings for the second sample at a speed of 5m/min and power setting of 50W. Three samples were cut for each power and pulse setting so that the mechanical testing software could calculate an average result for each setting. Samples were cut to the dimensions specified in the British Standard BS 4674 Tensile Tenacity Test used by Speedo. A force vs. extension graph was plotted for each of the samples tested and an average force to break was calculated for each laser power and pulse setting. Untreated samples of Fabric C did not break when tested with a force of 500N.

6.2.2.2 Results

Results show that the laser melting process reduces the tensile strength of the fabric, however, the adjustment of weld power and laser pulse density can help to limit the effect to the fabric. As weld power increases so does the average force to break until a power of 60W is reached, when there is a reduction in the average force to break (Table 6.2). As the density of the laser pulses on the surface of the fabric increase there is a reduction in the tensile strength of the fabric (Table 6.3); however, the detriment overall to the tensile strength of the fabric on a pulsed setting is less severe compared to a continuous laser setting which was used to explore the effect of weld power (Table 6.2).

Sample number (For images refer to 8.5)	Power (W)	Average force to break (N)
POWERBREAK 30	30	100.33
POWERBREAK 40	40	129.23
POWERBREAK 50	50	146.43
POWERBREAK 60	60	134.07

Table 6.2 Mechanical testing results for the effect of laser power on force to break (Fabric C)

Sample number (For images refer to 8.5)	Mpuls (ms)	Average force to break (N)
PULSEBREAK 30	30	478
PULSEBREAK 50	50	268.8
PULSEBREAK 70	70	269.07

Table 6.3 Mechanical testing results for the effect of laser pulse length on force to break (Fabric C)

6.2.2.3 Microscopic analysis of the effect of power

Microscopic evaluation of the effect that weld power had on the cross section of the stretch textile samples was carried out using equipment made available to the research at TWI. Working closely with a technical assistant it was possible to mount and polish the samples and examine the effect on the fibres through the depth of the fabric.

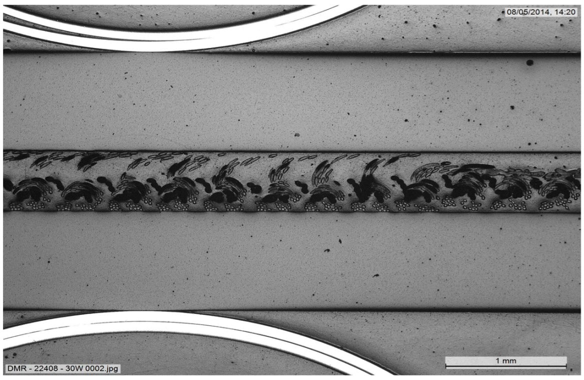
6.2.2.3.1 Preparation of samples

A small fabric sample, approximately 2cm x 2cm in size, was cut for each of the weld powers that had been mechanically tested. Each sample was sandwiched in between two small plates of glass with the laser melted edge positioned at the edge of the glass plates. The glass plates were pinched together using a metal clip and stood inside a rigid plastic mould with the laser melted edge of the fabric facing the bottom. Resin was poured into the mould and left to set overnight. Upon release from the mould the glass plates and fabric sample were suspended at the centre of the resin block. The base of the resin block was sanded and polished so that the edge of the fabric with the laser melted part was exposed on the exterior. This resin mount provided a rigid support for the sample and made it possible to view under the microscope. See Figure 6.4.

Figure 6.4 Process of mounting and polishing sample for microscopic analysis (Paine 2014)

6.2.2.3.2 Results

It was apparent from looking at the samples under the microscope that fibres were compacted together as a result of exposure to the laser and this effect increased with laser power. Thinning of the fabric is indicated by gaps in between the glass plate and the surface of the fabric, which increase with laser power (Figure 6.6). Separation between fibres is greater at lower power settings (Figure 6.5).



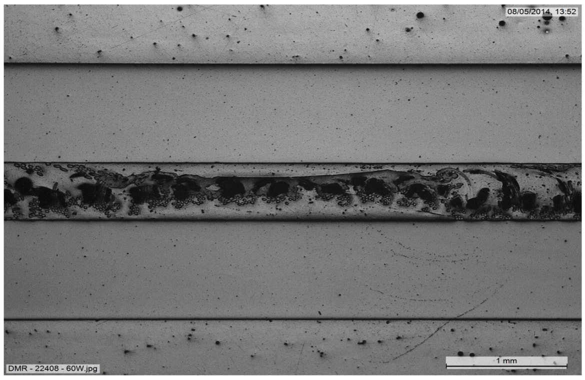


Figure 6.5 (Left) Cross section of fabric sample with surface melting created using a laser power of 30W (TWI 2014)
Figure 6.6 (Right) Cross section of fabric sample with surface melting created using a laser power of 60W (TWI 2014)

6.2.3 Summary

This first part of the study has explored the effect of variables; specifically pattern orientation, laser power, and pulse density on the process of laser melting identified through anomalous results that occurred during 'surface modification I' (5.3.4). The effect of the orientation of laser melted surface patterns on the elastic behaviour of stretch fabrics and the effect of surface melting on the tensile strength of the fabric have been tested.

<u>The main insights are:</u>

• The orientation of the melt pattern lines on the surface of the fabric has a direct impact on the elastic behaviour of the fabric

• Melt pattern lines orientated in a steep slope almost perpendicular to the line of force demonstrate decreased extension and require more force in comparison to melt pattern lines that are almost parallel to the direction of the line of force

• The effect of melt pattern orientation could be used to control body movement and apply resistance to targeted muscles for swimming

• Surface melting does have a negative effect on the tensile strength of the fabric; however, pulse density and power variables have been demonstrated as methods that can be used to mitigate this effect

6.3 Compression validation

Having widely explored the effect of laser melting on stretch fabrics and identified variables as a means of controlling the effect; the final phase of the investigation was to validate the research by testing the compressive effect on the body. Speedo offered the following statement for the research and description of their requirements for compression apparel:

> 'We approach fit differently for the preference of different consumers. Some consumers find high compression more comfortable, others find it uncomfortable. Certain areas on the body require different support, so it's important compression levels can vary. This can be done by material manipulation, pattern cutting or surface application. The method Helen has created offers a unique ability to increase precision of application, graduate the targeted zones to aid a smooth transition from one power to another. [redacted]

[redacted]

6.3.1 Equipment

Prototype garments were produced using the laser welding equipment at TWI (3.3.1) and sewn together by a technical assistant at Speedo. Sizestream 3D body scanning equipment and a [redacted] measurement system were used to quantify the compressive effect of the garments on the body.

6.3.2 Prototype development

The simplest method to test the compressive effect of the fabric on the surface of the body was to compare the effect of a laser treated garment with a garment that had not been treated with the laser. Both the garments that were produced were identical except for the laser-melted surface, which was only applied to one of the garments. This meant that any difference in the results obtained between the two garments could be attributed to the laser-melted surface. This chapter section outlines the work that was carried out to develop the prototypes for testing. Compression values obtained will be discussed in relation to baseline requirements suggested by Speedo.

6.3.2.1 Methods for creating targeted compression

Compression garments currently used in the sportswear industry sportswear industry apply variable targeted compression to streamline the silhouette into a more aerodynamic shape. The elastic behaviour of the fabrics used varies across the surface and can be engineered to suit the requirements of a particular application and manipulate the shape of the body into the desired silhouette. A thorough understanding of methods for controlling the elastic behaviour of the fabric using programmable laser settings had developed through 'surface modification I' (5) and the first part of 'surface modification II' (6.2); however methods of directing the laser beam to specific areas of the fabric to create targeted compression without marking across the whole surface had yet to be explored.

6.3.2.1.1 Selection of materials

A selection of laser cut swimsuit fronts were supplied for this investigation by Speedo. Single layer and double layer material configurations explored were the same as those used during 'surface modification I,' which had shown a good level of compatibility with the laser melting process. Absorbent knitted swimsuit fronts were treated as a single layer. Transparent woven swimsuit fronts were explored in combination with absorbent knitted lining fabric pieces.

6.3.2.1.2 Method

Methods for creating zones of targeted compression were explored through material investigation working with the laser welding equipment at TWI (3.3.1). A familiarity with the equipment and consultation with laser experts at TWI assisted with the development of processes that could be used.

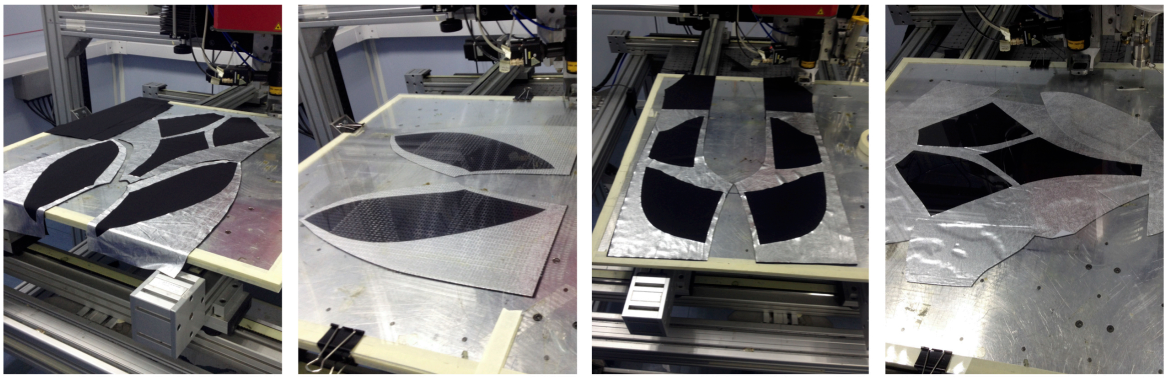
6.3.2.1.3 Motion control software

The first identified method for creating targeted compression across a single fabric layer was by manipulating the melted pattern that is drawn onto its surface by the laser beam. Some understanding of programming the motion control software that moves the x-y table beneath the static laser head had developed through the earlier stages of the investigation (3.3.3.2). All-over surface patterns that almost completely cover the surface area of the x-y table had been developed. The fabric sample to be treated can be placed at almost any position on the table and will be covered by the laser beam. In order to create targeted zones of compression that do not cover the whole surface of the fabric it would be necessary to create programmes where the laser is turned on and off repeatedly. It would take a considerable amount of time to create programmes with this level of complexity as all commands are currently programmed into the software by hand. Applying the laser beam in short bands across the width of the fabric demonstrated that the laser could be applied to selected portions of the garment. See Figure 6.7

Figure 6.7 Prototype swimsuit garment revealing targeted zones of compression created using motion control software (Paine 2014)

6.3.2.1.4 Reflective stencils

Masking the path of the laser beam by using reflective materials was also identified as a method for creating discrete zones of compression across the surface of a fabric. A selection of reflective papers and fabrics were selected for investigation. It was found some materials were more reflective to the laser than others. No marking to the top surface of the reflective materials after being treated with the laser indicated this. Highly reflective materials tended to be the most effective. A knitted nylon fabric with a reflective coating on the surface was selected for the laser treatment of swimsuit fronts. Reflective stencils that covered the surface of the swimsuit, but had holes cut in strategically placed areas so that the laser beam was exposed on the top surface of the fabric, were produced in collaboration with Speedo. A laser cut method of production for the stencils was used. A reflective stencil was positioned on top of a single absorptive swimsuit layer. The laser was operated using an all-over surface pattern that covered the surface of the x-y table. The laser only marked the absorbent fabric zones, revealed by the holes in the reflective stencil. It was advised by laser experts at TWI that this method of using reflective stencils to mask the path of the laser beam could cause damage to the diodes within the laser head if used extensively; however, the laser could be tilted to assist in the mitigation of this unwanted effect. See Figures 6.8 and 6.9



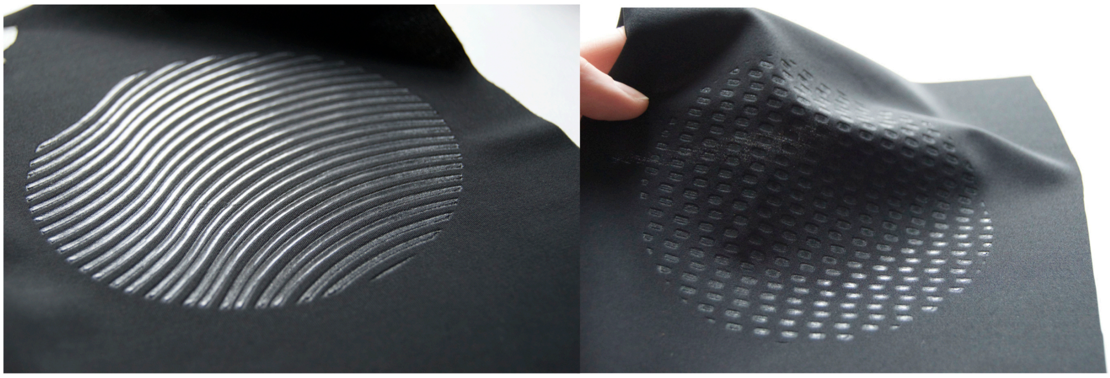


Figure 6.8 (Top) Method of creating targeted zones of compression using reflective stencils and TLW equipment (Paine 2014)
Figure 6.9 (Bottom) Fabric samples with zones of compression created using reflective stencils and TLW equipment (Paine 2014)

6.3.2.1.5 Absorbing lower panels

It was understood that for TLW the top material layer in the weld configuration should be transparent to the near infrared wavelength of the laser beam. The laser can either be absorbed by infrared absorbing dye placed at the interface of two material layers that are transparent to the laser or in the bulk of a lower layer that is absorbing to the laser (3.3.3.2). During 'surface modification I', placing a black absorbent layer beneath a transparent top layer of fabric developed a decorative method of exposing the weld pattern (5.3.1). Through mechanical testing it had been demonstrated that the amount of melted material at the interface of the joint could be controlled using the same variables that were used to control the amount of melted material on the surface of a single absorbent layer (5.3).

A method for creating targeted zones of compression using a double layer material configuration was developed by placing pre-cut shapes of black laser absorbent fabric beneath a swimsuit front made from fabric that was transparent to the laser. The laser was passed over the whole surface of the x-y table in a linear all-over pattern, but was only absorbed by the black laser absorbent shapes placed beneath the swimsuit. The rest of the swimsuit was left unaffected as the laser beam was transmitted through the fabric instead of being absorbed. See Figure 6.10

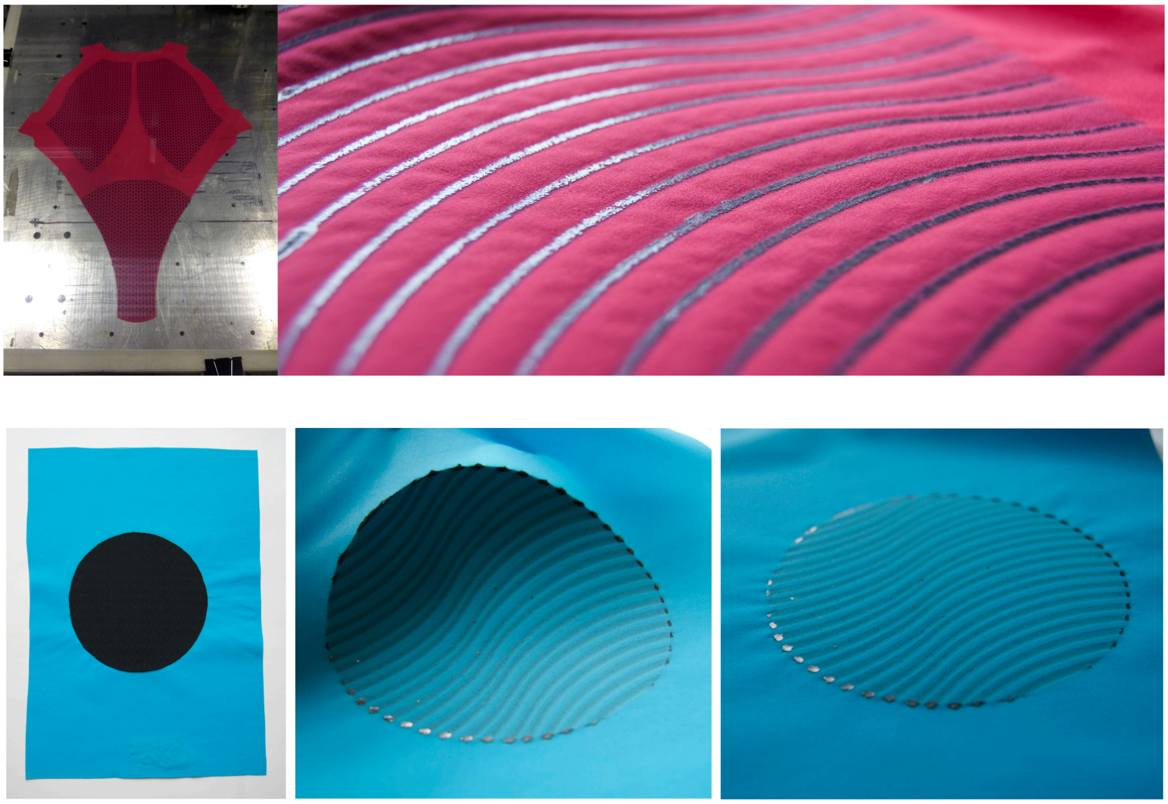


Figure 6.10 Fabric samples with zones of compression created using absorptive lower panels and TLW equipment (Paine 2014)

6.3.2.2 Garment design and construction

Having explored methods for creating areas of targeted compression the development of the swimsuit for testing was carried out in close partnership with Speedo. The simplest method of measuring the compressive effect of the fabric on the body was to compare it to a fabric that had not been treated with the laser. It was understood through consultation with Speedo that lining fabrics have a compressive effect on the body, so a single layer of absorbent fabric that would give a clearer indication of the effect of the laser melted pattern was used for the design of the prototype. A simple racing swimsuit pattern with long legs was selected so that there were numerous zones of the body that could be tested. The polyurethane panels applied to the surface of the original Speedo LZR Racer swimsuit informed placement of compression panels. It was understood that the polyurethane panels on the LZR Racer swimsuit had been strategically placed to improve resistance to drag and compress the body into the desired shape for swimming. Reflective stencils were used to create targeted zones of compression on the surface of one of the swimsuits. Cut panels were treated with the laser and sewn together afterwards. A laser pattern was applied using a pulsed beam setting of 70ms at a speed of 5m/min and a laser power setting of 50W. Results obtained during 'surface modification I' revealed that the average extension of this fabric at 36N is 54.6% and the average force at 40% extension is 10.6N.

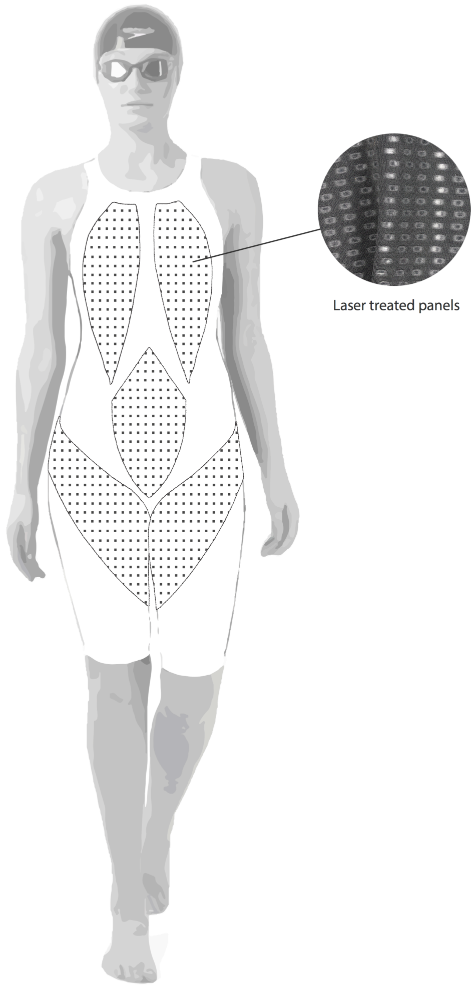


Figure 6.11 Illustration showing placement of panels for swimsuit prototype (author's own)

Figure 6.12 Garment construction with Jannette Tarnai at Speedo (Paine 2014)

6.3.3 Measuring the compressive effect of the laser melted fabric

Two possible methods of measuring the compressive effect of the laser-melted surfacing technique on the body were identified through consultation with Speedo. These were 3D body scanning and pressure testing. Two swimsuits had been prepared for testing. The swimsuit that had been treated with the laser had strategically placed zones of melt patterning on the chest, abdomen, and front and back of legs and buttocks. Differences between the laser patterned and non-patterned swimsuit were evaluated particularly in relation to these areas.

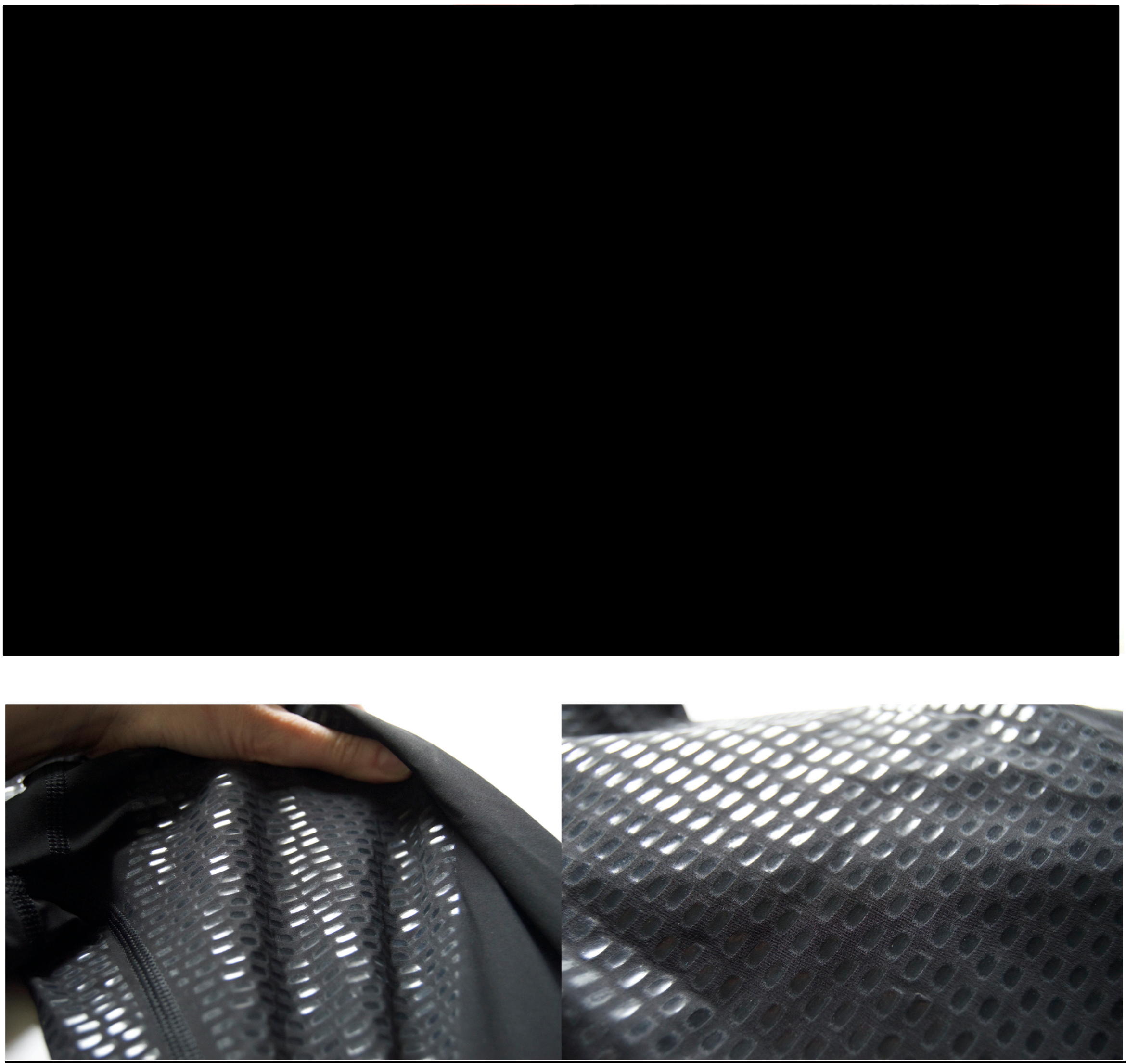


Figure 6.13 Swimsuit prototype with targeted laser-melted panels (Paine 2014)

6.3.3.1 3D body scanning

6.3.3.1.1 Method

3D body scanning equipment was made available for the research by Speedo. The person being scanned must stand inside a booth, positioned in a particular way so that a full scan of their body can be taken. Footprints are drawn on the floor of the booth that mark the correct placement for each foot. Arms must be held away from the sides of the body and gaze should be directed at the camera, which is positioned close to eye level. It is imperative that the person being scanned remains completely still during the process so that a clear image can be generated. A full body scan only takes a few seconds to complete once in position. An image of the person is generated at a workstation next to the scanner and body measurements are extracted by the system's software. This process was carried out for each of the swimsuits being tested. See Figure 6.14

Figure 6.14 3D body scanning equipment and process at Speedo (Paine 2014)

6.3.3.1.2 Results

Five body measurements that were extracted by the software were key in relation to the placement of laser-melted zones on the surface of the swimsuit. These were waist girth, girth at crotch height + 10cm, thigh crotch - 4cm left, thigh crotch - 4cm right and chest girth. For each of these measurements a comparison was drawn between the plain suit and the laser melt-patterned suit tested (Table 6.4). Results showed that for each of these body areas there was a reduction in measurement wearing the laser-melted patterned swimsuit in comparison to the plain swimsuit. The biggest difference of 1cm was recorded for both thighs and girth at crotch height + 10cm. A visible difference to the shape of body can also be seen in the images generated by the software. A flattening effect to the breasts and abdomen can be seen in Figures 6.15 and 6.16, and overall smoothing of the body's silhouette can be seen in Figures 6.17 and 6.18.

Area of measurement	Plain suit (cm)	Patterned suit (cm)
Waist girth	76.9	76.5
Girth at crotch height + 10cm	104.4	103.4
Thigh crotch - 4cm left	59.6	58.6
Thigh crotch - 4cm right	60.5	59.5
Chest girth	90.9	90.6

Table 6.4 Body measurements taken when wearing a plain and laser patterned swimsuit

Reduction in body measurements varies depending on the body type of the wearer and fit of the suit. For instance, reduction to body measurements would be less on an athletic body compared with a non-athletic body; and more on a tight fitting suit compared with a loose fitting suit. It was therefore not possible for Speedo to supply any absolute data to compare these results with, however, through consultation with Speedo an understanding that these results were meaningful for their application was gained.

Speedo's interests in the technique were concerned with its ability to provide resistance to targeted areas of the body; producing variable degrees of flexibility across a single fabric layer 'to aid smooth transition from one power to another.' This initial test has demonstrated that the technique can be used to have a compressive effect on the body to discrete areas. Through development of the prototype, methods of isolating fabric exposure to the laser beam were realised to create targeted zones of compression. Reflective stencils were used to mask the path of the laser for the manufacture of the final prototype; however, other methods such as using infrared absorptive lower panels of fabric were also developed. Further development of the work should focus on the integration of different pattern densities and orientations to create the desired graduated compressive effect.

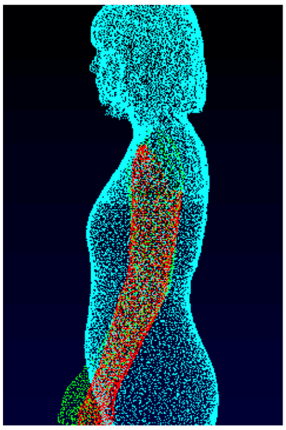
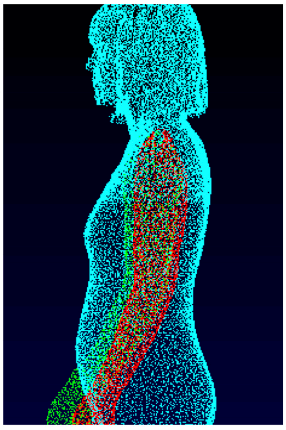
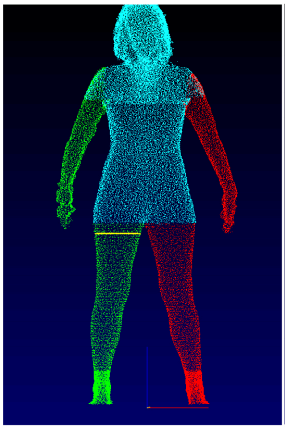
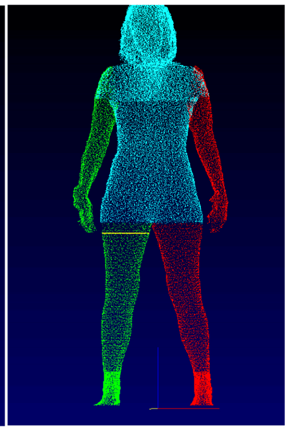





Figure 6.15 (Left) Torso in patterned swimsuit
Figure 6.16 (Centre Left) Torso in non-patterned swimsuit
Figure 6.17 (Centre Right) Whole body view in patterned swimsuit
Figure 6.18 (Right) Whole body view in non-patterned swimsuit

6.3.3.2 Pressure testing

A second method for testing levels of compression between the fabric and skin was suggested by Speedo.

6.3.3.2.1 Method

A compression measurement system [redacted] was made available for the research by Speedo. [redacted]. The [redacted] is positioned between the skin and the fabric [redacted]. A pressure measurement in mm Hg is displayed on the monitor of the device. Pressure measurements were taken for each area of the body covered by the laser-melted pattern. The same areas were tested using the plain swimsuit to provide a comparison. See Figure 6.19

[redacted]

Figure 6.19 Pressure testing equipment and process at Speedo (Paine 2014)

6.3.3.2.2 Results

Results shown in Table 6.5 reveal that the pressure exerted on the body for all areas tested increased with laser surface patterning. For all areas tested pressure exerted on the body increased by approximately 60% as a result of the laser-treated surface on the fabric.

Compression ranges vary between Speedo's consumer tiers, with swimwear for infants offering the least compression and swimwear for athletes offering the most compression. Although, compression values are largely affected by the fit and body type of the wearer Speedo have been able to provide some benchmark figures relating to the optimum pressure ranges across their product tiers. [redacted]

Part of body	Plain suit (mm Hg)	Patterned suit (mm Hg)
Left thigh	[redacted]	[redacted]
Right thigh	[redacted]	[redacted]
Left chest	[redacted]	[redacted]
Right chest	[redacted]	[redacted]
Left buttock	[redacted]	[redacted]
Right buttock	[redacted]	[redacted]
Waist	[redacted]	[redacted]

Table 6.5 Comparison of pressure exerted by fabric on the body for plain and patterned swimsuits

Through this investigation a reasonably high level of compression has been obtained using a single fabric layer with laser surface melting, which is suitable for use within Speedo's range of swimwear to enhance the female figure. Higher levels of compression for use within Speedo's elite range of competitive swimwear could be obtained by exploring the use of more resistant double layer laminates developed during 'surface modification I'. For instance, double layer laminates created using the same laser pulse setting of 70ms at a speed of 5m/min demonstrated significantly more resistance with no reading of force obtained due to the fabric not reaching 40% extension and an average extension measurement at 36N of 27% (5.3). With enhanced resistance to force and limited extension, double layer laminates could deliver much higher degrees of compression for elite applications.

6.4 Summary

A summary for the first part of this study 'testing of insights identified during surface modification I' can be found at chapter subsection 6.2.3.

The second half of this study ' compression validation' (6.3) has used 3D body scanning and pressure testing equipment to validate the compressive effect of the developed technique on the body. A single layer fabric swimsuit was developed with targeted zones of compression and compared with a non-patterned suit. Results have been discussed in relation to requirements for compression stipulated by Speedo.

<u>The main insights</u> are summarised below:

• Three main methods for creating targeted zones of compression across the surface of a fabric have been identified

• The simplest method of creating targeted zones of compression on a single fabric layer is to use reflective stencils that mask the path of the laser beam and avoid complex programming of the software

• Laser melted patterns have a significant compressive effect on the surface of body; reducing body measurements and increasing pressure values by approximately 60% across all areas tested

• Methods of creating targeted zones of resistance have been demonstrated, which is a central requirement for their application; to optimise the shape of the silhouette and increase resistance to drag

• Pressure measurements of [redacted] have been demonstrated, which falls between the requirements for Speedo's leisure (lady's shaping) and competitive range of swimsuits

• Further opportunity to optimise and tailor a variable compressive effect on the body for the specific requirements of their application has been demonstrated by the results obtained during surface modification I

7 Discussion and Conclusions

7.1 Introduction

This research was carried out in response to a brief that had been written by the funding company TWI, with an overarching objective of 'developing capability' in the field of advanced methods for joining textiles. The main hypothesis for the research *Laser melted patterns can be used to control the elastic behaviour of stretch textiles to have a targeted and variable compressive effect on the body* was developed following a period of preliminary research in response to this brief. A 'multi-strategy' framework was adopted by the research that oscillated between a 'craft-design' and 'scientific' approach (2.2.3).

Research gap 1 was identified at the end of the 'project scoping' phase (3.4): *to control the elastic behaviour of stretchy fabrics using laser melted patterns to have a variable compressive effect on the body.* A subsequent review of methods for shaping the body identified a gap where the laser melting technique could be applied in this field. Research gap 2 was identified at the end of the Literature Review (4.5): *to create a variable graduated compressive effect across a single fabric layer.*

The main outcome of this research is a technique that uses laser melted patterns to control the elastic behaviour of stretchy textiles for a controlled and variable compressive effect on the body, which the researcher has called 'Laser Shaping'. This technique makes a contribution both in the field of TLW and compression apparel. This chapter will provide a description of the main findings from the research and discuss the benefits in relation to prior art both in the fields of TLW and compression apparel to define the separate contributions that have been made. Prior art in the field of TLW is established in the Introduction to this thesis (1.3.2). Prior art in the field of compression apparel is established in the Literature Review chapter of this thesis (4.4).

7.2 Summary of main findings

Following the formation of the main hypothesis, *Laser melted patterns can be used to control the elastic behaviour of stretch textiles to have a targeted and variable compressive effect on the body (4.5),* an increasingly prevalent empirical approach was adopted to gather evidence for support. 'Surface modification I' was split into two sections: the first section explored methods, using precise programmable machine settings, for controlling the level of melting to the fabric (5.2); the second section gathered evidence using mechanical testing equipment to prove the effect of controlled melting on the elastic properties of the fabric (5.3). 'Surface modification II' was also split into two sections. The first section used mechanical testing to test additional insights gained as a result of 'surface modification I' (6.2), namely that the orientation of the laser melted patterns in relation to the direction of force has an effect on the elastic properties of the fabric and that laser melting has a detrimental effect on the tensile strength of the parent material. The second section sought to validate the compressive effect of the fabric on the body through the development and testing of swimsuit prototypes in collaboration with Speedo (6.3).

The main findings of the research that were gathered by 'surface modification I' and 'surface modification II' are summarised below:

• The elastic properties of stretchy fabrics can be controlled by laser melting either on the surface of a single fabric layer or at the interface of a double fabric layer

• The degree of laser melting can be controlled both through the depth and across the surface of the fabric using precise programmable machine settings

• Fabric samples with laser melted patterns orientated perpendicular to the direction of applied force demonstrate increased resistance compared to fabric samples with laser melted patterns orientated parallel to the direction of applied force

• Processing conditions, specifically laser power and the distance in between melt lines, have demonstrated capability to mitigate damage to the parent strength of a single fabric layer with laser melted patterns

• Laser melted patterns can be applied to targeted areas on the surface of a garment using CNC commands to manipulate the path of the laser beam; or, the laser beam can be masked using reflective stencils or laser absorbing lower panels

• A prototype garment made from a single layer of stretchy fabric with targeted laser melted zones has demonstrated capability to reduce body measurements by up to 1cm and increase pressure on the body across multiple areas by up to 60%

The following subsections of this chapter will discuss these main findings in relation to prior art in the field of TLW and compression apparel to define the contributions that have been made by the developed 'Laser Shaping' method within these separate fields.

7.3 Benefits in relation to prior art in the field of TLW

Research Gap 1: **to control the elastic behaviour of stretchy fabrics using laser melted patterns for a variable compressive effect on the body**

The first research gap that was identified by the investigation was in the field of TLW during the 'project scoping' phase. An understanding that welding has a detrimental effect on the elastic properties of stretchy fabrics was identified during the 'preliminary ultrasonic study' (3.2). An opportunity to use this effect to control the elastic behaviour of stretchy fabrics by applying all-over laser melted surface patterns was identified through practice-led investigation and an application for the technique to create a variable compressive effect on the body was understood through consultation with Speedo (3.3.4).

Table 7.1 provides a condensed description of prior art in the field of TLW established in the Introduction (1) and Literature Review (4) chapters of this thesis and highlights the additional benefits of the developed 'Laser Shaping' technique with the aim of clarifying the specific contribution that has been made within this field.

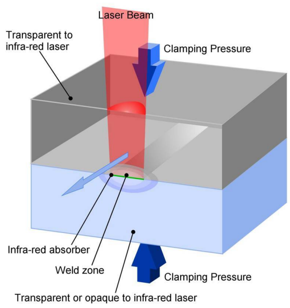
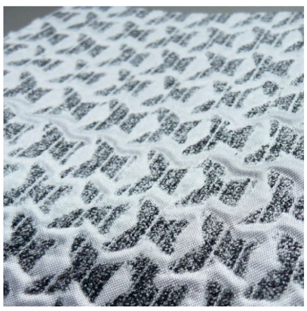
Prior art	Description of capability of Prior Art (Advantages & Limitations)	Additional Benefits of 'Laser Shaping' technique
 **Invisible Seaming** Joining with TLW (TLW), TWI, 1998	Laser seaming was developed with the objective of causing minimal change to the appearance or handle of the parent material through the joining process. This process utilises the application of an infrared laser absorbing dye, which is placed at the interface of two thermoplastic textile materials. A broad range of product applications such as waterproof clothing, car airbags, medical chair covers and inflatable airships has been demonstrated (1.3.2).	The 'Laser Shaping' technique has demonstrated a new capability for TLW equipment to be used as a tool to control the elastic behaviour of stretch textile materials, with a simultaneous decorative effect.
 **Decorative Finishing** Mono-finishing with TLW, Goldsworthy, 2012	Goldsworthy's doctoral research (2012) demonstrated a new application for TLW using it as a tool to create various decorative finishing and bonding techniques for polyester fabrics. Material limitations of the welding process, which are problematic for 'invisible seaming', were used to advantage with the objective of marking textile surfaces to create decorative effects. Goldsworthy's researches centred on maintaining the purity of the original material to enable repeat recycling within a closed loop system (1.3.2.1 and 4.2).	The 'Laser Shaping' technique has demonstrated further capability for these surface effects to have additional functional benefits when applied to stretchy fabrics: to control their elastic properties and have a variable targeted compressive effect on the body.

Table 7.1 Additional benefits of Laser Shaping technique in comparison with prior art in the field of TLW

It was understood through a review of the technical literature on advanced methods for joining textiles and consultation with industry experts in materials joining at TWI that prior to this research TLW had mostly been used for invisible seaming applications. The

Clearweld process invented by TWI enhanced the invisible appearance of the seams by removing the need for carbon black in the weld configuration and various applications for the technology have been demonstrated across product sectors including clothing, interiors, inflatables and medical (1.3.2).

Prior to this research the technology had only been investigated as a surfacing tool by the doctoral research of Kate Goldsworthy, which was completed in 2012. Goldsworthy's research adopted a practice-led approach to investigate the technology and sought to identify methods of decorating polyester textiles without the use of any additional material that would complicate product disassembly and impede recyclability. In total, over 20 different surface effects were demonstrated by the research. (1.3.2.1 and 4.2).

This research has been unique in its investigation of the functional advantages of all-over surface effects created using TLW technology, specifically the effect on the elastic properties of stretchy fabrics. Through the integration of an increasingly scientific approach (2.2.1) in combination with a craft-design approach (2.2.2), it has been possible to extend the findings of intuitive craft practice; to develop highly repeatable effects and demonstrate functional opportunities in response to industry requirements; which has enhanced the industry applicability of the research outcomes, specifically in the sportswear sector.

7.3.1 An additional outcome not related to the main hypothesis

An additional outcome for the research has been the development of a method for creating stretchy welded seams. An opportunity to investigate patterned seam designs as a method for welding stretchy fabrics was identified during the 'project scoping' phase (3.2.5), to break up the continuity of the weld line and maintain fabric flexibility in unwelded portions. The tensile strength of patterned laser welded seams, when mechanically tested, was not comparable to the strength of seams manufactured using Speedo's existing methods, which influenced the termination of this particular investigation route (3.4). TWI has recently been using a dashed seam pattern to create stretchy seams working with a glove manufacturer, which indicates the value of this method in applications where seam strength requirements are lower.

7.4 Benefits in relation to prior art in the field of compression apparel

Research gap 2: to create a variable compressive effect across a single fabric layer

Following the identification of Research gap 1, a review of methods for shaping the body was undertaken (4.3 and 4.4) to identify a gap within this field where the 'Laser Shaping' technique could be applied.

Through a review of historical methods for shaping the body (4.3) an understanding of the technical aspects for creating a variable compressive effect was gained. Corsets use complex pattern cutting techniques to create three-dimensional structures that closely fit to the shape of the body when worn. Rigid strips of material made from metal or whalebone, known as stays, are incorporated into these structures to provide a rigid framework that presses down on the body of the wearer to manipulate its shape. Whalebone stays can be moulded with the application of heat to bend and manipulate the contours of the body. The orientation and density of these boned areas has a controlled effect on the appearance of the figure; with densely boned sections that squeeze inwardly towards one another often applied across the abdomen to have a thinning effect. A lace-up fastening mechanism known as tight-lacing is widely used in corsetry so that the fit of the corset can be customised to suit the preference of the wearer; the tighter the corset is laced the higher the compression on the surface of the body and the subsequent thinning effect on the figure. Using the tight-lacing fastening mechanism compression to the body can be varied along the length of the torso; laces can be pulled tighter in regions where an enhanced thinning effect is required, such as across the abdomen, and tied more loosely across areas where a flattening effect is less desirable, such as the bust (4.3).

Following the invention of elastic materials, most notably Lycra in 1958, it was no longer necessary to use complex paneled construction methods to manufacture close-fitting body-shaping garments. Flat garments constructed from fabrics containing Lycra are able to cling to the figure independently and this influenced a simplification in the design of compression apparel. The 'Little X' girdle of the 1950s was constructed from a single layer of fabric that wrapped around the waist in an 'X' shape to cover the hips, buttocks and upper thighs. Early examples of compression garments made from fabric containing Lycra, such as the Little 'X' girdle, despite providing a simplified manufacturing process, were unable to achieve a targeted and controlled compressive effect that could be used to precisely manipulate the shape of the body due to the lack of variety in the modulus across the surface of the fabric (4.3).

Contemporary technologies for the manufacture of compression garments, which are now applied both in sportswear and shapewear applications, utilise various methods to regain this targeted and controlled compressive effect on the body. These contemporary technologies for achieving a variable compressive effect on the body have been split into three areas: 'cut and sew', 'seamless' and 'surface application' by the Literature Review chapter of this thesis (4.4). Table 7.2 provides a condensed description of each of these methods and highlights additional benefits of the 'Laser Shaping' method developed by this research in order to assist in clarifying the specific contribution that has been made within this field.

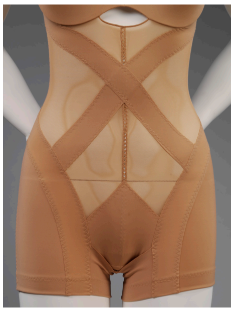
Prior art	Description of capability of prior art (Advantages and Limitations)	Additional Benefits of 'Laser Shaping' technique
 **Cut and sew**	The 'cut and sew' method for shaping the silhouette uses fabrics of variable flexibility that are joined together to create a targeted and variable compressive effect across the surface of the body. Limitations are that harsh seam divisions across the surface of the garment make it difficult to achieve a smooth gradual transition between different power zones; manual construction methods are time consuming and make product repeatability difficult to achieve; and the network of seams can cause discomfort to the wearer (4.4.1).	• Targeting of specific areas of the body is simplified and automated as the reliance on manual construction methods is removed • Enhanced ability to create smooth transitions between different power zones as harsh seam divisions are removed and variable degrees of fabric flexibility are extended. • Reduction in manufacturing time/ cost and improved comfort with elimination of complex seam networks • Improvement to garment appearance as 'laser shaping' technique has a simultaneous decorative effect. • Improvement in product repeatability with less reliance on manual methods of construction
 **Seamless**	The 'seamless' method for shaping the silhouette uses variable stitch types and/or densities of Lycra across the surface of a garment to create a variable and targeted compressive effect on the body. A relatively smooth transition between zones of compression is possible without harsh seam divisions; however, the ability to achieve a graduated compressive effect with various degrees of flexibility targeted to specific body parts is restricted by complex programming requirements (4.4.2).	• Targeting of specific areas of the body is simplified and automated as 'laser shaping' patterns are applied directly to the surface of flat garment pieces without the need for such complex programming • Improvement in the control and variety over the degrees of flexibility that can be applied across a single surface to achieve an increasingly graduated compressive effect • Improvement to product cost/ manufacturing time/ product handle due to elimination of extra materials • Improvement to garment appearance as 'laser shaping' technique has a simultaneous decorative effect.
 **Surface application**	The surface application method for shaping the silhouette uses patterned adhesive laminates applied either to the surface of a stretchy fabric or at the interface in between two stretchy fabric layers. A smooth transition between different power zones can be achieved by varying the pattern of the laminated panels applied with a simultaneous decorative effect. Targeting of specific areas of the body is simplified as treatment is applied directly to flat garment pieces. Limitations are the cost/ impact on product recyclability/ additional bulk of extra materials, and their tendency to delaminate over time (4.4.3).	• Improvement to product cost/ manufacturing time/ product handle due to elimination of extra materials • Improvement to the control and variety over degrees of flexibility that can be achieved to create an increasingly graduated compressive effect

Table 7.2 Additional benefits of Laser Shaping technique in comparison to prior art in the field of compression apparel

Through a review of contemporary methods for shaping the body (4.4) it was understood that there is a demand for methods that can achieve a targeted and gradual compressive effect across a single layer of fabric. The 'cut and sew' method of manufacture joins fabric panels of various flexibilities together. Complex pattern cutting techniques, which are similar to those used to construct corsets, are used to achieve a figure hugging fit. Stretchy fabrics of variable flexibility can be used to specifically target areas of the body and create tailored resistance to precisely manipulate the shape of the silhouette. The 'cut and sew' method of construction was used to manufacture garments for Nike's 'Swift Series' that were designed to streamline the shape of the body to improve resistance to drag for enhanced athletic performance. Six different fabrics with variable elastic behaviour are incorporated into the paneled construction of a single suit (4.4.1).

Despite this method of construction delivering the desired targeted and variable compressive effect, there are a number of disadvantages to the technique; namely manufacturing time, garment repeatability, and discomfort to the wearer caused by complex seam networks. The detailed paneled construction is heavily reliant on manual labour for the placement and sewing of materials, which is both time consuming and costly. A reliance on manual labour also limits repeatable quality across large product batches. In addition to this, the complex seam networks that are used to join the panels of fabric together are positioned in close proximity to the skin and are likely to cause discomfort to the wearer, which would be particularly irritating in sportswear garments due to excessive movement of the body.

The 'Laser Shaping' technique developed by this research along with commercially available methods, specifically 'seamless' and 'surface application' techniques, eliminates the requirement for seams to create a variable compressive effect on the body. Eliminating the requirement for complex networks of seams in the construction of compression apparel reduces manufacturing time/cost, improves product repeatability and comfort for the wearer.

The 'seamless' method of manufacturing compression apparel uses different stitch types and/or densities of Lycra across the surface of a garment to create zones of fabric that offer targeted levels of variable flexibility. Circular knitting equipment is used to manufacture tubes of fabric that are joined together or whole garments can be made in one piece (4.4.2). Benefits already provided by eliminating seams from the manufacturing process can be applied to this 'seamless' method; however the 'Laser Shaping' method developed by this research offers additional advantages, specifically enhanced ease in targeting different zones; improved product appearance and handle. Areas of compression are applied to the two-dimensional lay-up of flat pieces using the 'Laser Shaping' method. The seamless method of manufacture, in contrast, relies on complex computer programming to integrate targeted areas of compression within the construction of the fabric, making accurate placement on the body increasingly difficult to achieve. Areas of the fabric with high densities of Lycra created using the seamless method can also have a bulky handle, which is uncomfortable and undesirable for the wearer. The 'Laser Shaping' method has a less bulky handle and has an improved shiny aesthetic appearance, which could assist in enhancing comfort and desirability for consumers.

The 'surface application' method of shaping the body uses laminating and printing techniques to change the elastic behaviour of stretchy fabrics and add targeted resistance to selected areas. The 'surface application' method, like the 'Laser Shaping' method, varies the degrees of flexibility by applying a pattern either to the surface of a single fabric layer or at the interface of a double layer. The various levels of fabric resistance, and thus the degrees of compression that are applied to the body, are controlled by the density and orientation of the pattern that is applied. The main additional benefits of the 'Laser Shaping' method over this technique are increased control over the degrees of fabric flexibility that can be achieved and the elimination of any extra material in achieving a compressive effect. The main findings of this research have demonstrated that various process parameters, such as power, distance between weld lines and laser pulse density, can be used to control the precise level of melting both through the depth and across the surface of a stretchy fabric layer to have a repeatable effect on its elastic behaviour. The ‘surface application’ method is comparatively unsophisticated, as it cannot be controlled with the same level of precision, reducing repeatable results across product batches and limiting the variety in degrees of compression that can be achieved.

‘Laser Shaping’ creates areas of increased resistance within the fabric by selective melting of the parent material, in contrast to the ‘surface application’ method, which relies on the addition of printed material laminates to make the decorative pattern on the surface of the fabric (4.4.3). The elimination of any extra material in achieving a variable compressive effect using the ‘Laser Shaping’ method offers multiple benefits such as: reducing manufacturing time/cost; improving garment bulk/comfort; and increasing product recyclability. Also there is a reduction in the likelihood of decreased performance using the ‘Laser Shaping’ method, as laminated panels are prone to delaminate over time.

Through consultation with Speedo it was understood that there is desirability for technologies that can achieve an increasingly graduated compressive effect on the body with smooth transitions between different zones of compression (6.3) to eliminate the discomfort caused by harsh seam divisions in the ‘cut and sew’ method of construction and optimise the performance enhancing benefits of a variable compression on the body. Speedo currently attaches fabric panels to the inside of their competitive swimsuits to create targeted areas of compression on the body and assist in streamlining its shape for swimming (5.3.1). Speedo’s FS3 swimsuit, used in the 2012 Olympics, combines both ‘seamless’ and ‘cut and sew’ methods to achieve a more precise targeted and variable compressive effect on the body. A warp knitted fabric with variable degrees of Lycra across its surface is cut and sewn together in a paneled construction to combine both the gradual compressive benefits of the ‘seamless’ method with the precise targeting and shaping benefits of the ‘cut and sew’ method. The ‘Laser Shaping’ method developed by this research offers enhanced control over the elastic behaviour of stretchy fabrics, which could assist in eliminating the requirement to combine different techniques to achieve the desired targeted compressive on the body.

On review of the 'Laser Shaping' method in comparison with commercially applied techniques for compressing the body, **the main notable benefit** is the ability to control precisely the elastic behaviour of the fabric; allowing enhanced variety and repeatability in the degrees of compression that can be achieved for an increasingly graduated compressive effect.

The final sections of this concluding chapter to the thesis will explain how the original objectives of the brief written by TWI have been met by the research. A concise description of the specific contributions to knowledge that have been generated in the fields of TLW and compression apparel, which have been established by the current discussion, will also be provided. The closing subsection of this chapter will describe opportunities for further development.

7.5 Meeting the objectives of the brief

This thesis provides an account of cross-disciplinary practice that demonstrates how tacit knowledge when integrated within a methodological framework can be advantageous in inventive contexts. The main objectives of the original brief written by TWI were:

• Develop capability for current textile welding technologies, specifically ultrasonic and TLW equipment

• Assess the performance of developed techniques using mechanical testing equipment

• Define process parameters for repeatability in industry applications

• Develop case studies with industry to validate research and develop TWI's existing network

The main overarching objective of the TWI brief was to ‘develop capability’ in the field of advanced methods for joining textiles (1.1), and there was a particular interest in developing capability in the fields of ultrasonic and laser welding. A ‘multi-strategy’ framework was used to carry out the research that oscillated between a scientific and craft-design approach. Practical material investigation that is typical of a ‘craft-design’ approach was used to identify and develop hypotheses, which were tested using quantitative scientific methods (2). Using this combination of methods the researcher was able to establish an approach that enabled the identification and development of novel concepts for application in industry.

TWI has described the ability for researchers coming from a craft-design background to mix methods and incorporate aesthetic considerations into their approach to enhance commercial appeal as highly beneficial. Roger Wise from TWI has offered the following statement in support of the adopted mixed methods approach:

> ‘The approaches adopted by Helen Paine during her PhD were different to those commonly used by graduates in a pure physical science discipline and this was highly beneficial to the outcome of the work. An ability to incorporate an aesthetic perspective in addition to the functional and commercial, as well as the use of structured reflective practice produced some highly original approaches, which are beginning to be exploited now.’ Wise, Roger (email correspondence, 4 August, 2015)

7.6 Contributions to knowledge

The main contributions that have been made by this research are within the fields of TLW and compression apparel.

The first contribution that has been made is within the field of TLW and is a new application opportunity to control the elastic behaviour of stretchy fabrics when applied as an all-over surface effect. Capability for the technology to be used as a surfacing tool for polyester fabrics had been demonstrated previously (1.3.2.1 and 4.2), however, this research builds on this opportunity, demonstrating a further functional advantage when applied specifically to stretchy fabrics.

The second contribution that has been made is within the field of compression apparel. Through a review of methods for shaping the body it has been understood that the use of laser technology to change the elastic behaviour of stretchy fabrics for a compressive effect on the body is completely novel. Further to this, the 'Laser Shaping' method has demonstrated an increased ability over established methods to control the degrees of flexibility that can be achieved for a graduated compressive effect without the addition of any extra materials.

Additional benefits of the 'Laser Shaping' technique over other commercially available methods for shaping the body are:

• Enhanced ability to target specific areas of the body accurately
• Improved smooth transition between different zones of compression
• Advanced repeatability in large scale product batches
• Reduction in materials/processing steps for a positive impact on manufacturing time/cost/ product recyclability
• Improvement to aesthetic appearance and fabric handle for enhanced consumer desirability

7.7 Further work

On reflection of the research it has been possible to identify a number of areas for future development, namely: mitigating the damage to the strength of the parent material, placement of patterns for an optimised compressive effect and development of the laser equipment for commercial application. A description of each of these approaches is provided herein:

Mitigating damage to the strength of the material

Through 'surface modification I' (5) a negative impact caused by laser melting on the parent strength of the material was identified when a sample tore under a moderate force. Investigation of this effect in 'surface modification II' (6) demonstrated that particular process settings, specifically power and Tpuls that controls the length of the laser pulse, could be used to mitigate this effect. Further investigation of this effect with respect to a wider variety of settings and variables, such as double layer material configurations, is needed to extend understanding in this area and improve industry applicability.

Placement of patterns for an optimised compressive effect

An understanding that the level of melting by the laser can be programmed to produce repeatable effects that offer controlled degrees of flexibility has been gained, however an extension of the research would benefit from collaboration with industry to develop patterns that are tailored to the requirements of a specific application; to demonstrate further the graduated compressive benefit of Laser Shaping on the body. Consultation with an industry partner is needed to gain an understanding of specific compression requirements that can be used to inform the development of patterns. The GOM Aramis system, which has been introduced through consultation with Speedo, is a method of measuring fabric strain dynamically. This system provides optical 3D deformation analysis, which could be used to assist in the development of patterns that target specific areas of the body for an optimised graduated compressive effect.

Development of laser equipment for commercial application

The adopted practice-led approach to this research has assisted in the adaption of the TLW equipment, which was intended for seaming, to create all-over surface effects. Applying the beam in a raster pattern across the surface of the fabric and masking it, using absorptive lower panels and reflective stencils, has enabled targeted areas of all-over surface pattern to be created. The processing time for creating all-over surface effects is relatively slow with a maximum laser beam width of 10mm and processing speed of 10m/min. Collaboration with a laser manufacturer to adapt the process for creating all-over surface effects would assist in gaining industry commercialisation. A multiple head system or curtain laser set-up could be integrated to help automate the manufacture of all-over surface effects.

Throughout this research patterned seam and surface designs were programmed into the system manually using CNC commands. Since the completion of this research TWI has invested in software that translates CAD drawing into the numerical code that manipulates the movement of the x-y table beneath the laser head. This has made a significant improvement to the set-up that will influence the automation of producing all-over surface patterns of increased complexity.

A future project with Speedo is currently in negotiation as a continuation of the PhD work; to further define process parameters using their materials; to explore the effect of additional technologies; and to tailor the targeted and gradual compressive effect of the fabric across the body for their application. TWI are also interested in developing the work further with industry and are currently exploring the opportunity of filing a patent for the 'Laser Shaping' technique.

Compression fabrics are used across sportswear sectors not only to manipulate the shape of the body but also to enhance the removal of lactic acid post exercise and restrict the occurrence of delayed onset muscle soreness. In the medical sector compression stockings are used to prevent blood pooling and swelling in the lower extremities of the body. Compression fabrics are also used for the manufacture of body shaping garments in the lingerie industry to manipulate the shape of the body for an improved aesthetic effect. The 'Laser Shaping' technique developed by this research offers an alternative decorative method for controlling the elastic behaviour of stretchy fabrics that could offer advantages across multiple product sectors.

8 Appendix

8.1 Applications for TLW

8.1.1 Introduction

TWI has demonstrated a broad range of application opportunities for the Clearweld process to replace existing methods for joining textile materials across product sectors since its development in the mid 1990s. A description of the main demonstrated product opportunities is provided herein.

8.1.2 Curtain airbags

Curtain airbags are mounted on to the sides of car seats, or in the roof above the doors, to provide protection against side impact or multiple roll-over accidents. Airbags are generally produced by one of two methods: Cut and sew or one piece woven (Jones 2005). Airbag demonstrator pieces prepared and tested in collaboration with Invista using TLW demonstrated a good sealing capability, but did not perform as well as traditional manufacturing methods, with a reduction in seam strength of approximately 25%. Scott Westoby of Invista (Dupont), saw that a potential advantage of the technology over traditional methods could be its 'instantaneous' failure mechanism, that would probably prevent the material airbag from melting, which has occurred with other methods (Rooks 2004).

8.1.3 Vascular stent grafts

Endovascular stent grafts are used to treat abdominal aortic aneurisms. This condition is a weakening to the body's main circulatory vessel that causes it to bulge, forming an aneurism that is prone to splitting. Time consuming hand sewing methods are used to attach Nitinol rings to polyester fabric in the manufacture of stent grafts. Feasibility studies have demonstrated that TLW could replace sewing methods and assist in automating this process. Initial tensile tests have showed high joint strengths with welds failing in the parent material rather than at the site of the weld (Jones, Patil 2013).

8.1.4 Medical chair cover

Seams produced using TLW are hermetically sealed, which is desirable for the preparation of hygienic medical products. A collaborative project with Knightsbridge Furniture Productions explored the suitability of TLW to be used for the manufacture of medical chair covers. A 2D envelope was welded inside out and pulled over the back of the chair as a demonstrator piece. The appearance and the performance of the laser welded chair cover were acceptable, with no significant damage suffered following a durability test that simulates a year of service (Jones 2005).

8.1.4.1 Airships

Current methods for producing large textile structures such as balloons, airships and tunnel plugs use either heat or ultrasonic energy; however, TLW technology offers increased production speeds with prototype samples manufactured at 4.5m/min. Prototype samples produced in collaboration with Linstrand Balloons reached benchmark tensile strength requirements, though, demonstrated helium leakage (Rooks 2004). Ian Stewart of Lindstrand Balloons supports the development of the technology, but believes that more research needs to go into understanding its practical application (Rooks 2004).

8.1.5 Beds

An investigation with Silent Night beds explored the feasibility for TLW to be used for three separate manufacturing operations: Attaching a label to the mattress, joining a seam in the quilted fabric at the side of the mattress and attaching fabric to the drawer at the front of a divan base, which required a joint to be made between fabric and wood components. All three tasks were found to be feasible (Jones 2005)

8.1.6 Apparel

8.1.6.1 Waterproof clothing

The ability to produce hermetically sealed joints in a one step process using TLW is a particular advantage for the production of waterproof garments. Current methods for producing waterproof seams use adhesives and are at least a two-stage process as pierced holes caused by stitching must be covered by a waterproof tape. TLW could reduce process steps and assist automation (Jones, Patil 2013)

A waterproof jacket with laser welded seams was constructed during Altex (Automated Laser Welding for Textiles), a European collaborative project, which ran from 2005 to 2007 (Jones 2008). Capability to produce three-dimensional seams was demonstrated using a rigid mould to support the fabric, and laser welded using a 6-axis robot that moved around the work piece (Jones 2007).

8.1.6.2 General clothing

A polyester shirt complete with button holes, pleats and a collar using TLW has been produced in collaboration with Nigel Cabourn, a menswear designer based in the North East of England. The appearance of the seams and overall garment aesthetic was only subtlety different to the stitched equivalent (Hilton, Jones 2000).

Leapfrog was a European Collaborative project aimed at technology breakthrough in the clothing industry. Initiated by the European textile and clothing industry, this project sought to develop and implement new methods for clothing manufacture. Laser welding was integrated within the proposal for an automated system using new methods for preparation and handling. It was proposed that the preparation of fabrics such as cutting, spraying of absorber and positioning could be automated using a combination of flat beds and robots. Lasers could be coupled to several fibres that would allow several garments to be welded at the same time (Jones, Patil 2013)

8.1.6.3 Wearable technologies

TLW has been explored for its suitability to manufacture garments with integrated electronic components. Electronic components are becoming increasingly compatible with welding, encased within thermoplastic composites or even integrated within the construction of synthetic fabrics. Laser welding equipment demonstrates a dual capability to produce long garment seams as well as small conductive joints for interconnected electrical parts (Jones, Wise 2005).

8.2 Project Brief

Investigation of Advanced Joining Methods for Textiles and Related Materials

1. Concept

1.1. Proposed concept and relevance to Technology Group's chosen technology strands

This research project seeks to investigate alternative and novel methods of joining polymeric and textile materials, including dissimilar material combinations between textiles and film and rigid materials, and their applications.

It will enable progress in two of AMP's Polymer Group Technology Strands, textiles joining and laser welding for polymer materials.

It is proposed to take up to 6 general flexible material types, and to compare the performance of joints from all the relevant joining methods. Variations in performance will be studied in detail and suggestions for improvements to the processes should arise from the results, as well as recommendations for appropriate use of the methods, including estimates of which give reductions in manufacturing cost.

1.2. Industrial Need

Specific textiles joining applications include medical implants (Vascutek), roofing structures using tensioned film (Architen Landrel), airships (Lindstrand), inflatable structures (Mangar) and NBC protection suits (MOD). Many applications require detailed knowledge of the performance provided by the different methods and the range of materials or designs that are suited to each method. There is little information available to assist the user in process selection.

There is industry interest in techniques for joining textiles and dissimilar materials for use in complex vehicle components, aerospace, transportation, energy applications, as well as for sports wear and medical applications. Multimaterial technology is one of the most promising solutions for the design and fabrication of many high performance products and engineering structures. There are, however, theoretical and practical problems encountered in joining dissimilar materials with special reference to the joinability of various materials and how they can be combined.

1.3. Current state of the art and its relevance

Welding and adhesive bonding methods are replacing stitching for a wide variety of applications. The techniques include hot air, hot wedge, laser, ultrasonic, hot bar, dielectric and use of hot melt adhesive films. TWI has worked with all of these processes for polymer film welding and most recently has developed methods and expertise in laser and ultrasonic welding for industrial and medical applications and in dissimilar materials joining between polymers and other materials. In particular, TWI is the world leader in laser welding of textiles.

1.4. Novelty – Progress beyond the state of the art

TWI's strong and multi-faceted base of knowledge in this area will be developed significantly by this project. Studies comparing the existing and new techniques for welding textiles and dissimilar materials will allow TWI to become the leading source of knowledge. Techniques will be developed for new materials, applications and new material combinations, and provide expertise in appropriate design of procedures and fixtures for complex 3D parts. This will provide a basis for automation in an industry that has to date found automated manufacturing very difficult to achieve.

2. Objectives of the proposed project

The main aim of the project is to investigate the laser and ultrasonic welding in comparison with other processes for joining textile and polymeric materials. The research aims to establish reliable methods for joining a range of materials to themselves and dissimilar materials to each other with high accuracy and high repeatability for a variety of novel applications.

Research Objectives:

1. Assess the weldability of new and existing materials, in particular textiles and dissimilar combinations including textiles.
2. Compare the performance of all the main welding and bonding methods for engineering textiles.
3. Investigate novel joint designs (multi-layer) for laser and ultrasonic welding.
4. Design and assemble fixtures for novel laser welding applications to shape the seams as they are made, and test the use of templates and methods for making 3D parts from 2D layup of pieces.
5. Provide guidelines for selection of joining processes for engineering textiles applications.
6. Produce Best practice guides for each joining method.

3. Work Plan

The project will start with a literature review of current methods of joining textiles and their limitations compared to novel textile joining methods. The review will also identify dissimilar materials joining applications i.e. textiles to rigid plastics for furniture or automotive applications etc, where laser welding or ultrasonic welding can be applied.

The research objectives accelerate in their complexity. This project will start by establishing a framework for further development of new products specifically in the areas of textile welding, recycling and joining of bio- based polymers for end of life product recyclability, medical application of novel joining of textiles, electronics in textiles, merging micro-joining with textile activity, garment and footwear manufacture for possible sportswear applications, and possible textiles joining applications for architectural structures.

The three year programme of work is anticipated to be carried out as follows:

Year 1

- Literature review of existing joining methods for textiles and thin film polymers and their applications.
- Experimental work focusing on performance and procedure development and comparisons.
- Research weldability for various types of textile and dissimilar material joints.
- Design welding processes parameters for laser and ultrasonic welding methods for a range of textile and polymeric materials.
- Follow up with existing contacts within the industry, looking at a variety of industry areas to create case studies.

Year 2

- Continue research on a combination of materials and welding processes.
- Determination of optimum welding parameters for textile and polymeric materials for up to 6 general flexible material types. The performance of joints using all the relevant joining methods will be compared. Variations in performance will be studied in detail through mechanical testing and examination of joint cross-sections.

Year 3

- Samples and product prototypes will be manufactured to demonstrate the potential of the laser and ultrasonic welding processes for the applications identified in the individual case studies.
- The physical characteristics of the main textile joining methods will be defined, along with the cost of equipment purchase and operation.
- Dissemination of the research via publication and dissemination.
- A guide discussing the textile joining processes and their appropriate use will be prepared.

4. Exploitation plan

Dissemination will take the form of publications ranging from papers in technical textiles journals, industry publications (medical, automotive, consumer goods, aerospace, electronics and sensors, chemical), and presentation to industry conferences. Existing close interaction with TWI's business development team will continue with new samples and publicity materials made available.

Exploitation will be via existing and new contacts for TWI, to generate single client projects, collaborative projects and new membership.

5. Estimated cost and duration

Project Leader: Helen Paine (PhD student), Supervised by Ian Jones
Duration: 3 years
Expenditure: £***k

8.3 All Makers Now? conference paper

Laser Welding of Textiles: A creative approach to technology through a reflective craft practice

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Abstract

In an increasingly digital age of manufacture the role of the craft practitioner and particularly hand making processes has had to be reconsidered. There are those that would argue the depletion of goods made by hand simply negates the need for making skills in the development of new products; however, there is an emerging argument that places more value in the potential benefit of craft practice, and particularly making, to bridge between scientific knowledge and the needs of industry.
This paper calls upon the research of Dr. Kate Goldsworthy and Helen Paine, who have utilised laser-welding equipment to explore the benefits of a 'craft approach' in assisting the development of an emerging technology for decorative and functional textile finishing applications. Goldsworthy first worked with the technology in 2008 during her doctoral research, and has used it to develop unique surface finishes for textiles that preserve material purity and can be recycled within a closed-loop system. The inventors of the technology, TWI, fund Paine's current doctoral research, and wrote the original brief for the project that is essentially technologically driven; from which Paine has chosen to investigate new aesthetic and functional opportunities for stretch textiles offered by the equipment.
Despite the disparate contexts for the research of Goldsworthy and Paine, their shared background in textile design has led them both to follow a familiar practice-led approach. In this unified approach they have been able to collectively recognise the benefits of working in a hands-on way with the technology. This paper will explore techniques undertaken by both researchers during their investigations and share their insights from working with the laser welding equipment, made available to them by TWI. More widely, the paper will demonstrate the benefit of an intuitive craft approach in the development of an emerging technology.

Keywords: *Technology, craft, textile finishing, laser welding, tacit knowledge, creative problem solving.*

Introduction

Goldsworthy and Paine have both developed practice-based doctoral projects using laser technology based at The Welding Institute (TWI), in Cambridge. Goldsworthy first worked with the technology in 2008 and has used it to develop unique surface finishes for textiles that preserve material purity and can be recycled within a closed-loop system. The inventors of the technology, TWI, subsequently funded Paine's current doctoral research project, which began in 2012. Paine is investigating new aesthetic and functional opportunities for stretch textiles offered by the equipment. Both doctoral projects have resulted in new IP being considered for industry exploitation.

Despite different research contexts for the technology both have a background in traditional textile design; Goldsworthy in printed textiles and Paine in knit, and have adopted practice-led approaches that reflect these specific skills and experiences.

This paper will outline their collective insights through working with laser welding during their doctoral practice, illustrated with specific examples of their experiences of developing a craft practice using a digitally driven and lab-based technology. In particular, their approaches to overcoming the manifold barriers created by the nature of the process are explored and discussed in order to demonstrate the benefits of a craft approach in the development of such emerging technologies.

A Brief History of Laser Welding Technology (Transmission Laser welding)

Laser welding of textiles was first developed at TWI during the mid 1990s. The process was first demonstrated to join plastic materials and could only be applied, before TWI's developments, to join materials of a dissimilar colour. The nature of the process relies on the transmittance of the laser through the top material and the absorbance of the laser in a lower material. Dyes in the materials have a direct effect on the transmittance of the laser and TWI developed a laser absorbing dye, which could be placed at the interface of the materials to be joined. This made joining materials of the same colour possible for the first time. TWI has successfully demonstrated feasibility for the technology to be used in various seaming applications as varied as clothing, furniture, medical devices and airships. Seams, in some cases, have exceeded strengths achieved using traditional stitched seam methods. Other benefits offered by the technology over alternative methods include increased manufacturing speed, an ability to produce waterproof seams in a one-step process and an almost invisible appearance on the outer surface of the material.

New Applications of the Technology Developed by Goldsworthy and Paine

Goldsworthy's doctoral project (2005–2012) first demonstrated potential for new applications of transmission laser welding for textile finishing and creation of composite fabrics by using it as a tool to transform polyester fabrics into varied and complex designs that were monomaterial in composition to enable repeat recycling within a closed loop system. Material limitations and faults in the welding process, such as melted and marked surfaces, that are considered undesirable for welding in other applications, were employed to useful effect in creating these varied decorative finishing techniques.

Helen joined TWI in 2012 to undertake a PhD project to further develop an understanding and capability for this advanced method of joining textiles. Responding to this technology driven brief she chose to take a practice-led approach in pursuit of new opportunities. There was an interest in exploring the aesthetic opportunities enabled by the technology and the research has centred on the development of seaming and surfacing techniques for stretchy fabrics.

Coming from a background in textile design both researchers have developed a familiarity, and preference for, a hands-on and intuitive way of working that is combined with a methodical research approach. Their understanding of the technology has been developed largely by taking a playful and intuitive approach of trial and error; to first gain an understanding of the equipment's established capabilities, but also to seek new opportunities for its development based on a tacit understanding of the materials in use.

> *It is not craft as handcraft that defines contemporary craftsmanship: it is craft as knowledge that empowers a maker to take charge of technology. (Dormer, 1997)*

This paper will discuss the particular barriers of working with the laser welding equipment, which have been identified through the practical investigations of both Goldsworthy and Paine; some of which are specific to the craft practitioner and others that are more generally applicable. Through their joint investigations the researchers have been able to devise solutions to these barriers, some of which are only temporary, but others that could be more influential in the wider development of this emerging technology.

> *Today's quiet revolution of craft is most obviously about technological change: about makers raiding the creative potential of digital technologies for new processes, media and creative strategies. (Press, 2007)*

Image 1

During the researcher's time working with the laser, several barriers and opportunities relating to the new technology were explored. The following sections review the challenges encountered by the researchers and the solutions found. It is divided into three main sections:

- Physical barriers between maker and machine
- System barriers between maker and software
- Material barriers between maker and material

These barriers are described and examples given of solutions that were informed by the particular craft knowledge of the maker during a period of reflective craft practice.

Physical Barriers Between Maker & Machine

This first set of challenges relates to the physical set up of the technology and overcoming an imposed *remoteness* from the tools of making. The challenge facing makers exploring production processes that rely wholly on CAD/CAM is described by Philpott (2010) as a 'removal of the intimacy of touch from the design process'.

Barrier: Remoteness from process

Due to the nature of the process it is necessary for the equipment to be set up in a separate and sealed environment to which the operator can only gain access when the laser is turned off. The computer control workstation is located outside of where the process is controlled and managed, meaning the user needs to view the material through a camera linked to the equipment. Whilst this interface allows the user to see if there is a problem with the equipment itself, it is not possible to see the effect on the material without stopping the machine, going into the room and removing the material from the flatbed. This results in a very *broken* and disjointed process which needs to constantly be stopped and started, with a certain amount of guesswork needed in order to make decisions about the settings and their effects. If the material is completely taken off the machine it would be impossible to replace it without creating a gap in the design.

'In the making process the hand becomes intellectual, enabling the simultaneous creation and analysis of work' (Philpott, 2010). However, in this case the physical distance between the maker and the machine during the process causes a *distancing* not usually experienced during traditional *hands-on* processes. The usual continuous opportunity to oversee or manipulate the material during the manufacturing process is removed. It is true to say that this dependence on the presence of the maker can vary to a greater or lesser degree in traditional making methods; however, there is rarely an occasion when the maker would be completely removed from the activity of transformation to this extent.

Solution: Creating moments of pause for 'reflection in action'

Through a cycle of trial and error with the unfamiliar set up it was discovered that by pausing the equipment during a cycle the researchers could go back into the room and make visual assessments without creating any negative effects on the material. This was not a function that the scientists in the department used during their experiments and therefore had not been originally known to be possible. Although this did not give the full detail that taking the material off the machine would have done, it did at least allow major faults or incorrect settings to be picked up through the protective barrier.

> *If the maker scrutinizes and assess their actions as they make this can advance the practice as they can respond rapidly to insights gained whilst making and amend their actions as necessary. (Philpott, 2013)*

This solution also had a secondary benefit of creating a method for hand-marking the materials through the physical interruption of any program during its cycle.

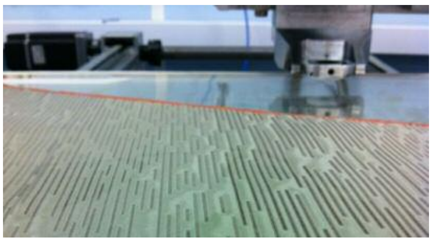

Image 2

Image 3

Image 4

Schon (1983) advocates that *good designers* should reflect upon their action both during and after practice in order to move from exploration to 'commitment' as they recognise the implications of each material situation. In working with the laser from outside the lab it was difficult to reflect upon the work during progress. Using the pause button did help to some extent to imitate *normal* working practices which were in so many ways lost working with this unfamiliar set up.

Barrier: Lack of creative space

The spaces themselves are set up very much as a scientific *lab* and not a design studio. This element is usually a vital part of what it means to be a maker – surrounding a space with visual elements and materials in order to analyse and review samples during the process. In practical terms, there was little surface area on which to work and *lay-out* design work for review during the process. This was extremely difficult in such a utility space with no surfaces to work on.

Solution: Creating a temporary studio set-up

Without the space in the lab to pin work up and reflect upon it during the creative process of making, mount boards were used by both researchers as a sort of transportable alternative. Finding ways to mock-up familiar studio environments where possible assisted in getting in to the *zone* for creative work.

Barrier: Removal of the hand & the 'reveal'

This removal of the maker's hand in the process creates a barrier to tactile understanding. The laser works its magic separate from the maker who loses the haptic feedback of working directly with materials. This creates a moment of *reveal* when you remove the materials off the laser once the process is complete and you see for the first time the effect that it had created.

In response to these challenges, the researchers employed various tactics in order to negate the negative impacts of the distancing between themselves and the machine (tool).

Solution: Integration of hand before and after laser processing

The removal of the hand at the point of production does not mean that there were no hand-manipulated processes at all. It was found that by manipulating the materials before, and sometimes after laser processing new and interesting effects could be achieved. Paine found that by stretching out fabrics using an embroidery hoop before they were processed using the laser, fabrics were set into new positions creating a three dimensional surface effect.

Goldsworthy often built up designs in layers, each responding to the previous results. By combining physical manipulation techniques such as pleating, creasing and gathering of particular layers, controllable variation of 3D effects could be achieved.

System barriers between maker & software

The software which runs the robotic axis of the flat-bed system also creates a language barrier between the maker and the tool. The challenge is how these input systems can be navigated and controlled most directly from design to realisation.

Barrier: Unfamiliar 'machine language' driven by coding

The unfamiliarity of the software, a *machine language* driven purely by coding, makes the usually instinctive translation of imagery and line from the hand-drawn to the digital almost impossible. Every movement of the laser head has to be programmed as coordinates, a kind of dot-to-dot process, making anything more complex than a series of repeating lines almost impossible to make. For designers used to using design driven software, such as Adobe, this is an agonising process, and completely counter-intuitive.

> *What is of particular interest is the way in which artists, applied or otherwise, wisely, wilfully, tend to do low-tech things with high tech technology. (Harrod, 2007)*

Solution: Integration of familiar craft practices

Both Goldsworthy and Paine relied on tacit knowledge from their own specialism (knit and print) in order to find a solution to this barrier. In particular, using mark-making methods as a way to reveal the programming directly through the laser movement. Paine attached a pen to the laser head and ran existing programs stored in its memory. This enabled the program to be seen *in action* and to produce a physical full-scale *map* of each one for reference.

A second technique involved using black photocopy paper (simply laser-printed black sheets) as a *carbon copy* to reveal where the laser was working by fusing the carbon from the copy onto a clean sheet and thus reveal the movement.

Solution: Creating raster patterns through bypassing the software

As a print designer, Goldsworthy was interested not only in the seaming or stitch-like effects that the laser could produce through vector lines, but an all over patterning or image based finish in order to replicate the desired print based finishes. In order to do this she drew on experience as a print designer and developed

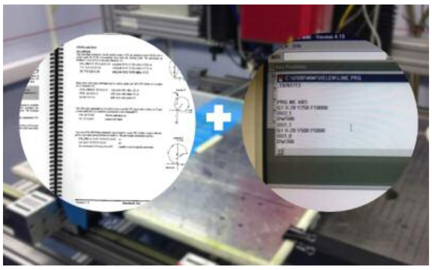

Image 5

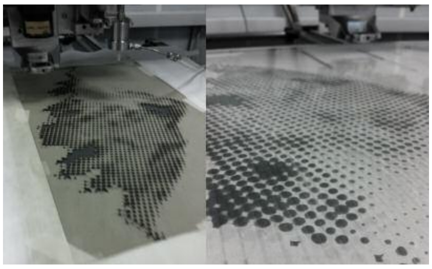

Image 6

a stencilling process (based on traditional screen-printing methods for all-over surface effects) to mask the laser so that it only effected the desired parts of the material. The more detailed the stencil the more *photographic* the effect. This was a breakthrough in the creation of the number of finishes that could be replicated with a very simple laser-programme. Flocking, devore, gloss-coating, and printing effects could all be replicated, as well as some more complex composite materials if the laser was used to laminate multiple layers together. This was the first time the technology had been used for anything other than seaming, and it opened up a vast array of potential manufacturing opportunities, which could be achieved without the need to change the laser programme during production.

Working with an all-over raster pattern to create surface effects in this way can be a slow process as the laser is focussed to a point that is less than 1cm wide. This has to travel across the whole surface of the material. Goldsworthy devised a system of creating multiple samples at once that explore a variety of processing conditions and material lay-ups. By adopting a systematic and methodical approach to the technology, she was able to maximise her material investigations in a restricted time frame. Once the desired effect had been achieved, laser settings could be adjusted to prioritise the speed of production without negating the material and aesthetic results.

Solution: Copy and pasting bits of existing programs together- hacker mentality

Using visual methods to *map out* the movement of the laser, Paine found it was possible to isolate parts from existing programmes on the system and copy and paste them into new programme files. Hashing various parts of different programmes together it was possible to build new designs without a thorough understanding of all the coding instructions. This process of *borrowing* elements from pre-existing patterns to build your own designs can be compared to the process of designing knitted textile patterns or collage. Working with a range of established stitch patterns new designs can be developed by combining these patterns in different sequences and varying proportions.

Material Barriers Between Maker & Material
Material restrictions are complex and depend on knowledge that cannot be ascertained from information often provided by retailers of textile materials. A detailed understanding of material behaviours was developed through the hands-on experience of reflective practice with the technology.

Barrier: Understanding material limitations
Material suitability for laser welding depends on a number of factors not usually necessary for a maker to consider. It is understood that materials must have a high level of theroplastic content so that they melt

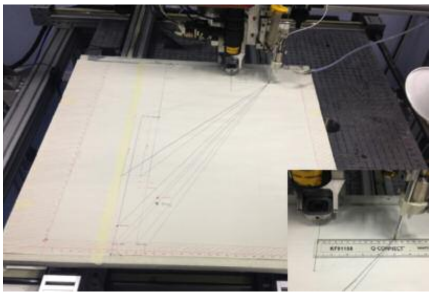

Image 7

Image 8

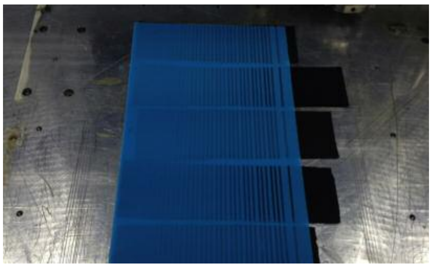

Image 9

when heated. Familiar synthetic textile materials, such as polyester and nylon, can be used for the process; however, it also relies on the material being able to transmit a high proportion of the laser energy. This material property is unlikely to be known even by the manufacturers as it is only relevant for this particular technology. Mostly, all coloured synthetic materials are suitable; however, some additives such as colourants and binders that may not be listed by the manufacturers can be problematic to the process causing unpredictable results that mark the top surface of the material or create undesired effects. Any new materials need to be first tested for suitability before being used even if fibre content is known. The construction, colour, finish and hidden additional materials may also effect its response to the process.

Solution: Using restrictions as an opportunity
For laser welding the top material must be transparent to the laser so that the energy can pass through and form the weld at the material interface. Working from an intuitive craft approach, exploring new visual opportunities for the technology, these material restrictions could sometimes create unplanned surface changes which it might be possible for a designer to exploit to useful effect.

> *Designers are often seen playing around with ideas, tossing up possibilities (proposals) in what may look like a hit and miss process. What they are in fact doing is trying out and thinking through many possibilities, thus building up a repertoire of experiences that help them develop an intuition of what will work in the problematic situation. (Dorst, 2010, p.133)*

At TWI, Paine was shown how to test the transparency of a material to the laser using an energy meter. A 2 J pulse of laser energy is passed through the material and then re-measured on the underside to see how much energy has been absorbed. Any material that absorbs more than 80% of the laser energy will not be suitable for using as the top surface in laser welding. Using this scientific method Paine was able to develop further insight into how transparent a particular material was to the laser. However, in a quest to explore alternative decorative mark-making opportunities the researchers played about with material configuration, exploring the effect of different material lay-ups on the visual quality of the weld. As the investigations in the beginning were not concerned with weld strength there was freedom to explore the visual impact of material lay up without considering the strength of the weld.

Barrier: Process depends heavily on machine parameters and not factors that are controllable by memory through the hand
The laser welding process is controlled by a number of variables that have to be programmed into the machine. Repetition of effects depends on the

interrelationship between these variables. Once a new technique has been developed the process, including machine parameters has to be fully documented if effects are to be repeated. Work produced by textile designers, although likely to be dependant on some machine settings, can also be reliant on hand-manipulated processes that cannot be recorded in the same way. Effects are repeated by applying the memory of how they were achieved before. This process is not concerned with remembering specific numerical settings, but more about finding a familiar *feeling* through the hand, which is cast in the memory of the maker from previous experience.

Image 10

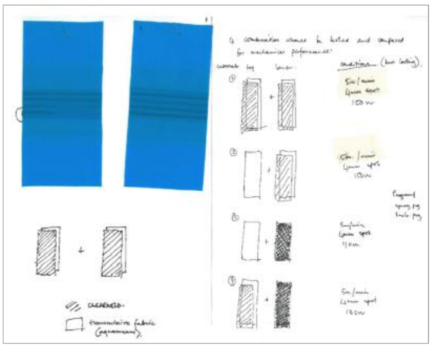

Image 11

Solution: Adapting record-keeping methods
Pre-preparing methods for recording brought a more systematic framework to the process of making, that was rigorous yet minimally invasive to the intuitive craft approach. This rigorous recording of the making process can disturb the intuitive craft practice through repeated breaks. The intuitive process of making can seem oppositional to the rigorous scientific methods of record keeping required for laser welding. It was therefore necessary to devise techniques for recording that minimised disruption that might disturb creative trains of thought.

With the aim of keeping track of the parameters and processes that were linked to different effects, sketchbooks became more like technical journals. Spec-sheets were pre-prepared ahead of making with spaces for all the relevant variables to be recorded. As each sample was produced it was attached to the relevant spec sheet and immediately stored in a file. Photographs were also used as a way of documenting any parts of the process that were particularly unique or vital to a particular effect. It also became increasingly important to date any work in sketchbooks or notebooks so that textural and photographic records could be connected and reflected upon together retrospectively.

> *The representations of problems and solutions (in words and sketches, sometimes using quite sophisticated visualisation techniques) is important because it allows the designer to develop their ideas in conversation with their representation. (Dorst, 2010, p.133)*

The act of methodically recording results and parameters became part of the creative process and allowed reflection to continue before and after continued experimentation.

Conclusion / Insights
Following the analysis of the examples presented in this paper there were several points considered as useful for further investigation and consideration. Insights from the combined experience of Goldsworthy and Paine in their approach to the technology is summarised below.

- Cheating the technology: Using tacit knowledge from their embedded print and knit craft knowledge in order to find ways to control the system in order to achieve desired results.
- Understanding material behaviour: It is not possible to choose materials for aesthetic and tactile properties alone when using such transformative technologies. The behaviour of fibres under the conditions of the process become the leading feature of the selection process.
- Creating moments of reflection: Digital technologies are not often designed with *experimentation of process* in mind. Designers need to find ways to get closer to the process in action in order to reflect and evolve their practice.
- Embracing new tools and scientific methods: Often new skills borrowed from a scientific field become essential to deepening understanding and developing a new techno-craft approach.
- Developing ways to record and analyse results before, during and after processing: Complex processing parameters including technical, material and craft methods need to be carefully recorded in order to make results repeatable and transferable.

When working with such an unfamiliar production technology, both textile makers used these tactics to control the process and ultimately find new techniques and applications that continue to develop through their current practice.

References

Dormer P., 1997. 'Craft and the Turing Test for Practical Thinking', in Dormer, P., *The Culture of Craft*, Manchester: Manchester University Press.

Dorst, K., 2010. 'The Nature of Design Thinking', available at: *http://www3.nd.edu/~amurniek/assets/DTRS8-Dorst.pdf* [accessed 20th August 2013].

Harrod, T., 2007. 'Otherwise Unobtainable: The applied arts and the politics and poetics of digital technology', in Alfody, S., *Neocraft: Modernity and the Crafts*, Halifax, Canada: The Press of the Nova Scotia College of Art and Design.

Philpott, R., 2013. 'Engineering Opportunities for Originality and Invention: The importance of playful making as developmental method in practice-led design research' in *Studies in Material Thinking*, Vol. 9 (August), available at: *https://www.materialthinking.org/ papers/127* [accessed 14th September 2014].

Philpott, R., 2010. 'Ways of Knowing and Making: Searching for an optimal integration of hand and machine in the textile design process', available at: *https://dspace.lboro.ac.uk/dspacejspui/bitstream/2134/12965/3/WaysOfKnowingTI2010(AcceptedVersion).pdf* [accessed 20th September 2014].

Press, M., 2007. 'Handmade Futures: The emerging role of craft knowledge in our digital culture', in Alfoldy, S., *Neocraft: Modernity and the Crafts*, Halifax, Canada: The Press of the Novia Scotia College of Art and Design.

Rees, H., 1997. 'Patterns of Making: Thinking and making in industrial design', in Dormer, P., *The Culture of Craft*, Manchester, UK: Manchester University Press.

Schon, D. A., 1983. *The Reflective Practitioner: How Professionals Think in Action*, London, UK: Maurice Temple Smith Ltd.

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Helen Paine *is a Doctoral student funded by TWI and based at the Royal College of Art London. Coming from a background in textile design her research has followed a practice-led approach working closely with industry to seek new functional and aesthetic opportunities for existing advanced joining technologies.*

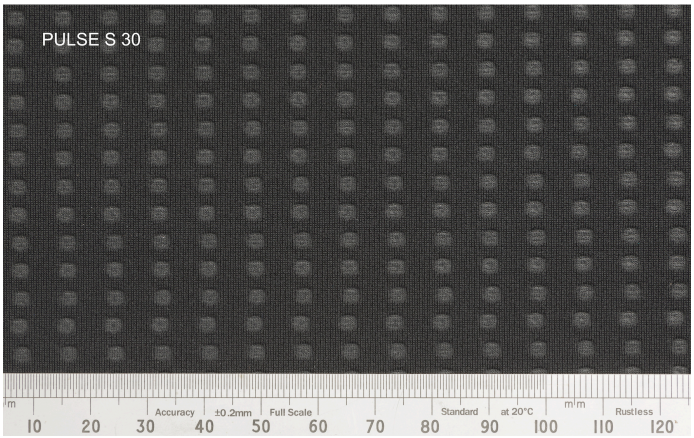
8.4 Additional garment prototypes

Figure 8.1 Swimsuit with curved laser melted patterns across midriff

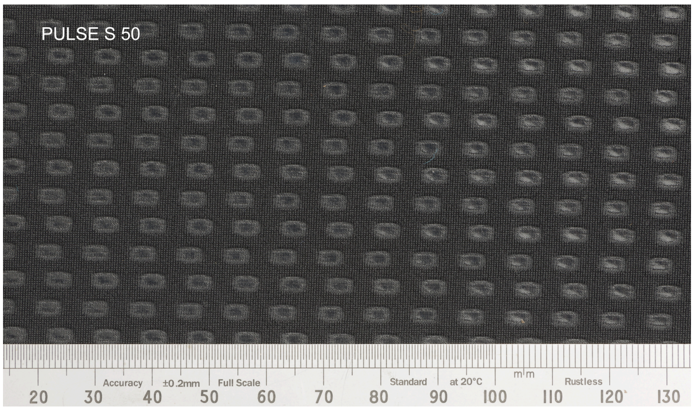
Figure 8.2 Swimsuit with ultrasonic rippled surface effect

8.5 ‘Laser Shaping’ sample specification sheets

Sample Number	Pulse S 30
Material (s)	Fabric D
Wave type	Pulsed
Tpuls (ms)	30
Trep (ms)	100
Power (W)	50
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	5
Extension at 36N (%)	90.1
Force at 40% extension (N)	3.69



Sample Number	Pulse S 50
Material (s)	Fabric D
Wave type	Pulsed
Tpuls (ms)	50
Trep (ms)	100
Power (W)	50
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	5
Extension at 36N (%)	63.8
Force at 40% extension (N)	6.52



Sample Number	Pulse S 70
Material (s)	Fabric D
Wave type	Pulsed
Tpuls (ms)	70
Trep (ms)	100
Power (W)	50
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	5
Extension at 36N (%)	54.6
Force at 40% extension (N)	10.6

Sample Number	Power S 30
Material (s)	Fabric D
Wave type	Continuous
Tpuls (ms)	n/a
Trep (ms)	n/a
Power (W)	30
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	10
Extension at 36N (%)	105.07
Force at 40% extension (N)	2.56

Sample Number	Power S 40	
Material (s)	Fabric D	
Wave type	Continuous	
Tpuls (ms)	n/a	
Trep (ms)	n/a	
Power (W)	40	
Laser spot size (mm)	4	
Speed (m/min)	5	
Distance in between melt lines (mm)	10	
Extension at 36N (%)	92.63	
Force at 40% extension	3.29	

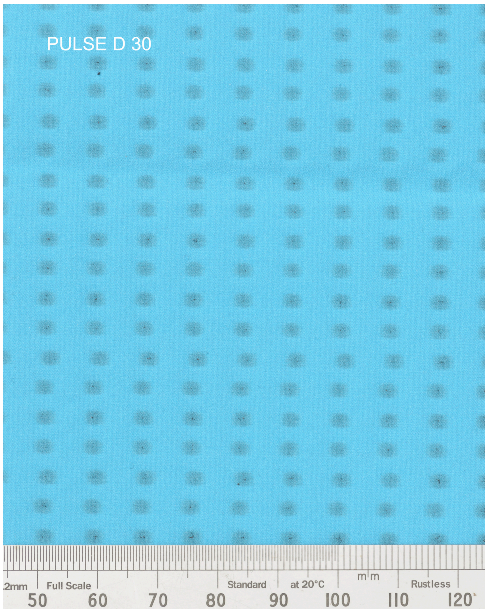
Sample Number	Power S 50	
Material (s)	Fabric D	
Wave type	Continuous	
Tpuls (ms)	n/a	
Trep (ms)	n/a	
Power (W)	50	
Laser spot size (mm)	4	
Speed (m/min)	5	
Distance in between melt lines (mm)	10	
Extension at 36N (%)	83.93	
Force at 40% extension	3.52	

Sample Number	Distance S 5	
Material (s)	Fabric D	
Wave type	Continuous	
Tpuls (ms)	n/a	
Trep (ms)	n/a	
Power (W)	50	
Laser spot size (mm)	4	
Speed (m/min)	5	
Distance in between melt lines (mm)	5	
Extension at 36N (%)	57.6	
Force at 40% extension	8.6	

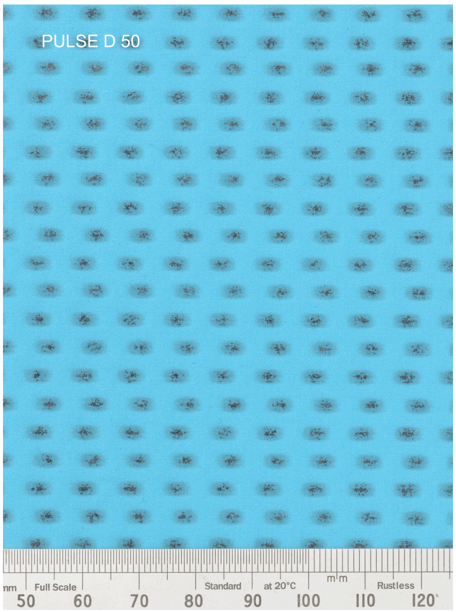
Sample Number	Distance S 10	
Material (s)	Fabric D	
Wave type	Continuous	
Tpuls (ms)	n/a	
Trep (ms)	n/a	
Power (W)	50	
Laser spot size (mm)	4	
Speed (m/min)	5	
Distance in between melt lines (mm)	10	
Extension at 36N (%)	82.2	
Force at 40% extension (N)	4.36	

Sample Number	Distance S 15
Material (s)	Fabric D
Wave type	Continuous
Mpuls (ms)	n/a
Trep (ms)	n/a
Power (W)	50
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	15
Extension at 36N (%)	96.9
Force at 40% extension (N)	3.12

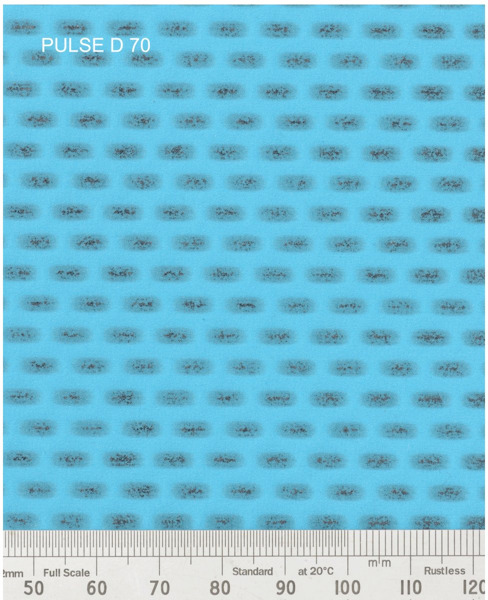
Sample Number	Pulse D 30
Material (s)	Fabric A/ Fabric C
Wave type	Pulsed
Tpuls (ms)	30
Trep (ms)	100
Power (W)	120
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	5
Extension at 36N (%)	39.09
Force at 40% extension (N)	No reading



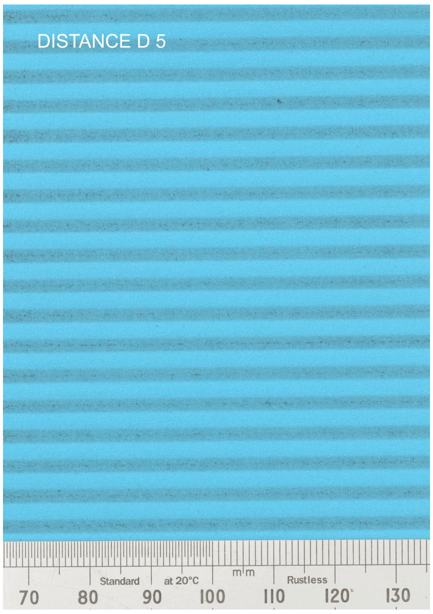
Sample Number	Pulse D 50
Material (s)	Fabric A/ Fabric C
Wave type	Pulsed
Tpuls (ms)	50
Trep (ms)	100
Power (W)	120
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	5
Extension at 36N (%)	32.57
Force at 40% extension (N)	No reading



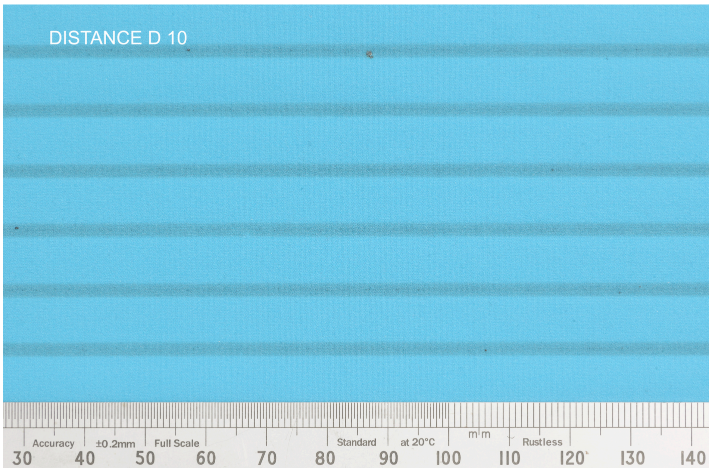
Sample Number	Pulse D 70
Material (s)	Fabric A/ Fabric C
Wave type	Pulsed
Tpuls (ms)	70
Trep (ms)	100
Power (W)	120
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	5
Extension at 36N (%)	27.16
Force at 40% extension (N)	No reading



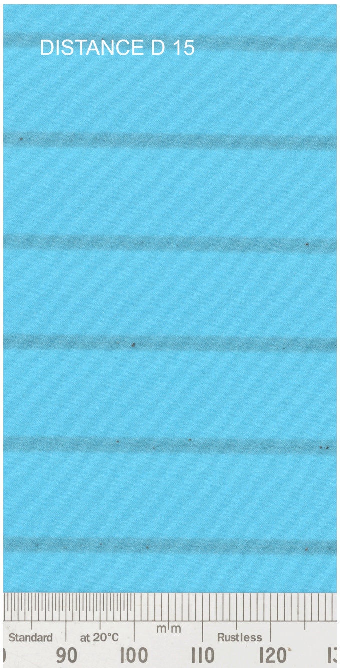
Sample Number	Distance D 5
Material (s)	Fabric A/ Fabric C
Wave type	Continuous
Tpuls (ms)	n/a
Trep (ms)	n/a
Power (W)	120
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	5
Extension at 36N (%)	29.79
Force at 40% extension (N)	No reading



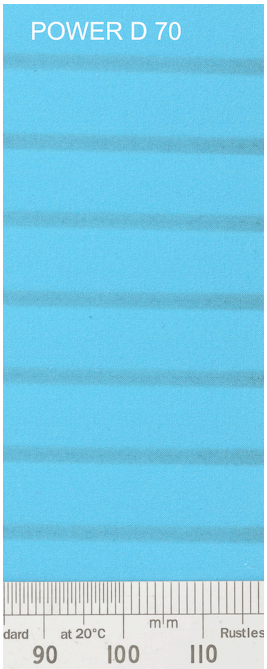
Sample Number	Distance D 10
Material (s)	Fabric A/ Fabric C
Wave type	Continuous
Tpuls (ms)	n/a
Trep (ms)	n/a
Power (W)	120
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	10
Extension at 36N (%)	44.87
Force at 40% extension (N)	24.93

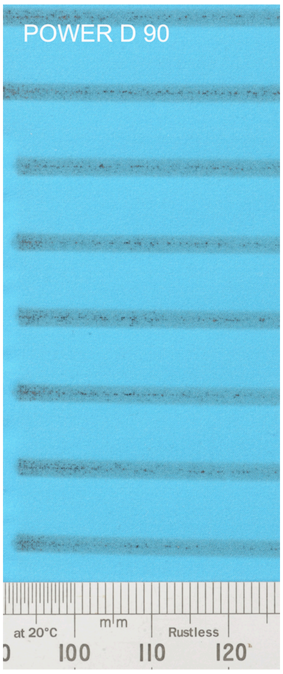


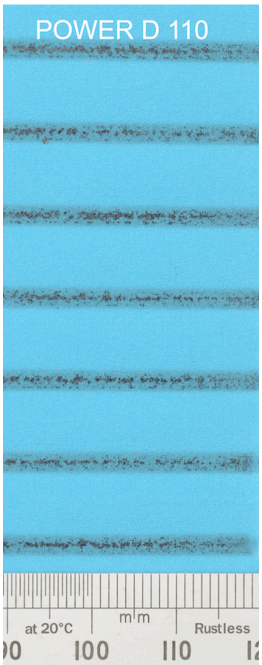
Sample Number	Distance D 15
Material (s)	Fabric A/ Fabric C
Wave type	Continuous
Tpuls (ms)	n/a
Trep (ms)	n/a
Power (W)	120
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	15
Extension at 36N (%)	51.1
Force at 40% extension (N)	16.93



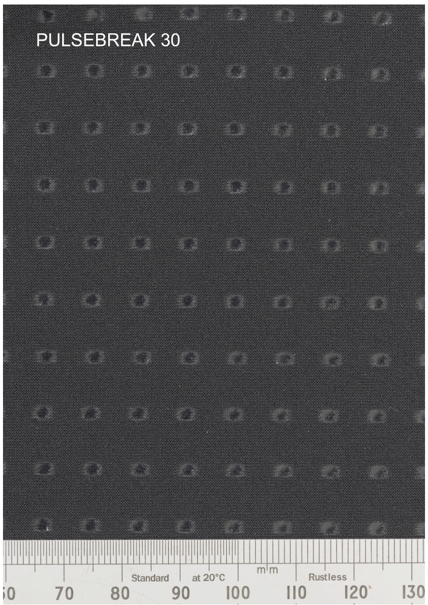
Sample Number	Power D 70
Material (s)	Fabric A/ Fabric C
Wave type	Continuous
Tpuls (ms)	n/a
Trep (ms)	n/a
Power (W)	70
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	10
Extension at 36N (%)	51.27
Force at 40% extension (N)	16.52



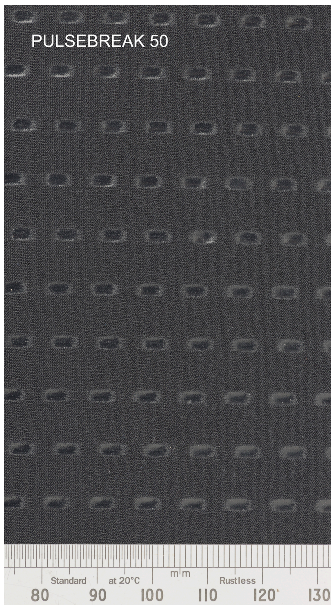
Sample Number	Power D 90	
Material (s)	Fabric A/ Fabric C	
Wave type	Continuous	
Tpuls (ms)	n/a	
Trep (ms)	n/a	
Power (W)	90	
Laser spot size (mm)	4	
Speed (m/min)	5	
Distance in between melt lines (mm)	10	
Extension at 36N (%)	47.53	
Force at 40% extension (N)	19.81	

Sample Number	Power D 110	
Material (s)	Fabric A/ Fabric C	
Wave type	Continuous	
Tpuls (ms)	n/a	
Trep (ms)	n/a	
Power (W)	110	
Laser spot size (mm)	4	
Speed (m/min)	5	
Distance in between melt lines (mm)	10	
Extension at 36N (%)	46.27	
Force at 40% extension (N)	21.27	

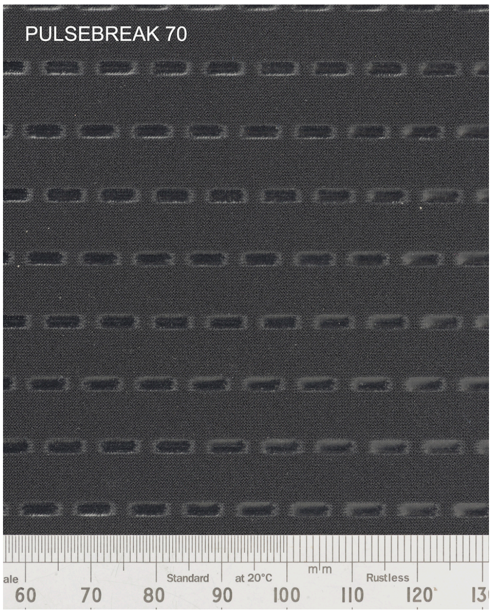
Sample Number	Pulsebreak 30
Material (s)	Fabric C
Wave type	Pulsed
Tpuls (ms)	30
Trep (ms)	100
Power (W)	50
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	10
Force to break (N)	478



Sample Number	Pulsebreak 50
Material (s)	Fabric C
Wave type	Pulsed
Tpuls (ms)	50
Trep (ms)	100
Power (W)	50
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	10
Force to break (N)	268.8



Sample Number	Pulsebreak 70
Material (s)	Fabric C
Wave type	Pulsed
Tpuls (ms)	70
Trep (ms)	100
Power (W)	50
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	10
Force to break (N)	269.07



Sample Number	Powerbreak 30
Material (s)	Fabric C
Wave type	Pulsed
Tpuls (ms)	30
Trep (ms)	100
Power (W)	50
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	10
Force to break (N)	100.33

Sample Number	Powerbreak 40
Material (s)	Fabric C
Wave type	Pulsed
Tpuls (ms)	40
Trep (ms)	100
Power (W)	50
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	10
Force to break (N)	129.23

Sample Number	Powerbreak 50
Material (s)	Fabric C
Wave type	Pulsed
Tpuls (ms)	50
Trep (ms)	100
Power (W)	50
Laser spot size (mm)	4
Speed (m/min)	5
Distance in between melt lines (mm)	10
Force to break (N)	146.43

Sample Number	Powerbreak 60	
Material (s)	Fabric C	
Wave type	Pulsed	
Tpuls (ms)	60	
Trep (ms)	100	
Power (W)	50	
Laser spot size (mm)	4	
Speed (m/min)	5	
Distance in between melt lines (mm)	10	
Force to break (N)	134.07	

8.6 List of conferences attended and meetings with Speedo

Conferences/ Exhibitions:

Rescon: School of Engineering Research Conference (18th-20th June 2012) | Brunel University

Techtextil and Avantex Symposium (11th-13th June 2013), Messe Frankfurt, Germany

Rescon: School of Engineering Research Conference (24th-26th June 2013), Brunel University | Contributed: Poster presentation

Textiles Symposium 2013: Connecting with Textiles (11th July 2013), LCF, London

Managing Innovation in Textiles (21st November 2013), The Textiles Institute, Chancellors Hotel and Conference Centre, Manchester, UK

AllMakersNow?: Craft Values in 21st Century Production (10th-11th July 2014), Falmouth University | Contributed: Presentation and Conference paper

Design Products Work in Progress (5th-9th February 2014), RCA, Darwin Building, London | Contributed: Exhibition of research

Time Symposium (19th March 2014), RCA, Darwin Building, London

Symbiosis: conversations in art and design (26th March 2014), RCA, Darwin Building, London

Co-design and Collaboration (18th September 2014), Central Saint Martins, London

Make: Shift (20th-21st November 2014), Museum of Science and Industry, Manchester. (Viewed live online)

The Peter Dormer Lecture (27th November 2014), RCA, Dyson Building, London

ISPO Munich (5th-6th February 2015), Messe München GmbH, Germany

Meetings with Speedo:

19th November 2012
14th February 2013
2nd May 2013
25th-26th September 2013
19th-20th November 2013
21st January 2014
4th March 2014
23rd March 2014
3rd June 2014
13th August 2014
3rd September 2014
9th September 2014
24th March 2015

9 References

9.1 Glossary of terms

Abductive thinking	-	A way of thinking that relies on intuition to make creative leaps in knowledge
Adhesive taped seam	-	Textile seam sealed with an adhesive tape
Adhesive lap-seam	-	Textile seam constructed with one material layer on top of another
Anomaly	-	A result that does not fit the general pattern
Anvil	-	Rotating metal wheel used in continuous ultrasonic welding equipment to guide materials and apply pressure
Clearweld	-	Dye invented by TWI that is absorptive in the near-infrared wavelength
CNC commands	-	Computer numerically controlled commands
Compression stockings	-	Stockings containing a variable graduated Lycra content used for the treatment of lymphedema
Continuous wave setting	-	Operational setting that allows continual release of the laser beam without interruption
Cross-disciplinary research	-	Research that crosses the boundaries between different disciplines
Dielectric welding	-	A method of welding whereby alternating waves from an electromagnetic generator are used to create frictional heating between two thermoplastic materials
Elastic behaviour	-	How a material responds elastically to applied force
Empirical approach	-	A way of gaining information through observable evidence
Frictional heating	-	Heat that is generated as a result of friction
Flat-locking	-	A multi-thread method of seaming textile materials one on top of the other

Hot wedge welding	-	A method of welding by applying electrically heated jaws to thermoplastic materials and heat is transferred to the interface
Hot air welding		A method of welding by applying a focused stream of heated compressed air at the interface of two thermoplastic materials
Infrared absorbing dye	-	Dye containing pigments that are absorptive to light in the infrared wavelength
Infrared wavelength	-	Portion of light in the invisible spectrum
Industry standard	-	An established norm or requirement in regard to technical systems
Irradiate	-	Emission of energy in waves
Laser spot size	-	The dimensions of the beam at the focal point of the laser
Laser diodes	-	Electronic current convertor in diode laser equipment
Lap joint configuration	-	Arrangement of two fabric layers for joining one on top of the other
Material compatibility	-	The level of consistency in the joining of two material layers
Material configuration	-	Arrangement of materials
Mechanical energy	-	The energy associated with the motion and position of an object
Mechanical testing	-	A method of testing if a material is suitable for its intended mechanical applications by measuring, for example, its elasticity, tensile strength, elongation, hardness, fracture toughness, impact resistance, stress rupture, and fatigue limit
Over-locking	-	A multi-thread method of seaming textile materials face-to-face
Peel joint	-	Arrangement of two fabric layers face-to-face for joining

configuration

Process Parameter	-	A controllable condition of a process
Polymer	-	Macromolecules with long chains of carbon atoms. Plastics are examples of polymers
Pulsed wave setting	-	Operational setting that allows fragmented release of the laser beam
Quantitative Evidence	-	Measurable proof often involving the collection of numerical data
Reflective practice	-	A method of bridging between practical and intellectual thought processes
Ruching	-	A French term to describe decorative fabric surfaces with a gathered, ruffled or pleated appearance
Scanning electron microscopy	-	A type of microscopy that produces images of a sample by scanning it with a focused beam of electrons
Sonotrode	-	A tool that creates ultrasonic vibrations and applies vibrational energy to a material
Substrate	-	The material being acted upon in an investigation
Tensile strength	-	The measurement of force required to pull something to the point of failure
Tacit knowledge	-	Implicit knowledge gained through experience
Thermoplastic	-	A material that softens when heated
TLW	-	Method of welding using energy applied by a laser in the near-infrared wavelength. Laser energy is absorbed by material at the weld interface
Ultrasonic welding	-	Method of welding by applying vibrational energy via an ultrasonic sonotrode
Watt	-	Unit of electrical power

9.2 Bibliography

ACHERJEE, B., MISRA, D., BOSE, D. and VENKADESHWARAN, K., 2009. Prediction of weld strength and seam width for laser transmission welding of thermoplastic using response surface methodology. *Optics and Laser Technology*, 41(8), pp. 956-967.

AKIWOWO, K., 2015a. *Digital laser dyeing: coloration and patterning technique for polyester textiles*, Thesis (PhD), Loughborough University.

AKIWOWO, K., 2015b. Digital laser-dye patterning for PET textiles. Presented at: *IASDR 2015 Interplay*, Brisbane, Australia, 2-5 November 2015.

AMANAT, N., JAMES, N.L. and MCKENZIE, D.R., 2010. Welding methods for joining thermoplastic polymers for the hermetic enclosure of medical devices. *Medical Engineering & Physics*, 32(7), pp. 690-699.

BABYAK, R., J., 2001. Lasers point to progress. *Appliance Manufacturer*, 49(2), p. 8.

BACHMANN, F., 2003. Industrial applications of high power diode lasers in materials processing. *Applied Surface Science,* 208 (1), pp. 125-136.

BAHTIYARI, M.I., 2011. Laser modification of polyamide fabrics. *Optics and Laser Technology*, 43(1), pp. 114-118.

BALIT, R., 1999. *Swim suit and body support system,* United States Patent, No. 5,996,120.

BARTLETT, S., 2006. *Laser and textiles: an exploration into laser dye-fibre interaction and the process of technology transfer*, Thesis (PhD), Loughborough University.

BAYLIS, B.K., BATES, P.J., PRABHAKARAN, R., ZAK, G. and KONTOPOULOU, M., 2006. Contour laser - laser-transmission welding of glass reinforced Nylon 6. *Journal of Thermoplastic Composite Materials,* 19(4), pp. 427-439.

BECKER, F. and POTENTE, H., 2002. A step towards understanding the heating phase of laser transmission welding in polymers. *Polymer Engineering & Science*, 42(2), pp. 365-374.

BELL, W., 1987. *Garment having additional support to selected portions,* United States Patent, No. 4,701,964.

BHAT, G.S., JANGALA, P.K. and SPRUIELL, J.E., 2004. Thermal bonding of polypropylene nonwovens: effect of bonding variables on the structure and properties of the fabrics. *Journal of Applied Polymer Science*, 92(6), pp. 3593-3600.

BIGGS, M. and BUCHLER, D., 2007. Rigor and practice-based research. *Design Issues*, 23(3), pp. 62-69.

BORRAS, X., BALIUS, X., DROBNIC, F., TIL, L., TURMO, A. and VALLE, J., 2011. Effects of lower body compression garment on muscle oscillation and tissular injury during intense exercise. *Portuguese Journal of Sports Sciences*, 11(2), pp. 685-688.

BRADDOCK CLARKE, S.E. and O'MAHONY, M., 2005. *Techno Textiles 2- Revolutionary Fabrics for Fashion and Design.* London: Thames and Hudson.

BROWDER, G., 2001. *Seamless torso controlling garment and method of making the same,* United States Patent, No. US 6,276,175 B1.

BRYDEN, B., G., 2004. Welding of plastics with high power diode lasers. *Industrial Robot: An International Journal*, 31(1), pp. 30-33.

BURRELL, M. and WOOSMAN, N. M., 2002. Invisible seams. *Appliance Manufacturer*, 50(8), pp. 22.

CHAMBERS, A., KAGAN, V. and BRAY, R., 2003. Forward to better understanding of optical characterization and development of colored polyamides for the infra-red/laser welding, part II - family of colored polyamides. *Journal of Reinforced Plastics and Composites,* 22(7), pp. 593-602.

CHEN, M., ZAK, G. and BATES, P.J., 2011. Effect of carbon black on light transmission in laser welding of thermoplastics. *Journal of Materials Processing Tech,* 211(1), pp. 43-47.

CHIPPERFIELD, F.A. and JONES, I.A., 2001. Laser weling of thermoplastic materials. *Medical Device Technology,* 12(5), pp. 40-45.

CHOWDHARY, U. and POYNER, D., 2006. Impact of stitch density on seam strength, seam elongation and seam efficiency. *International Journal of Consumer Studies,* 30(6), pp. 561-567.

CRESSWELL, J.W., 2009. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches.* 3 edn. California: Sage Publications.

CROSS, N., 2011. *Design Thinking.* Oxford: Berg.

CROSS, N., 2006. *Designerly Ways of Knowing.* London: Springer.

CROUCH, C. and PEARCE, J., 2012. *Doing Research in Design.* London: Berg.

CW-X, 2015. CW-X Compression technology [Homepage of Wacoal Corporation, online], available from: http://www.cw-x.com.au/compression-technology [Accessed 9 July, 2015].

DASCULU, T., ACOSTA-ORTIZ, S.E., ORTIZ-MORALES, M. and COMPEAN, I., 2000. Removal of the indigo color by laser beam-denim interaction. *Optics and Lasers in Engineering,* 34(3), pp. 179-189.

DENNARD, J., 2005. ActiveSeam(TM) offers improved seam bonding. *Textile World,* 155(3), p. 38.

DEVINE, J., 1998. Ultrasonic bonding of plastics and textiles for medical and other devices. Presented at: *ICAWT '98 International Conference on Advances in Welding Technology*, 30 September-2 October 1998, Edison Welding Institute.

DI RIENZO, L., ed, 2011. *Bond-In: From Technology to Fashion,* Milan: Gribaudo.

DORMER, P., 1997a. Craft and the turing test for practical thinking. In: P. DORMER, ed, *The Culture of Craft.* Manchester: Manchester University Press, pp. 137-157.

DORMER, P., ed, 1997b. *The Culture of Craft.* Manchester: Manchester University Press.

DORST, K., 2010. The nature of design thinking. Presented at: *Interpreting Design Thinking: Design Thinking Research Symposium 2010.*

DRILLER, M. and HALSON, S., 2013. The effects of lower body compression garments between exercise bouts in highly trained cyclists. *Journal of Science and Cycling,* 2(1), pp. 45-50.

DUFFIELD, R. and PORTUS, M., 2007. Comparison of three types of full body compression garments on throwing and repeat-sprint performance in cricket players. *British Journal of Sports Medicine,* 41(7), pp. 409-414.

EMMANUEL, J., 2001. *Using ultrasonic technology in textile manipulation to develop three dimensional products*, Thesis (PhD), Liverpool John Moores University.

FELLMAN, A., 2004. The seam that stretches. *Textile Network,* 2(6), pp. 52-53.

GEIGER, M., FRICK, T. and SCHMIDT, M., 2009. Optical properties of plastics and their role for the modelling of the laser transmission welding process. *Production Engineering,* 3(1), pp. 49-55.

GIRARD, P., 1999. *Laminated fabric with uniform pattern of adhesive securement and garments made therefrom,* United States Patent, No. 5,916,829.

GOLDSWORTHY, K., PAINE, H., 2014. Laser welding of textiles: a creative approach to technology through a reflective craft practice. In; K. Bunnel, J. Marshall, (eds), *All Makers Now? Craft Values in 21st Century Production*, 10-11 July 2014, Falmouth University Press, pp. 45-51.

GOLDSWORTHY, K., 2009. Resurfaced: Using laser technology to create innovative surface finishes for recyclable, synthetic textiles. Presented at: *Cutting Edge: Lasers and Creativity Symposium 2009,* Loughborough University.

GOLDSWORTHY, K., 2012. *Laser-finishing: a new process for designing recyclability in synthetic textiles*, Thesis (PhD), University of the Arts London.

GRAY, C. and MALINS, J., 2004. *Visualizing Research: A Guide to the Research Process in Art and Design.* Aldershot: Ashgate Publishing Ltd.

GREWELL, D., ROONEY, P. and KAGAN, V.A., 2004. Relationship between optical properties and optimized processing parameters for through-transmission laser welding of thermoplastics. *Journal of Reinforced Plastics and Composites,* 23(3), pp. 239-247.

GRIBAA, S., AMAR, S.B. and DOGUI, A., 2006. Influence of sewing parameters upon the tensile behaviour of textile assembly. *International Journal of Clothing, Science and Technology,* 18(4), pp. 235-246.

GRYNAEUS, P.S., 2004. Adhesive bonding in garment manufacturing. *Melliand International,* 10(2), p. 125.

GURARDA, A., 2008. Investigation of the seam performance of PET/ Nylon-elastane woven fabrics. *Textile Research Journal,* 78(1), pp. 21-27.

GUTNIK, V.G., GORBACH, N.V. and DASHKOV, A.V., 2002. Some characteristics of ultrasonic welding of polymers. *Fibre Chemistry,* 34(6), pp. 426-432.

HALL, M., 2003. *Compression support sleeve,* United States Patent Application, No. US 2003/0069531 A1.

HARPA, R., PIROI, C. and AND DORU RADU, C., 2010. A new approach for testing medical stockings. *Textile Research Journal,* 80(8), pp. 683-695.

HARROD, T., 2007. Otherwise unobtainable: the applied arts and the politics and poetics of digital technology. In: S. ALFOLDY, ed, *NeoCraft: Modernity and the Crafts.* Canada: The Press of the Nova Scotia College of Art and Design, pp. 225-239.

HAVERHALS, L.M., REICHERT, W.M., DE LONG, H.C. and TRULOVE, P.C., 2010. Natural Fiber Welding. *Macromolecular Materials and Engineering,* 295(5), pp. 425-430.

HAYES, S. and MCLOUGHLIN, J., 2013. The sewing of textiles. In: I. JONES and G.K. STYLIOS, eds, *Joining Textile: Principles and Applications.* Cambridge: Woodhead Publishing, pp. 62-121.

HECKNER, R., 2004. Stetchable elastic seams-possibilities and limitations in the field of technical textiles. *Melliand International,* 10(3), pp. 224-225.

HEPBURN, C. and AZIZ, Y.B., 1985. The bonding of polyaramid fibres to rubber. *International Journal of Adhesion and Adhesives,* 5(3), pp. 153-159.

HILTON, P.A. and JONES, I., 2000. Laser welding of fabrics using infrared absorbing dyes. Presented at: *Joining of Advanced and Speciality Materials III*, 9-12 October 2000, Missouri, USA.

HOFFMAN, J., M. and KORANE, K., 2003. Automation speeds clear-plastic welding. *Machine Design,* 75(3), p. 64.

HUDDLESTON, R. and WHITTAKER, P., 2009. Jacob Schlaepfer: a vision for innovation enabled by laser technologies. Presented at: *Cutting Edge: Laser and Creativity Symposium* 2009, Loughborough University.

ILIE, M., KNEIP, J., MATTEÏ, S., NICHICI, A., ROZE, C. and GIRASOLE, T., 2007. Laser beam scattering effects in non-absorbent inhomogenous polymers. *Optics and Lasers in Engineering,* **45**(3), pp. 405-412.

JAKUBČIONIENĖ, Z., MASTEIKAITĖ, V., KLEVECKAS, T., JAKUBČIONIS, M. and KELESOVA, U., 2012. Investigation of the strength of textile bonded seams. *Materials Science,* **18**(2), pp. 172-176.

JONES, I., 2013. Ultrasonic and dielectric welding of textiles. In: I. JONES and G.K. STYLIOS, eds, *Joining Textiles: Principles and Applications.* Cambridge: Woodhead Publishing, pp. 374-397.

JONES, I., 2008. Altex: automated laser welding for textiles [online], available from: http://www.twi-global.com/news-events/connect/2008/january-february-2008/altex-automated-laser-welding-for-textiles/ [Accessed 5 June, 2012].

JONES, I., 2007. Altex: automated laser seaming for textiles [online], available from: http://cordis.europa.eu/documents/documentlibrary/121406901EN6.pdf [Accessed 6 May, 2012].

JONES, I., 2005. Laser joining fabrics improves productivity. *Industrial Laser Solutions* [online], available from: http://www.industrial-lasers.com/articles/2005/01/laser-joining-fabrics-improves-productivity.html [Accessed 24 May 2012].

JONES, I.A. and WISE, R.J., 2005. Novel joining methods applicable to textiles and smart garments. Presented at: *Wearable Futures Conference*, 14-16 September 2005, University of Wales.

JONES, I. and PATIL, A., 2013. Laser seaming of fabrics. In: I. JONES and G.K. STYLIOS, eds, *Joining Textiles: Principles and Applications.* Cambridge: Woodhead Publishing, pp. 398-434.

KAGAN, V.A. and PINHO, G.P., 2004. Laser transmission welding of semicrystalline thermoplastics - part II: analysis of mechanical performance of welded Nylon. *Journal of Reinforced Plastics and Composites,* **23**(1), pp. 95-107.

KAGAN, V.A., BRAY, R. and PHINO, G., 2000. Welding with light. *Machine Design,* **72**(15), p. 79.

KAGAN, V.A. and WOOSMAN, N.M., 2004. Efficiency of clearwelding technology for polyamides. *Journal of Reinforced Plastics and Composites,* **23**(4), pp. 351-359.

KALAOGLU, F. and BUTUN, H., 2001. Investigation of ultrasonic seam strength. *International Textiles Bulletin: Nonwovens, Industrial,* **47**(4), pp. 25-28.

KAN, C.W., 2008. Impact on textile properties of polyester with laser. *Optics and Lasers in Engineering,* **40**(1), pp. 113-119.

KAN, C.W., YUEN, C.W.M. and CHENG, C.W., 2010. Technical study of the effect of CO2 laser surface engraving on the colour properties of denim fabric. *Coloration Technology,* **126**(6), pp. 365-371.

KANE, F., 2009 Laser patterned non-wovens. Presented at: *Cutting Edge: Lasers and Creativity Symposium 2009,* Loughborough University.

KANE, F., 2007. *Designing nonwovens: craft and industrial perspectives*, Thesis (PhD), Loughborough University.

KELLAR, E.J.C. and JONES, I.A., 2000. Innovations in plastic welding and adhesive bonding. *Welding and Metal Fabrication,* **68**(10), pp. 13-15.

KEMPLE, J., 2001. Tidy seam-sealing. *Backpacker,* **29**(8), p. 85.

KRAEMER, W., BUSH, A., WICKHAM, R., DENEGAR, C., GBMEZ, A., GOTSHALK, A., DUNCAN, N., VOLEK, S., PUTUKIAN, M. and SEBASTIANELLI, W., 2001. Influence of compression therapy on symptoms from soft tissue injury from maximal eccentric exercise. *Journal of Orthopaedic & Sports Physical Therapy,* **31**(6), pp. 282-290.

KRAEMER, W., BUSH, J., BAUER, J., TRAVIS TRIPLETT-MCBRIDE, P.N. and CLEMSON, A., 1996. Influence of compression garments on vertical jump performance in NCAA division I volleyball players. *Journal of Strength and Conditioning Research,* 10(3), pp. 180-183.

LAUDER, V., 2010. *Corsets: A Modern Guide*. London: Quantum Publishing Ltd.

LAWSON, B., 2005. *How Designers Think: The Design Process Demystified.* 4 edn. Oxford: Architectural Press.

LIM, N., YU, W., FAN, J. and YIP, J., 2006. Innovation of girdles. In: W. YU, J. FAN, S.C. HARLOCK and S.P. NG, eds, *Innovation and Technology of Women's Intimate Apparel.* Cambridge: Woodhead Publishing, pp. 114-131.

LYNN, E., 2014. *Underwear Fashion in Detail*. London: V&A Publishing.

MAJUMDAR, J., D. and MANNA, I., 2003. Laser processing of materials. *Sadhana,* 28(3), pp. 495-562.

MANSFIELD, R.G., 2003. Ultrasonics: sound technology for textiles and non-wovens. *Textile World,* 153(5), pp. 42-45.

MARTIN, C., 2012. Stretching the Boundaries. *Nature Materials,* 11(1), pp. 659-660.

MATTHEWS, J., 2011. *Textiles in three dimensions: an investigation into processes employing laser technology to from design-led three-dimensional textiles*, Thesis (PhD), Loughborough University.

MCNIFF, J. and WHITEREAD, J., 2005. *All You Need To Know About Action Research.* London: Sage.

MERRITT, A., 2010. Material girl Janet is a cut above the rest. *Express & Echo* [online], available from:http://www.exeterexpressandecho.co.uk/Material-girl-Janet-cut-rest/story-11791757-detail/story.html[Accessed 24 May, 2012].

MICHIELSEN, S. and JAIN, S., 2010. Thermal bonding of nonwovens as simulated by polypropylene films: effect of time, temperature, and molecular weight. *Journal of Applied Polymer Science,* 117(6), pp. 3322-3330.

MUKHOPADHYAY, A. and MIDHA, V.K., 2013. The quality and performance of sewn seams. In: I. JONES and G.K. STYLIOS, eds, *Joining Textiles: Principles and Applications.* Woodhead Publishing, pp. 175-207.

WOOSMAN, N., M. and FRIEDER L., P., 2005. Clearweld: welding of clear, coloured, or opaque thermoplastics. *Proceedings of the Institution of Mechanical Engineers,* 219(9), pp. 1069-1074.

NIEDDERER, K. and TOWNSEND, K., 2010. Editorial. *Craft Research,* 1(1), pp. 3-10.

O'MAHONY, M. and BRADDOCK, S.E., 2002. *Sportstech- Revolutionary Fabrics, Fashion and Design.* New York: Thames and Hudson.

ONDOGAN, Z., PAMUK, O., DALBASTI, T., AYDIN, H. and OZCELIK, M., 2005a. Laser machine creates patterns in fabric. *Laser Focus World,* 41(1), pp. 167-170.

ONDOGAN, Z., PAMUK, O., ONDOGAN, E.N. and OZGUNEY, A., 2005b. Improving the appearance of all textile products from clothing to home textile using laser technology. *Optics and Laser Technology,* 37(8), pp. 631-637.

ORTIZ-MORALES, M., POTERASU, M., ACOSTA-ORTIZ, S.E. and COMPEAN, I., 2003. A comparsion between characteristics of various laser-based denim fading processes. *Optics and Lasers in Engineering,* 39(1), pp. 15-24.

OVERTON, G., 2008. New technologies heat up the laser-welding market. *Laser Focus World,* 44(10), p. 90.

OZGUNEY, A., 2007. The comparison of laser surface designing and pigment printing methods for the product quality. *Optics and Laser Technology,* 39(5), pp. 1054-1058.

PASCUAL, D., 1998. *Process for the manufacture of a figured elastic fabric made by the jaquard System*, United States Patent, No. 5,749,400.

PATTEN, D.R., 2005. Fundamentals of ultrasonic plastic welding. *Machine Design,* **77**(3), p. 59.

PHILPOTT, R., 2013. Engineering opportunities for originality and invention: the importance of playful making as developmental method in practice-led design research. *Studies in Materials Thinking* [online], **9**(1), available from: https://www.materialthinking.org/papers/127 [Accessed 28 February 2015]

PHILPOTT, R., 2011. *Structural textiles: adaptable form and surface in three dimensions*, Thesis (PhD), Royal College of Art.

PHILPOTT, R., 2010, Ways of knowing and making: searching for an optimal integration of hand and machine in the textile design process. *Loughborough University Institutional Repository* [online], available from: https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/12965 [Accessed 27 June, 2015].

POLANYI, M., 1966. *The Tacit Dimension*. Chicago: The University of Chicago Press.

PRESS, M., 2007. The emerging role of craft knowledge in our digital culture. In: S. ALFODY, ed, *Neocraft: Modernity and the Crafts.* Halifax: The Press of the Nova Scotia College of Art and Design, pp. 249-266.

PRESS, M., 1997. What has craft given us? *Crafts Magazine,* **227**(1), pp. 104-106.

PROFIT, A.L. and MARTINI, L.G., 2006. Using ultrasonic technology to manufacture products. *Medical device technology,* **17**(7), pp. 32.

PUNDYK, B., 1985. *Multipanel foundation garment,* United States Patent, No. 4,538,615.

PYE, D., 1968. *The Nature and Art of Workmanship.* Cambridge: Cambridge University Press.

QUINN, B., 2009. *Textile Designers at the Cutting Edge.* London: Laurence King Publishing.

REES, H., 1997. Patterns of making: thinking and making in industrial design. In: P. DORMER, ed, *The Culture of Craft.* Manchester: Manchester University Press, pp. 116-136.

ROBERSTON, S., 2011. *An investigation of the design potential of thermochromatic textiles used with electronic heat-profiling circuitry*, Thesis (PhD), Heriot Watt University.

ROBERTSON, S., 2009. The use of laser to etching to enhance liquid crystal colour-change on textiles [online], available from: http://www.cuttingedgesymposium.com/pdf/sara-robertson.pdf [Accessed 23 December, 2015].

ROBSON, C., 2011. *Real World Research.* 3 edn. West Sussex: John Wiley & Sons Ltd.

RODIE, J., B., 2004. Seamless solution. *Textile World,* **154**(3), p. 66.

ROOKS, B., 2004. Laser processing of plastics. *The Industrial Robot,* **31**(4), pp. 338-342.

ROSTAMI, S.D., JONES, I.A. and NORREY, C.D., 2005. Laser welding in computer simulation. *Kunststoffe Plast Europe,* **95**(11), pp. 104-108.

RÜFFLER, C. and GÜRS, K., 1972. Cutting and welding using a CO2 laser. *Optics and Laser Technology*, **4**(6), pp. 265-269.

RUST, C., 2004. Design enquiry: tacit knowledge and invention in science. *Design Issues,* **20**(4), pp. 76-85.

SCHON, D.A., 1983. *The Reflective Practitioner: How Professionals Think in Action.* London: Maurice Temple Smith.

SCRIVENER, S., 2002. The art object does not embody a form of knowledge [online], available from: https://www.herts.ac.uk/__data/assets/pdf_file/0008/12311/WPIAAD_vol2_scrivener.pdf [Accessed 21 March, 2014].

SENNET, R., 2008. *The Craftsman*. New Haven: Yale University Press.

SHANNON, C., 2007. *Elastic material having variable modulus of elasticity,* United States Patent, No. US 7,159,621 B2.

SILVE, S., 2009. Lasers: forming a relationship in the making. Presented at: *Cutting Edge: Lasers and Creativity Symposium*, Loughborough University.

SILVE, S., 2006. A synthesis of programming techniques for laser forming. *Digital Creativity,* **17**(2), pp. 100-112.

SMOCK, D., 2007. Laser Welding Gains Traction. *Design News,* **62**(5), p. 69.

STEELE, V., 2001. *The Corset: A Cultural History*. New Haven: Yale University Press.

STOYEL, J., 1996. *Method and apparatus for the manufacture of textiles,* UK Patent Application, No. 9422413.6

STOYEL, J., 1999. *Manufacture of textiles using ultra sound*, UK Patent Application, No. 9828501.8

STYLIOS, G., K., 2005. New measurement technologies for textiles and clothing. *International Journal of Clothing Science and Technology,* **17**(3/4), pp. 135-149.

TASHAKKORI, A. and TEDDLIE, C., eds, 2003. *Handbook of Mixed Methods in Social and Behavioural Research.* California: Sage Publications.

TORRES PRICE, A., 2010a, ShaToBu adds shaping tights [online], available from: http://www.bodymagazine.us/news.php?idArticles=1791 [Accessed 18 February, 2015].

TORRES PRICE, A., 2010b, ShaToBu burns calories and shapes [online], available from: http://www.bodymagazine.us/news.php?idArticles=1486[Accessed 17 February, 2015].

TÜCHERT, C. and BONTEN, C., 2002. Welding of plastics-Introduction into heating by radiation. *Journal of Reinforced Plastics and Composites,* **21**(8), pp. 699-709.

USIGAN, Y., 2011. The Science of Shapewear [online], available from: http://www.shape.com/lifestyle/beauty-style/science-shapewear [Accessed 21 May, 2014].

VOYCE, J., DAFNIOTIS, P. and TOWSLON, S., 2005. Elastic textiles. In: R. SHISHOO, ed, *Textiles in Sport.* Cambridge: Woodhead Publishing, pp. 204-230.

VUJASINOVIC, E. and ROGALE, D., 2013. Properties and performance of welded or bonded seams. In: I. JONES and G.K. STYLIOS, eds, *Joining Textiles: Principles and Applications.* Cambridge: Woodhead Publishing, pp. 435-463.

VUJASINOVIĆ, E., JANKOVIĆ, Z., DRAGČEVIĆ, Z., PETRUNIĆ, I. and ROGALE, D., 2007. Investigation of the strength of ultrasonically welded sails. *International Journal of Clothing Science and Technology,* **19**(3/4), pp. 204-214.

WALLACE, J. and PRESS, M., 2004. All this useless beauty: the case for craft practice in design for a digital age. *The Design Journal,* **7**(2), pp.42-53.

WALLACE, L., SLATTERY, K. and COUTTS, A., 2006. Compression garments: do they influence athletic performance and recovery? *Sports Coach,* **28**(4), pp.1-3.

WILSON, I., 2011. Janet Stoyel's technological adventures. *Surface Design Journal,* **35**(3), pp. 38-41.

WILSON, J., 2000. *Handbook of Textile Design.* Cambridge: Woodhead Publishing.

Woolley, M., 2011. Beyond control: rethinking industry and craft dynamics. *Craft Research,* **2**(1), pp.11-36.

YOUNG, R.J. and LOVELL, P.A., 1991. *Introduction to Polymers.* 2 edn. London: Chapman and Hall.

YUAN, G., JIANG, S., NEWTON, E., FAN, J. and AU, W., 2011a. Application of laser treatment for fashion design. *Journal of The Textile Institute,* 103(1), pp. 48-54.

YUAN, G., JIANG, S., NEWTON, E., FAN, J. and AU, W., 2011b. Fashion design using laser engraving technology. Presented at: *8ISS Symposium- Panel on Transformation.*

ZIMMERMANN, N., 2006. Overlap-free laser welding for technical textiles. *Technische Textilien,* 49(3), pp. 152-153.