LASER NET SHAPE WELDING OF STEELS

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Laser Processing Research Centre
ABSTRACT

Laser technologies have made distinguished contributions to modern industry. These have typically been realised through the important role played by lasers in the advancement of manufacturing technology in many areas such as welding, which has become an important joining technique and thus promoted the use of lasers in a wide variety of applications in the oil, gas, aerospace, aircraft, automotive, electronics and medical industries.

A detailed review of previous work in the use of lasers for advanced manufacturing, and in particular, laser beam welding is given.

The work reported in this thesis aims to develop a new method of laser welding. This is connected with investigations relating to the production of net shape welds for bead-on-plate welding and butt welding of mild steel plates. Based on the nature of its operation, use of a fibre laser was considered most suitable compared to other solid state lasers. Net-shape welds were demonstrated on mild steel plates using an IPG 1 kW single mode fibre laser with a maximum power output of 1000 W.

The thesis shows results from experimental and modelling (based on finite element and computational fluid dynamic modelling) to validate the idea and the understanding of underlying scientific principles. The thesis is presented in the form of a collection of published work generated by the author during the course of this project. In addition, some results that are not yet published are also included. Design of experiments and statistical modelling has been used in the experimental work to understand the process parameter interactions. Microstructural and mechanical testing have been carried out to evaluate the performance of the welds. Net shaped (the weld bead is flat to the parent material surface) welds have been achieved and compared with standard welds. The understanding of net-shape weld formation and the effect of the laser welding parameters was enhanced by the theoretical modelling.

The thesis concludes with a summary of scientific findings and an overview of future work.
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<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>DPSSL</td>
<td>Diode pumped solid state lasers</td>
</tr>
<tr>
<td>HPDL</td>
<td>High power diode laser</td>
</tr>
<tr>
<td>YAG</td>
<td>Yttrium – aluminium garnet</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer aided design</td>
</tr>
<tr>
<td>CAM</td>
<td>Computer aided manufacturing</td>
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<td>Computer numerical control</td>
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<td>Electrical discharge machining</td>
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<td>EDX</td>
<td>Energy dispersive X-ray analysis</td>
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<td>SEM</td>
<td>Scanning Electron Microscopy</td>
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<td>HAZ</td>
<td>Heat affected zone</td>
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<td>NSW</td>
<td>Net shape welding</td>
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<td>One Variable At a Time</td>
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<td>Response surface Methodology</td>
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<td>ANN</td>
<td>Artificial Neural Network</td>
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<td>BPP</td>
<td>Beam parameter product</td>
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<tr>
<td>Nd: YAG laser</td>
<td>Neodymium-doped yttrium aluminium garnet laser</td>
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# NOMENCLATURE

<table>
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<tr>
<th>Symbol</th>
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<tr>
<td>$C_p$</td>
<td>Heat capacity (J/kg °C)</td>
</tr>
<tr>
<td>$P$</td>
<td>Laser power (W)</td>
</tr>
<tr>
<td>$D$</td>
<td>Spot diameter of the laser beam (µm)</td>
</tr>
<tr>
<td>$k$</td>
<td>The thermal conductivity (W/m °C)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>The density (Kg/m³)</td>
</tr>
<tr>
<td>$v$</td>
<td>The velocity (m/s)</td>
</tr>
<tr>
<td>$b$</td>
<td>The weld bead width (m)</td>
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<tr>
<td>$h$</td>
<td>The weld depth penetration (m)</td>
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<tr>
<td>$\omega_0$</td>
<td>The radius of the beam waist (mm)</td>
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<tr>
<td>$\alpha$</td>
<td>The divergence angle (degrees)</td>
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<tr>
<td>$T$</td>
<td>The temperature (K)</td>
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<tr>
<td>$H$</td>
<td>The melting latent heat (J/Kg)</td>
</tr>
<tr>
<td>$V$</td>
<td>The volume melted in unity of time (m³/s)</td>
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<tr>
<td>$E$</td>
<td>The energy required for melting a volume unit (J/m³)</td>
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<td>$\mathbf{F}_{e}$</td>
<td>The total element force vector</td>
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<td>${K_e}$</td>
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<td>${F_{th}}$</td>
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<tr>
<td>$T_{ref}$</td>
<td>The reference temperature</td>
</tr>
<tr>
<td>$H$</td>
<td>The enthalpy (J/kg)</td>
</tr>
<tr>
<td>$S$</td>
<td>The volumetric heat source (W/m³)</td>
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DECLARATION

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I would like to dedicate this research to those who sacrifice themselves or their money, or both, in order to liberate our beloved Libya. A special dedication for my nephew Essadeek Eghlio and son of my sister Husain Hunish, Meftah Rasheed and Tarek Rasheed, Mohammed Alhalboos, Ibrahim Alhalboos, Ali Hadoth Al-Obidi, Khalid Boshahama, Ali Addarrat, Omar Sawaib, Omar Attohami, Adel Attohami, Ahmed Aghliw (Attageen), Abdulaziz Aghliw, Moktar boshiba, Ahmed Gzait, Mohammed Boshala, Hamza Ghliw, Ali Ghliw, Nasr-Addeen Ghliw, Mustafa Aghliw, Khalil Baba, Khlid Essafoni, Husin Elkerzab, Mohammed Ben Husin, Khalid Eshawaref, Reza Shagdon, Abdulhakeem Almontaser, Abdulbaset Gargom, Abdulgani Zubic, abdulaziz Agob, Ahmed shaclawoon, Husin Attar, Mosbah Swaib, Hamza Suwaib, Hamza Bodaboos, Jamal Legwari, Abdulwahab Ashareef, Adel Ghiw and Osama Eghlio. Also there are hundreds are not covered here. This dedication is also extended to other people inside or outside Libya who were supporting the same goal.
Prizes or and Special Certificate

- Awarded the best prize for the paper presented in the annual postgraduate conference at the University of Manchester 2010.
- Awarded the third prize for the paper presented in the annual postgraduate conference at the University of Manchester 2009.
- Paper with the title, Investigation of Net – Shape welding of mild steel sheets with a 1 kW single mode fibre laser, presented in the ICMR09 International Conference on Manufacturing Research at the University of Warwick, 8-10 September 2009, was chosen by the conference committee for publishing in the Journal. International Journal of Advanced Manufacturing Technology.
- Paper with the title, Net-shape butt welding of Mild Steel sheets, presented in the 36th International MATADOR Conference, University of Manchester, Manchester 14-16/ July 2010, was chosen by the conference committee for publishing in the specific Journal, Journal of (Laser in Engineering).
• R. M. Eghlio, A. J. Pinkerton and L. Li, "Investigation of Net - Shape Welding of Mild Steel Sheets with a 1 kW Single Mode Fibre Laser" The 7th International Conference on Manufacturing Research (ICMR09) University of Warwick, UK, Conference proceeding P (303-307), September 8-10, 2009.


• R. M. Eghlio, S. Marimuthu, A. J. Pinkerton, and L. Li, ‘’Weld bead characteristics of fibre laser butt welded 1 mm mild steel sheets and CFD modelling’’ This paper has been submitted for International Journal of Heat and Mass Transfer.

• S Marimuthu, R M Eghlio, A J Pinkerton1 and L Li, ‘’ Computational fluid dynamic and finite elements modelling of laser weld bead geometry formation and joint strengths’’. This paper has been submitted and
List of Publications

accepted for Journal of Manufacturing Science and Engineering, MANU-11-1292.


- R. M. Eghlio, A. J. Pinkerton and L. Li, "Investigation of Net-Shape Welding of Mild Steel Sheets with a 1 kW Single Mode Fibre Laser” has been chosen by conference committee for the International Journal of Advanced Manufacturing Technology 2009.
CHAPTER ONE
GENERAL AN INTRODUCTION ON THE RESEARCH

1 Introduction
1.1 Research motivation and rationale
“A laser is a device that amplifies light and produces a highly directional, high-intensity coherent beam that most often has a very pure frequency or wavelength” [1]. Laser technology began over 40 years ago. Today, imagination appears to be the only limit on the uses of the laser technologies. Modern manufacturing industry is exploring potential opportunities offered by the lasers, in conjunction with other new technologies such as automation, computing and flexible manufacturing systems. The greatest opportunities for the lasers are in those areas where flexibility, automation, computer aided design and manufacturing (CAD/CAM) integration, precision, cost reduction, and time to market are important factors.

Over the last 15 years, the availability of high quality high power fibre lasers have opened up new opportunities for materials processing with reduced energy and space usages compared with traditional CO\textsubscript{2} lasers. The unique advantages of the fibre laser’s features over conventional lasers are the ease of use and power stability. Also, fibre lasers have the lowest divergence, high beam quality and the highest brightness and the greatest focusability of any laser power density capability.

One of the key applications of high power fibre lasers is welding for automotive, biomedical, aerospace, oil and gas and electronic industries. A common problem of laser welding and arc welding is that the weld beads are above the parent material surface even without the additional of a filler material. This often requires post weld machining to enable flat surfaces. For welding large structures (e.g. in nuclear and shipping industry), very small structures (e.g. in the medical industry) or tubular structures (medical, nuclear and oil/gas industries), post-weld machining can be difficult, especially for internal structures.
Chapter 1 General an Introduction on the Research

One of the main purposes of the techniques of friction welding is to produce the Net Shape Welding (NSW) by minimizing the machining in net and near net-shape parts, but the quality of the surface finishing wasn’t good enough to reach the net shape case, which mean the net shape is still far, furthermore the cost and time which require are more also, other issue which is more important there will be surplus materials for remaining with the end of each job. [2, 3], i.e. the weld bead geometry is flat to the parent surface, thus eliminating the need for post weld machining.

Friction Welding are that not every configuration is feasible, that a machine of sufficient power is needed, and that for short runs the process may not be economical. Apart from the cost of tools, which must be appropriate for the anticipated joints, the Friction-welding process has some costs in tooling and setup that must be taken into account when calculating the cost per weld. Tight concentricity desires, when essential, may be hard to meet. Also finishing operations might be requested which sum up to the total cost. On the other hand, the fibre laser has key advantages and receives more attention over other laser technologies such as a unique combination of high beam quality, energy and laser power stability, given higher power density and a greater breadth of control. As well as its low total cost of ownership, also fibre lasers have the ability to produce deep penetration at high welding speeds. From these points and others the fibre laser is the new technology to develop new laser processing instead of using the existing friction welding technology, which can achieve and produce the net shape and near net shape welding with high quality.

Figure 1.1 (a) shows a typical weld bead cross sectional geometry in laser welding. It is desirable to achieve net-shape welding as shown in Figure 1.1 (b). The cost saving on the elimination of post weld machining would be significant.
1.2 Aim and objectives

1.2.1 Aim

The aim of this research is to develop and characterise a new laser welding technology – net shape welding of thin mild steels for both bead-on-plate welds and butt welds and to understand the weld bead formation mechanisms.

1.2.2 Objectives

The objectives of the research are:

- To understand the effect of multiple laser welding parameter interactions on weld bead geometry formation in bead-on-plate and butt welding of mild steel sheets using design of experiments and statistical modelling approach.
- To demonstrate net shape welding for both bead-on-plate and butt welding of mild steel sheets.
- To evaluate microstructural and mechanical performances of net-shape welds in comparison to standard welds.
- To model using computational fluid dynamic – CFD, and finite element modelling – FEM techniques the weld bead formation under different welding conditions.
- To understand the mechanism of net-shape laser shape welding.
Chapter 1 General an Introduction on the Research

1.3 Thesis outline
This thesis consists of nine chapters.

Chapter 1 This chapter provide a general an introduction on the research.
Chapter 2 This chapter provide a review of laser and optics, which include laser definition, background, concept, laser construction and applications. It also includes a general overview of different laser types, their characteristics; also a comparison of fibre laser with other lasers and trends in fibre laser is given.

Chapter 3 This chapter provide a review of laser welding fundamentals and applications, which starts with an introduction of non-laser welding techniques followed by laser welding from basic definition to the advanced processes. This chapter also includes the principle of laser welding and its characteristics, comparison of laser welding processes with other welding processes, weldability, heat transfer in laser welding, keyhole and plasma formation. The last part in this chapter is on laser welding parameters, welding of steels with fibre laser, control and monitoring/examination of laser welded components.

Chapter 4 This chapter provide a review of previous work on experimental and numerical modelling details, which includes previews modelling such as the development of modelling, numerical simulation models, heat transfer models and statistical models which have been using design of experiment. This chapter ends with a conclusion.

Chapter 5 This chapter presents the experimental procedure and equipment used in this research for the development of the net shape laser welding. This chapter describes the research procedure and methodology which have been used in each stage of the investigations, starting with design of the experiments, followed by experimental procedures and material characterisation. The last part of the chapter is on procedures for testing mechanical properties.

Chapter 6 is on Bead on plate Net shape welding of 1.5 mm thick mild steels sheets.
Chapter 1 General an Introduction on the Research

This chapter contains the paper with title: “Investigation of net shape welding of mild steel sheets with a 1 kW single mode fibre laser.” This paper has been presented in The 7th International Conference on Manufacturing Research (ICMR09) University of Warwick, UK, September 8-10, 2009, Conference Procedure p (303-307), and was chosen to be published in the International Journal of Advanced Manufacturing Technology by the conference Committee following peer review.

Chapter 7 This chapter contains the paper with title: “Process characteristics of single mode fibre laser net shape welding”. This paper has been presented in The Pacific International Conference on Applications of Lasers and Optics, (PICALO) 23-25 / March / 2010, paper 406, Wuhan People’s Republic of China

Chapter 8 is on Laser net shape butt welding of 1.5 mm thick mild steels sheets.

This chapter contains the paper with title: “Characterization of weld bead geometry in fibre laser butt welding of mild steel sheets by means of statistical modelling”. This paper has been published in Laser in Engineering., Vol. 22, pp. 281-298 ©2011 Old City Publishing, Inc.

Chapter 9 is on modelling of net shape welding. This chapter contains one paper with the title; “Computational Fluid Dynamic and Finite Element Modelling of Laser Weld Bead Geometry Formation and Joint Strengths”. This paper has been submitted and accepted for Journal of Manufacturing Science and Engineering, MANU-11-1292.

Conclusion and Future work
A general conclusion was made to summarise the key scientific findings in this research. Future work is recommended.

Appendixes
This part contains another five papers, which cover other areas in the research, which were supporting knowledge in the research field.
CHAPTER TWO
LASER AND OPTICS

2 Lasers
2.1 Background and concept
The word laser is an acronym for Light Amplification by Stimulated Emission of Radiation. Albert Einstein described the theory of stimulated emission in 1916 [1], when he proved mathematically that stimulated emission was possible, the race was on to develop a ‘death ray machine’ or at least a device using stimulated emission. The first laser beam produced at optical wavelengths was operated in a ruby crystal as the amplifier, and a flashlamp as the energy source, by Theodore Maiman of Hughes Research Laboratories 1960 [1, 4-6]. The first gas laser was developed in 1961 by A. Javan, W. Bennett, and D. Harriott of Bell Laboratories, using a mixture of helium and neon gases. Lasers generally have a narrower frequency distribution, or much higher intensity, or a much greater degree of collimation, and in the same time, pulse duration for the laser is much shorter than from other common types of light sources. Since then, growth of the laser industry has been approximately 10-20% per annum, until the recent recession [7]. Applications including optical energy from material processing to communications, medicine and CD/DVD players, etc were the driving forces for the growth, and military potential was the main driving force for research in this regard. In 1994 the U.S. Congress issued a mandate to transfer the cold war military defences technology to civilian application [7]. From this date the technology developed for the U.S. Department of Defence’s Star Wars project become available to civilian industry [5, 7, 8].

From the starting period of laser history, laser research has produced a variety of improved and specialised laser types, optimized for different performance goals such as wavelength bands, increasing the average output power and the peak output power, and in the same time reducing output pulse duration, reducing the input power, as well as maximizing the output of the power efficiency. Research has also extended to cover
ways to maximize charging and firing. Very high-intensity became available due to research done by the University of Rochester's Energy [9, 10].

2.2 Laser fundamentals and construction
A laser is constructed from three principal parts, an energy source such as a pump, a gain medium or laser medium, and two or more mirrors that form an optical resonator. Figure 2.1 shows the schematic diagram of a basic laser [11]. The basic laser consists of two mirrors which are placed parallel to each other to form an optical oscillator and a chamber in which light travelling down the optic axis in between the mirrors would oscillate back and forth between the mirrors forever. An active medium is placed between the two mirrors capable of amplifying the light oscillations by the mechanism of stimulated emission. One of the two mirrors is partially transparent to allow some of the oscillating power to emerge as the operating beam; the other mirror is completely reflective. This mirror is also usually curved to reduce the diffraction losses of the oscillating power and to make it possible to align both the mirrors. The basic principle of laser work built on the idea of the stimulated emission phenomenon which was predicted by Einstein in 1916 using a mathematical argument. Laser aided materials processing is based on light matter interaction and may result in four phases, such as solid, liquid, vapour, and plasma, over a wide range of temperatures [12-14].

![Fig 2.1 Schematic parts of a basic laser [9]](#)

2.3 Laser Applications
Lasers have a great variety of applications in numerous areas such as guidance via laser gyros, holography, machining and welding, metrology and geodesy, and
communications and they continue to be applied to novel applications. In industrial manufacturing, there are many applications such as cutting, drilling, welding, cladding, soldering, hardening, ablating, surface treatment, marking, engraving, micromachining and pulsed laser deposition [15]. In medical applications there are a wide range of medical applications such as those that are related to the human body like eye surgery, dentistry, and dermatology [16]. In Metrology, the laser is widely used in optical metrology such as precise position measurements with interferometers, long-distance range finding and navigation. Lasers provide fundamental qualities which are the huge intensity (this means a better signal/noise ratio or a shorter duration of the measurements, and duration matters not only in industrial measurement but in metrology as well [17]. Lasers are also used in the production of electronic storage devices; including applications such compact disks (CDs), digital versatile disk (DVDs) and barcode scanners etc. In communications, lasers are used for optical fibre communication and extensively used for long-distance optical data transmission. Laser are also used in other different scientific applications, such as laser cooling, which has applications in fundamental research and also for industrial purposes, surveying and ranging, laser spectroscopy, and other industries such as garment industry and heat treatment. In the future, in energy technology e.g. laser fusion, the high-power laser systems might play a role in electricity generation and application in the nuclear fusion. Additionally, lasers have a variety of military applications.

Laser welding has probably become an important joining technique for numerous industrial applications and has wide uses in oil and gas, aerospace, aircraft, automotive, electronics, medical, and other industries [15, 18, 19]. In other laser applications, there is the potential for using lasers in cleaning, de-rusting, de-oiling, de-painting, de-oxidising, de-greasing and even the removal of ultra fine dirt and laser can also be used for drilling in the oil and gas industry [8, 12].

In the medical industry, Steiner [14] predicted that the laser tissue diagnosis would become even more important than laser therapy. Rudolf added that online diagnosis and therapy would be a good progress step forward and break-through for safe and effective
laser treatment. Steen summarised the benefits of laser applications as shown in Table 2.1 [20].

<table>
<thead>
<tr>
<th>No</th>
<th>Characteristics</th>
<th>Advantages and availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power intensity</td>
<td>One of the highest available to industry today</td>
</tr>
<tr>
<td>2</td>
<td>Power shaping</td>
<td>Almost individually possible for optical energy in both time and space.</td>
</tr>
<tr>
<td>3</td>
<td>Degree of automation</td>
<td>Increasing in different areas in-process sensing</td>
</tr>
<tr>
<td>4</td>
<td>Photolytic process</td>
<td>This characteristic is a unique to photons and opens a new level of chemistry.</td>
</tr>
<tr>
<td>5</td>
<td>Coherence and spectral purity</td>
<td>This allows strange optical effects through diffraction, interference and multi-photon events.</td>
</tr>
</tbody>
</table>

Some of the more unusual properties of optical energy are found in non-linear optics, which may arise when certain materials are subject to heavy fluxes of photons such as diffractive optical elements, adaptive optics and polarization rotation in magnetic fields.

The range of material processes is illustrated in the Figure 2.2.
Laser cutting was one of the first application areas of lasers in industry since there was a ready-made market for cutting, particularly flat-bed profile cutting. There are many different ways for cutting such as evaporative, melt and blow, melt and blow in a reactive gas, thermal stress cutting for brittle materials, scribing and mechanical snapping, cold cutting, and laser-assisted oxygen (LASOX) cutting. There is a niche market for cutting difficult materials such as fiberglass, soft or rubber fabrics that could suffer from mechanical distortion and radioactive parts. Laser welding is one of the high-quality welding techniques which are similar to electron beam welding in which the energy is so intense that a ‘keyhole’ is developed. Compared to alternative processes, welds leads to little distortion and a small heat affected zone (HAZ) but in the same time, laser welding is much faster and leaves a more cosmetically attractive weld bead. Miyamoto [19] has argued that the heavy industrial application of welding and cutting requires high-power lasers capable of welding thicker plates with low thermal distortion. The author investigated the laser market in Japan which is expanding steadily with growth rates higher than 10% in terms of number of system units, this is shown in Figure 2.3. From these figures it is clear that the role of lasers has become increasingly important; it is a rapidly expanding market.

Fig. 2.3 Schematic of trends of laser system sold in Japanese market [20]
2.4 General overview of different laser types

2.4.1 Carbon dioxide lasers (CO$_2$ laser)
Laser welding using CO$_2$ laser source was first reported in 1971. Since then, the use of laser welding has grown swiftly [12, 21]. The essence of design of CO$_2$ lasers is the cooling of the carbon dioxide gas mixture. There are three types of CO$_2$ lasers, slow flow lasers, fast axial flow lasers, and the final one is a transverse flow lasers which are once more convectively cooled but the flow is transverse to the discharge. Cooling is thus more effective, and very compact high-power lasers have been built this way [12, 22]. Ancona et al [23] have analyzed mechanical characterization of CO$_2$ laser beam butt welds of AA5083. They found the porosity is important to evaluate the quality of a butt-joint since it is recognized to be one of the major concerns through laser welding of aluminum alloys.

2.4.2 Carbon monoxide lasers (CO laser)
These lasers are not currently commercially available; the CO laser output is very sensitive to temperature. By including Xe in the gas mixture, the operation temperature will increase (2003) [12].

2.4.3 Solid state lasers
The core essence of the design of a solid state laser is how to get the pumping power into the laser block and cool the block in such a way that it does not distort or break [12].

2.4.3.1 Nd: YAG Lasers
Nd: YAG laser consists of crystalline Yttrium Aluminium Garnet with a chemical formula Y$_3$Al$_{15}$O$_{12}$ as a host material. Nd: YAG Lasers are used for welding applications with an average output power range from 0.3 – 3.0 kW. This kind of laser operates in three modes, continuous output, pulsed pumping, and Q-switched mode. Pulsed laser seam-welding is characterized by having a large number of process parameters which influences to a certain extent the welding performance. Figure 2.4 illustrates the various factors affecting the quality of pulsed laser welding [9, 12, 24, 25].
Chapter 2 Laser and Optics

2.4.3.2 Diode pumped solid state lasers
Diode pumped solid state lasers (DPSSL) use diodes instead of arc lamp as a pumping source. Due to the high optical/electrical power conversion of the diodes and the more selective excitation of the laser – active medium, the laser's overall efficiency can be enhanced by a factor in excess of approximately 5 when compared to lamp-pumped systems. Meanwhile, diode pumped fibre lasers are being developed. These lasers are doped plastic or glass fibre that are end or side pumped by diode lasers [12, 26]

2.4.4 Diode laser
High power diode lasers are made from semiconductors with direct electrical excitation Diode lasers are currently the most efficient devices for converting electrical into optical energy [12, 27-29]. A high power diode laser system is used to make lap joint in low carbon steel sheet by forming a short stitch weld. Li [28] reported that the advantages of high-power diode lasers in terms of compactness, energy efficiency, lifetime and running have been increasingly recognized. Li concluded that the better surface finish, less heat-affected zone, better beam absorption, better morphological characteristics, more consistent and repeatable results, fewer cracks and less porosity generation are the special features for HPDL which was recognised from their studies.

Fig. 2.4 A parameter diagram demonstrating the process parameters affecting the quality of pulsed laser welding [23]
2.4.5 Excimer lasers

Excimer lasers are transversely discharge gas lasers as shown in Figure 2.5. The word “Excimer” is derived from the term “excited dimer”, and refers to a molecular complex of two atoms that is stable in the excited state and not so stable in ground state. These lasers, which are available only as pulsed lasers, produce intense output in the ultraviolet and deep ultraviolet. The progress in basic excimer laser technology has prepared the excimer lasers to dependable machines suitable for the industrial environment. The most industrial excimer laser applications in the medium term are expected to be the marking of any kind of products. The excimer laser growth over the last 19 years in many applications has shown in Figure 2.6. The main growth results are from increasing industrial use followed by medical applications. The main application of excimer lasers is still in spectroscopy and research in general. Over 7000 lambda physic excimer lasers are installed worldwide today and the number installed will increase according to the increasing number of application in such different areas [12, 24, 30, 31].

![Fig. 2.5 Schematic of excimer laser [32]](image-url)
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2.5 Comparison between lasers

Gobel et al [31] compared weld penetration in mild steel materials between different laser sources with different fibre core diameters to see the weld penetration depth as illustrated on Figure 2.7. The comparison was between fibre laser (50 µm), disc laser (200 µm), and Nd:YAG (600 µm).

Fig. 2.6 Total worldwide market of excimer lasers, between 1993 and 2000 [29]

Fig. 2.7 Comparison between three different sources of lasers [31]
Chapter 2 Laser and Optics

The resulting smaller spot size on the work piece is not the only reason for the deeper penetration. The divergence of the focused beam must be considered too. Rudolf [14] concluded that the laser source will become smaller, there will be increase in power of diode laser and the replacement of solid-state lasers will be done by diode pump fibre laser. It was also suggested that the application spectrum will extend to create the laser as more universal tool.

There are less operation consumables for the fibre laser compared with other laser sources such as Nd:YAG lasers that require a periodic change of flash lamp or CO₂ lasers which need supply of consumable gases. Plus, the high electrical efficiency of fibre laser – up to ten times more efficient in power consumption than Nd:YAG equivalents mean that they offer significantly lower running costs. Some other laser sources require more energy consumption to warm-up the system and fibre laser can be used for welding ‘on demand’ after operating. IPG Photonics, who are a leading global manufacturer of high-performance fibre lasers and amplifiers for diverse applications in numerous markets, reported that there is a rapid technology growth opportunity for materials processing with fibre lasers and the opportunities are substantial. Fibre laser growth has greatly outpaced the overall market growth and continues to gain momentum. Figure 2.8 shows the applications segmentation for lasers shipped by IPG Photonics [33]

![Fig. 2.8 A summary of IPG Photonics high-power laser sales by application [33]](image-url)
Zhu et al [34] studied and investigated the process characteristic and mechanisms involved in CO₂ laser and diode laser welding of AZ31 alloy, they conclude from their studied that the 8000 W/cm² is satisfactory to achieve a full penetration at welding speed of 150 mm/s using CO₂ laser or 50 mm/s using diode laser, while 1 mm thick AZ31 sheet welding is quite low. They found that the spot size of the diode laser is limited to conduction welding during defocusing, while good quality keyhole produced by CO₂ laser. They also concluded that the CO₂ laser produces more porosity in comparison with a diode laser. Zhu et al [34-36] have also shown a comparison of mechanisms and effects of Nd:YAG and CO₂ laser cleaning of titanium alloy. Triantafyllidis et al [37] reported that the HPDL welded 0.2 mm diameter thermocouples performed better than the commercial and Nd:YAG laser welded thermocouple at high temperatures (above 150°C). They added that HPDL welded thermocouple had much faster response time (35% faster) than the commercial thermocouples and the Nd:YAG laser welded ones (17% faster). High quality welds made the performance of HPDL much better. Vollertsen and Thomy [38] made a comparison to see the penetration for various lasers such as lamp-pumped, solid-state Nd: YAG laser and of the diode-pumped solid-state Nd:YAG laser Rofin DY 044 in AlSiMgMn, as shown in Figure 2.9 schematic the relation curves between welding speed and penetration depth.

![Fig. 2.9 Schematic comparison of penetration for various lasers [38]](image)
Tsukamoto [39] made a comparison between four types of laser to see the laser characteristics and application in welding. The main characteristics are the beam quality, interaction with the material, oscillation efficiency, oscillator and head size, fibre transmission capability, equipment cost, etc. Table 2.2; illustrate the comparison [39].

Table 2.2 Comparisons between CO$_2$, YAG-Lamp, Yag - Diode, and Diode Lasers for characteristics and applications [39]

<table>
<thead>
<tr>
<th>Characteristics of laser</th>
<th>CO$_2$ Laser</th>
<th>Lamp-pumped YAG</th>
<th>Diode-pumped YAG</th>
<th>Diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (µm)</td>
<td>10.6</td>
<td>1.06</td>
<td>1.06</td>
<td>0.8-0.94</td>
</tr>
<tr>
<td>Oscillation efficiency (%)</td>
<td>8-15</td>
<td>1-4</td>
<td>8-15</td>
<td>30-50</td>
</tr>
<tr>
<td>Maximum power (kW)</td>
<td>50</td>
<td>10</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Cost per kW (CO$_2$ = 1)</td>
<td>1</td>
<td>1.4</td>
<td>1.7</td>
<td>≤ 1</td>
</tr>
<tr>
<td>Advantages</td>
<td>Easy high power up rating</td>
<td>Fibre transmission capability</td>
<td>Fibre transmission capability high efficiency</td>
<td>High efficiency low cost fibre transmission capability small size</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>No fibre transmission capability high plasma absorption</td>
<td>Low efficiency</td>
<td>High cost</td>
<td>Poor beam quality</td>
</tr>
</tbody>
</table>

2.6 The fibre laser
This is a laser that is constructed within an optical fibre and is similar in concept to gas lasers and laser diodes. The fibre laser is excited by a diode laser source as a pump, and mirrors accept the pump wavelength on one side and transmit the lased wavelength on
Chapter 2 Laser and Optics

The main parts in the fibre laser illustrated as shown in Figure 2.10. Fibre lasers are fast becoming an alternative laser source to pulsed lamp pumped Nd:YAG lasers for micro applications. These lasers, with diffraction limited beam quality offer many futures such as small spot size, high power density, enhance processing speeds and reduced heat affected zone for both cutting and welding application. The fibre laser has key advantages and receives more attention over other laser technologies such as a unique combination of high beam quality, energy and laser power stability, given higher power density and a greater breadth of control. As well as its low total cost of ownership, fibre lasers have the ability to produce deep penetration at high welding speeds [40-42].

![The main parts in the fibre laser](image)

Fig. 2.10 The main parts in the fibre laser [42]

The fibre laser is a solid-state laser in which the active gain medium is an optical fibre, doped with rare-earth elements such as erbium, ytterbium, neodymium, dysprosium, praseodymium, and thulium. The fibre laser current interest is the erbium-doped fibre amplifier; however the fibre laser is more reliable and useful. Its ability to deliver the laser beam to any area of application and the high quality of the beam mean that in practice, the beam is very straight, and it can be focused on a very small dot. Lasers start to get to the point where they can harm your skin at around 1 Watt of power. This isn't very much power compared to a kettle or a toaster, but Fibre lasers are continually getting more powerful, and have been made with over 1,000 Watts of power (1kW). This will be more powerful tool which has a huge variety of different applications. A laser device that enabled today's internet is now being exploited in a range of applications from imaging molecules to high precision cutting and welding of metals [1, 11, 43, 44].
2.6.1 Construction and how a fibre laser work

The fibre laser uses the same physics principles as any other laser only there are a number of properties that make it special and extremely useful. The most common type of fibre laser is the erbium-doped fibre laser. It is normally operated in Nd-doped glass fibre (doped core), which is the main element of the fibre laser with the double clad fibre (pump core) and an outer cladding. The fibre is transversely pumped by around a flashlamp and the high beam quality of enables the beam to be focused to a small spot with a correspondingly high energy density. The active medium of a fibre is a core of the fibre doped with a rare element. Most commonly, single-mode fibre lasers are made of silica. The pump beam is launched longitudinally along the fibre length at it may be guided by the core itself (double-clad fibre laser). The fibre laser is excited by diode laser source. As shown in Figure 2.11.

Fig. 2.11 Double-clad fibre laser [43]

In a fibre laser, a silica “active” fibre doped with erbium, ytterbium, neodymium or thallium, is excited by a diode laser source. An active fibre with a patented pumping technique was the high power fibre laser in the market place, which allows the utilization of broad area multimode diodes rather than diode bars. Figure 2.12 shows a compact laser source with high beam quality, where the outer cladding is made of glass or polymeric material, with low refraction coefficient, in order to prevent the signal attenuation [43].
There are two types of fibre laser; single mode fibre laser and multi mode fibre laser. Today, the fibre laser of current interest is the erbium-doped fibre amplifier. 1.53 µm is the operating wavelength and for communication wavelength is 1.55 µm, where there are the lowest transmission losses. Single mode fibre lasers are currently available with beam powers from quite a lot of Watts up to around 1kW with the wavelength of typically 1070 nm. The power of the multi mode fibre laser is more than 17 kW and the efficiency of both fibre lasers (up to 30%) greatly exceeds the efficiency nowadays achievable with other type of laser such as lap- or diode-pumped Nd:YAG lasers. The unique characteristics of the fibre laser such as beam quality, focal spot, and high energy density, energy density (Jm⁻²) can be calculated from this equation:

\[ E = \frac{P}{VD} \]  \hspace{1cm} (2.1)

Where \( E \) = Energy Density (Jm⁻²), \( P \) = Laser Power (W), \( V \) = Traverse Velocity (ms⁻¹), \( D \) = Beam Diameter at workpiece (m). The fibre laser produces deep penetration welds with low laser power. Compared with other laser sources, the fibre laser can produce welds with significantly lower heat input resulting in less distortion of the welded plates. The high energy stability in the fibre laser gives welds of consistent profile and penetration with extremely low levels of weld root porosity. The fibre laser offers a solution that welds faster with higher quality at a lower operational running cost [38, 44, 45].

2.6.2 Applications of fibre lasers

It is evident that the fibre lasers, particularly high power versions with improved beam properties, will become increasingly important in materials processing and their share of the total laser industry will grow substantially [43]. The new generation of the high power fibre laser present numerous benefits for industrial purposes, specifically high
power with low beam divergence, high efficiency, low maintenance cost and flexible beam delivery. There are numerous applications for fibre laser in manufacturing areas such as cutting, drilling, welding, heat treatment, cladding, soldering, hardening, ablating, surface treatment, marking, micromachining. Fibre lasers also have applications in the oil and gas industry, medical industry and electronic industry. The high-power laser systems might play a role in electricity generation and application in the nuclear fusion [16, 17, 43, 46].

2.6.3 Trends in fibre laser
The advances being made in optical fibre fabrication are such that a number of new possibilities exist in making both fibres for laser delivery and fibres for laser resonators. Improved fabrication technology driven primarily by telecommunications means that microfluidic technology also benefits. Fibre lasers mode are fast becoming an alternative of many other laser source such as pulsed lamp pumped Nd:YAG lasers for micro application, and CO₂ laser in many industrial applications. Fibre lasers have been receiving more attention due to their unique advantages such high-power, high beam quality and high – efficiency to produce deep penetration welds at high welding speeds. Precision machinery and medical device applications suffer from excessive distortion formation of discontinuities (pore, void and hot crack). One of the sources in future will be to open a new field in medical laser application, not only an industrial application which produces tools or equipment etc utilized for medical purpose. It optimized applicators will widen the spectrum of applications for the same laser, e.g. in dentistry. Microsurgery is still a challenge where nanosurgery in cells already appears; new laser technology is continuously improving laser therapy and laser medical diagnosis.

Lasers are useful in surgery to cut, coagulate, vaporize, or weld tissues etc. Also, there are potential applications in space such as exploring the solar system and beyond, extend human presence across the solar system –starting with a human return to the moon by the year 2020 [47]. Another important issue will be in manufacturing industry. By increasing welding speed, the high-power fibre laser may well be an investment with low maintenance and operating costs in the long run [14, 40, 41, 46, 48-50].
CHAPTER THREE
LASER WELDING FUNDAMENTALS AND APPLICATIONS

3.1 Introduction
In its broadest context welding is defined by Messler as “a process in which materials of
the same fundamental type or class are brought together and caused to join (and become
one) through the formation of primary (and, occasionally, secondary) chemical bonds
under the combined action of heat and pressure” [51]. Welding requires the application
of heat, pressure, or both to obtain sufficient continuity between the atoms (or ions or
molecules) of one material and another to create chemical bounds in large numbers.
Almost every imaginable exothermic source of heat energy has been used at one time or
another to make welds. The different types of welding include processes such as
combustion and exothermic synthesis chemical reactions, electric arcs, electrical
resistance, plasmas, electronic beams, microwaves, light beams (lasers or focused IR or
imaged arcs), mechanical friction, and mechanical plastic deformation. Welding
requires two forms of the energy, in some combination i.e. thermal energy or heat, and
mechanical energy or pressure. Amongst the different sources of welding, the laser has
been extensively used for welding due to its flexibility of use, ability to process in air
and vacuum and resolution of the welding area. Laser beam welding is a good source to
weld hard metals, since it is possible to have a control of the heat input and HAZ [51-
53].

3.2 Fundamentals of Welding
3.2.1 Basic Definitions
According to American Welding Society (AWS) welding is a materials joining process
utilizing localized coalescence of metals or non-metals produced by heating the
materials to suitable temperature. The process may be carried out with or without the
application of pressure or by the application of pressure alone. Filler materials may
sometime be used during the welding process [49, 53].
3.2.2 Grouping of the welding process

AWS has grouped the processes together according to the "mode of energy transfer" as the first factor. The second reason was the "influence of capillary attraction in effecting distribution of filler metal" in the joint. Capillary attraction distinguishes the welding processes grouped under (brazing) and (soldering) from "arc welding," "gas welding," "resistance welds," "solid state welding," and "other processes". Table 3.1 shows the welding processes in their AWC groupings and shows the letter designation for each process.
<table>
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</table>
Chapter 3 Laser Welding Fundamentals and Applications

There are several regions of interest in the welding process. There is interaction, between the heat source and the base metal. Figure 3.1(a) shows the three distinct regions in the weldment: the fusion zone, the heat affected zone, and the base metal. The schematic of the distinct regions in a welding zone and the re-circulatory motion within the weld pool are shown in Figure 3.1(a) and Figure 3.1(b) respectively [49, 54].

3.2.3 Weld defects
Defects in welding are potentially disastrous, because they can give rise to high stress intensities, which may result in sudden unexpected failure below the design load. Rapid heating and then cooling, and local structural changes cause significant spatial variations in the composition, microstructure and residual stress. There are huge numbers of defects, such as lack of penetration, cracking, porosity, solidification cracking, distortion and transverse shrinkage that occurs perpendicular to the weld line and longitudinal shrinkage that occurs parallel to the weld line. Also there can be defects such as porosity and hot cracks [53-55].

3.3 Solid state welding
Solid state welding (SSW) is a group of welding processes which produces coalescence at temperatures essentially below the melting point of the base materials being joined without the addition of a brazing filler metal. Pressure may or may not be used depending on the process. Forge welding is the oldest of all solid state welding processes. Other solid state welding process, include cold welding, diffusion welding,
explosion welding, friction welding, hot pressure welding and ultrasonic welding and, these different process utilise different forms of energy to produce welding. Welding processes are shown on Table 3.1 [51].

3.3.1 Diffusion welding

"Diffusion welding (DFW) is a solid-state welding process which produces a weld by the application of pressure at elevated temperature with no macroscopic deformation or relative motion of the work pieces. In diffusion welding a filler metal may or may not be used [53].

3.3.2 Friction Welding

Friction welding was invented in 1956 [52]. Friction welding is a solid-state welding process, which produces coalescence of materials by heat obtained from mechanically induced sliding motion between rubbing surfaces. The process involves rotation of one part against another to generate frictional heat for welding. In the original process one part is held stationary and the other part is rotated by a motor which maintains an essentially constant rotational speed. This involves also increasing frictional pressure in a certain friction time. The heat for welding is generated by direct conversion of the mechanical energy for rotating equipments into thermal energy at the interface of the work pieces with the aid of frictional pressure. When the temperature of the interfaces of the two components reaches some specific degree, the rotating part is stopped quickly. Meanwhile, the axial forge pressure is increased for a predetermined time to complete the welding. There is no electric or thermal energy required from other sources to the work pieces interface which makes it different from other fusion welding process. Fusion welding thus requires a suitable energy source to produce the melting. The main principle of the friction welding is an assembly process to minimize machining in net and near net-shape parts. The advantage of this technique on the arc welding techniques is continuous drive friction welding including highly materials saving, low producing time, energy savings, minimal need for hard tooling and it readily welds a wide range of dissimilar materials joints. Friction welding is a good candidate for perform assembly as it is very tolerant of pre-welding interface conditions [2, 51, 56, 57].
3.3.3 Friction stir welding (FSW)

A relatively new variation of friction welding is friction stir welding. Friction stir welding (FSW) is a novel solid-state welding method, which has found particular applications in the aerospace and automotive industries. Friction Stir Welding (FSW) is a new solid-state joining technique, which was invented at The Welding Institute (TWI) (Cambridge, United Kingdom) 1991. FSW has been gaining acceptance and has found various applications in aerospace, automotive and naval industries and has emerged as an innovative process for joining low melting temperature alloys like aluminium (Al) and magnesium (Mg). The mechanism in this technique is where a non-consumable rotating tool or tip is rapidly rotated while being squeezed between two abutting materials (workpieces) to be welded and then the central pin, or probe, followed by the shoulder, is brought into contact with the two parts to be joined as in the Figure 3.2. The process combines frictional heating with intense plastic deformation to produce cost efficient joints with better mechanical properties than conventional fusion welding techniques. During the tool movement along the joint line, material from the front of the tool is swept around this plasticized annulus to the rear thus eliminating the interface. Most of the applications of FSW are in the shipbuilding, automotive and aerospace industries and the first application of this technology was on aluminium fabrication. The weld quality is excellent with minimal porosity in fusion welding whilst at the same time, the mechanical properties are good. Minimum fumes and spatter are generated from the process and there is no arc glare or reflected laser beams with which to contend so the process environmentally friendly. The major advantage is that by avoiding the creation of molten material, the distortion after welding and the residual stresses are low [53, 58-63].

![Fig. 3.2 Friction stir welding](image)
On a study performed on two types of aluminium alloys to investigate the friction stir welding capability of the EN AW 2024-0 and EN AW 5754-H22 Al alloys, the results suggested that there is an increase in the hardness value in the area for EN AW 2024-0 of about 10-40 Hv because of recrystallization and smaller grains. The opposite was noticed on the other hand for EN AW 5754 where there is a decrease in the hardness value because of re-crystallization. The experimental study recommended that the aluminium alloys EN AW 2024-0 and EN AW 5754-H22 can be successfully welded by friction stir welding if the welding parameters are carefully selected. The maximum temperature in the FSW process can be improved with an increase of the rotating speed. The power needed for FSW is improved with an increase of the welding speed and the rotating speed [53, 60, 64].

3.4 Principles of laser welding and its characteristics

3.4.1 Laser welding

Applications of lasers in welding have exhibited tremendous growth over the last decade for improving efficiency and reducing costs across a broad range of industries. Much of these successes are based on the development and availability of enabling technologies [65]. Laser welding has attracted more and more attention in recent years on industrial applications due to its unique features such as small heat affected zone (HAZ) and the narrow weld bead due to the low heat input and the ability to weld at high speed and in areas that are difficult to access [66]. The process of focused laser beam is similar to the power density of an electron beam; both of them represent part of new technology of high-energy-density processing [9]. In reality, the joining of two metals together using laser radiation is a complex process, it still requires achieving a balance between a number of competing physical and metallurgical effects. When this balance has been obtained, the result is a weld of unprecedented quality and mechanical properties. These characteristics and the capability to weld reproducibly at high speed under CNC control with competitive cost have made laser welding very attractive in numerous industrial applications [7]. The welding of metals was one of the first industrial applications of lasers [7, 10, 65]. Moreover, laser welding has the ability to provide very deep, narrow welds at high welding speed with minimum heat input. This specification makes it a most powerful and attractive candidate for numerous industries.
such as the aerospace industry, petroleum industry, automobile production, and medical industry, especially with the increased requirements concerning precision, flexibility and degree of automation [67]. Martukanitz [65] has reported that the use of higher power lasers with fibre optic beam delivery allows these systems to be easily integrated into manufacturing systems, service multiple work-cells and provide dependable processing conditions. These systems will continue to gain attractiveness for a wide range of applications with the potential for reduced operating costs and greater process capability. However the advances in process technology will effect the application of these innovative sources.

Kim [68] has reported that the ability to absorb the laser power depends on the wavelength of the laser beam and the optical properties of the workpiece material. Kim argued that the main variables of laser beam welding are the laser power, welding speed and spot size diameter. Carlson [69] mentioned that deep penetration welding can be performed when the power density of the beam is more than $10^6 \text{ W.cm}^{-2}$. When the workpiece is exposed to a beam with a power density that exceeds this threshold, the exposed area melts and vaporizes almost instantaneously creating a cavity or keyhole. When the workpiece moves relative to the beam, the vapour pressure of the metal sustains the keyhole and along with the surface tension forces, directs molten metal flow from the front of the keyhole along the sidewalls of keyhole to the rear of the keyhole where it rapidly solidifies forming the weld nugget. Therefore, the metal vapour or plasma must be controlled to sustain the keyhole as it is highly absorbent of laser power. As a result of maintaining the keyhole, a steady state condition could be attained with a characteristic deep penetration weld along with its high aspect ratio (depth/width). Matsunawa [70] observed keyhole dynamics in high power continuous wave CW laser welding and he revealed that keyhole depth and shape change greatly with time. On the rear wall of the keyhole he recognized that a deep depression formed which moved from the top to bottom regularly. Equivalent to this phenomenon, large bubbles were formed when the depression reached the bottom of the keyhole which entered the molten pool and resulted in the formation of characteristic spherical and elongated porosity. He then concluded that the evaporation site in the keyhole was not identical but changed its location with time and it was concluded that the evaporation of metal did not take place
uniformly but locally on the keyhole front wall, as shown in Figure 3.3, both the keyhole and the molten pool were powerfully perturbed by the dynamic pressure of the metallic steam jet. Figure 3.4 shows the x-ray transmission imaging system for observation of keyhole behaviour, which was used by Matsunawa [70].

Costa et al [52] have displayed that the minimization of residual stresses which happen during welding process of joining method should minimize the HAZ (heat affected zone).

Duhamel and Banas [71] show from experimental results that the increase in penetration will increase the heat input. Tsukamoto [72] demonstrated that the CO\textsubscript{2} laser is currently showing pre-eminence in welding of heavy plates and pipes. However, the
high-wavelength CO\textsubscript{2} laser shows increased plasma absorption that obstructs any penetration depth increase in the low-speed range. One application using CO\textsubscript{2} laser for welding of heavy plates, a 25 kW CO\textsubscript{2} laser and high-frequency heating combination was used to weld 10 mm thick pipes at a speed of around 10 m/min. Miyamoto [19] has suggested that by increasing the possibility of lasers, the performance of deep penetration welding will improve.

3.4.2 Comparison of laser welding to other welding processes
Laser welding has a number of advantages in comparison with conventional welding techniques. The first advantage is the ability to narrowly focus laser radiation for producing a high-intensity heat source which can be sent directly to the joint or area to be welded. Table 3.2 [7, 10, 73] shows the comparison of laser welding to other welding processes. Another point to be addressed here is that the cooling rate significantly affects the structure and properties of the welds. In laser welding the cooling rates are typically high, often in the range of \(10^4-10^6 \text{ °C/s}\), whereas the cooling rate in GTA (gas tungsten arc) spot welding can reach a maximum of about \(10^3 \text{ °C/s}\) [74]. Laser welding can be done continuously, drastically reducing the stress concentrations in the joint. Additionally laser welding does not have the restrictions in weld area (number of nuggets per unit areas) typical for spot welding, imposed by leakage current.
Table 3.2 Comparison of laser welding to other welding processes [7, 10, 73, 75]

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<td>_</td>
<td>_</td>
<td>+</td>
<td>_</td>
<td></td>
<td>_</td>
</tr>
<tr>
<td>12</td>
<td>Combine with filler</td>
<td>_</td>
<td>+</td>
<td>_</td>
<td>_</td>
<td>+</td>
<td></td>
<td>_</td>
</tr>
<tr>
<td>13</td>
<td>Automate process</td>
<td>_</td>
<td>+</td>
<td>_</td>
<td>_</td>
<td>+</td>
<td>_</td>
<td>_</td>
</tr>
<tr>
<td>14</td>
<td>Operation cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>_</td>
</tr>
<tr>
<td>15</td>
<td>Equipment cost</td>
<td>_</td>
<td>_</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>_</td>
</tr>
<tr>
<td>16</td>
<td>Capital cost</td>
<td>_</td>
<td>_</td>
<td></td>
<td></td>
<td>_</td>
<td></td>
<td>_</td>
</tr>
<tr>
<td>17</td>
<td>Narrow HAZ</td>
<td>+</td>
<td>+</td>
<td>_</td>
<td></td>
<td></td>
<td></td>
<td>_</td>
</tr>
<tr>
<td>18</td>
<td>Environment, noise, fume</td>
<td>_</td>
<td>+</td>
<td>_</td>
<td>_</td>
<td>_</td>
<td></td>
<td>_</td>
</tr>
<tr>
<td>19</td>
<td>Fixturing</td>
<td>+</td>
<td>_</td>
<td>_</td>
<td>_</td>
<td>_</td>
<td>_</td>
<td>_</td>
</tr>
<tr>
<td>20</td>
<td>Reliability</td>
<td>+</td>
<td>_</td>
<td>_</td>
<td>_</td>
<td>_</td>
<td>_</td>
<td>_</td>
</tr>
</tbody>
</table>

'+'= advantageous; '-'= disadvantageous; 'LB'= laser beam; 'EB'= electronic beam; 'RW'= resistance welding; GTA= gas tungsten arc; 'GMA'= Gas metal arc.
3.4.3 Weldability

“Weldability is the capability of a material to be welded under the imposed fabrication conditions into a specific suitably designed structure and to perform satisfactorily in the intended service”. This definition of weldability is developed by the American Welding Society. The weldability of any metal is related to the alloy type and composition of the two materials planned to weld together, and also relate to the practicality of welding these particular materials together under the conditions required. Laser welding obtained after optimization of the key process variables, such as joint design and preparation, weld thermal cycle, gas flow and composition, some times require preheating also may require filler type and feed rate, change in alloy composition, and thermal effects in heat–affected zone. Table 3.3 shows the weldability of various metals [7, 53].
Table 3.3 Laser weldability of various metals [7]

<table>
<thead>
<tr>
<th>No</th>
<th>Metals</th>
<th>Weldability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low-carbon and high strength, low alloy steel</td>
<td>(\text{CO}_2) and Nd:YAG laser good weld and high formability</td>
</tr>
<tr>
<td>2</td>
<td>Medium- and high-carbon steels</td>
<td>Subject to cracking; brittle, low ductility</td>
</tr>
<tr>
<td>3</td>
<td>Alloy steels e.g. pipeline, ship building, structural</td>
<td>Root porosity in partial penetration welds; high weld hardness</td>
</tr>
<tr>
<td>4</td>
<td>Galvanized, galvalnal steels</td>
<td>Good welds and high speed, lap weld need care in join design</td>
</tr>
<tr>
<td>5</td>
<td>Austenitic stainless steel ferritic stainless steel</td>
<td>Excellent welds, low porosity, good corrosion resistance, toughness subject to reduced and corrosion resistance; HAZ may have high hardness</td>
</tr>
<tr>
<td>6</td>
<td>Martensitic stainless steel</td>
<td>Hard, brittle welds; require preheating or postweld tempering</td>
</tr>
<tr>
<td>7</td>
<td>Heat-resistance alloys e.g., hastelloy, inconel, INCO 718</td>
<td>Evaluate case by case; brittleness, segregation, cracking could be problem; filler could be useful</td>
</tr>
<tr>
<td>8</td>
<td>Titanium and Ti alloys</td>
<td>Good welds in Ti-6Al-4V and Ti; inert gas shielding necessary, good mechanical properties</td>
</tr>
<tr>
<td>9</td>
<td>Aluminum and Al alloy</td>
<td>Good welds possible with (\text{CO}_2) and Nd:YAG lasers under controlled conditions; loss of volatile elements leads to porosity; cracking a problem in 6000 series</td>
</tr>
<tr>
<td>10</td>
<td>Magnesium I</td>
<td>Good (\text{CO}_2) laser welds in Mg Al 9 Zn</td>
</tr>
<tr>
<td>11</td>
<td>Copper</td>
<td>Acceptable welds possible in thin sheet with Nd: YAG radiation; can be spot welded</td>
</tr>
<tr>
<td>12</td>
<td>Brass</td>
<td>Difficult due to loss of Zn and high thermal conductivity</td>
</tr>
</tbody>
</table>

3.4.4 Heat transfer in laser welding

Whenever a temperature gradient exists in a solid medium, heat will flow from the higher temperature to the lower temperature region. Heat transfer is the science that seeks to predict the energy transfer that may take place between material bodies as a
result of a temperature difference. In thermodynamics this energy transfer is defined as heat. The most critical point is the ability to focus the laser beam to the welding specimen when the spot size is set to the minimum size that is possible for good focusability and better depth of field. When focusability is good, focusing optics with a longer focal length can be used which in turn leads to a large work clearance. The focusability of a laser beam is normally referred to as the beam quality. There are different variables used to describe the beam quality. For example the beam quality of CO₂ laser is usually indicated by the beam propagation factor k, or the beam parameter product (BPP) for an Nd:YAG laser. Another way to define the beam quality is the M₂ factor which allows the detection of beam profile deviations from the Gaussian ideal shape.

The beam parameter product (BPP) can be defined as follows [43, 76, 77]:

\[
BPP = \alpha \omega_0
\]  
(3.1)

With \( \omega_0 \) being the, radius of the beam waist and \( \alpha \), the divergence angle.

The beam quality (\( M^2 \)) can be expressed by:

\[
M^2 = \frac{\alpha \omega_0 \times \pi}{\lambda}
\]  
(3.2)

Where \( \lambda \) is the laser radiation wavelength

Relating the beam quality and the beam parameter product:

\[
M^2 = \frac{BPP \times \pi}{\lambda}
\]  
(3.3)

Considering the beam propagation factor (k) in equation 3.4:

\[
K = \frac{\lambda}{\pi} \times \frac{1}{\alpha \omega_0}
\]  
(3.4)

Then the beam quality can be expressed by equation 3.5, where:

\[
M^2 = \frac{1}{K}
\]  
(3.5)

Melting efficiency was analyzed to observe the loss of energy in the first experiments undertaken with the purpose to improve the welding process in the subsequent set of weldments. To analyze this factor it was considered that full efficiency occurs when all
the power (P) delivered is used to melt a unit of material volume (V), the weld bead has a cylindrical shape and no losses take place:

\[ P = V \cdot E \] (3.6)

Where, ‘P’ the laser power (w). ‘V’ the volume melted by unity of time (m^3/s). “E” is the energy required for melting a volume unit (J/m^3).

Considering "\( \rho \)” the density (Kg/m^3) "Cp” the specific heat (J/Kg K), "T” the temperature (K) and "H" the melting latent heat (J/Kg), power becomes:

\[ P = V \cdot \rho \cdot (Cp \cdot (T_m - T_o) + H) \] (3.7)

Multiplying the travel speed by the weld bead width and depth, volume is attained, with “\( v \)” the velocity (m/s), “b” the weld bead width (m) and “h” the weld depth penetration (m).

\[ P = \rho \cdot v \cdot b \cdot h \cdot (Cp \cdot (T_m - T_o) + H) \] (3.8)

If the specific heat is put in evidence, then

\[ P = \rho \cdot v \cdot b \cdot h \cdot \left( C_p \cdot \left( T_m - T_o \right) + \left( \frac{H}{C_p} \right) \right) \] (3.9)

Multiplying and dividing the first term by the diffusivity (\( \alpha \) (m^2/s), Eq. (3.9)) can be rewritten as:

\[ P = \left( \frac{\rho \cdot v \cdot b \cdot h}{\alpha} \right) \cdot \left( C_p \cdot \left( T_m - T_o \right) + \left( \frac{H}{C_p} \right) \right) \] (3.10)

Since the thermal conductivity is defined by \( K = \rho \cdot C_p \cdot \alpha \) (W/mK), then

\[ P = \left( \frac{\rho \cdot v \cdot b \cdot h}{\alpha} \right) \cdot k \cdot \left( T_m - T_o \right) + \left( \frac{H}{C_p} \right) \] (3.11)

If,

\[ (T_m - T_o) + \left( \frac{H}{C_p} \right) = d \] (3.12)

Then

\[ P = \left( \frac{\rho \cdot v \cdot b}{\alpha} \right) \cdot (h \cdot K \cdot d) \] (3.13)

Reordering Eq. (2.13):

\[ \left( \frac{v \cdot b}{\alpha} \right) = \frac{P}{h \cdot K \cdot d} \] (3.14)
Then using the Eq. (3.14), the melting efficiency can be calculated and draw the relation between welding speed parameter \( \frac{vb}{\alpha} \) and laser power parameter \( \frac{P}{hkd} \). When there is a full melting efficiency, these parameters present the same value (\( y = m \cdot x \), with \( m=1 \)).

### 3.5 Process mechanisms – keyholes and plasma

One of the associated physical mechanisms, the key holing phenomenon, which occurs at high laser intensities, is critical to deep penetration welding. Recoil pressure induced by the evaporation processes due to flux and thermocapillary force. This is due to spatial distribution of laser beam energy and huge temperature gradient on the liquid vapour (L/V). This drives liquid ejection forming a vapour – filled cavity called the keyhole. The unique advantage of the key holing lies in its ability to improve energy utilization and propagation tremendously. The keyhole technique allows lasers to produce welds that are deep and narrow.

There are two modes of welding with the laser. When the power density is insufficient to cause boiling conduction limited welding occurs and therefore generate a keyhole - at the given welding speed. There are two principle areas of interest in the mechanism of keyhole welding. The mechanism for absorption within the keyhole is the second one, which may affect both this flow stability and entrapped porosity. The absorption of the beam happens during the reflection from the surface, and inverse bremmstrahlung leading to plasma reradiation. The Fresnel absorption can be calculated for a given shape of the leading edge of keyhole to be non-uniform. The plasma effects vary with polarisation and speed. There is also charge plasma formed due to effect of the very hot vapour in the keyhole, which comes out from the material being welded together with the shroud gas [10, 12, 78-80]

### 3.6 Plasma suppression

The laser-induced breakdown process generally involves nonlinear absorption of light or cascade ionization resulting in the generation of plasma. There are two mechanisms of laser-induced breakdown resulting in plasma formation. Plasma generation by optical breakdown is a threshold phenomenon. Ablation threshold is considered to be reached
when the free electron density in the plasma corresponds to about 1018/cm³. However, an actual ablation depth depends on the number of other effects such as plasma shielding and radiation-induced changes in the material absorption coefficient. Once the plasma is formed at the focal region corresponding to threshold intensity, further increase in the pulse energy causes the growth of plasma toward the incoming laser beam. The rapid expansion of the plasma laser-induced breakdown generates the shock waves [22].

3.7 Laser welding parameters
There are huge numbers of laser welding parameters to be considered when performing any welding application. The parameters include laser type, material type, laser power, and laser welding speed, focal plane position, shielding gas, position accuracy, focal spot size (diameter), gas flow rate and nozzle geometry. The optimization of these parameters is critical to a good quality weld [10, 81, 82].

3.7.1 Laser power
A critical welding input parameter is the laser beam power followed by welding speed. These parameters significantly influence the resulting weld. Too low power will cause lack of penetration or too high power will cause a drop through of the weld [83, 84]. The first parameter defined through the relation between laser power and welding speed is the operational range of a laser welding system. Some critical parameters for CO₂ laser welding mild steel materials are shown in Table, 3.4 [7].
Table 3.4 Some critical parameters for welding mild steel with CO₂ laser power [7, 52, 83-86].

<table>
<thead>
<tr>
<th>No</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laser power</td>
</tr>
<tr>
<td>2</td>
<td>Amplitude</td>
</tr>
<tr>
<td>3</td>
<td>Beam quality and position</td>
</tr>
<tr>
<td>4</td>
<td>Continues wave or pulsed wave</td>
</tr>
<tr>
<td>5</td>
<td>Pulse shape and repetition</td>
</tr>
<tr>
<td>6</td>
<td>Focusing</td>
</tr>
<tr>
<td>7</td>
<td>Focus above or below surface</td>
</tr>
<tr>
<td>8</td>
<td>Depth of focus</td>
</tr>
<tr>
<td>9</td>
<td>Intensity distribution within spot on surface</td>
</tr>
<tr>
<td>10</td>
<td>Shield gas</td>
</tr>
<tr>
<td>11</td>
<td>Type of laser and steels</td>
</tr>
<tr>
<td>12</td>
<td>Flow rate</td>
</tr>
<tr>
<td>13</td>
<td>Orientation relative to focus (for the laser light)</td>
</tr>
<tr>
<td>14</td>
<td>Trailing, coaxial, leading /</td>
</tr>
<tr>
<td>15</td>
<td>Reverse side (reflectivity)</td>
</tr>
<tr>
<td>16</td>
<td>Nozzle flow pattern</td>
</tr>
<tr>
<td>17</td>
<td>Laser spot size</td>
</tr>
</tbody>
</table>

### 3.7.2 Welding speed

The effect of welding speed is clearer in performing continuous butt, seam or fillet welds for CO₂ lasers which are operated in the continuous wave mode than for pulsed Nd: YAG lasers. On the other hand pulse frequency and the percentage overlap of each spot might be affected by welding speed. As the thickness increase the penetration depth of the welding decrease as shown in Figure 3.5. Also by increasing the speed the exposure time for the materials to the laser beam, reduced resulting in reduced absorption of the heat [22, 73].
3.7.3 Shielding gases and gas flow rates

To prevent oxidation of the weld surface, shielding gas is normally used. Sibillano et al [87] have studied the effect of gas situation (the geometry of the gas delivery system, the gas flow rate and the nozzle stand-off distance NSD) during welding AA5083 aluminium alloy using CO$_2$ laser. It was demonstrated that all shielding gas conditions investigated can significantly affect the features of the weld seam, and the plasma plume characteristics. Also it was found that high flow rate, combined with a low NSD, created a narrower and deeper keyhole. El-Batahgy et al. [88] used Argon and Helium gases as a shielding gas for his research on austenitic stainless steel using CO$_2$ laser. They noticed that the Helium was more effective than Argon as a shielding gas to obtain acceptable weld profile where the fusion zone interfaces are almost parallel to each other. This is due to the effect of a plasma cloud being reduced as a result of the higher ionization potential of helium. Kim [68] investigated the effect of gas flow rate (Helium and Argon) during the welding of AISI316 stainless steel and low carbon steel. They reported that when the flow rate goes to minimum (less than 10 L/min, and less than 5 L/min respectively for the two gases) the penetration depth was reduced and the bead width was increased. It suggested that the low flow rate did not remove the plasma which absorbed the laser power. By increasing the flow rate to 10-30 l/min and 5-15 l/min a sound bead and deep penetration was achieved. It was also noticed that the increase in the gas pressure caused porosity [89].
3.7.4 **Focal plan position**

Good performance of welding depends on the selection of optimum parameters. Typically the penetration decreases if the focal point is not on the surface, and if the laser beam diameter on the surface is too small the keyhole welding may not be formed. Optimum focussing conditions are very important issues which have a large effect on welding parameters. In welding, focussing the laser beam at the surface of the weld piece is needed to ensure good results. Focused spot size, depth of focus and focus position are very significant to the best performance. Focus spot, or the minimum waist diameter position about the work surface has to be carefully selected to guarantee the correct laser power density to form the weld keyhole. Small distance from the workpiece surface will cause large variation. The focal point position has a big effect on the weld quality in fibre laser – MIG / MAG hybrid welding [7, 73, 89, 90].

3.8 **Fibre laser welding**

The high beam quality of fibre laser can be used to improve welding e.g. in terms of productivity, reduced heat input and reduced distortion. It allows the use of a very low beam divergence while maintaining small spot sizes. Because fibre lasers can produce very high beam quality, there are more advantages. Some of these advantages have been summarized in Table 3.5. Zhang et al [31, 91] have investigated the welding of thick section stainless steel at 0.2 m/min -2 m/min welding speed with 10kW fibre laser. They concluded that because of severe oxidization of the molten pool, meandering bead occurs at laser power of 10 kW and welding speed of 0.3 m/min, and there exists a possibility to prevent this through the adjustment of the shielding conditions. They highlighted the significant influence of the beam spot size on the penetration depth when the penetration depth was 0.2 mm, the bead spot size was bigger than that of 0.1 mm. The relationship between defocused distance and penetration has been demonstrated that, which shows approximately at -7 mm defocused distance maximum penetration has been obtained as shown on Figure 3.6 [91].
Table 3.5 Advantages of high beam quality of fibre laser [31, 43, 92-94]

<table>
<thead>
<tr>
<th>No</th>
<th>In terms of</th>
<th>Fibre laser can do</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Beam divergence</td>
<td>Could be reduced while maintaining spot size and focal distance</td>
</tr>
<tr>
<td>2</td>
<td>Beam diameter</td>
<td>Reducing raw beam diameter helps to reduce optics, then size and inertia for moving optical elements like mirror.</td>
</tr>
<tr>
<td>3</td>
<td>Focal distance</td>
<td>Increased while maintaining focal spot size</td>
</tr>
<tr>
<td>4</td>
<td>Focal spot</td>
<td>Decreasing while maintaining focal distance</td>
</tr>
<tr>
<td>5</td>
<td>Spot size &amp; focal length</td>
<td>A 1-kW laser can be focused to 50 µm spot size diameter with a 100mm focal length lens.</td>
</tr>
<tr>
<td>6</td>
<td>Quality &amp; efficiency</td>
<td>Obtain deep penetration welding in a diversity of materials</td>
</tr>
<tr>
<td>7</td>
<td>Distortion</td>
<td>Joining parts which required minimum distortion</td>
</tr>
<tr>
<td>8</td>
<td>Stress-built-up effect</td>
<td>Joining parts which required minimum welding Stress-built-up</td>
</tr>
<tr>
<td>9</td>
<td>Temperature Sensitive effect</td>
<td>Joining parts with the effect of Temperature Sensitive close</td>
</tr>
<tr>
<td>10</td>
<td>Penetration</td>
<td>Has a deeper waist depth, and can obtain high penetration at high speed</td>
</tr>
<tr>
<td>11</td>
<td>Thin sheets</td>
<td>Perform welding without humping at increased speed</td>
</tr>
<tr>
<td>12</td>
<td>Reflectivity</td>
<td>Welding of parts with high reflection effect</td>
</tr>
<tr>
<td>13</td>
<td>Dissimilar metals &amp; geometry</td>
<td>Ability to weld many dissimilar metals and dissimilar geometry</td>
</tr>
</tbody>
</table>
3.8.1 Welding of mild steel and stainless steel with fibre laser

Fibre laser welding was performed with the objective of obtaining a fundamental knowledge of welding property produced in bead-on-plate welding for common material such as Type 304 Stainless Steel with 6KW fibre laser beams of several peak power densities [95]. Several people have studied and reported the potential application of high power fibre lasers. Thomy et al [49] concluded in their experimental studies that because of a high beam power and competitive beam quality of the fibre laser there will be significant enlargement of the process window towards higher welding speed and thicker materials. They demonstrated that it is possible to achieve a penetration of 10mm in ENAW 6082 at a welding speed of 3 m/min. Kawahito et al [95] have argued that the fully penetrated welds could be obtained in bead-on-plate welding for 8mm-thick SUS304 plates with 130 μm-small spot diameters at 4.5 m/min welding speed. At tightly focused 6kW fibre laser beams narrow and deep penetrations of weld beads were obtained. McPherson et al [96] has discussed that the challenge from laser welding will exist in the future due minimal distortion. Kwok et al [97] mentioned that the laser weld of S31603 remained purely austenitic and the laser weld of S30400 was essentially austenitic with the presence of a small amount of ferrite. On the other hand, the ferrite / austenite phase balance for the two duplex stainless steels was slightly disturbed. They also added all laser welds for stainless steels exhibited passivity in the 3.5% NaCl
solution but their pitting resistance deteriorated as evidenced by lower pitting potentials and higher corrosion current densities compared with those of the base metals. They attributed that to the microsegregation (for S30400) or to incorrect phase balance (S31803 and S32769). GuoMing et al [98] reported that the temperature field gradient of laser welding are large and the heat affected zone is small compared with other welding methods. Iammi et al [99] reported that the depth and width of penetration depends on the welding speed and laser power. The lower penetration width and depth appear when the speed is higher, and the greater penetration width and depth, when the laser power is high. Kawahito et al [100] welded 304 austenitic stainless steel 8 and 20mm plate thickness. Their investigation was the effect of laser power density on the formation of sound welds with a high-power fibre laser using four different laser beams of 130, 200, 360 and 560 µm spot diameters; a continuous wave (CW) fibre laser (IPG YLR-10000) was used for bead-on-plate welding, they applied only 6kW fibre laser. The maximum laser power was 10kW and the beam parameter product (BPP) was 4.5 mm mrad. They concluded from their work that the at 130 µm spot diameter at 0.6 mmin⁻¹ welding speed a keyhole type of penetration at any diameter and the maximum penetration of 11mm depth was obtained. Furthermore, it was found that the laser power density exerted a significant effect on the rise in weld penetration at higher welding speeds. They found that incompletely penetrated welds without welding defects such as porosity, underfilling or humping could be produced with fibre laser beams of 360 µm and 560 µm spot diameter under extensive welding conditions of welding speeds between 4.5 and 10 mmin⁻¹. Figure 3.7 shows, the experimental set-up. Ream [101] investigated and concluded that there is no significant role for the shielding gas in weld penetration in stainless steel when the fibre laser power was less than 600 W.
Stainless steels are classified into austenitic, ferrite, duplex and martensitic stainless steels. Austenitic stainless steel are generally regarded as being readily weldable. Austenitic weld metals normally contain 5-10% ferrite in the deposit. A rapid gas evolution can occur during solidification giving rise to spattering of liquid metal, or to porosity when the gaseous bubbles remain entrapped in the solidified metal. Both of these are because the solubility of oxygen and hydrogen in stainless steel is much higher in the liquid state than in the solid state. The presence of oxides increases the tendency of brittle behaviour of the joint and decreases its mechanical strength, so the cleaning of stainless steel before welding becomes an important, issue. Additionally, due to the hardness effect, it is possible to minimize and reduce by the implementation of a pre, or post-heating technique [102-107].

Miyamoto [19] has investigated that one of the serious problems in welded steel construction is stress corrosion cracking (SCC), where the susceptibility of cracking is enhanced at the weld bead due to residual tensile stress. He summarized this variety of interesting applications of laser processing to steel production as early as the late 1970s, as shown in Figure 3.8. The applications are divided into categories; one is continuation and automation of steel production line and another is related to the development of novel materials suitable for laser materials processing. Joining steel coils in the built-up line is one of the earliest applications for the continuous and automation of steel
production. CO$_2$ lasers up to 10 kW were used for welding coils in cold rolling, annealing and pickling lines. Pipes of high quality were also constructed using the 20 kW-class CO$_2$ laser. The process technique is not the only way of solving industrial problems; the other major feature also is the development of the novel materials suitable for laser materials processing.

Kong et al [108] concluded that the sensitivity to both focus position and power for the penetration depth is very high for laser microwelding, and they attributed this to the fact that the intensity is near the required limit for the keyhole formation. They also added that due to formation of the keyhole, joining efficiency is increased tremendously. Benyounis et al. [109] concluded that in order to obtain the best mechanical properties of welded components, RSM is an accurate technique to optimize the laser welding process.

Manonmani et al. [110] developed a model to investigate the effects of process parameters on the bead geometry of a laser beam butt weld. The direct effect of beam angle on bead geometry is shown in the Figure 3.9. They found that generally the laser beam is not positioned perpendicular to the workpiece, for the prime reason that the reflected laser energy may impair the optic system; hence, a small angular tilt is given to the laser beam. The beam incident angle is varied with reference to the positive x-axis,
and finally they concluded that by increasing the beam power and the depth of penetration, the bead width and area of penetration will increase and they will decrease with an increase in the beam angle. When the welding speed is increased, the depth of penetration, bead width and area of penetration are reduced and there is no significant affect on beam power or welding speed. Variations in beam position did not influence weld fillet geometry, which is typical of keyhole welding [111].

![Graph showing the effect of beam angle on bead geometry](image)

Fig. 3.9 Direct effect of beam angle on bead geometry [110]

### 3.9 Control of laser welding

During welding, a variety of signals are normally generated which contain information regarding the welding process. These signals contain information about the right things in the process as well as wrong things in the process. Extraction and recognition of signal components that characterize right and wrong elements is the key to process monitoring and subsequent process control. A laser welding operation can wait for commands from a monitoring system which has capability to identify defects welding from welding and identify the quality of the product [7].

### 3.9.1 Control defects of welding

Most common welding defects include porosity, cracking, residual stress and spatter. Optimum welding parameters can be selected to minimize the welding defects. Weld defects are critical in particular applications depending on the service requirements of weld. Deniability of these will depend on the environment, joint, configuration,
postweld forming operations, heat treatment, and many other parameters. Table 3.6 shows some guidelines relating alloy type to common defects [7].

### Table 3.6 Schematic common weld defects alloy type [7]

<table>
<thead>
<tr>
<th>No</th>
<th>Alloy</th>
<th>Porosity</th>
<th>Solidification cracking</th>
<th>Cold cracking</th>
<th>Corrosion cracking</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Medium-, high-carbon steel</td>
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<td>High-alloy steel</td>
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<tr>
<td>6</td>
<td>Nickel alloy</td>
<td>X</td>
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<td>X</td>
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</tr>
</tbody>
</table>

### 3.9.2 Residual stress

During the laser welding process, by increasing the temperature during the melting or heating and subsequent cooling of the weld and surrounding material, residual stresses are introduced. Because of the variety of factors involved in welding parts, it is very difficult to predict and control residual stresses caused by welding. The welded part of a component or piece of equipment is often the least resistant to fatigue, however, all welded joints inevitably contain residual stress and this can have a marked effect on fatigue behaviour, stress corrosion and fracture. Numerous experimental methods have been developed and applied to research in the field of residual stresses caused by welding in addition to theoretical and numerical analyses. By applying heat treatment using the laser source, it is possible to reduce the stress level. Heating of the substrate plate, results in a decrease of the residual stress level because of the reduction in the temperature gradients during welding [112-114].

### 3.9.3 Porosity, pits, blow holes

Porosity is one of the most common defects in welding and is typically caused by shielding gas entrapment before weld solidification. Porosities appear due to various
sources in laser welds due to the influence of shielding gas on penetration. Aser-induced gas plasma occurs in CO$_2$ laser welding in Ar or N2 shielding gas. Bubbles are normally predominantly generated from the keyhole tip and moved along the melt flow inside the molten pool. The bubbles are trapped whilst floating up, resulting in the formation of porosity. Using an SEM test to observe the results of a fractured surface, it was demonstrated that evaporated materials injected in the bubble formed oxides. Various locations of the weld may be characterized by distinct morphologies and distributions. Minor porosity can happen due to trapping of gas bubble during solidification. For depths exceeding 10mm, porosity formation in the partial penetration welding can only be avoided by optimizing the welding variables. It is caused by capillary instability of a narrow and long cylindrical keyhole. The large voids in the solidification of molten material before the complete filling of the keyhole are shown in Figure 3.10. Deep penetration is obtained and also no pores are formed in aluminium alloy and stainless steel; even in mild steel, porosity formation is sharply reduced, when using a pure nitrogen shielding gas. The porosity reduction effect of the laser pulse is more significant in Inconel 690 than in the SUS 304 L and the tensile strength of Inconel 690 increases significantly as the level of $\Delta P$ increases. The resistance of 304 SS to pitting and SCC, high heat-input (and low cooling rate) is likely to reduce the segregation of alloying elements and the formation of Cr-deleted zone, it is affected by heat input and cooling rate [22, 72, 115-119].

![Fig. 3.10 SEM Image showing porosity](image)

3.9.4 Crack

The objective is always to design and build weldments that perform adequately in service. The risk of failure of a weldment is relatively small but it can occur specially in...
structures such as bridges, pressure vessels, storage tanks, ships, penstocks, etc. One of the most serious laser welding defects is cracking. Most of the cracks in the welds begin from the restrictions to the free contractions of the material during the cooling cycle. Such restrictions result in the setting up of high tensile stresses causing cracking. Hot cracking problem depends upon cooling rates and polluting elements in weld material. Hot cracking in the weld can either be solidification cracking or liquation cracking. Solidification cracking is cracking in the fusion zone which occurs during solidification. Cracking may be caused due to the differences in strain between weld and materials, or are due to large differences in heating and cooling system. Sometimes heat treatment minimizes the cracking. Wide-ranging studies have been conducted to recognize the mechanism of solidification cracking during laser welding and the effects of the various parameters on the receptiveness to cracking. In one study it was concluded that reducing the speed from 152 cm/min to 51 cm/min was the main factor for reducing the cracking behaviour by 61% [22, 51, 120, 121].

3.9.5 Weld spatter
The plasma and keyhole are significant factors when laser energy is transferred to the work-piece. The weight of the spatter also plays a critical role in weld quality. There are two sensors for measuring the plasma signal, the low aiming angle sensor (UV1) is for plasma plume and the high aiming angle sensor (UV2) is for plasma in the keyhole. The amount of plasma and spatter and bead size increases as laser power increases. With the increase of heat input, the volume of plasma in the keyhole and spatter increase and at full penetration, the signals abruptly decline. Plasma plume signal decreases with the increase of heat input. The size of the keyhole affects the signal and bead shape. Thus, the signals can be used as data for estimation of bead shape [122, 123].

3.9.6 Lack of penetration
Determination of the penetration depth and the bead width as a function of both the incident laser power and the welding speed, and the effect of the welding speed on the penetration depth is illustrated in Figure 3.11 and Figure 3.12 [124].
3.9.7 Humping (known as undercut)

A serious challenge in welding processes in general and laser beam welding in particular is to rise above constraint in processing speed set by the humping effect also known as undercut. This effect will start if a certain welding speed is exceeded for a given configuration of material and processing parameters as shown in Figure 3.13 [125].

Fig. 3.11 Effect of welding speed on penetration depth for of cast WE43 alloy joints [124]

Fig. 3.12 Effect of welding speed on Bead width of cast WE43 alloy joints [124].

Fig. 3.13 Schematic for bead-on-plate weld showing humping single mode fibre laser [125]
CHAPTER FOUR
EXPERIMENTAL AND NUMERICAL MODELLING DETAILS

4.1 Previous Modelling

4.1.1 The Development of Modelling

The research on modelling of laser welding dates back to early 1940s. Rosenthal [126] first proposed an analytical mathematical model of the moving heat source under the assumptions of quasi-stationary state and concentrated on point heating in the 3D analysis. Since this work, various studies [127-141] have been performed on laser welding simulation to investigate the nature of heat transfer, stress distribution and to also understand its physical phenomena. Welding simulation broadly falls in three categories i.e. heat transfer based on pure conduction model [127-129], thermal analysis of welding incorporating the fluid motion (convection problem) [130-132] and the sequentially coupled thermo-structural problem focusing on stress distribution (pure-conduction model with structural analysis) [134-136].

4.1.2 Numerical simulation models

Ghoreishi et al [142] have concluded that the comparison between the effects of parameters on circularity in laser drilling of mild steel with the circularity in drilling stainless steel displayed that there is no significant effect for mild steel, while the stainless steel pulse frequency has a significant effect. Benyounis and Olabi [143] reported a high level of interest in the adaptation of response surface method (RSM) and artificial neural network (ANNs) to predict response(s) and optimize the welding process. They reported a lack of a comparative study regarding the performance of the optimization methods. Olabi et al [144] have investigated and concluded the validity of the optimal solution in the range of the welding parameters that were used for training the neural networks. They reported that extrapolation over the limits would limit the applicability of the solution. Ki et al [12] proposed a model on self-consistent three-dimensional laser-keyhole welding that simulates the movements of L/V and S/L
interfaces using the level set method and mixture continuum model. Tsirkas et al [145] developed a three-dimensional finite element model. They perform their study with the help of SYSWELD [146, 147] finite element software. The purpose of their model was to simulate the laser welding process and predict laser welded panel distortions. The model was tested with a number of welding experiments; good agreement was obtained between calculations and experimental results.

In most laser welding processes, the solidified weld bead projects above or dips below the parent surface and only in a very narrow range of parameters is the weld bead at the same level as the parent material.

A two-dimensional model was used by Sluzalec [139] to study the flow of metal irradiated by a laser beam. An advanced model incorporating three-dimensional formulations was developed by Ye and Chen [140] to study heat transfer and fluid flow in full-penetration laser welding. An important finding in laser welding simulation had been made by Srinivasan and Basu [141], who studied the surface tension flow during laser melting and showed that the effect of buoyancy force is negligible compared to the Marangoni force. Sahin [135] used FEA technique to find residual and thermal stresses due to welding in a bi-material joint. Josefson [134] estimated residual stresses in a multi-pass weld using Abaqus, a commercially available FEA code for non-linear analyses. The thermal models used by Sahin [135] and Josefson [134] are based on a pure conduction problem, without considering the convection melt flow. To account for convection melt flow in an FEM problem some researchers make use of enhanced thermal conductivity [148-150].

4.1.3 Heat transfer models

The effect of Prandtl and Marangoni (Ma) numbers on the laser weld bead geometry has been studied by Wei [133], who found that the weld bead root surface became convex for Marangoni numbers in the range of $10^2 < \text{Ma} < 10^5$. Arora [130] studied the role of the Marangoni effect on laser weld pool and found that a wavy weld pool fusion boundary is formed when the Marangoni number is greater than 26,000. Furthermore, Rai and Debroy [137] developed a technique for weld bead geometry design by combing 3D
modelling, generic algorithm optimisation and a small number of experiments. They recognised that heat transfer in the upper part of the melt pool is dominated by convection due to vigorous circulation of molten material driven by the Marongoni effect. Also, Rai et al [131] developed a convective heat transfer model to study the partial and full penetration keyhole mode laser welding of steel and showing the important weld parameters by combining a capable keyhole model with convective three dimensional (3-D) heat transfer calculations in the weld pool. They determined the weld bead geometry in laser welding of structural steels. They found that a humped root surface could be formed due to recoil pressure and smaller weld area compared with the top surface. Robert and Debroy [132] used dimensionless parameters such as Marangoni and Peclet numbers to predict the weld geometry in stationary laser spot welding of a large range of engineering materials. Recently, Pang [151] developed a three dimensional CFD based model, incorporating coupled heat transfer, fluid flow and keyhole geometry. He emphasised the importance of welding speed and surface tension co-efficient in on hump shapes on the keyhole wall.

4.1.4 Statistical models
Caiazzo et al [152] did a Design of Experiment (DoE), and concluded that the bead crows were found to be wider for AISI 304 steel compared to the AISI 430 type. They also found the area of the bead depended on the interaction between the material used and the overlapping ratio plus the welding speed. Brankvik [153] reported experimental design and response surface methods could be done by simulation as an efficient and low cost tool. Gooding concluded that the use of parallel synthesis guided by statistical experimental design is an efficient way to conduct chemical process optimization. It is more and more known one-variable-at-a-time (OVAT) experimentation is not the most efficient way to explore experimental space during variable screening and optimization [154]. Benyounis et al [155] concluded in some optimization study that the Design – Expert software can be used for optimizing the weld bead parameters and finding the corresponding optimum process factors. They added that full–depth penetration has a strong effect on the other bead parameters investigated. Benyounis et al [81] developed a mathematical model using response surface methodology studying the effect of the welding parameters on the heat input and weld-bead profile, and concluded that the
welding speed was the most important factor to be considered on joint strength, while the focal position and laser power was slightly affecting the joint strength.

Design of Experiment (DoE) and statistical techniques are in massive use to optimize process parameters. It is essential to be aware of the process behaviour, the amount of variability and its effect on the process outputs. In engineering fields, experiments are often carried out to explore, estimate or confirm. Engineers solve problems of interest to society by the efficient application of scientific principles. Exploration refers to understanding the data from the process and estimation refers to determining the effect of the process variables on the output performance characteristics (or quality characteristics). Confirmation implies verifying the predicted results obtained from the experiment and the engineering or scientific method is the approach to formulating and solving these problems. Solving many types of engineering problems requires an appreciation of variability and some understanding of how to use both descriptive and analytical tools in dealing with variability. The steps in the engineering method for solving the scientific problems are illustrated in the Figure 4.1.

Fig. 4.1 the engineering problem-solving method [35, 156]
4.2 Conclusion

Standard CFD models can predict the temperature history incorporating the convection melt flow, but will not be able to calculate the stress distribution. FEM models can predict temperature history and stress, but will be based on solid conduction problem. To overcome these limitations, sequentially coupling CFD and FEM analyses would be a good approach to be explored in this PhD project to fill in a knowledge gap. This new approach would be different from most previous sequential models, which considers sequentially coupled thermal and structural analysis [134-136], in which the thermal analysis was based on pure-conduction formulations. In the proposed model to be investigated in this project, the CFD analysis calculates the thermal history incorporating the melt flow convection. The FEM analysis makes use of the thermal history (calculated by CFD analysis) to predict the residual stress induced in the material. By using this method, the results are expected (to be demonstrated in this PhD thesis) to be more realistic than the previous sequentially coupled thermo-structural analysis which uses the thermal history from pure conduction models. Also, many previous models assume the surface of the weld to be perfectly flat which may not be the fact for most laser welding parameters [157-159]. During the laser welding process the surface of the weld bead either goes above or below the surface and one of the main objectives of this model is to predict these phenomena. According to the Ref: Bäuerle, D., 2000 [160], Figure 4.2, Maragoni effect drives the directions of the melt flow and causes the melt geometry changes. It shows a possible mechanism of weld bead geometry variation to be examined in this PhD thesis. Bulge welds formation at low temperature (where is high speed, low power) \( d\sigma/dT > 0 \), and Notch weld formation at high temperature (where is low speed, high power) \( d\sigma/dT < 0 \) are expected. When the surface tension gradient is zero, then it is expected to produce a net shape weld,
The use of design of experiments would allow more systematic examination of process parameter effects and experimental data to validate the theoretical models. This approach is used in the PhD project, not only to understand the process behaviour but also to validate the theoretical models.
CHAPTER FIVE
EXPERIMENTAL PROCEDURE AND EQUIPMENT

Introduction
This chapter contains information about the experimental procedures and equipment used to collect the data presented within this thesis. The descriptions of the procedures are presented first followed by the equipment required for each stage. The arrangements and procedures varied slightly from test to test according to the requirements necessary for each investigation.

5.1 Pilot tests
Initially, a trial and error research method was applied in experiments to find out the nearest values for the welding parameters. In some cases, over 100 experiments were conducted to narrow down the welding parameters.

5.2 Design of the experiments
A series of experiments were performed using statistical design of experiments (DoE) techniques and analysis of variance (ANOVA), to identify significant variables and their interactions affecting the weld characteristics. At this stage, Design Expert statistical software package Figure 5.1 was used for designing the experiments in most of the investigations. Design of Experiments was very useful for classifying the significant processing factors and enumerating the relationships with measured outputs. DoE and statistical techniques are widely used to optimize process parameters because it is known that the conventional, one-variable-at-a-time (OVAT) procedure is not the most efficient way to explore experimental space during reaction variable screening and optimization. The design of experiments (DoE) was based on either the three or two welding parameters; laser power, welding speed and where appropriate, laser beam focal point position (positive means above the surface and negative means below the surface).
Statistically based experimental design techniques are particularly useful in the engineering world for development, or for improving the performance of a manufacturing process. They also have extensive applications in the development of new processes. These processes are normally described in terms of several controllable variables such as temperature, pressure and feed rate. In this case, the variables for welding include laser power, laser welding speed, argon gas flow rate, and focal plan position etc. By using statistical design of experiments (DoE) techniques and analysis of variance (ANOVA), engineers can determine which subset of the process variable has the most significant effect on process performance.

These experiments show the way to:
- Improve process yield
- Reduce or increase variability in the process to support your requirements
- Minimize design and development time
- Reduction in the cost of operation.

Experimental design method is therefore useful in engineering design activities where new products are developed and existing ones are improved.

Other features of typical applications of statistically designed experiments in engineering design are:
- Evaluation and comparison of basic design configurations
- Assessment of different materials
- Selection of the design parameters ensuring the product will work well under a wide variety of field conditions meaning the design will be robust
Chapter 5 Experimental Procedure and Equipment

- Determine the key product design parameters that affect the product performance.

5.3 Preparation and methodology

Laser welding was performed on AISI 1018 / EN 10130 mild steel plates with its composition as shown in Table 5.1. The metal was cut into many scales of two plates of 50 mm x 50 mm x 1.5 mm thickness, and 25 mm x 25 mm x 1 mm thickness.

Table 5.1 Chemical composition (%) of mild steel AISI 1018 / EN 10130

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<th>CR</th>
<th>MN</th>
<th>MO</th>
<th>N</th>
<th>NI</th>
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<td>EN10130</td>
<td>0.025</td>
<td>16.85</td>
<td>1.91</td>
<td>2.086</td>
<td>0.051</td>
<td>10.08</td>
<td>0.029</td>
<td>0.001</td>
<td>0.62</td>
<td>0.03</td>
<td>0.12</td>
</tr>
</tbody>
</table>

The plates were then machined on one side of the edge to have vertical walls for welding which were butt joined, while for bead on plate welding there was no machining required. The experiments were performed using IPG YLR-1 kW single mode fibre laser as in Figure 5.2 (1075 nm wavelength, $M^2 = 1.1$, delivered through a 14 µm optical fibre core diameter). The fibre output assembly was connected to a z-axis Precitec processing head with a lens assembly and a coaxial gas nozzle. The laser beam was focused via a lens of 190.5 mm focal length to give a beam spot diameter of approximately 50 µm at focus.

Fig. 5.2 Ytterbium Fiber Laser

A PC was used for controlling the welding process and CNC motion as in Figure 5.3. The samples were fixed and clamped during the welding process on a CNC motion...
Chapter 5 Experimental Procedure and Equipment

system, high speed linear motor CNC translation table as shown in Figures 5.4 to Figure 5.7.

![Fig. 5.3 PC for controlling the laser and CNC motion](image)

![Fig. 5.4 bed-on-plate weld](image)

![Fig. 5.5 device for butt weld](image)

![Fig. 5.6 bed-on-plate weld](image)

![Fig. 5.7 clamping during the welding process](image)

During some of the experiments, argon was used at the welding coaxial assist gas as in figure 5.8. The conical coaxial gas nozzle had an exit diameter of 2 mm and the workpiece was placed at a stand off distance not less than 5 mm from the nozzle.
Chapter 5 Experimental Procedure and Equipment

Fig. 5.8 coaxial assists gas argon during welding process

5.4 Preparation during the welding process
During the welding process, samples were subjected to visual and microscopic inspection as in Figure 5.9 and Figure 5.10.

Fig. 5.9 welding samples Fig. 5.10 Microscope during experiments

5.5 Preparation after welding process
Following the welding experiments the samples were cross-sectioned perpendicular to the weld direction to reveal the view as in Figure 5.11. This was done using a precision cutting machine as in Figure 5.12, and mounted in the appropriate resin in Figure 5.13.

Fig. 5.11. Schematic diagram of the cross section of laser welding sample
Specimens for the metallographic examinations were prepared by polishing successively in 80, 180, 320, 600 and 1200 emery grits, followed by a final disc polishing using 9, 6 and 3 µm diamond slurry as in Figure 5.14 (a) and Figure 14 (b). The polished surface of the samples was etched with Krolls reagent for further examination as in Figure 5.15.
5.6 Samples examination and testing

5.6.1 Samples examination

The next step was examination of the samples using an optical Polyvar microscopic as in Figure 5.16.

![Polyvar microscopic](image)

**Fig. 5.16** a Polyvar microscopic

5.6.2 Results and Output from examination

The Polyvar is an optical microscopic which shows the effect of welding parameters on the responses (top height (TH), root height (RH), top width (TW) and root width (RW)) as in Figure 5.17 of some certain experiments, and the deviation on weld bead geometry. In most cases, an enclosed weld profile was obtained representing welding that occurred in the keyhole mode. The profile was narrow when moving from the upper to lower surface. Depending on the parameter combinations used, diverse combinations of convex surface beads, undercutting and dropout can be seen.

![Schematic diagram for cross section of the welding](image)

**Fig.5.17.** Schematic diagram for cross section of the welding
5.6.3 Samples of the results of the experiments

Normally there are four types of welding such as bulge weld, notch welding, under cut welding and net shape welding. Net shape welding has been recently discovered in this research as in Figures 5.18 (a,b,c and d).

Fig. 5.18-A. Bulge weld, with parameters; P: 475W, S: 120 mm/s & Fpp:-1.5 mm

Fig. 5.18-B. Notch welds, with parameters; P: 500W, S: 90 mm/s & Fpp:-2.0 mm

Fig. 5.18-C. Under cut, with parameters; P: 600W, S: 115mm/s & Fpp:-2.5mm

Fig. 5.18-D. Net shape weld, with parameters; P: 500W, S: 110 mm/s & Fpp:-2.0mm

Where P: Power, S: Speed and Fpp: Focal point poison

5.7 Weld properties

The purpose of the mechanical tests was to understand the effect that weld bead geometry has on the strength of the welds.
5.7.1 Micro-hardness test

Preliminary tests on micro-hardness for butt welding of mild steel sheets were performed. The microscope used for the hardness examination is shown in Figure 5.19.

![Hardness test setup machine](image)

Fig 5.19 Hardness test setup machine

5.7.2 Micro-structure test

Optical, electron, and scanning probe microscopes are normally used in microscopy. Microscopic examination is an extremely valuable tool in the study and characterization of materials. In this research, four types of butt welding have been inspected for microstructure testing as shown in figures 5.20 (a, b, c and d).

1. Net shape weld

![Net shape weld](image)

Fig 5.20 (a) Net shape weld produced at P: 375W, S: 150 mm/s and Fpp: 0 mm
5.7.3 Tensile test

Tensile tests were carried out for a range of laser butt welded samples based on EN1002-1 2001 standard, sample as in Figure 5.21.
CHAPTER SIX

BEAD ON PLATE NET SHAPE WELDING OF 1.5
MM THICK MILD STEELS SHEETS

Investigation of Net – Shape Welding of Mild Steel Sheets with a
1 kW Single Mode Fibre Laser

Abstract
This study aims to develop Net Shape Welding (NSW) and identify the transition
(critical) welding speed under different laser parameters which affect weld beam
graphy from normal to NSW. A 1 kW single mode fibre laser was used to perform
bead-on-plate welding of 1.5 mm mild steel sheets at a range of laser powers, welding
speeds and laser focal point position parameters. The combinations were carefully
selected with the objective of producing NSW with minimum weld bead geometry
deformation from the surfaces. The experiments were designed using the statistical design
of experiment (DoE) technique for optimizing the above selected welding parameters.
The geometry of the weld beads was studied and the combinations of parameters that
led to the changeover to net shape welding were identified. The results show the
important factors controlling external weld geometry and help identify a process
window for developing net shape welds. The work would lead to potential applications
for high accuracy geometry welding where post-weld fit ups, assembly and painting
require negligible geometry distortion of the weld zones.

6.1 Introduction
Laser technologies have made distinguished contributions in modern industry. These
have typically been realised through the important roles played by lasers in the
advancement of manufacturing technology in many areas such as welding, which has
become a very important joining technique. Laser welding has enabled the use of lasers
in a wide variety of applications most commonly in the automotive, oil, gas, aerospace, medical and electronics industries.

For some applications, especially if a high post-weld fit-up tolerance is needed, precision welding that produces minimal distortion in the part and requires no post weld machining or finishing process is desirable. This can be termed net-shape welding. Processes like painting and cosmetic finishing typically require net shapes.

The most sensitive parameter for determining the weld bead shape are three parameters; Peclet number (which is a dimensionless number used in calculations involving convective heat transfer), the conductivity of the material and the absorption coefficient of material used for the circular disk source. The weld cross section, which is triangular or rectangular, could be determined by the Peclet number of the heat source model. By increasing the Peclet number it transforms the cross section away from rectangular toward a triangular geometry [161].

As welding speed increases, an increase in the inclination angle of the keyhole front wall occurs as a result of shorter beam/material interaction times [162].

Most welding processes do not result in net-shape. However, friction stir welding (FSW) is a solid-state welding method that has shown the capability of net-shape weld, which has found particular applications in the aerospace and automotive industries. This joining technique, which was invented by W. Thomas and his colleagues of The Welding Institute (TWI) (Cambridge, United Kingdom) in 1991 [60, 61] can be used to join high-strength aerospace aluminium alloys and other metallic alloys that are hard to weld by conventional fusion welding. The process combines frictional heating with extreme plastic deformation to manufacture joints with improved mechanical properties compared with usual fusion welding techniques [163]. Moreover, the process has generally been used as an assembly process to minimize post-weld machining in net and near net-shape parts rather than a means for developing performs for deformation processing [2].

The amazing successes of friction stir welding (FSW) in the context of aluminium alloys has logically encouraged investigation of its applicability to other materials such
as steel, titanium, magnesium, nickel and copper alloys. The typical temperature
dependence of the strength of a steel alloy compared with that of aluminium means that,
a FSW steel tool would have to go to a much greater temperature to enable a sound
weld to be fabricated as the steel must be sufficiently plasticised to permit the material
flow. Because of the tooling problems and the large number of cheaper and more useful
methods for welding steels, it remains uncertain if the process can have an impact on the
joining of steels, certainly not in proportion to the quantities in production and use. At
the same time, there are still limitation in friction welding for applications in other
higher strength materials (limitations include backing, transverse forces, weld end
craters also the need for high investment [164].

High power fibre lasers have received increasing attention by the manufacturing
industries due to their unique advantages such as high beam quality and high efficiency
to produce deep penetration welds at high welding speeds [40, 41]. High power fibre
lasers notably outperform the earlier lasers (e.g. CO₂ and YAG) in terms of penetration
and welding speed [38]. High power fibre laser welding technology would provide a
new opportunity for producing high quality welds. However, the use of fibre lasers or
other high power lasers as a heat source to produce net shape welding has not been
previously investigated. This paper presents the results of work concerned with
investigations relating to the production of net shape welds from bead-on-plate welding
of mild steel plates. Experimental methods and results are detailed and results are
discussed. This concept of net shape welding by lasers is proposed for the first time.

6.2 Experimental Design and Procedures

6.2.1 Using Design of Experiments (ANOVA)

Design Expert statistical software package was used for designing experiments in the
first part of the investigation. The design of experiments (DoE) was based on three
welding parameters with three levels of each. The selected welding parameters for this
study are: laser power, welding speed and laser beam focal point position (positive
means above the surface and negative means below the surface). Table 6.1 shows the
laser input variables and experiments design levels. A L25 orthogonal array, which
composed of three columns and 25 rows, was applied.
Table 6.1 Process parameters and design levels used

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</table>

6.2.2 Variable speed and fixed other parameters

In this part of the investigation, experiments were run under a constant laser power, focal point position and gas flow rate with variable speed start from 50 mm/s to 150 mm/s by 5 mm/s increment. Table 6.2 shows the laser input variables and experiments design.

Table 6.2 Process parameters and design experiments

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</tr>
<tr>
<td>gas pressure</td>
<td>kPa</td>
<td>100</td>
</tr>
<tr>
<td>welding speed</td>
<td>Mm/s</td>
<td>50-150 with 5 mm/s increment</td>
</tr>
</tbody>
</table>

6.2.3 Preparation before welding

We describe here some of the details of the experiments. The experimental setup is shown schematically in Figure 6.1. The materials employed in this investigation were sheets of mild steel (0.16–0.29% carbon) in dimensions of 40 mm x 40 mm x 1.5 mm. The samples were fixed on a CNC motion system for performing the welding. Argon gas was used to shroud the process both above and below the welds.
6.2.4 Preparation after welding

After welding, samples were sectioned across the weld, and mounted in the appropriate resin. Specimens for the metallographic examinations were prepared by polishing successively in 80, 180, 320, 600 and 1200 emery grits, followed by a final disc polishing using 6 and 3 μm diamond slurry. The polished surface of samples was etched with Kroll’s reagent (10ml Nitric Acid and 90ml Methanol) for further examination. The cross section weld bead shape and microstructure were observed and measured by optical microscopy using Polyvar. The measurements of the welding pool area in the TH= top height, TW= top width, BL= bottom length, and BW= bottom width were carried out for each sample as shown in Figure 6.2.

![Fig.6.1. Experimental arrangement](image1)

![Fig.6.2 Schematic diagram of the cross section of the laser welding sample](image2)
6.3 Results and Discussions

6.3.1 Weld Profiles

Figure 6.3 shows the effect of welding parameters on the responses (TH, TW, B.L, and B.W) of some selected experiments and the variation on weld bead geometry. In all cases a narrow weld was obtained, indicating welding occurred in the keyhole mode. In most cases some taper on moving from the upper to lower surface is evident, although this is considerably less than would be expected had the welding been conduction mode. Depending on the parameter combinations used different combinations of convex surface beads, undercutting and dropout can be seen.

Fig. 6.3. Effect of welding parameters on the responses, (5) P: 540 W, S: 115 mm/s, Fpp 0 mm, (7) P: 540 W, S: 85 mm/s, Fpp -1 mm, (16) P: 555 W, S: 115 mm/s, Fpp – 0.5 mm, (17) P: 555 W, S: 100 mm/s, Fpp -1 mm, (22) P: 555 W, S: 100 mm/s, Fpp – 0.5 mm.

Figure 6.4 shows the effect of welding with variable speed. For these samples, the welding focal point position was on the top of the surface of the specimen. The defocusing distance of laser beam was set from -1 mm to 0 mm.
Fig. 6.4 Effect of welding with constant parameters; power = 555 W, Focal point position = -0.5 mm, and gas flow rate = 1 bar and the welding speed was variable from 50 mm/s to 150 mm/s.

6.3.2 Parameter relationships
Analysis of Variance (ANOVA) was used to investigate which welding process parameters significantly affect the quality characteristics. Four quality characteristics were used: TH (representing top quality), BL (representing bottom quality), (TW+BW)/2 (representing average weld width) and (TW-BW)/2 (representing weld taper) each of these is discussed below.

6.3.2.1 Weld bead top surface quality
Figure 6.5 contour graph shows the effect of speed and power on the weld bead top surface displacement above the surface, at F = -0.5 mm. The results indicate that at certain combinations of the laser power and welding speed the weld bead top surface displacement from the substrate surface was zero, signifying a perfectly net shape weld for the top surface.

At higher speeds and lower powers Figure 6 indicates positive values of TH, while lower speeds and higher powers lead to negative values (undercutting). This indicates that control of the relative value of these parameters, commonly given in terms of either specific energy or line energy, is crucial to achieving net shape welding.

A complete analysis of variance (ANOVA) technique was used to identify the significance of the different process parameters. The significant factors in the Top
Height response according to ANOVA are power, speed and the interaction between them.

Fig. 6.5 Contour graph shows the effect of Power and Speed parameters on the response TH

Figure 6.6 Effect of speed on weld bead top height, and there is only one speed which can make the net shape and some others could be very close to the net shape under 555 W laser power.

Fig.6.6 Relation between welding speed and weld Beam top height at a laser power of 555 W.

The critical welding speed and specific energy requirement is calculated from the results of the experiments run in the two stages. The critical welding speed which is 100 mm/s
was the most important process parameter under this particular laser power. The specific energy corresponding to 100 mm/s was:

\[
\text{Specific Energy} = \frac{\text{Power}}{\text{Speed} \times \text{Spot diameter}} = \frac{555}{100 \times 125 \times 10^{-3}} = 44.2 \text{ J/mm}^2 \quad \ldots \quad (6-1)
\]

6.3.2.2 Weld bead bottom surface quality

Figures 6.7 show the effect of laser power and welding speed on the weld bead bottom surface characteristic at a spot diameter 125 µm. As shown all the values are positive. This could be related to the melt pool depth, the variation of depth and width of fusion zone as a function of welding speed, that means when the welding speed increases the depth of pool will decrease [165]. The only significant interaction found was between the power and spot diameter.

![Fig. 6.7 Contour graph shows the effect of laser power and welding speed parameters on the response B.L.](image)

6.3.2.3 Average weld width

Figures 6.8 show the effect of laser power and welding speed parameters on the responses average width (TW + BW) / 2. As the power increase, the Average will increase and vice versa for the speed. Although no one interaction was found to be of high significance, the interactions between Power and Speed and between Speed and Spot Diameter (fpp) are the highest for this parameter set.
6.3.2.4 Average Weld Taper

Figure 6.9 shows the response of weld bead taper as laser power and welding speed vary. Higher laser power and higher welding speed lead to increased taper. It is known that both laser power input and welding speed affect the size of the keyhole and its formation.

The weld pool shape, and therefore the penetration, depends to a large extent on the convective and conductive heat transfer in the weld pool and are also driven by surface tension gradients (Marangoni convection). It is therefore not surprising that different surface heat fluxes and surface temperature gradients affect the shape of the melt pool and hence the weld. The convection in the molten pool serves to redistribute heat within the weld pool which significantly affects the weld shape [166, 167]. From the model a highly significant interaction was observed between Speed and Spot Diameter (focal plane position).
6.4 Conclusion

In this paper a single mode fibre laser was used for producing near net shape welds during bead-on-plate laser welding. The main influencing parameters were investigated using Design of Experiments. Under certain conditions net shape weld beads on the upper surface (zero top height) could be obtained, when the surface tension gradient is zero, then it produces net shape weld. The critical welding speed to form a net shape weld on the upper profile for a 555 W laser power was 100 mm/s. Further work is needed to simultaneously obtain a net shape weld on the upper and the bottom surfaces, in other words zero top and bottom heights at the same parameters. The authors are pursuing this through further parametric analysis, exploring the use of secondary process variables such as beam and gas flow parameters, to modify the relationships illustrated as contour graphs in this paper.
CHAPTER SEVEN
PROCESS CHARACTERISTICS OF SINGLE MODE FIBRE LASER NET SHAPE WELDING

Process Characteristics of Single Mode Fibre Laser Net Shape Welding

Abstract
In certain laser welding applications, it is desirable to achieve net-shape (weld bead flat to the parent material surface) welding and minimum geometry distortion. In this paper, an investigation is reported on factors affecting weld bead geometry and feasibility of achieving net shape welding for bead-on-plate welding of mild steel sheets with a 1 kW single mode fibre laser. Statistical design of experiments (DoE) techniques and analysis of variance (ANOVA), and statistical modelling were used in the experimental study to understand parameter interactions. The selected independent process variables explored in this study are laser power and welding speed. The weld bead geometry characteristics were analysed and the conditions to achieve net-shape welding were determined.

7.1 Introduction
Laser welding involves multiple phases (solid, liquid, gas and plasma), fluid flow and rapid solidification. It is necessary to reach balance between a number of competing physical and metallurgical effects [145]. When this balance has been obtained, the result is a weld of surprising quality and mechanical properties. The ability to weld reproducibly at very high speed using Computer Numerical Control (CNC) with competitive price, have made laser welding competitive in a variety of industrials applications [7].
It has been effectively used where high welding speed, high laser power, high energy density and deep penetration are important. Laser welding falls within the group of high-energy-density beam processing technology with the capability of producing welds of high aspect ratios and has the advantage over electron beam in the elimination of a need for a vacuum system [10].
Because of low heat input and high welding speed, small heat affected zone (HAZ) and a narrow weld bead can be achieved [66]. For welding thin materials, strict requirement for workpiece fitup and thermal distortion control are recognized challenges [168]. For welding thicker plates low thermal distortion and heat affected zone are desirable [19]. The availability of high power fibre lasers over the last few years has enabled high energy efficiency welding to take place [40, 100].

Component distortion and formation of discontinuities (pore, void and hot crack) after laser welding are undesirable in medical device applications [14]. Due to the high temperature gradient in the laser generated melt pool, rapid melt flow as a result of Marongoni effect takes place. As a result, rapid solidification of the weld can cause the weld bead to form above or below the parent material surfaces. The driving mechanisms of the fluid flow are the substantial forces from temperature-dependent surface tension (thermocapillary power) and movement of the capillary relative to the work piece [169].

Peclet number has been found to affect weld bead geometry. The cross section of weld bead can change from a rectangular to a triangular geometry by increasing the Peclet number [161]. The fluid flow and the melt pool shape are significantly affected by interfacial forces such as surface tension and recoil vapor pressure [170]. Thermal diffusivity, beam absorption coefficient, the melting and boiling points, among the variety of physical properties have been found to be the main factors affecting the weld pool geometry [171].

Earlier work by the authors has shown that a net shape weld bead on the upper surface and the bottom surface could be obtained separately and that welding speed is the most critical parameter for weld bead geometry control [157, 172].

This paper further investigates net-shape welding characteristics in order to identify parameters that can achieve net-shape weld bead geometry simultaneous on the top and bottom surfaces in a bead-on-plate welding of mild steel plates. Design of experiments and statistical modeling technique was used in this investigation.
Chapter 7 Process Characteristics of Single Mode Fibre Laser Net Shape Welding

7.2 Experimental Procedures

7.2.1 Design of Experiments

A Design Expert 7.0 statistical software package was used for designing experiments in the investigation. The experiment was designed based on three groups of welding parameters with five levels of each. The selected welding parameters for this study are: laser power, welding speed and laser beam focal point position (positive means above the surface and negative means below the surface). An L 47 orthogonal array, which composed of three columns and 47 rows, was applied.

A response surface method (RSM) was used to identify the significant processing factors and quantity the relationships with measured outputs. Because the response may be influenced by multiple process factors, the central composite design (CCD) was created for three numerical factors (i.e. three welding parameters, laser power, welding speed and focal point position). The CCD can be graphically represented as a square (two factors) or cube (three factors) consisting of centre, axial and factorial design points as illustrated in Figure 7.1.

![Fig.7.1 Central composite design points for three factors](image)

As every design factor has different units, the factors are coded. The design requires five levels of coded parameters given as \(-\alpha, -1, 0, 1\) and \(+\alpha\). The statistical model was selected to be quadratic, and ‘rotatable’ is a required characteristic as this ensures that the prediction difference is a constant at any design point of equivalent distance (not
direction) from the centre point. In a CCD with \( k \) factors, the number of factorial runs can be given by \( 2^k \) (depending on design) [173].

RSM, which was applied, was built on three factors, based on five levels of laser power from 400 W to 700 W, five levels of welding speed from 90 mm/s to 160 mm/s, and focal point position from -2.00 mm to 0 mm. The advantage of the using the DoE and statistical modeling method in this study is to understand parameter interactions, significant factors and optimum parameters for net shape welding. One parameter at a time study would not be able to provide the parameter interaction effects [162, 174]. RSM, however, has other limitations such as lack of reproducibility, inability to find out relations between risk of arriving at the false optimum and the process parameters [174].

### 7.2.2 Laser welding procedure

Laser welding was performed on mild steel plates (0.16% – 0.29% carbon) with dimensions of 25 mm × 25 mm × 1.5mm.

A 1 kW single mode fiber laser was used for performing the experiments. The samples were fixed on a CNC motion system. The sample was clamped during the welding process. Bead-on-plate welding experiment was conducted. The coaxial assist gas was Argon with a gas pressure of 100 kPa. In addition, an Argon gas jet was used below the welds to prevent oxidation. A schematic diagram showing the arrangement of the experiments is given in Figure 7.2 &7.3.

The focal distance of the lens was set at 1.5 mm below the nozzle exit. The nozzle used for experimentation had an aperture of 2 mm, and the ‘assist’ gas flow of argon is only to prevent debris from making contact with the lens. This should have minimal bearing on the weld surface. Investigation in this study included 47 experiments.
Material characterization

Following the welding experiments, the samples were cross-sectioned, i.e. perpendicular to the weld direction, and mounted in a resin, polished with diamond slurry to 3 µm surface finish and finally etched with Krolls reagent (2ml Nitric Acid and 18 ml Methanol) for approximately 60 seconds for further examination. The microstructures were imaged using Polyvar microscopy. Finally the measurements of the welding pool area in the TH = top height, TW = top width, BL = bottom length and BW = bottom width were carried out for each sample as shown in Figure 7.4 were taken.
The analysis of variance (ANOVA) was used to examine the importance of the input parameters and their relationship with the weld characteristics. Six output parameters were examined: Top Height (TH) and Top Width (TW) signifying top weld bead geometry features, Bottom Length (BL) and Bottom Width (BW) signifying bottom weld beam geometry characteristics. Moreover, average weld width (Wavg) and taper (WT) were considered using the following equations

\[ W_{\text{avg}} = \frac{(TW + BW)}{2} \]  \hspace{1cm} (7.1) \\
\[ W_T = \frac{(TW - BW)}{2} \]  \hspace{1cm} (7.2)

The design factors, variables and their levels are given in Table 7.1.

<table>
<thead>
<tr>
<th>No</th>
<th>Variables</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laser power (W)</td>
<td>400 461 550 639 700</td>
</tr>
<tr>
<td>2</td>
<td>Laser welding (mm/s)</td>
<td>90 104 125 146 160</td>
</tr>
<tr>
<td>3</td>
<td>Focal point position (mm)</td>
<td>-2 -1.59 -1 -0.41 0</td>
</tr>
</tbody>
</table>

### 7.3 Results and Discussion

#### 7.3.1 Statistical modelling and data analysis

By using the least square quadratic regression analysis and cubic regression analysis, six models were built to relate the six responses to the three design factors given in the Table 7.1. A complete analysis of variance (ANOVA) technique was used to identify the significance of the coefficients. The significant terms for two models are highlighted in Tables 7.2 and 7.3.
### Table 7.2 ANOVA table of Top Height (TH) Model

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob &gt; F</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>1.988E+005</td>
<td>9</td>
<td>22084.53</td>
<td>8.36</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>A-Power (w)</td>
<td>1.113E+005</td>
<td>1</td>
<td>1.113E+005</td>
<td>42.14</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>B-Speed (mm/s)</td>
<td>59387.36</td>
<td>1</td>
<td>11152.13</td>
<td>22.49</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>C-fpp (µm)</td>
<td>3128.17</td>
<td>1</td>
<td>3128.17</td>
<td>1.18</td>
<td>0.2834</td>
<td>Not significant</td>
</tr>
<tr>
<td>AB</td>
<td>532.04</td>
<td>1</td>
<td>532.04</td>
<td>0.20</td>
<td>0.6561</td>
<td>Not significant</td>
</tr>
<tr>
<td>AC</td>
<td>9.38</td>
<td>1</td>
<td>9.38</td>
<td>3.551E-003</td>
<td>0.9528</td>
<td>Not significant</td>
</tr>
<tr>
<td>BC</td>
<td>301.04</td>
<td>1</td>
<td>301.04</td>
<td>0.11</td>
<td>0.7375</td>
<td>Not significant</td>
</tr>
<tr>
<td>A2</td>
<td>18206.00</td>
<td>1</td>
<td>18206.00</td>
<td>6.90</td>
<td>0.0125</td>
<td>Significant</td>
</tr>
<tr>
<td>B2</td>
<td>17030.26</td>
<td>1</td>
<td>17030.26</td>
<td>6.45</td>
<td>0.0154</td>
<td>Significant</td>
</tr>
<tr>
<td>C2</td>
<td>9898.86</td>
<td>1</td>
<td>9898.86</td>
<td>3.75</td>
<td>0.0605</td>
<td>Significant</td>
</tr>
<tr>
<td>Residual</td>
<td>97694.57</td>
<td>37</td>
<td>2640.39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>20965.77</td>
<td>5</td>
<td>4193.15</td>
<td>1.75</td>
<td>0.1519</td>
<td>Not significant</td>
</tr>
<tr>
<td>Pure Error</td>
<td>76728.80</td>
<td>32</td>
<td>2397.78</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>2.965E+005</td>
<td>46</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \alpha \leq 0.01 = \text{H significant, } \alpha \leq 0.1 = \text{significant, } 0.01 < \alpha \leq 0.1 = \text{not significant} \)

A- Power and B-Speed C- Focal plane position.
Table 7.3 ANOVA table of Bottom Length (BL) Model

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob &gt; F</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7.873E+005</td>
<td>9</td>
<td>87480.43</td>
<td>17.53</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>A-Power (w)</td>
<td>5.808E+005</td>
<td>1</td>
<td>5.808E+005</td>
<td>116.36</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>B-Speed (mm/s)</td>
<td>1.307E+005</td>
<td>1</td>
<td>1.307E+005</td>
<td>26.20</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>C-fpp (µm)</td>
<td>3784.53</td>
<td>1</td>
<td>3784.53</td>
<td>0.76</td>
<td>0.3895</td>
<td>Not significant</td>
</tr>
<tr>
<td>AB</td>
<td>20184.00</td>
<td>1</td>
<td>20184.00</td>
<td>4.04</td>
<td>0.0517</td>
<td>Significant</td>
</tr>
<tr>
<td>AC</td>
<td>416.67</td>
<td>1</td>
<td>416.67</td>
<td>0.083</td>
<td>0.7742</td>
<td>Not significant</td>
</tr>
<tr>
<td>BC</td>
<td>6016.67</td>
<td>1</td>
<td>6016.67</td>
<td>1.21</td>
<td>0.2793</td>
<td>Not significant</td>
</tr>
<tr>
<td>A2</td>
<td>5217.60</td>
<td>1</td>
<td>5217.60</td>
<td>1.05</td>
<td>0.3132</td>
<td>Not significant</td>
</tr>
<tr>
<td>B2</td>
<td>18484.28</td>
<td>1</td>
<td>18484.28</td>
<td>3.70</td>
<td>0.0620</td>
<td>Significant</td>
</tr>
<tr>
<td>C2</td>
<td>485.37</td>
<td>1</td>
<td>485.37</td>
<td>0.097</td>
<td>0.7569</td>
<td>Not significant</td>
</tr>
<tr>
<td>Residual</td>
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<td>37</td>
<td>4991.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>25075.58</td>
<td>5</td>
<td>5015</td>
<td>1.01</td>
<td>0.4304</td>
<td>Not significant</td>
</tr>
<tr>
<td>Pure Error</td>
<td>1.596E+005</td>
<td>32</td>
<td>4987.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>9.720E+005</td>
<td>46</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\alpha \leq 0.01 = H$ significant, $\alpha \leq 0.1 =$ significant, $0.01 < \alpha \leq 0.1 =$ not significant, A- Power and B- Speed C- Focal plane position.

From the top height (TH) model in Table 7.2, it can be seen that A-laser power is highly significant and B-welding speed is significant. Also it can be seen that interaction of AB is not significant. From the bottom length (BL) model in Table 7.3, it can be seen that, as for top height, both A-laser power and B-welding speed are highly significant. However, in this case it can also be seen there is significant interaction in AB.

### 7.3.2 Weld Profiles

Figure 7.5 and 7.6 show the effect of welding parameters on the responses (top height, bottom length, top width, and bottom width) of some certain experiments and the deviation on weld bead geometry. It’s very clear that the top surfaces are near net shape in three occasions. In the majority cases the weld bead profiles were above the surface
while the bottom weld beams were not in net shape (Figure 7.4). In addition, the weld bead profiles were positively tapered. On the other hand, near net shape welds were demonstrated for the bottom weld beams, but the bottom weld beams were not in net shape (Figure 7.5). Depending on the parameter combinations used, diverse combinations of convex surface beads, undercutting and dropout can also be seen. Only under specific sets of parameters, net-shape welds can be achieved for both the top and the bottom welds as shown in Figure 7.7. Figure 7.8 shows the examples where neither the top nor the bottom welds have net-shapes.

Fig. 7.5 Examples of near net shape from top side only with welding parameters, (2-47) P: 639 W, S: 146 mm/s, and Fpp: -1.59 mm, (6-47) P: 639 W, S: 146 mm/s, and Fpp: -1.59 mm, (30-47) P: 550 W, S: 125, and Fpp: -2.00 mm.

7.3.3 Weld bead top surface quality

Figures 7.9 and 7.10 show the effect of speed and power on the weld bead top surface displacement, at focal plane position \( = -1.00 \text{ mm} \) (below the surface). It is clear that positive values of top height are produced at higher speeds and lower powers whereas lower speeds and higher powers gave rise to negative values (undercutting). This means that control of the welding parameters, commonly given in terms of either specific energy or line energy, is important to get net shape welding. The top height values range from \(-73 \mu\text{m}\) to \(233 \mu\text{m}\).
7.3.4 Weld bead bottom surface quality

Figures 7.11& 7.12 show the effect of welding speed and laser power on the weld bead bottom surface characteristic. It’s clear the values of the bottom length vary from -286 µm to 268 µm, much more than the top weld beads. Furthermore, it can be noticed that as the welding speed increases the bottom length will decrease.
7.3.5 Top Width TW

It is known that welding speed and laser power affect keyhole shape and its size. As the welding speed increases, the inclination angle of the keyhole front wall is increased due to the loss of absorbed laser power allied with the shorter interface time between the substrate and laser beam [162]. Figure 7.13 shows the effect of the welding speed and laser power on the top width, from 226 µm to 295 µm. It can be noticed that when the welding speed increase the top width decrease, as a result of lower energy input.
Chapter 7 Process Characteristics of Single Mode Fibre Laser Net Shape Welding

7.3.6 Bottom Width BW

In contrast to the top weld bead width, the bottom width increases with increasing welding speed as shown in Figure 7.14, at a range of 48 µm to 235 µm.

7.3.7 Average weld width

Figure 7.15 show the response of average weld width, to the response of laser power and welding speed. It can be seen that when the laser power increases the average weld width increases and the welding speed reduces. The average weld width varies from 137 µm to 265 µm.
7.3.8 Average weld taper

The penetration and the fusion zone shape are controlled by the fluid flow in the welding pool and convective heat transfer. In the weld pool the fluid flow and the heat flow can extensively influence the temperature gradients, and the solidification structure and the cooling rates [88]. Figure 16 show the response of weld bead taper with laser power and welding speed. It is known that both laser power input and welding speed affect the size of the keyhole and its formation and it is clear from the figure that low laser power and high welding speed combination produces more tapered weld bead with the former effect more significant. The weld pool profile, and therefore the penetration, depends to a great amount on the convective and conductive heat transfer in the weld pool and are besides driven by surface tension gradients (Marangoni convection). It is consequently not unexpected that different surface heat fluxes and surface temperature gradients affect the shape of the melt pool and consequently the weld. It’s also noticed that the value of the taper varies from 29 µm to 113 µm.

Fig. 7.15 Contour graph shows the effect of laser power and welding speed parameters on the average weld width.
Fig. 7.16 Contour graph shows the effect of Power and Speed parameters on the response Taper

7.4 Conclusions

Net shape bead-on-plate welding of mild steel sheets has been demonstrated using a single mode fibre laser. A specific set of welding parameters were found to achieve the net shape welding (both top and the bottom welds) at: 550 W laser power, 125 mm/s welding speed and with zero focal point position. It has also been found that the top weld bead height increases with the welding speed while the bottom weld beam length decrease with the increasing welding speed. Further investigations are in-progress to understand the mechanical and physical properties of the welds and model the behaviour of weld bead geometry variation.
Chapter 8 Characterization of Weld Bead Geometry in Fibre Butt Welding of Mild Steel Sheets by Means of Statistical Modelling

CHAPTER EIGHT
CHARACTERIZATION OF WELD BEAD GEOMETRY IN FIBRE LASER BUTT WELDING OF MILD STEEL SHEETS BY MEANS OF STATISTICAL MODELLING

Characterization of Weld Bead Geometry in Fibre Laser Butt Welding of Mild Steel Sheets by Means of Statistical Modelling

Abstract
This paper presents the effect of process parameters on the geometry characteristics in butt welding of 1.5 mm mild steel sheets using a 1 kW single mode fibre laser at a range of laser powers, welding speeds and laser focal point position. Experiments were planned using the statistical design of experiment (DoE) technique for optimizing the above selected welding parameters and statistical modelling technique was employed to understand their interactions and significance. Suitable parameters to achieve net-shape welds were identified. Experimental methodology and results are detailed and the results are discussed. Micro-hardness measurements and tensile stress testing were carried out. It has been shown that laser net-shape welded samples have superior mechanical properties.

Keywords: Fibre laser, mild steel, welding, geometry, net-shape, strengths, statistical modelling, design of experiment (DoE) technique

8.1 INTRODUCTION
In the past few decades applications of laser welding and joining technique have increased steadily with the advent of high powered industrial laser systems. Attributes such as high energy density and accurate focusing of high power lasers allow high speed processing of precision assemblies [175]. Compared to the other welding processes such as arc welding, induction welding, solid state welding, friction welding, etc., laser welding has less heat dissipated into the workpiece; thus it often results in a small heat
affected zone (HAZ) and small component deformation [145]. Laser beam welding is of increasing significance in manufacturing due to lower dimension and shape deformation of components and higher processing rate [110]. Because the laser has the ability to weld reproducibly at very high speed using computerized numerical control (CNC) at competitive cost, it has been competitive in a variety of industrial applications [7]. It has been successfully used where high welding speed, high energy density and deep penetration are needed. Laser welding falls in the group of high-energy-density beam processing technology with the potential of producing welds of high depth to width aspect ratios and has the benefits over electron beam welding for larger components in the elimination of the need for a vacuum system [10]. In addition to the benefits mentioned above laser welding typically produces narrow weld beads [66]. Laser welding is applied particularly for welding thin materials, where strict requirement for workpiece fit-up and thermal distortion control are recognized challenges [168]. For welding thicker plates, low heat affect and low thermal distortion are important and attractive [19]. The studies over the last few years show that the availability of high power fibre lasers has enabled high energy efficient welding [40, 100]. In medical device applications, formation of defects (pore, void and hot cracking) and distortion after laser welding has been avoided [14].

In the laser generated melt pools, high temperature gradients typically are generated, and rapid melt flow as a result of Marangoni effect takes place. Consequently, rapid solidification of the weld can cause the weld bead to be above or below the parent material surfaces. Three forces that drive the mechanisms of the fluid flow are: (i) metal vapour pressure and recoil pressure that keep the keyhole open and drive the movement of the keyhole relative to the workpiece; (ii) Marangoni force resulted from temperature-dependent surface tension (that causes melt flow), and thermal expansion of the weld pool and (iii) capillary force [169]. One of the most important points, which effect on weld bead geometry, is the Peclet number. By increasing the Peclet number, the cross section of weld bead can vary from a rectangular to a triangular geometry [161]. Both thermocapillary force and recoil pressure are the major driving forces for the melt flow. The fluid flow and the melt pool shape are significantly affected by interfacial forces such as surface tension and recoil vapour pressure [12, 170]. Beam
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Absorption coefficient, thermal diffusivity, melting and boiling points, among the range of physical properties, have been found to be the major factors affecting the weld bead geometry [171].

Earlier work by the authors has shown that a net shape weld bead-on-plate from the upper surface and the bottom surface could be obtained and that welding speed is one of the most critical parameters for weld bead geometry control [157, 172].

This paper presents an experimental investigation of fibre laser net shape butt welding (NSBW) of mild steel materials. Design of experiments and statistical modelling technique were used in this investigation to understand weld geometry characteristics.

8.2 Experimental design and procedures

8.2.1 Design of experiments and methodology

The experiment designed was based on three groups of welding parameters with five levels of each. The selected welding parameters for this research are: laser power, welding speed and laser beam focal point position (positive means above the surface and negative means below the surface). An L35 orthogonal array, with 3 columns and 35 rows, was applied. Table 1 shows the design factors including laser input variables and experimental design levels.

8.2.2 Laser welding preparation and methodology

Laser welding was performed on AISI 1018 / EN 10130 mild steel plates with a composition as shown in Table 2. The metal was cut into plates of 50 mm x 50 mm x 1.5 mm thick, and 50 mm x 25 mm x 1.5 mm thick.

The plates were machined on the edges which were butt joined using a 1 kW single mode fibre laser (YLR-1000-SM; IPG Photonics, Inc.) emitting at 1070nm. The samples were fixed onto a CNC motion system and clamped during the welding process as shown in Figure 1. The coaxial assist gas was argon with a gas flow rate 25 l/min. The gap between the welding nozzle and the sample was 5 mm. Investigation in this study included 35 experiments in Section A and four experiments in Section B.
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8.2.3 Samples preparation for weld characterisation
Following the welding experiments, the samples were cross-sectioned perpendicular to the weld direction, and mounted in a resin, polished with diamond

Table 8.1 Design factors and variables

<table>
<thead>
<tr>
<th>No</th>
<th>Variables</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laser Power (W)</td>
<td>500 525 550 575 600</td>
</tr>
<tr>
<td>2</td>
<td>Laser Welding (mm/s)</td>
<td>90 95 100 105 110</td>
</tr>
<tr>
<td>3</td>
<td>Focal Point Position (mm)</td>
<td>-3 -2.5 -2 -1.5 -1</td>
</tr>
</tbody>
</table>

Table 8.2 Chemical composition (%) of mild steel

<table>
<thead>
<tr>
<th>%</th>
<th>C</th>
<th>CR</th>
<th>MN</th>
<th>MO</th>
<th>N</th>
<th>NI</th>
<th>P</th>
<th>S</th>
<th>SI</th>
<th>CO</th>
<th>CU</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN10130</td>
<td>0.025</td>
<td>16.85</td>
<td>1.91</td>
<td>2.086</td>
<td>0.051</td>
<td>10.08</td>
<td>0.029</td>
<td>0.001</td>
<td>0.62</td>
<td>0.03</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Figure 8.1 Photograph of the experimental set-up

Figure 8.2 Schematic diagram of the cross section of laser welding sample
slurry to 6 µm and 3 µm surface finish and finally etched with Krolls reagent (1 ml nitric acid and 9 ml methanol) for approximately 60 seconds for further examination. The microstructures were imaged using Polyvar microscopy. The final points the measurements of the weld pool area in the TH = top height, TW = top width, RH = root height and RW = root width were carried out for each sample as shown in Figure 2.

2.4 Response surface methodology for weld analysis
The Response surface method (RSM) was used to classify the significant processing factors and quantifying interactions with measured outputs in the investigation. The analysis of variance (ANOVA) performance was used to inspect the importance of the input parameters and their correlation with the weld characteristics. Six output parameters were examined: ‘two of these output were average weld width ($W_{avg}$) and taper ($W_T$), calculated using

$$W_{avg} = \frac{(TW + BW)}{2}$$

and

$$W_T = \frac{(TW - BW)}{2}$$

8.3 RESULTS AND DISCUSSION
8.3.1 Statistical modelling and analysis
(ANOVA) was used for characterizing the response surface quadratic models. Five models were built to relate the five responses, top height, root height, top width, root height, average weld bead width, and taper. All the statistical models were related to the three design factors, which are given in the Table 8.1. A complete analysis of variance (ANOVA) technique was used to classify the significance of the coefficients. The significant terms for two models Top Height (TH) Model and Root height (RH) Model are highlighted in Tables 8.3 and 8.4.
**Table 8.3 ANOVA table of Top Height (TH) Model**

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob &gt; F</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>18833.03</td>
<td>9</td>
<td>2092.56</td>
<td>1.55</td>
<td>0.2096</td>
<td>Not Significant</td>
</tr>
<tr>
<td>A-Power (w)</td>
<td>431.34</td>
<td>1</td>
<td>431.34</td>
<td>0.32</td>
<td>0.5797</td>
<td>Not Significant</td>
</tr>
<tr>
<td>B-Speed (mm/s)</td>
<td>4440.87</td>
<td>1</td>
<td>4440.87</td>
<td>3.28</td>
<td>0.0877</td>
<td>Significant</td>
</tr>
<tr>
<td>C-fpp (µm)</td>
<td>33.38</td>
<td>1</td>
<td>33.38</td>
<td>0.025</td>
<td>0.8770</td>
<td>Not significant</td>
</tr>
<tr>
<td>AB</td>
<td>5648.19</td>
<td>1</td>
<td>5648.19</td>
<td>4.18</td>
<td>0.0568</td>
<td>Significant</td>
</tr>
<tr>
<td>AC</td>
<td>3007.09</td>
<td>1</td>
<td>3007.09</td>
<td>2.22</td>
<td>0.1543</td>
<td>Not significant</td>
</tr>
<tr>
<td>BC</td>
<td>410.55</td>
<td>1</td>
<td>410.55</td>
<td>0.30</td>
<td>0.5889</td>
<td>Not significant</td>
</tr>
<tr>
<td>A²</td>
<td>4417.01</td>
<td>1</td>
<td>4417.01</td>
<td>3.27</td>
<td>0.0885</td>
<td>Significant</td>
</tr>
<tr>
<td>B²</td>
<td>5538.37</td>
<td>1</td>
<td>5538.37</td>
<td>4.09</td>
<td>0.0591</td>
<td>Significant</td>
</tr>
<tr>
<td>C²</td>
<td>1070.16</td>
<td>1</td>
<td>1070.16</td>
<td>0.79</td>
<td>0.3862</td>
<td>Not significant</td>
</tr>
<tr>
<td>Residual</td>
<td>22997.64</td>
<td>17</td>
<td>1352.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>1168.64</td>
<td>1</td>
<td>1168.64</td>
<td>0.86</td>
<td>0.3684</td>
<td>Not significant</td>
</tr>
<tr>
<td>Pure Error</td>
<td>21829.00</td>
<td>16</td>
<td>1364.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CorTotal</td>
<td>41830.67</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

α≤0.01 = H significant, α≤0.1 = significant, 0.01 < α ≤ 0.1 = not significant, A- Power and B-Speed C- Focal plane position.

The "Model F-value" of 1.55 implies the model is not significant relative to the noise. There is a 20.96 % chance that a "Model F-value" this large could occur due to noise.
Table 8.4 ANOVA table of Root Height (RH) Model

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob &gt; F</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>15717.11</td>
<td>6</td>
<td>2619.52</td>
<td>2.78</td>
<td>0.0146</td>
<td>Significant</td>
</tr>
<tr>
<td>A-Power (w)</td>
<td>2904.00</td>
<td>1</td>
<td>2904.00</td>
<td>3.56</td>
<td>0.0857</td>
<td>Significant</td>
</tr>
<tr>
<td>B-Speed (mm/s)</td>
<td>1201.19</td>
<td>1</td>
<td>1201.19</td>
<td>1.63</td>
<td>0.2161</td>
<td>Not significant</td>
</tr>
<tr>
<td>C-fpp (µm)</td>
<td>319.37</td>
<td>1</td>
<td>319.37</td>
<td>0.43</td>
<td>0.5176</td>
<td>Not significant</td>
</tr>
<tr>
<td>AB</td>
<td>5837.16</td>
<td>1</td>
<td>5837.16</td>
<td>7.93</td>
<td>0.0107</td>
<td>Significant</td>
</tr>
<tr>
<td>AC</td>
<td>241.23</td>
<td>1</td>
<td>241.23</td>
<td>0.33</td>
<td>0.5734</td>
<td>Not significant</td>
</tr>
<tr>
<td>BC</td>
<td>3848.29</td>
<td>1</td>
<td>3848.29</td>
<td>5.23</td>
<td>0.0333</td>
<td>Significant</td>
</tr>
<tr>
<td>Residual</td>
<td>14721.85</td>
<td>20</td>
<td>736.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>2552.52</td>
<td>4</td>
<td>638.13</td>
<td>0.84</td>
<td>0.5204</td>
<td>Not significant</td>
</tr>
<tr>
<td>Pure Error</td>
<td>12169.33</td>
<td>16</td>
<td>760.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>30438.96</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \alpha \leq 0.01 = H \text{ significant, } \alpha \leq 0.1 = \text{ significant, } 0.01 < \alpha \leq 0.1 = \text{ not significant, A- Power and B-Speed C- Focal point.} \)

From ANOVA for response surface 2FI Model Root Height (TH) model in Table 3, it can be seen that laser power is significant, interaction between laser power and welding is significant and interaction between welding speed and focal plane position is significant, where other parameters are not significant.

8.3.2 Weld profiles

Figure 8.3 shows the effect of welding parameters on the responses (top height (cap), root height, top width, and root width) of certain experiments and the deviation on weld bead geometry. It is clear that the top surfaces are near net shape. Weld bead profiles are slightly above the surface while the root weld beads are not in net shape. In addition, the weld bead profiles are positively tapered. On the other hand, in Figure 8.4, near net
shape welds are demonstrated for the root weld beams. In Figure 8.5 both top and root net shape is demonstrated.

Figure 8.3 Examples of near net shape from top (cap) side with welding parameters (A-35) P: 550 W, S: 100, and Fpp: -3.00 mm, (B-35) P: 550 W, S: 90 mm/s, and Fpp: -2 mm, (C-35) P: 600 W, S: 125 mm/s, and Fpp: -2.5 mm.

Figure 8.4 Examples of near net shape from root side with welding parameters: (D-35) P: 575 W, S: 95 mm/s, and Fpp: -1.5 mm, (E-35) P: 550 W, S: 100 mm/s, and Fpp: -3.00 mm, (F-35) P: 550 W, S: 100, and Fpp: -1.00 mm.

Figure 8.5 Optical micrographs of an example of near net shape from top (cap) and root sides with welding parameters: (D-35) P: 500W, S: 110 mm/s & Fpp:-2.0mm.

8.3.3 Weld bead top surface characteristics

Figures 8.6 and Figure 8.7 show the effect of speed and power on the weld bead top surface displacement, at focal plane position = -2.0 mm (below the surface). It is clear that, at certain values of laser speed and welding power, the top height get zero value.
Chapter 8 Characterization of Weld Bead Geometry in Fibre Butt Welding of Mild Steel Sheets by Means of Statistical Modelling

As the speed change the top height also changes. This means that control of the welding parameters, commonly given in terms of either specific energy or line energy, is important to obtain net shape welding.

![Figure 8.6 Contour graph showing the effect of power and speed](image1)

![Figure 8.7 3D Graph showing the effect of power and speed on top weld bead geometry](image2)

8.3.4 Weld bead root characteristics

Figure 8.8 and 8.9 show the effect of welding speed and laser power on the weld bead root surface characteristic. It is clear that weld bead root lengths went to zero value (net shape) at a speed greater than 95 mm/s and a laser power less than 575 W. Net shape at the root would be useful for pipe welding, where the machining will be more complicated. The values of the root length vary from negative -76 µm to positive 74
μm, much more than the top weld beads. Furthermore, it can be noticed that as the welding speed decreases the root length increases.

8.3.5 Top width

Welding power and welding speed are associated with the formation of the keyhole and its size. Inclination angle of the keyhole front wall is increased as the welding speed is increased to make up for the loss of absorbed laser power due to the shorter interaction time between the substrate and laser beam [162]. Figure 8.10 shows the effect of the
laser power and welding speed on the weld bead top width. It can be noticed that a
decrease in top width was caused by increasing the welding speed, as a result of lower
energy input per unit length.

![Figure 8.10 A contour graph showing the effect of laser power and Welding speed parameters on the response Top width](image)

**8.3.6 Root width**

At a constant welding speed and varying the laser beam power, there is approximately
linear relationship between the weld pool length and weld pool depth [169]. Figure 8.11
shows decreasing root width when the welding speed was decreased and vice versa with
the laser power. The root width ranges from 145 µm to 276 µm.

![Figure 8.11 Contour graph showing the effect of power and Speed parameters on the weld root width](image)
8.3.7 Average weld width

The relationship between the depth and the length of the weld pool is known to have a linear correlation with the laser power intensity [12]. Figure 8.12 shows the response of average weld width to laser power and welding speed. It can be noticed that by increasing the laser power, and reducing the welding speed, the average weld width will increase.

![Contour graph showing the effect of laser power and welding speed parameters on the average weld width](image)

8.3.8 Average weld taper

The heat input into the keyhole in laser welding is from the beam irradiation point, and the keyhole shape mainly influences the molten pool shape [176]. In the weld pool the heat flow and fluid flow influence the solidification structure, temperature gradients, and the cooling rates [88]. Figure 8.13 shows the response of weld bead taper with welding speed and laser power. It is known that both laser power input and welding speed affect the size of the keyhole and its formation and it is clear from Figure 8.14 that combination of high welding speed and low laser power produced a more tapered weld bead with the former effect more significant. It is also noticed that the value of the taper ranges from 44 µm to 130.5 µm.
8.3.9 Typical weld geometry characteristics

It has been found that four types of the laser weld bead geometry are present in single mode fibre laser butt welding of mild steel sheet metals, namely, bulge weld, notch weld, under-cut weld and net shape weld. Net shape butt welding was not previously reported. Bulge weld as shown in Figure 8.14(a) is a common weld bead shape in laser butt welding and in other welding techniques. Often weld bead above and below the parent materials are machined flat to the surface if there are requirements to fit with a specific or limited dimension. Notch welding is shown in Figure 8.14(b). This type of welding is considered as weak welding because some of the materials are missing due to the evaporation process during the welding. The root height above the bottom surface in this type of welding would affect the fluid flow in pipes. Under-cut welding is shown in Figure 8.14(c). Finally, net shape type welding is shown in Figure 8.14(d).
8.3.10 Mechanical properties

8.3.10.1 Micro-hardness testing

Preliminary tests of micro-hardness for butt welding of 1.5 mm thickness mild steel sheets were performed as shown in Figures 8.15 a and b and the hardness distribution (Hv) across the weld zone as shown in Figure 8.16. According to the figure, the highest hardness 319 Hv was for the net shape welding parameters and was higher than notch weld hardness and bulge weld hardness. The hardness range of the net shape welding was narrower because the HAZ was less extensive in the net shape welding.

Figure 8.15 Micro-hardness test scan lines for (a) normal welding with power = 575W, speed = 105 mm/s and focal point = -2.5mm; and (b) net=-shape welding with power = 550W, speed = 100mm/s and focal point = -3.0mm.
8.3.10.2 Tensile testing

The maximum stress that a material can withstand before necking, when the specimen's cross-section starts to significantly contract is called the ultimate tensile strength (UTS). The samples were prepared according to the British standard [177] and then cut it into two identical pieces across the main axis of tension testing. Experiments to weld the halves were run under a constant power 600W, 25 l/min gas flow rate, -2 mm focal point, a 5 mm gap between the sample and welding nozzle and variable welding speeds. Table 8.5 shows the test results. Figure 8.17 and Figure 8.18 show typical test specimen after the tensile tests. For the net-shape welded pieces the test pieces broke at the parent material. The relationship between the welding speed and ultimate tensile strength is shown in Figure 8.19, which shows considerable higher UTS for the net-shape welds.

The purpose of the mechanical testing was to understand the effect weld bead geometry on the strengths of the welds. According to the results of the tensile test and hardness tests, it appears that the net-shape welding has superior mechanical properties.

8.4 CONCLUSIONS

Net shape butt welding of mild steel sheets has been demonstrated using a single mode fibre laser. A specific set of welding parameters were found to achieve net-shape weld bead geometry (both top and the bottom welds). The mechanical properties of the net-
Chapter 8 Characterization of Weld Bead Geometry in Fibre Butt Welding of Mild Steel Sheets by Means of Statistical Modelling

shape and near net-shape welds such as tensile strength exceed those of conventional weld geometries, possibly due to the removal of stress concentration factors.

### TABLE 8.5

Tensile test results for the 1.5 mm thickness of mild steel after butt welding

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample code</th>
<th>Speed (mm/s)</th>
<th>Max. load (kN)</th>
<th>Average load (kN)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AAA</td>
<td>149</td>
<td>3.787</td>
<td>5.705</td>
<td>4.746</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>129</td>
<td>2.152</td>
<td>3.972</td>
<td>4.331</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>107</td>
<td>6.049</td>
<td>6.988</td>
<td>7.008</td>
</tr>
<tr>
<td>5</td>
<td>D</td>
<td>75</td>
<td>3.326</td>
<td>3.407</td>
<td>3.444</td>
</tr>
<tr>
<td>6</td>
<td>E</td>
<td>65</td>
<td>2.837</td>
<td>3.550</td>
<td>3.194</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>55</td>
<td>2.886</td>
<td>4.575</td>
<td>3.731</td>
</tr>
</tbody>
</table>

Where AAA, A, B, C, D, E, and F are code samples

Figure 8.17 (a)
Photograph of welded specimens after tensile testing for (a) normal welding and (b) net-shape welding.
Figure 8.19 Relationship between the welding speed and UTS
CHAPTER NINE
MODELLING OF NET SHAPE WELDING

Computational Fluid Dynamic and Finite Element Modelling Of Laser Weld Bead Geometry Formation and Joint Strengths

Abstract
Laser welding is used extensively in industry for joining various materials in the assembly of components and structures. Localized melting followed by rapid cooling results in the formation of a weld bead and generation of residual stress. Selection of the appropriate combination of input variables and understanding their effects is important to achieve the required weld quality with a smooth welding surface. In the present work a sequentially coupled thermo-structural analysis was carried out with the objectives of predicting the effect of laser parameters on the change in surface topology of the weld bead and its subsequent effect on structural properties. The work shows that the laser welding parameters strongly affect the weld bead shape, which eventually affects the weld quality. A net shaped weld bead demonstrates better performance in terms of stress distribution and distortion than other weld bead shapes. The numerical simulation results were compared with the observations from experiments performed using a mild steel sheet and fibre laser and the results are in good agreement in terms of weld bead cross-sectional profile and strength.

Keywords: Laser, Welding, FEM, CFD, Mild steel, Numerical simulation.

9.1. Introduction
Laser welding is a well-established joining technology and has been widely applied in the automotive, aerospace, energy, electronic and medical industries. The advantages of laser beam welding include precise energy control, low thermal distortion, small heat affected zones, high welding speed, deep penetration (high weld depth to width ratio) and the elimination of the need for a vacuum chamber. Laser welding is particularly
suitable for joining 3D structures, complex assemblies, high precision components and very thin materials including metals, ceramics and polymers.

Figure 9.1 shows a schematic of the keyhole laser welding process. A continuous laser beam of sufficient intensity is incident upon the work piece and is moving at a constant velocity (scanning speed). A fraction of the incident energy is absorbed by the work piece leading to the formation of a weld pool. As the laser beam passes through the work piece, the melt pool extends along the scanning direction and solidifies after the laser beam moves away.

In most laser welding processes, the solidified weld bead projects above or dips below the parent surface and only in a very narrow range of parameters is the weld bead at the same level as the parent material. Eghlio et al and Li et al [157, 158] studied the laser welding using a fibre laser and classified the weld bead geometry into three types (notch, net shape and bulge) according to its surface displacement with reference to the parent material. The study demonstrated the significance of weld bead geometry in influencing the final mechanical properties (e.g. tensile strength) of the weld. Also, their study emphasised the superiority of net shaped weld bead profile compared to other bead shapes. The mechanical strength of a laser welded joint strongly depends on the thermal history in the weld zone and also the final shape of the weld bead.
The research on modelling of laser welding dates back to early 1940s. Rosenthal [126] first proposed a mathematical model of the moving heat source under the assumptions of quasi-stationary state and concentrated on point heating in the 3D analysis. After this work various studies [128-133, 135-137, 139-141, 151, 178-180] have been performed on laser welding simulation to investigate the nature of heat transfer, stress distribution and also to understand its physical phenomena. The welding simulation broadly falls in three categories i.e. heat transfer based on pure conduction model [128, 129, 178] thermal analysis of welding incorporating the fluid motion (convection problem) [130-133, 179] and the sequentially coupled thermo-structural problem focusing on stress distribution (pure-conduction model with structural analysis) [135, 136, 180].

The effect of Prandtl and Marangoni (Ma) numbers on the laser weld bead geometry has been studied by Wei [133], who found that the weld bead root surface became convex for Marangoni numbers in the range of $10^2<\text{Ma}<10^5$. Arora [130] studied the role of the Marangoni effect laser weld pool and found that a wavy weld pool fusion boundary is formed when the Marangoni number is greater than 26,000. Furthermore, Rai and Debroy [137] developed a technique for weld bead geometry design by combining 3D modelling, generic algorithm optimisation and a small number of experiments. They recognised that heat transfer in the upper part of the melt pool is dominated by convection due to vigorous circulation of molten material driven by the Marongoni effect. Also, Rai [131] developed a convective heat transfer model for determining the weld bead geometry in laser welding of structural steels. They found that a humped root surface could be formed due to recoil pressure and smaller weld area compared with the top surface. Robert and Debroy [132] used dimensionless parameters such as Marangoni and Peclet numbers to predict the weld geometry in stationary laser spot welding of a large range of engineering materials. Recently, Pang [151] developed a three dimensional CFD based model, incorporating coupled heat transfer, fluid flow and keyhole geometry. He emphasised the importance of welding speed and surface tension co-efficient in on hump shapes on the keyhole wall.

A two-dimensional model was used by Sluzalec [139] to study the flow of metal irradiated by a laser beam. An advanced model incorporating three-dimensional
formulations was developed by Ye and Chen [140] to study heat transfer and fluid flow in full-penetration laser welding. An important finding in laser welding simulation was made by Srinivasan and Basu [141], who studied the surface tension flow during laser melting and showed that the effect of buoyancy force is negligible compared to the Marangoni force. Sahin [135] used FEA technique to find residual and thermal stresses due to welding in a bi-material joint. Josefson [134] estimated residual stresses in a multi-pass weld using Abaqus, a commercially available FEA code for non-linear analyses. The thermal model used by Sahin [135] and Josefson [134] are based on a pure conduction problem, without considering the convection melt flow. To account for convection melt flow in an FEM problem some researchers make use of enhanced thermal conductivity [148, 149].

Pure CFD models can predict the temperature history incorporating the convection melt flow but will not be able to calculate the stress distribution. FEM models can predict temperature history and stress, but will be based on pure solid conduction problem. To overcome these limitations, this paper considers sequentially coupling CFD and FEM analyses. This is entirely different from most previous sequential models, which considers sequentially coupled thermal and structural analysis [134-136], in which the thermal analysis was based on pure-conduction formulations. In the present model, the CFD analysis calculates the thermal history incorporating the melt flow convection.

The FEM analysis makes use of the thermal history (calculated by CFD analysis) to predict the residual stress induced in the material. By using this method, the results will be more realistic than the previous sequentially coupled thermo-structural analysis which uses the thermal history from pure conduction models. Also, many previous models assume the surface of the weld to be perfectly flat which may not be the fact for most laser welding parameters [157-159]. During the laser welding process the surface of the weld bead either goes above or below the surface and one of the main objectives of this paper is to predict this phenomenon.

The present study investigates the effects of laser parameters on the change in weld bead surface topology and ways of controlling it. In the first part, a three dimensional
Chapter 9 Modelling of Net Shape Welding

CFD analysis is performed incorporating the buoyancy, recoil pressure and surface tension effect to predict the temperature history and the weld bead surface profiles. In the second part a three dimensional FEM analysis is performed using the modified weld bead surface profile and thermal history obtained from the CFD analysis. Also, to find the effect of the weld bead surface topology on structural performance, a non-linear three dimensional FEA based tensile test analysis was performed on a tensile test specimen incorporating the change in weld bead geometry. The CFD and FEM analysis were performed using FLUENT and ANSYS codes respectively. The experimental results obtained with a fibre laser, were used to validate the simulation results, carried out under similar processing parameters.

9.2 Formulation and Grid Structure – Laser Welding

Figure 9.2 shows the initial mesh used for the CFD analysis. The computational domain with a dimension: length, L = 2.5 mm, width, W = 4 mm and thickness B = 0.8 mm was been considered for computation. The model consists of 194,300 elements. A grid system of variable spacing was been utilized with fine grid near the heat source and course grid away from the heat source. The workpiece is assumed to be symmetric with respect to the Y-Z plane. The ambient temperature was set at 300 K. The analysis made use of material properties of EN 10130 (DC01) cold rolled mild steel (C = 0.12%, P = 0.045%, S = 0.045%, Mn = 0.6%, O = 0.02%, and balance Fe in wt.%) [138].

![Fig. 9.2 Mesh used for the analysis](image)

9.2.1 Thermal Analysis

The CFD analysis is performed to model the physical phenomena in the laser welding such as phase transition, recoil pressure, heat transfer and fluid flow and is performed using finite volume based code, Fluent 13.0. The mathematical model used in this work is based on the Navier-Stokes equations with the Reynolds method of averaging the
time-dependent equations (RANS). The governing equations [181] were composed of the conservation of mass, conservation of momentum, and conservation of energy, which are given by equations (1)–(3):

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \vec{v}) = 0 \tag{9.1}
\]

\[
\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla (\rho \vec{v} \vec{v}) = -\nabla p + \mu \nabla^2 \vec{v} + S_w \tag{9.2}
\]

where \( \rho \) is the density, \( \vec{v} \) is the melt pool velocity in respective directions, \( p \) is the pressure force, \( \mu \) is the viscosity and \( S_w \) is the momentum sink.

The energy equation is written in terms of the sensible enthalpy, and an appropriate formulation of the latent heat function play a pivotal role in ensuring that the results from the energy equation are consistent with phase-change considerations.

\[
\frac{\partial}{\partial t} (\rho H) + \nabla (\rho \vec{v} H) = \nabla (k \nabla T) + S \tag{9.3}
\]

where \( H \) is enthalpy, \( k \) is the thermal conductivity, \( T \) is the temperature and \( S \) is the volumetric heat source. Enthalpy of the material is computed as the sum of sensible enthalpy \( (h) \) and latent heat \( (\Delta H) \).

\[
H = h + \Delta H \tag{9.4}
\]

\[
h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \tag{9.5}
\]

where \( h_{ref} \) is the reference enthalpy, \( T_{ref} \) is the reference temperature and \( C_p \) is the specific heat at constant pressure. Latent heat content \( (H) \) can be written in terms of latent heat of the material \( (L) \).

\[
\Delta H = \beta L \tag{9.6}
\]

where \( \beta \) is the liquid fraction, which is defined as

\[
\beta = \begin{cases} 
1 & T > T_i \\
(T - T_i) / (T_i - T_s) & T_i \leq T \leq T_s \\
0 & T < T_s 
\end{cases} \tag{9.7}
\]

Where \( T_i \) is the liquids temperature and \( T_s \) is the solidus temperature. The values of \( \beta \), ranges between 0 and 1 defining the extent of melting. The mushy zone is treated as a porous medium in momentum equations. A momentum sink is added to the momentum...
equation (Eq. 2) to extinguish velocities in the solid region. The momentum sink ($S_w$) due to reduced porosity in the mushy zone can be written as:

$$s_w = \frac{(1-\beta)^3}{(\beta^3 + \xi)} A_w(w)$$  \hspace{1cm} (9.8)

where $\xi$ is a small number (0.001) to avoid division by zero and $A_w$ is the mushy zone constant.

Heat loss due to convection and radiation is considered over all surfaces and a Gaussian volumetric heat source as proposed by Goldak [182] was used as the input laser heat source given by:

$$S = \frac{3P}{\pi abc} \exp\left(-\frac{3x^2}{a^2}\right) \exp\left(-\frac{3y^2}{b^2}\right) \exp\left(-\frac{3z^2}{c^2}\right)$$  \hspace{1cm} (9.9)

where $P$ is the absorbed laser power. The parameters $a$ and $b$ are taken to be equal to the focal radius of the laser beam and $c$ is the height of the volumetric heat source (equal to the plate thickness). The heat source was added as a source term in the energy equation (Eq. 9.3).

The fluid flow in the weld pool is primarily driven by the combination of surface tension, viscous force, recoil force and buoyancy force. On the top and bottom surfaces, the shear stress caused by the variation of surface tension due to temperature is given by

$$\tau = \frac{\partial \sigma}{\partial T} \nabla_T T$$  \hspace{1cm} (9.10)

where, $\frac{\partial \sigma}{\partial T}$ is surface tension gradient and $\nabla_T T$ is surface temperature gradient. During the computation, the surface tension gradient is expressed as a function of the surface temperature [183] at any time. The shear stress given by equation (9.10) is applied to the momentum equations (Eq. 9.2).

The weld bead surface displacements in this model were incorporated due to the effect of two phenomena. The first one is the surface deformation produced by vaporisation induced recoil force. The next one is due to the surface tension gradient, which influences the direction of melt pool movement, which eventually influences the weld
bead surface profile. The surface nodes on the weld bead were displaced according to effects of recoil force and weld pool velocity [128, 184, 185]. Also, the model is based on the assumptions that the laser gas dynamic parameters like, shielding gas jet, nozzle stand-off and nozzle exit diameter have insignificant effects on melt pool geometry, thermal characteristic and weld bead shape characteristic.

In order to regulate the laser heat source and to track the weld bead surface profile, a compiled user defined function (UDF) file was introduced to the prepared Fluent case file. The UDF are written in the C programming language and linked to the Fluent solver. The material was assumed to be homogeneous and isotropic with temperature dependent material properties adopted from Smithells Metals Reference Book [150] and presented in Table 9.1.
Table 9.1 Thermal material properties of mild steel as used in CFD analysis [150]

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>273</th>
<th>373</th>
<th>473</th>
<th>573</th>
<th>673</th>
<th>773</th>
<th>873</th>
<th>973</th>
<th>1073</th>
<th>1173</th>
<th>1273</th>
<th>1373</th>
<th>1473</th>
<th>1573</th>
<th>1673</th>
<th>1773</th>
<th>1873</th>
<th>1973</th>
<th>2073</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity (W/m K)</td>
<td>51.9</td>
<td>51.1</td>
<td>49</td>
<td>46.1</td>
<td>42.3</td>
<td>42.7</td>
<td>39.4</td>
<td>35.6</td>
<td>31.8</td>
<td>26</td>
<td>27.2</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td></td>
</tr>
<tr>
<td>Specific Heat (J/kg K)</td>
<td>450</td>
<td>464</td>
<td>516</td>
<td>566</td>
<td>574</td>
<td>615</td>
<td>634</td>
<td>773</td>
<td>1139</td>
<td>931</td>
<td>779</td>
<td>400</td>
<td>357</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>7872</td>
<td>7845</td>
<td>7816</td>
<td>7740</td>
<td>7717</td>
<td>7733</td>
<td>7711</td>
<td>7669</td>
<td>7625</td>
<td>7578</td>
<td>7552</td>
<td>7268</td>
<td>7055</td>
<td>6715</td>
<td>5902</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
9.2.2 Structural Analysis

This nonlinear analysis calculates the residual stress resulting from the strains generated from expansion and contraction due to temperature change and phase transformations, and inelastic effects from plasticity and creep in the general case. The structural analysis was performed using FEA solver, Ansys Multiphysics 13.0.

During laser irradiation, heating is localized and large temperature variations occur over a small area of incidence. Because of the resulting temperature gradients, large thermal stresses are generated in the workpiece material. Thus, in accordance with normal practice in such cases, an elasto-plastic finite-element solution is sought to calculate the distribution of stresses within the material. The total strain vector $\varepsilon$ is given as

$$\{\varepsilon\} = [D]^{-1}\{\sigma\} + \{\varepsilon^{th}\}$$  \hspace{1cm} (9.11)

Where is the thermal strain vector given by

$$\varepsilon^{th} = \alpha_e \Delta T = \alpha_e (T - T_{ref})$$  \hspace{1cm} (9.12)

The coefficient of linear expansion $\alpha_e$ is a function of temperature and the equation (9.12) can be written as

$$\varepsilon^{th} = \int_{T_{ref}}^{T} \alpha_e (T) dT$$  \hspace{1cm} (9.13)

The stress is related to strains by

$$\{\sigma\} = [D] [E] \{\varepsilon\}$$  \hspace{1cm} (9.14)

The principal stresses ($\sigma_1, \sigma_2, \sigma_3$) are calculated from the cubic stress equation by

$$\sigma^3 - I_1\sigma^2 - I_2\sigma - I_3 = 0$$  \hspace{1cm} (9.15)

The three roots $\sigma_1, \sigma_2, \sigma_3$ of equation (15) give the three principal stress at the origin through which equivalent stress can be estimated as

$$\sigma' = \left[ \frac{1}{2} \left( \sigma_1^2 \sigma_2^2 + \sigma_1^2 \sigma_3^2 + \sigma_2^2 \sigma_3^2 \right) \right]^{1/3}$$  \hspace{1cm} (9.16)

This is related to the strain by the relation $\sigma' = E\varepsilon'$.

The elemental displacements are related to the nodal displacement $\{\bar{U}\}$ by
\{U\} = [N]\{\bar{U}\} \tag{9.17}

where \{N\} is the interpolation functions. These displacements are related to the strain through the strain–displacement \{B\} matrix, and the strains are related to the stresses through the stress–strain \{D\} matrix, so that

\[
\begin{bmatrix}
K_e
\end{bmatrix}\{U\} - \{F^{th}\} = \{F_e\} \tag{9.18}
\]

Where \{F^{th}\} is the total element force vector, \{K_e\} is the element stiffness matrix and \{F^{th}\} is the element thermal load vector. They expressed as

\[
\begin{bmatrix}
K_e
\end{bmatrix} = \int \{B\}^T[D]\{B\} dV \tag{9.19}
\]

\[
\begin{bmatrix}
F^{th}
\end{bmatrix} = \int \{B\}^T[D]\{\varepsilon^{th}\} dV \tag{9.20}
\]

Assembly of element matrices and vectors of equation (18) gives

\[
[K]\{\bar{U}\} = \{F\} \tag{9.21}
\]

where \{K\}, \{\bar{U}\} and \{F\} are the global stiffness matrix, the global nodal displacement vector, and the global nodal load vector, respectively. A solution of the above set of equations gives unknown nodal displacements and reaction forces in the model. Once the displacement fields due to the temperature gradients in the material is known, the corresponding strain and stress fields can be calculated.

The structural material properties were assumed to adopt elasto-plastic behaviour. The supporting temperature-dependent material properties were the Young’s modulus, Poisson’s ratio, coefficient of thermal expansion, and yield stress, whose values as used in the analysis are adapted from Smithells Metals Reference Book [150] and presented in Table 2. The applied boundary conditions were such that, all the nodes on the sides of the base plate parallel to the direction of weld were constrained in all directions to simulate clamping effect on the substrate at that location. Each time step in the structural analysis corresponded to the same time step in the thermal analysis, with the corresponding weld bead profile and the thermal history. The scheme employed in this
study for sequentially coupling the CFD and FEM analysis along with the solution steps is given as a flow chart in Figure 9.3.

Fig. 9.3 Flowchart explaining the sequential coupling and analysis steps
Table 9.2 Mechanical material properties of mild steel as used in FEM analysis [150]

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>273</th>
<th>373</th>
<th>473</th>
<th>573</th>
<th>673</th>
<th>773</th>
<th>873</th>
<th>973</th>
<th>1073</th>
<th>1173</th>
<th>1273</th>
<th>3273</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson's ratio</td>
<td>0.296</td>
<td>0.311</td>
<td>0.33</td>
<td>0.349</td>
<td>0.367</td>
<td>0.386</td>
<td>0.405</td>
<td>0.423</td>
<td>0.442</td>
<td>0.461</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>206</td>
<td>203</td>
<td>201</td>
<td>200</td>
<td>165</td>
<td>100</td>
<td>60</td>
<td>40</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Thermal expansion coefficient (x10^-6)</td>
<td>11.2</td>
<td>11.2</td>
<td>12.1</td>
<td>13</td>
<td>13.6</td>
<td>14</td>
<td>14.6</td>
<td>14.8</td>
<td>11.8</td>
<td>13.6</td>
<td>13.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>422.64</td>
<td>409.95</td>
<td>386.3</td>
<td>342.57</td>
<td>290.22</td>
<td>230.77</td>
<td>162.71</td>
<td>96.05</td>
<td>84.35</td>
<td>60.63</td>
<td>21.32</td>
<td>21.32</td>
</tr>
</tbody>
</table>
9.3 Formulation – Tensile Test of Laser Welded Sample
Tensile tests on welded samples give a good indication of the structural quality of the weld bead under uniaxial loading. To understand the effect of weld bead geometry on the tensile strength characteristics, a non-linear finite element analysis incorporating multilinear isotropic hardening was performed to predict the generated stress and distortion from various weld bead surface profiles. The analysis was performed using Ansys Multiphysics 13.0.

9.4 Results
In order to study the effects of the laser welding parameters on the temperature, weld bead profiles and weld bead structural characteristic, three sets of simulations are performed, with a speed of 75, 100, 125 mm/s and a constant laser power of 600 W. In-line with the experimental parameter, the laser spot diameter of the beam over the sample surface was maintained constant at 0.15 mm. The CFD and FEM analysis was performed for 200 time steps of which 175 steps is for the laser welding phase (corresponds to the welding length) and the rest is for cooling phase.

9.4.1 CFD Results
To highlight the thermal phenomena in the laser welding, the results are firstly presented in the form of temperature contours overlaid on the modified weld bead surface profile. Part of the absorbed energy was used to increase the enthalpy of the metal and part of conducted into the solid base metal. Heat conduction is the major mode of heat transfer in the initial stage. In the intermediate stage, the metal melts and the subsequent fluid convection leads to a deformation of the free surface of the weld pool.

Figure 9.4 shows the temperature contours and the corresponding weld bead profile. The plots are generated after the temperature and weld bead profile reach a quasi-steady state. As can be seen from Figure 9.4(a), low speed (75 mm/s) results in higher temperature due to the longer laser interaction time. The X-Y and Y-Z view of the Figure 9.4 clearly shows the change in weld bead profile with speed. A low laser welding speed (75 mm/s) results in a notched weld bead surface (Figure 9.4(a)),
whereas a high speed (125 mm/s) results in a bulge weld bead surface (Figure 9.4(c)). For an optimal welding speed (100 mm/s) the weld bead surface was in line with the parent material (Figure 9.4(b)).

![Image](image_url)

Fig. 9.4 Temperature contour (K) with weld bead profiles for 600 W laser power and speed: a) 75 mm/s, b) 100 mm/s, c) 125 mm/s

The velocity vector on the material top surface is shown in Figure 9.5. The forces that influence the molten pool dynamics are primarily surface tension force, viscous force, recoil pressure and buoyancy force. Amongst all these forces, surface tension force and recoil pressure are predominant, as they initiate the flow within the small molten pool. As can be seen from the Figure 9.5, a relatively high magnitude of velocity vector (0.16-2.37 m/s) is found for a welding speed of 75 mm/s and 125 mm/s and a relatively very low magnitude of velocity vector (0.02-0.16 m/s) is noticed for a welding speed of 100 mm/s. The velocity vectors were highly influenced by the surface tension gradient of the
material, which again depends upon the surface temperature. A transition of surface tension gradient takes place from negative at the lower welding speed (75 mm/s) to positive at the high welding speed (125 mm/s). For the net shape welds, produced at 100 mm/s welding speed, the surface tension gradient is close to zero. At the lower welding speed (negative surface tension gradient) the weld pool molten material on the surface flows outwards causing a depression in the weld pool centre after solidification. At high welding speeds (positive surface tension gradient), the weld pool molten material flows inward causing a humped weld after solidification. At a particular welding speed in the range of 100 mm/s, there is minimum melt flow due to close to zero surface tension gradients.

![Fig. 9.5 Comparison of top surface velocity vector (m/s) for 600 W laser power and speed: (a) 75 mm/s, (b) 100 mm/s, c) 125 mm/s](image)

The liquid fraction contour for scanning speeds 75 mm/s, 100 mm/s and 125 mm/s with a constant laser power of 600 W is presented in figure 6. The Y-Z and X-Y views represent the liquid fraction contour along the weld direction and normal to the weld direction respectively. The liquid fraction contour for a speed of 75 mm/s shows a relatively long weld pool length and width. This is primarily attributed to high temperature, and high weld pool convection, which results in a larger weld pool. Also the weld pool convection directs the weld pool away from the beam centre causing a notched weld bead. The liquid fraction for a speed of 100 mm/s shows an optimal penetration with good melting profile. Although the liquid fraction for a high welding
speed shows an elongated weld pool below the surface there is insufficient penetration.
This is due to the short laser interaction time at a high welding speed which results in insufficient time to create the key hole.

![Image](image1)

**Fig. 9.6** Comparison of Melting and solidification distribution profiles for 600 W laser power and speed: a) 75 mm/s, b) 100 mm/s, c) 125 mm/s

### 9.4.2 FEM Results

The FEM investigation makes use of the modified geometry and the temperature history predicted by the CFD analysis. As revealed in the flowchart (Figure 9.3), each time step in the structural analysis makes use of a different mesh, generated by the CFD analysis at the corresponding time step. The thermal history was mapped to the geometry as input boundary conditions. The structural mesh consists of solid 186 elements. During the structural analysis, stress results are passed from one time step to next time step (Figure 9.3) as an initial stress condition, thereby maintaining the transient effect.

Figure 9.7 depicts the contour plots of von-misses stress for various speeds and a laser power of 600 W, as predicted by the structural analysis. The stress normal to the direction of weld on the centre of the Z axis along the X-Y plane is shown. The figure indicates there is a high stress magnitude for a laser welding speed of 75 mm/s and that the magnitude of the stress reduces with an increase in laser welding speed. This is due to the fact that the stress in the structural analysis is primarily due to the thermal gradient and the same trend is noticed for thermal gradient in the thermal analysis. In Figure 9.7, the stress component is predicted to be almost zero at the side of the wall due to the applied constrains. In contrast, in the middle and towards the top surface there are large magnitudes of tensile stress.
Fig. 9.7 Von Mises stress (Pa) contour along the mid cross section profiles for 600 W laser power and speed: a) 75 mm/s, b) 100 mm/s, c) 125 mm/s

Plots of the stress distribution along the top surface centre on the X-Z plane is shown in Figure 9.8. As elucidated from the figure, net shape (speed = 100 mm/s) and bulge (speed = 120 mm/s) welds show smaller residual stresses due to reduced heat input to the material. Furthermore, the residual stress distribution of the net shape welding shows a smooth transition, free from stress concentrations, which is not the case for other two weld bead geometries.

Fig. 9.8 Von Mises stress along the top-mid cross section of the weld sample after cool down to room temperature
9.4.3 Tensile Test Results

The tensile test simulation was performed so as to study the effect of different weld bead geometries on the structural properties. The size of the tensile test simulation samples were in line with the EN1002-1 2001 standard and the material properties are adopted from Smithells Metals Reference Book [150]. The elements in the tensile test mesh are 20 node-solid186 elements. The mesh geometry used for tensile test was in-line with tensile test experimental sample (the EN1002-1 2001 standard). Although, the tensile test simulation was independent of the previous CFD and FEM analysis, the weld bead surface profile obtained from the CFD analysis was incorporated in the tensile test mesh geometry, so as to find its effects on structural properties. As shown in the Figure 9.9, the tensile test samples have the modified weld bead surface geometry in their centre. The Figure shows the cross sectional weld bead profile along the centre of the sample used for the tensile test simulation, normal to welding direction. The simulated profile of the weld bead surface has been smoothed to avoid convergence problem in the non-linear elasto-plastic structural analysis. To focus only on the geometry effect, the material properties were assumed uniform for the weld zones and identical to the parent material. A tensile load of 4500 N was applied to pull the weld apart, in line with the experimental tensile test conditions.

![Fig. 9.9 Dimensions (in µm) of the weld bead geometry used in the FEM analysis of tensile test for various speed: a) 75 mm/s, b) 100 mm/s, c) 125 mm/s](image)
Figure 9.10 shows the Y-Distortion contour of the tensile test simulation. The tensile test simulation shows that the mode of stress concentration and eventually the displacements are different for same applied load. For the net shaped weld (b, speed = 100 mm/s), the stress concentration and high distortion zones are away from the welding zone, while both the notched weld (a, speed = 75 mm/s) and humped weld (c, speed = 125 mm/s) showed stress concentrations and high distortion in the weld zone area. The net shaped weld bead shows better displacement characteristics than the notched and humped weld bead shape; this demonstrates the superiority of net shaped weld bead over the other two shapes.

Fig. 9.10 Distortion (m) along Y direction for 600 W laser power and speed: a) 75 mm/s, b) 100 mm/s, c) 125 mm/

9.5 Discussions
The numerical simulation results were compared with the experimental results, performed at 600W laser power using a single mode fibre laser with a 190.5 mm focal length, 2 mm Precitec nozzle, 5 mm stand-off distance and 25 L/min Ar shroud gas. Figure 9.11 shows the comparison of experimental (left side) and simulated (right side) surface contours along the centre of the sample for a laser power of 600 W. In agreement with the experimental bead profile, the CFD model predicts notched, net shape and bulged weld bead for a speed of 75 mm/s, 100 mm/s and 125 mm/s respectively.
Figures 9.4, 9.5 and 9.6 of the CFD analysis highlight the influence of laser speed on the surface temperature which in turn influences the weld bead geometry. The material surface tension coefficient changes from negative to positive [183] with increase in maximum temperature. Within a particular narrow range of temperature, the surface tension coefficient was close to zero which gave a net shape weld bead profile. A low surface tension coefficient results in low convection velocity in the melt pool which results in a net shape weld bead. A similar phenomenon was observed by Zhao [183] during the study of Marangoni flow in laser spot welding. They found that as temperature increases, the surface tension gradient reduces and flips from positive to negative. As the oxygen content increases, the surface tension gradient also increases.

The liquid fraction profile shown in figure 6 is in line with the Krasnoperov’s [186] classification of laser weld keyhole profiles i.e. partial penetration, closed keyhole full penetration, and open keyhole full penetration. Open keyhole is the one in which weld bead width is similar at the upper and lower part of the weld bead. The open keyhole profile is similar to the net shape weld bead profile noticed at a speed of 100 mm/s, which is recommended as the choice due to its operation stability.
Figure 9.12 shows the comparison of experimental (bottom side) and FEA simulated tensile test results (top side). The simulated profile shows the distortion in the Y-direction and the experimental samples shows the region of failure after tensile test. In line with the region of experimental failures, the FEA simulated net shape welding samples (100 mm/s) show high distortion in the parent material whereas the notched welded sample (75 mm/s) and humped welded samples (125 mm/s) show high distortion in the weld region. The experimental micro-hardness and microstructures in the weld zones and heat affected areas are almost identical for the three cases. Thus the reason that the net shaped welding has superior mechanical properties would be largely because of its flat surface weld geometry which shifts and spreads the stress concentration to places away from the weld zones, in contrast to other weld bead geometries. This can be further explained from figure 13, which shows the variation of stress along the thickness of the weld bead from top to bottom surface in the centre (along the line D-D in Figure 9.9b). The net shape weld bead (100 mm/s) has a constant stress distribution whereas the other two shapes (75 and 100 mm/s) show varying stress along the thickness. This variation of the stress profile leads to stress concentration in some regions of the weld bead, which eventually weakens the weld bead during tensile test. This could be the main factor for net shape welds to show superior tensile test characteristics to notched or bulged welds.
Chapter 9 Modelling of Net Shape Welding

9.6 Conclusions
A comprehensive CFD and FEM model has been developed for predicting and analysing the weld bead geometry in laser welding. The weld bead geometry on the top and bottom surfaces varies with laser power and welding speed. Also, with increase in scanning speed, the weld pool length, width and depth decreases. CFD modelling has shown the main reason for the different weld bead surface geometry formation as the Marangoni effect with flipping surface tension gradient signs as the melt pool temperature changes. Furthermore, smoother weld bead profile (net shape) shows superior strength under tension compared to other weld bead geometries largely due to the lack of stress concentrations at the weld zones. The proposed model shows good correlation with the experimental results in terms of thermal effects and final structural behaviour.
CONCLUSION AND FUTURE WORK

Conclusion

In this research, the important parameters affecting the production of net shaped bead on plate welds with a fibre laser were investigated using Design of Experiments and statistical modelling (ANOVA). A single mode fibre laser was used for producing near net shape welds during bead-on-plate and square butt laser welding. A specific set of welding parameters were found to achieve net-shape weld bead geometry. The mechanical properties of the net-shape and near net-shape welds such as tensile strength exceed those of conventional weld geometries, possibly due to the removal of stress concentration factors.

The experiments were undertaken on 1 mm and 1.5 mm thickness mild steel sheets. The weld bead geometry characteristics of fibre laser butt welding of 1 mm thick mild steel sheets have been examined and four different cases have been compared: bulge weld (at low laser power and high welding speed), notch weld (at high power laser or low welding speed) under cut weld and net shape weld (certain laser power and welding speed and focal point position combination).

It was found there was generally a trade-off between a narrow weld (low weld width) and a high uniform weld (low weld taper).

Control of laser power, welding speed, and focal position is essential in achieving the net-shape welds, which is governed by the heat and mass flow during the laser welding and the solidification processes involved.

A coupled CFD and FEM model has been developed for predicting and analysing the weld bead geometry in laser welding. The weld bead geometry on the top and bottom surfaces varies with laser power and welding speed. CFD modelling has shown the main reason for the different weld bead surface geometry formation as the Marangoni effect with flipping surface tension gradient signs as the melt pool temperature changes. The superior ultimate tensile strengths of the net-shape welds compared with
Conclusion and Future Work

conventional weld bead geometry are largely due to the lack of stress concentrators at the weld zones. The proposed model shows good correlation with the experimental results in terms of thermal effects and final structural behaviour.

Future work

Experimental work
Further research is required for net shape welding on different thickness and different materials with potential applications for pipe welding. Other mechanical property tests such as fatigue test and corrosion test will need to be carried out to fully understand the benefits of net shape welding compared with other weld geometry.

More investigations are required to understand the mechanical and physical properties of the welds and to model the behaviour of weld bead geometry variation with the effect of other parameters such as gas flow rate, different gases except Argon, such as Nitrogen, and the gap between welding samples and nozzle.

Modelling work
Further FEM analysis is needed to study the effect of weld bead geometry on fatigue characteristic which effect on the welded joint and inclusion of keyhole formation and vapour interaction in the CFD analysis.
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Appendixes

These appendixes are five science papers have been published during the PhD research time, one of these papers has been submitted to the Journal and still in the process of publishing.

Appendix A
Appendix B
Appendix C
Appendix D
Appendix E
Appendix A
FIBRE LASER NET-SHAPE WELDING OF STEELS

P101

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Abstract

Welding had traditionally faced two major challenges – obtaining a flawless bond (high internal weld quality) and obtaining a smooth surface transition (high external weld quality). While the former has been, and is being, well researched, the latter has received much less attention, despite the fact that post-weld surface finishing treatments such as machining and grinding can be costly or sometimes impossible. This paper presents an investigation of the production of welds with extremely high external weld quality – Net Shape Welds. A fibre laser was used to perform bead-on-plate welding of mild steel plates at a range of parameters. The quality of the welds was studied and the combinations of parameters that led to the transition to net shape welding were identified. The results show the significant factors controlling external weld quality and help identify a process window for producing net shape welds. The work can open the door to the use of fibre laser welding in many novel applications, such as precision welding technology, and complex welding, with potential benefit to a range of industries.

Introduction

In reality, the joining of two metals together using laser radiation is a complex process; it is necessary to achieve a balance between a number of competing physical and metallurgical effects. When this balance has been obtained, the result is a weld of unprecedented quality and mechanical properties. These characteristics, and the capability to weld reproducibly at high speed under CNC control with competitive cost, have made laser welding very attractive in numerous industrial applications [1]. Laser beam welding is a modern welding process; it is a field of growing importance in industry and has been recognized as a high efficient and precise joining method that is used where high power, high speed, high energy density and deep penetration are required. Focused laser beam methods are similar to electronic beam methods; both represent part of the new technology of precision high-energy-density processing [2]. The heavy industry for the application of welding and cutting requires high-power lasers capable of welding thicker plates with low thermal distortion [3]. Modern manufacturing industry is focusing its interests on the potential offered by the laser. The greatest opportunities for the laser are areas where flexibility, automation, CAD/CAM integration, precision, cost reduction, and time to market are important factors.

Recently, the fiber laser has been receiving much attention due to advantages such as high-power, high beam quality and high--efficiency, which allow it to produce deep penetration welds at high welding speeds [4, 5]. With constant speed and varied laser beam power there is linear correlation between the depth and the length of the weld pool. With constant beam power there is slight change in to the length of the weld pool with increasing welding speed. The simplest approach of simulating the shape and size of the weld is based on the linear heat conduction model [6, 7] This gives a solution for the temperature field $T(r, \phi)$ in the workpiece [8].

$$T(r, \phi) = T_a + \frac{P}{2\pi \lambda_{th}} K_0(P e \ r) e^{-Pe r \cos \phi}$$

(1)

with a modified Peclet number

$$Pe = \frac{v_w}{2\kappa}$$

(2)

Where $T_a$ is the ambient temperature, $\lambda_{th}$ denotes the thermal conductivity, $v_w$ is the welding speed and $\kappa$ is the thermal diffusivity. $K_0$ is the modified Bessel function of second kind and zeroth order. The temperature field has a singularity at the origin, where the line source with power per unit depth $P$ is located, $r$ and $\phi$ being the equivalent polar coordinates which refers to a point on the keyhole wall corresponding to $x$ and $y$ welding direction [9].

The general form of the weld cross section can be determined by the Peclet number. Increasing the
Peclet number transforms the cross section away from a rectangular to a triangular geometry [10].

More realistic weld models also account for fluid flow. The driving mechanisms of the fluid flow are the forces resulting from temperature-dependent surface tension (thermocapillary force) and movement of the capillary relative to the work piece [8]. The fluid flow and the melt pool shape are significantly affected with interfacial forces such as surface tension and recoil vapor pressure [11].

In a number of applications, mainly if a high post-weld fit-up tolerance is desirable; accurate welding that produces minimal distortion in the base part and requires no post weld machining or secondary processing is desirable. This can be termed net-shape welding. Processes similar to painting and cosmetic finishing that add more layers typically require net shapes. High power fibre laser welding technology with high welding speed could provide a new opportunity for producing top quality welds. However, the use of fibre lasers or other high power lasers as a heat source to produce net shape welding has not been previously investigated.

This paper presents the results of work relating to the production of net shape welds from bead-on-plate welding of mild steel plates at a range of parameters. Experimental methods and results are detailed and discussed. The concept of net shape welding by lasers is a new addition to the field of laser applications, and the work could herald use of fibre laser welding in many novel applications.

**Design Experiments and Procedure**

**Design of Experiments**

To classify the significant processing factors and enumerate the relationships with measured outputs, a Design of Experiments (DoE) method was used. DoE and statistical techniques are in widespread use to optimize process parameters because it is known that the conventional, one-variable-at-a-time (OVAT) procedure is not the most efficient way to explore experimental space during reaction variable screening and optimization [12]. The OVAT method lacks the ability to locate the correct optimised conditions even if twice as many experiments are performed [13] and has other limitations such as lack of reproducibility, inability to discover interactions between the process parameters, and a risk of arriving at the false optimum. DoE has thus in many cases become a direct replacement of traditional approaches to experimentation [14]. The Design Expert 7.0 software package was used to design experiments by the D-Optimal Factorial Design method two continuous factors, based on two welding parameters, were selected: laser power (five levels) and welding speed (fourteen levels) with fixed laser beam focal point position (positive means above the surface and negative means below the surface). Table 1 show the laser input variables and experiment design levels at constant -1.5 focal plane position. Investigation using this method required 84 experiments.

<table>
<thead>
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<th>Variables</th>
<th>Code</th>
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<th>Levels</th>
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<td>W</td>
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<tr>
<td>Welding speed</td>
<td>S</td>
<td>mm/s</td>
<td>50</td>
</tr>
</tbody>
</table>

**Table 1: Process parameters and design levels used**

**Samples Preparation**

The materials employed in this investigation were plates of mild steel (0.16% – 0.29% carbon) with dimensions of 30 mm × 40 mm × 1.5mm. The samples were fixed on a CNC motion system for performing the welding (Figure 1). Argon gas was used to shroud the process both above and below the welds.

Following welding, samples were sectioned across the weld, and mounted in the appropriate resin. Specimens for the metallographic examinations were prepared by polishing successively using 180, 320, 600 and 1200 emery grits, followed by a final disc polishes using 9 and 3 μm diamond slurries. The polished surface of samples was etched with Krolls reagent (2ml Nitric Acid and 18 ml Methanol) for further examination.
After preparation the cross section weld bead shape and microstructure were observed and measured by optical microscopy. For each sample, four measurements of the welding pool area were taken: TH = top height, TW = top width, BL = bottom length and BW = bottom width, as shown in Figure 2.

Analysis Parameters

An inclusive analysis of variance (ANOVA) technique was used to investigate the significance of the input parameters and relationship with the final weld characteristics. From the measured characteristics, six quality characteristics were derived: Top Height, TH (representing top quality), Bottom Length, BL (representing bottom quality), Top Width, TW (representing Top Width), Bottom width, BW (representing the bottom Width), Average Weld Width, \(\frac{(TW+BW)}{2}\) (representing mean weld width) and Weld Taper \(\frac{(TW-BW)}{2}\) (representing average weld taper). Each of these is discussed below.

Experimental Results and Discussion

Weld Profiles

Recoil pressure induced by the evaporation processes which normally occurring on the front keyhole wall generate the keyhole during the laser welding [15]. Figure 3 shows the effect of welding parameters on the responses (top height, bottom length, top width, and bottom width) of some certain experiments and the deviation on weld bead geometry. In all cases an enclosed weld profile was obtained, indicating welding occurred in the keyhole mode. In most cases some narrow on moving from the upper to lower surface is clear, although this is considerably than would be expected had the welding been conduction mode. Depending on the parameter combinations used, different combinations of convex surface beads, undercutting and dropout can be seen.
Figure 4 show that some of the welds have a net shape or nearly net shape on the top side, while others have net shape on the bottom side. Clearly, upper and lower face geometries are dictated by different parameter relationships.

Fig.4. Shows the effect of welding parameters on the responses with different parameters, (11-84) P: 500 W, S: 110 mm/s, (30-84) P: 700 W, S: 160 mm/s, (40-84) P: 700 W, S: 110 mm/s, (63-84) P: 700 W, S: 180 mm/s.

**Weld Bead Top Surface Quality**

Figure 5 contour graph shows the effect of speed and power on the weld bead top surface displacement above the surface, at focal plane position \( z = -1.5 \) mm (below the surface). The results identify that at certain combinations of the laser power and welding speed the weld bead top surface displacement from the substrate surface was zero, representing a perfectly net shape weld. At higher speeds and lower powers figures 5 indicates positive value of top height, while lower speeds and higher powers lead to negative values (undercutting). This indicates that control of the relative value of these parameters, commonly given in terms of either specific energy or line energy, is essential to achieve net shape welding. Furthermore the response top height height response indicates that there were many values that gave near to net shape welding. At the laser power 600 W and speed 180 mm/s the top height was just 9 \( \mu \)m and there was net shape welding, with zero top height, at laser power 700 W and speed 160 mm/s.

**Weld Bead Bottom Surface Quality**

Figure 6 show the effect of laser power and welding speed on the weld bead bottom surface characteristic. As shown, the values range from positive to negative. The results identify that at certain combinations of laser power and welding speed the weld bead surface displacement from the substrate surface was zero. The value of the bottom length ranges from -698 \( \mu \)m to 736 \( \mu \)m, which is a considerable larger range over these parameters than top height.

Fig.6. Contour graph shows the effect of Power and Speed parameters on the response Bottom Length
The welding speed and the laser power both affect the depth and width of the weld [16]. The keyhole formation and its size are related to the combination of the two. By increasing the welding speed, the inclination angle of the keyhole front wall is increased in response to the loss of absorbed laser power per unit length due to the shorter interaction time between the laser beam and the substrate [17]. Figure 7 shows the response and effect of the power and speed on the top width. From Figure 7, it can be noticed that the top width increases as the laser power increases. This is because the higher temperature achieved would lead to greater size of fusion and. Finally, the top width decreases as the welding speed increases due to reduced exposure time and hence time for heat diffusion. This is important in the optimization of the welding process.

Top Width TW

Fig.7. Contour graph shows the effect of Power and Speed parameters on the response Top Width

Bottom Width BW

When the laser power increase the weld depth will increase for different values of welding speed and workpiece thickness [18]. Figure 8 shows the response of the bottom width on laser power and welding speed. It can be noticed that the bottom width increases as the laser power increases and the value of bottom width range from zero µm to 589 µm over the tested input parameter ranges.

Fig.8. Contour graph shows the effect of Power and Speed parameters on the response Bottom Width

Average Weld Width

Figure 9 show the response of Average Weld Width, with laser power and welding speed. It can be noticed that the average increases as the laser power increases and vice versa for the welding speed. the value of the average width ranges from 101 µm to 465 µm (i.e. can change over four times in magnitude over the tested parameter range).

Fig.9 Contour graph shows the effect of Power and Speed parameters on the response Average Weld Width
Weld Taper

The fusion zone shape and the penetration are controlled by the convection heat transfer and the fluid flow. The fluid flow and the heat flow in the weld pool can significantly influence the temperature gradients, the solidification structure and the cooling rates [19]. Accounting purely for heat flow, a high temperature gradient from top to bottom in the weld is likely to produce a high positive weld taper, while uniform temperature throughout the weld (a 2D heat profile) is likely to produce a uniform weld. Figure 10 show the response of weld bead taper as laser power and welding speed diverge. It is known that both laser power input and welding speed affect the size of the keyhole and its formation. The value of the taper ranges from -124 to 173.5 \( \mu \text{m} \), indicating that the weld can both reduce or increase in diameter on moving from the top to bottom surface.

![Fig.10. Contour graph shows the effect of Power and Speed parameters on the response Weld Taper](image)

Parameter Relationships

The results derived for indicators of internal and external weld quality are compiled in Figure 11. As can be seen there is no position at which the zero contours for Top Height and Bottom Length meet, indicating we cannot get net shape on both the top surface and bottom surface with the same parameters. The arrows indicating increasing Average Weld Width and increasing weld taper are approximately opposed meaning there is a Trade off between taper and width. Average weld width is generally increased by increasing the power and/or the speed. Average weld taper is generally decreased by increasing the power.

![Fig.11. Parameters relationship](image)

Conclusion

In this paper a single mode fibre laser has been used for producing near net shape, keyhole-mode welds during bead-on-plate laser welding of mild steel plates. The roles of the main parameters were investigated using a Design of Experiments method and process maps produced for the effects on top and bottom quality, weld width and weld taper.

Net shape weld beads could be obtained on the upper surface and on the lower surface but different parameters combinations were required for each. Process maps indicate they have different relationships with the main input parameters. It was found there was generally a trade-off between a narrow weld (low weld width) and a high uniform weld (low weld taper). Further work is needed to simultaneously obtain a net shape weld on the upper and the bottom surfaces with the same parameters, in other words zero top and bottom heights at the same parameters in the one experiment. The authors are pursuing this through further parametric analysis, exploring the use of secondary process variables such as beam and gas flow parameters, to modify the relationships illustrated as contour graphs in this paper.
Acknowledgements

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New Applications of Laser Technology for

Development of Net-shape Welding

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Abstract

Laser technologies have made distinguished contributions in modern industry. These have principally been realised through the important role played by lasers in the advancement of manufacturing technology in areas such as welding. Laser welding has now become a very important joining technique in a wide variety of applications in the oil gas, aerospace, aircraft, automotive, medical and electronics industries.

This study presents investigations relating to the production of high quality laser welds that blend closely with surface of the welded materials, (welds termed ‘net shaped’). It has not been possible to produce such welds in the past using conventional welding technology. Net-shaped welds not only look attractive, but afford functional and economic benefit because no secondary machining or polishing operation is required.

Mild steel plates and bead-on-plate welding with a 1 KW fibre laser are used for this investigation. Design of experiments and statistical modelling are used in the experimental study to understand parameter interactions. The independent process variables studied in this study are laser power and welding speed. Experimental methods and results are detailed and results are discussed. The work shows that the laser and our work to date have made production of net shaped welds possible. The work could lead to new applications for very high geometry accuracy welding.
Keywords: fibre laser, laser applications, laser welding, net shape welding, designing experiments.

Introduction

At a rapid rate lasers are finding new application, and in laser welding has develop into a very important joining technique in an extensive range of applications. Joining two metals together using laser radiation is one of the most difficult processes in industry; it is necessary to reach equilibrium between a number of competing physical and metallurgical effects. When this equilibrium has been obtained, the result is a weld of extraordinary quality and mechanical properties. This uniqueness, and the capability to weld reproducibly at high speed under CNC control with competitive cost, have made laser welding very pretty in various industrials applications [1]. Laser welding has attracted more and more attention in recent years on industrial application due to its unique features such as small heat affected zone (HAZ) and the narrow weld bead due to the low heat input, also welding at high speed and welding in the areas of difficult access [2]. Laser beam welding is a recent welding process; it is a field of increasing significance in industry and has been known as a high professional and accurate joining method that is used where high power, high speed, high energy density and deep penetration are essential. Focused laser beam methods are similar to electronic beam methods; together signify branch of the new technology of precision high-energy-density processing [3]. High-power lasers capable of welding thicker plates with low thermal distortion are desirable for heavy industry for the application of welding and cutting [4].

Recently, the fibre laser has been receiving more attention due to its unique advantages such as high-power, high beam quality and high–efficiency, which allow it to produce deep penetration welds at high welding speeds [5, 6]. The characteristic of the fibre laser are shown in figure 1.
Precision machinery and medical device applications suffer from excessive distortion formation of discontinuities (pore, void and hot crack) [7]. The universal form of the weld cross section can be determined by the Peclet number. As the Peclet number increase the cross section changes from a rectangular to a triangular geometry [8]. More comprehensive weld models also account for fluid flow. The driving mechanisms of the fluid flow are the forces consequential from temperature-dependent surface tension (thermocapillary power) and movement of the capillary relative to the work piece [9]. The fluid flow and the melt pool shape are significantly affected by interfacial forces such as surface tension and recoil vapor pressure [10].

In a numeral of applications, high quality laser welds that blend closely with surface of the welded materials, at the join line are desirable. Previous work has shown that a net shape weld bead on the upper surface can be obtained and that welding speed is the most critical parameter for top surface quality [11]. This study presents investigations relating to the production of net shape welds from bead-on-plate welding of mild steel plates at a range of parameters – it advances the previous work by considering both
upper and lower surfaces of the welded plate and. Experimental methods and results are detailed and discussed. The concept of net shape welding by lasers could add value to the field of laser applications, and the work can release the entrance to the use of fibre laser welding in numerous novel applications.

**Experimental Investigation**

**Experiment Design**

The Design Expert 7.0 software package was used to design experiments by the D-Optimal Factorial Design method two continuous factors, based on two welding parameters, were selected: laser power (five levels from 400 W to 800 W) and welding speed (fourteen levels from 50 mm/s to 180 mm/s) with fixed laser beam focal point position (positive means above the surface and negative means below the surface). Design of Experiments (DoE) and statistical techniques are in enormous use to optimize process parameters because it is known that the conventional, one-variable-at-a-time (OVAT) procedure is not the mainly efficient way to explore experimental space during reaction variable screening and optimization [12]. OVAT design lacks the ability to describe the model surface and to locate the correct optimum however if twice as many experiments were performed [13]. DoE has other boundaries such as lack of reproducibility, incapacity to determine relations between the process parameters, and a risk of arriving at the false optimum. DoE has thus in many cases turn into a direct replacement of traditional approaches to experimentation [14].

**Sample Preparation**

The material used in this study were plates of mild steel (0.16% – 0.29% carbon) with dimensions of 25 mm × 25 mm × 1.5mm. Prior to welding, each sample was sand blasted cleaned and prepared.

The laser used was a 1 kW single mode fiber laser. The samples were fixed on a CNC table system motion for performing the welding, clamping the samples using specific tools. This clamp will prevented any motion to the sample during the welding process. The welding is performed along the sample in single welding side. The welding gas pressure was 100 kPa. A schematic diagram showing the arrangement of the
experiments is shown in Figure 2. Argon gas was used to shroud the process both above and below the welds to prevent any oxidation to the welding samples.

![Fig.2. Experimental preparation](image)

The focal distance of the lens was set at -1.5 mm below the nozzle exit, the nozzle used for experimentation has an aperture of 2 mm, and the ‘assist’ gas flow of argon is only to prevent debris from making contact with the lens, this should have minimal bearing on the weld surface. Investigation in this study included 84 experiments.

**Sample Analysis**

After performing the welding, the samples were sectioned in the transverse plane, i.e. perpendicular to the weld direction, and mounted in the appropriate resin. Specimens for the metallographic examinations were ground using SiC paper from 180 to 1200 grit. The samples were then finished with a final polishing disc using 9 µm and 3 µm diamond slurry. The mounted samples were chemically etched using Kalling’s reagent (2ml Nitric Acid and 18 ml Methanol) for approximately 60 seconds. The microstructures were imaged using Polyvar microscopy. Finally The measurements of the welding pool area in the TH = top height, TW = top width, BL = bottom length and BW = bottom width were carried out for each sample as shown in Figure 3 has taken.
A wide-ranging analysis of difference (ANOVA) performance was used to investigate the importance of the input parameters and relationship with the concluding weld characteristics. Six quality characteristics were used: Top Height TH (representing top quality), Bottom Length BL (representing bottom quality), Top Width TW (representing Top Width), Bottom width BW (representing the bottom Width), \{(TW+BW)/2\} (representing average weld width) and \{(TW-BW)/2\} (representing Average weld taper) each of these is discussed after.

**Results and Discussion**

**Weld Properties**

Recoil pressure induced by the evaporation processes which usually happens on the front keyhole wall generates the keyhole through the laser weld [15]. Figure 4 shows the effect of welding parameters on the responses (top height, bottom length, top width, and bottom width) of some certain experiments and the deviation on weld bead geometry. In most cases an enclosed weld profile was obtained, representing welding occurred in the keyhole mode. In most cases the profiles narrow on moving from the upper to lower surface, even though this is less noticeably than could be expected had the welding been conduction mode. Depending on the parameter combinations used, diverse combinations of convex surface beads, undercutting and dropout can be seen.
Fig. 4. shows the effect of welding parameters on the responses with different parameters, (1-84) P: 800 W, S: 70 mm/s, (21-84) P: 800 W, S: 110 mm/s, (50-84) P: 800 W, S: 120 mm/s, (70-84) P: 600 W, S: 160 mm/s, (80-84) P: 400 W, S: 60 mm/s and (83-84) P: 500 W, S: 170 mm/s.

Figure 5 show that some of the welds have a net shape or nearly net shape on the top side, while others have net shape on the bottom side. Clearly, upper and lower face geometries are dictated by different parameter relationships.

Fig. 5. Shows the effect of welding parameters on the responses with different parameters, (11-84) P: 500 W, S: 110 mm/s, (30-84) P: 700 W, S: 160 mm/s, (40-84) P: 700 W, S: 110 mm/s, (49-84) P: 600 W, S: 100 mm/s, (63-84) P: 700 W, S: 180 mm/s, (73-84) P: 500 W, S: 140 mm/s.
Analysis of Variance (ANOVA)

Using Cubic regression analysis and Quadratic regression analysis, six models were built to relate the six responses to the two design factors given in the Table 1. A complete analysis of variance (ANOVA) technique was used to identify the significance of the coefficients. The significant terms for two models are highlighted in Tables 1 and 2.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob &gt; F</th>
<th>Effect</th>
</tr>
</thead>
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<tr>
<td>Model</td>
<td>1.509E+006</td>
<td>9</td>
<td>1.676E+005</td>
<td>91.90</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>A-Power</td>
<td>35024.03</td>
<td>1</td>
<td>35024.03</td>
<td>19.20</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>B-Speed</td>
<td>11152.13</td>
<td>1</td>
<td>11152.13</td>
<td>6.11</td>
<td>0.0157</td>
<td>Significant</td>
</tr>
<tr>
<td>AB</td>
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<td>3.402E+005</td>
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<td>H. Significant</td>
</tr>
<tr>
<td>A²</td>
<td>63516.36</td>
<td>1</td>
<td>63516.36</td>
<td>34.82</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>B²</td>
<td>2.384E+005</td>
<td>1</td>
<td>2.384E+005</td>
<td>130.68</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>A²B</td>
<td>1300.92</td>
<td>1</td>
<td>1300.92</td>
<td>0.71</td>
<td>0.4012</td>
<td>Not significant</td>
</tr>
<tr>
<td>AB²</td>
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<td>1</td>
<td>1.425E+005</td>
<td>78.11</td>
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</tr>
<tr>
<td>A³</td>
<td>11656.95</td>
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<td>11656.95</td>
<td>6.39</td>
<td>0.0136</td>
<td>Significant</td>
</tr>
<tr>
<td>B³</td>
<td>25512.72</td>
<td>1</td>
<td>25512.72</td>
<td>13.99</td>
<td>0.0004</td>
<td>H. Significant</td>
</tr>
<tr>
<td>Residual</td>
<td>1.332E+005</td>
<td>71</td>
<td>1824.25</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Cor Total</td>
<td>1.642E+006</td>
<td>82</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\alpha \leq 0.01 = H$ significant, $\alpha \leq 0.1 = $ significant, A- Power and B-Speed

The top height (TH) model in Table 2, it can be seen that A-welding Power model is highly significant and B-Welding Speed is significant. Also can be seen there is highly significant interactions in AB.
Table 3-2 ANOVA table of Bottom Length (BL) Model

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob &gt; F</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
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</tr>
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<td>A-Power</td>
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<td>100.81</td>
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<td>H. Significant</td>
</tr>
<tr>
<td>B-Speed</td>
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<td>73260.18</td>
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<td>72568.68</td>
<td>13.28</td>
<td>0.0005</td>
<td>H. Significant</td>
</tr>
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<td>1.009E+006</td>
<td>184.62</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>B²</td>
<td>1.615E+005</td>
<td>1</td>
<td>1.615E+005</td>
<td>29.56</td>
<td>&lt;0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>A²B</td>
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<td>13226.47</td>
<td>2.42</td>
<td>0.1241</td>
<td>Not significant</td>
</tr>
<tr>
<td>AB²</td>
<td>87508.41</td>
<td>1</td>
<td>87508.41</td>
<td>16.01</td>
<td>0.0001</td>
<td>H. Significant</td>
</tr>
<tr>
<td>A³</td>
<td>8892.69</td>
<td>1</td>
<td>8892.69</td>
<td>1.63</td>
<td>0.2062</td>
<td>Not significant</td>
</tr>
<tr>
<td>B³</td>
<td>6695.47</td>
<td>1</td>
<td>6695.47</td>
<td>1.23</td>
<td>0.2720</td>
<td>Not significant</td>
</tr>
<tr>
<td>Residual</td>
<td>3.990E+005</td>
<td>73</td>
<td>5465.47</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>7.192E+006</td>
<td>82</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

α≤0.01 = H significant, α≤0.1 = significant, A-Power and B-Speed

The bottom length (BL) model in Table 3, it can be seen that A-welding Power and B-Welding Speed are highly significant. It can also be seen there is highly significant interactions in AB.

Regression Analysis

Figures 6 and 7 show the effect of speed and power on the weld bead top surface displacement above the surface, at focal plane position = -1.5 mm (below the surface). It is recognized in the results that at particular combinations of the laser power and welding speed, the weld bead top surface displacement from the substrate surface was zero, signifying an absolutely net shape weld. It is clear positive value of top height are produced at higher speeds and lower powers while higher powers and lower speeds lead to negative values (undercutting). This means that control of the relative value of these
parameters, commonly given in terms of either specific energy or line energy, is important to get net shape welding. Moreover in the response of the top height there were several values near to net shape welding, at the speed 180 mm/s and laser power 600 W the top height was 9 µm and there was value net shape welding with zero value in the top surface at speed 160 mm/s and laser power 700 W the top height was zero.

Figures 8 and 9, Show the effect of welding speed and laser power characteristic. It’s clear the values range from positive to negative, the results identify that at certain combinations of the welding speed and laser power the weld bead top surface displacement from the substrate surface was zero. Additionally it can be seen that the value of the bottom length is from minus -698 µm to plus 736 µm.
The laser power and welding speed affect the depth and width of the weldment [16]. The keyhole shape and its size are allied to the combination of welding speed and laser power input. As the welding speed increases, the inclination angle of the keyhole front wall is increased to make up for the loss of absorbed laser power due to the shorter interaction time between the laser beam and the substrate [17]. Figure 10 shows the effect of the power and speed on the top width. It can be noticed that the top width increases as the laser power increases. This is because the high temperature achieved leads to a large fusion and heat affected zone.

Fig. 10. The effect of power and speed parameters on the response Top width

Figure 11 shows the relation between Speed and Top width at constant Power 500 W, it’s very clear that the top width decreases as the welding speed increases due to the shorter exposure time of any point on the weld line to the heat. This is important in the optimization of the welding process.
The weld depth will increase when the laser power increases for different values of welding speed and workpiece thickness [18]. Figure 12 shows the response of the bottom width on laser power and welding speed. It can be noticed that the bottom width increases as the laser power increases and the value of bottom width array from zero µm to 589 µm.

Fig. 11. The relation between Speed and Top width at constant Power 500 W

Fig. 12. The effect of Power and Speed parameters on the response Bottom Width
Figure 13 shows the relation between speed and bottom width at constant Power 500 W. It is very clear that the Bottom width decreases as the welding speed increases due to the shorter exposure time of any point on the weld line to the heat. This is important in the optimization of the welding process.

![Relation between Speed and Bottom Width](relation_speed_bottom_width.png)

**Fig.13. Relation between speed and bottom width at constant Power 500 W**

Figure 14 shows the response of average weld width, with the response of laser power and welding speed. It can be noticed that when the laser power increases the average weld width increases and vice versa with the welding speed, the value of the average range from 101 µm to 465 µm.

![Effect of power and speed parameters on the average weld width](effect_power_speed_average_weld_width.png)

**Fig.14 Effect of power and speed parameters on the average weld width**
The fusion zone shape and the penetration are controlled by the convective heat transfer and the fluid flow in the welding pool. In the weld pool the fluid flow and the heat flow can significantly influence the temperature gradients, and the solidification structure and the cooling rates [19]. Figure 15 shows the response of weld bead taper with laser power and welding speed. It is known that both laser power input and welding speed affect the size of the keyhole and its formation and it is clear from the figure that relationship is not simple. It’s notice that the value of the taper ranges from -124 to 173.5 µm.

Fig.15. The effect of power and speed parameters on the response Taper

Summary and Conclusion

High power fibre laser for welding is extensively used in many industrial applications because of its unique characteristics, such as higher energy density, and high beam quality. Most of the welding works which require accuracy and precision in production also require machining works after performing the work. This will require more time and money. Sometimes may require special tools and that will add to the total cost of the production. However, the main purposes of the machining works which are required after performing the welding operation are for fitting and accuracy.

In this study, the important parameters affecting production of net shaped bead on plate welds with a fibre laser were investigated using Design of Experiments. Under certain circumstances net shape weld beads on the upper surface and lower surface (zero top height and zero bottom height also) could be obtained but different parameters were required in each case. As examples of the parameter combinations that proved successful: In one experiment an ideal, net-shaped upper surface was obtained with
laser power of 700 W and welding speed of 160 mm/s, and in another experiment, a net shaped upper surface was obtained with a laser power of 500 W and welding speed of 110 mm/s. An ideal, net-shaped lower surface could be obtained with laser power of 600 W and welding speed of 130 mm/s.

The top width decreases as the welding speed increases due to the shorter exposure time of samples to the heat and the bottom width decreases as the welding speed increases for the same reason. This relation between weld width and speed is important in the optimization of the welding process.

Further work is needed to simultaneously obtain a net shape weld on the upper and the lower surfaces with the same parameters, in other words zero top and bottom heights at the same parameters. However, by considering both upper and lower surfaces together this work is a step towards achieving fully net shape welds and thus improving the overall quality of welds that can be produced.

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References

Net Shape Laser Butt Welding of Mild Steel Sheets

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Abstract. In laser welding, the weld bead is normally extended above or below the parent material surfaces due to melt flow and rapid solidification. This paper presents a study of achieving net shape (i.e. weld bead is flat to the parent material surfaces) butt welding of 1.5 mm mild steel sheets using a continuous wave single mode fibre laser (maximum 1 kW) at a range of laser powers, welding speeds and laser focal point positions. A series of experiments were performed using statistical design of experiment (DoE) techniques and analysis of variance (ANOVA) to identify significant variables and their interactions affecting the weld characteristics. The work shows that it is possible to obtain net shape welds on either the upper and lower surfaces of the material studied. There is an approximately linear relationship between upper surface weld bead offset from the surface and the welding speed. A welding speed of above 100 mm/sec is required for achieving net-shape butt welding at 500-550 W laser power.

Keywords: f laser, butt welding, net shape.

1 Introduction

Over the last few decades, the application of laser welding and joining techniques has increased steadily with the advent of high powered industrial laser systems. Attributes such as high energy density and accurate focusing allow high speed processing for precision assemblies [1]. Compared with some of other traditional welding processes (e.g. arc welding and plasma welding) laser welding can generate higher aspect ratio welds (a ratio of depth over width) with lower heated affected zone (HAZ) sizes and little thermal deformation [2]. Because of laser’s ability to weld reproducibly at very high speeds using Computer Numerical Control (CNC) at a competitive price, laser welding is competitive in a variety of industrials applications [3].

Laser welding falls within the group of high-energy-density beam processing technology with the potential to produce welds of high characteristic ratios and it has the benefit of not needing a vacuum system [4, 5]. Over the last few years the availability of high power fibre lasers has also enabled high energy efficiency welding to take place [6, 7]. Lasers are useful for welding thin materials, where strict requirement for workpiece fit-up and thermal distortion control are recognized challenges [8] and for welding thicker plates where thermal distortion is the main problem [9]. This is particularly useful for devices in, for example, the medical industry and aerospace components where formation of discontinuities (pore, void and hot crack) and distortion after laser welding could lead to the part failing quality criteria or failing in service [10].

In the melt pool a high temperature gradient is generated and rapid melt flow takes place. As a result, rapid solidification of the weld can cause the weld bead to form above or below the parent material surfaces. The main driving mechanisms of the fluid flow are the friction force of metal vapour from the capillary, the movement of the capillary relative to the work piece, the temperature-dependent surface tension gradient (Marongoni forces) and thermal expansion of the weld pool and capillary relative to the joined workpiece [11-13]. An important factor that affects the weld geometry is the Peclet number. By increasing the Peclet number, the cross section of weld bead can vary from a rectangular to a triangular geometry in cross section [14]. Beam absorption coefficient, thermal diffusivity, melting and boiling points, among the range of physical properties have been found to be the major factors affecting the weld pool geometry [15].

Earlier work by the authors has shown that a net shape weld for laser bead-on-plate welds for the upper surface and lower surface of a plate can be obtained and that welding speed is the most critical parameter for weld bead geometry control [16, 17].

This paper investigates the feasibility of achieving Net Shape Butt Welding (NSBW) of mild steel materials using a fibre laser. Laser net-shape butt welding has so far not been
shown before. Therefore this study would open up a new area of research. A design of experiments and statistical modelling technique was used in this investigation.

2 Experimental Design and Procedures
2.1 Design of Experiments and Methodology
The experiments are divided in two parts; the first part (A) was carried out through design of experiment using Design Expert 7.0, and the second part (B) experiments were run under a constant laser power, focal point position and gas flow rate with variable speeds.

2.1.1 Part (A)
In this part of the investigation, an L35 orthogonal array, which consisted of three columns and 35 rows, was applied. The experimental design was based on three groups of welding parameters with five levels of each. The selected welding parameters for this research are: laser power, welding speed and laser beam focal point position (Fpp, positive means above the surface and negative means below the surface). Table 1 shows the design factors and parameter levels.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Levels</th>
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<tr>
<td>Laser power (W)</td>
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</tr>
<tr>
<td>Welding speed (mm/s)</td>
<td>90 95 100 105 110</td>
</tr>
<tr>
<td>Fpp (mm)</td>
<td>-3 -2.5 -2 -1.5 -1</td>
</tr>
</tbody>
</table>

2.1.2 Part (B)
In this part of the investigation, experiments were carried out under a constant laser power, focal point position and gas flow rate with variable speeds from 65 mm/s to 125 mm/s. Table 2 shows the laser welding variables.

<table>
<thead>
<tr>
<th>Parameters</th>
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<tr>
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</tr>
<tr>
<td>Welding speed</td>
<td>mm/s</td>
<td>65-125</td>
</tr>
<tr>
<td>Focal point position</td>
<td>mm</td>
<td>2.5</td>
</tr>
<tr>
<td>Ar gas pressure</td>
<td>kPa</td>
<td>100</td>
</tr>
</tbody>
</table>

2.2 Laser welding preparation and methodology
Laser welding was performed on mild steel plates (0.16% – 0.29% carbon), of 50 mm × 50 mm × 1.5 mm thickness, and 50 mm × 25 mm × 1.5 mm thickness. They were butt welded using a 1 kW single mode fibre laser. The samples were mounted on a CNC motion system and clamped during the welding process as shown in Figure 1. The coaxial assist gas was Argon with a gas pressure of 100 kPa. The focal distance of the lens was set according to Tables 1 and 2, and the gap between the welding nozzle and the sample was 5 mm. The nozzle which used for experimentation has an exit aperture of 2 mm. The investigation in this study included 35 experiments in part A and 12 experiments in part B.

Fig. 1 Experimental setup: 1) laser head, 2) cooling jacket, 3) shielding gas, 4) high speed linear motor traverse table, 5) Experimental samples clamped on the table and 6) adjustable vertical manual table.

Fig. 2 Schematic diagram of the cross section of sample
2.4 Response surface methodology
A response surface method (RSM) was used to classify the significant processing factors and quantify interactions between the parameters. The analysis of variance (ANOVA) was used to identify the importance of the input parameters and their correlation with the weld characteristics. In this paper only two output parameters were examined: Top Height (TH) and Bottom Length (BL).

3 Results and Discussion

3.1 Weld Profiles
Figure 3 shows some examples of welds achieved. Near net shape on the top surface has been demonstrated. In addition, the weld bead profiles were positively tapered. On the other hand, in Figure 4, bottom weld bead near net shape welds are demonstrated. Depending on the parameter combinations used, diverse combinations of convex surface beads, undercutting and dropout were also seen.

![Fig. 3 Examples of near net shape from the top side with welding parameters: (a) laser power (P): 550 W, welding speed (S) 100 mm/s, and Fpp: -3.00 mm, (b) P: 525 W, S: 105 mm/s, (c) P: 550 W, S: 90 mm/s, and Fpp: -2 mm, and Fpp: -1.50 mm, (d) P: 550 W, S: 100 mm/s, and Fpp: -1.0 mm.

3.2 Weld bead offset from the top surface
Figures 5 shows the parameter interaction effect of welding speed and power on the weld bead offset from the top surface, at a focal plane position of -2.5 mm (below the surface). The values in the graph show the weld bead offset values in µm. It is clear that positive values of top height are formed at higher speeds at laser powers below 550 W. At the speed increases the top height will increase. This trend will reverse if the laser power is above 550 W. This means that control of the welding parameters, commonly given in terms of either specific energy or line energy, is important to achieve net shape welding. The top height values vary from –300 µm to 175 µm. An important point here to be mentioned is that zero top weld bead offset (net shape) occurs at welding speeds above 100 mm/s and a laser power between 500 W and 550 W.

![Fig. 5 Effect of power and speed on Top Height]

3.3 Relationship between welding speed and top height
Based on the results in part (A) it was recognized that focal point position -2.0 mm was more effective to achieve net-shape welding, experiments were run under a constant laser power 600 W, focal point position -2.0 mm and a gas flow rate 100 kPa, and the speed was variable from 65 mm/s to 125 mm/s. From Figure 6 it can be seen that the weld bead offset over the top surface, i.e. top height, changes from negative to positive as the speed increases, passing through zero at the speed of approximately 100 mm/s.
3.4 Weld bead bottom offset

Figures 7 show the effect of welding speed and laser power on the weld bead bottom surface characteristic. It’s clear that bottom lengths, i.e. weld bead bottom offset from the surface, approaches to a zero (net shape) at a speed over 95 mm/s and power less than 575 W. Net shape on the bottom surface would be useful for pipe welding, where the machining will be complicated, and non-zero bottom weld bead offset might affect the fluid flow. The values of the bottom length vary from negative 76 µm to positive 74 µm. Furthermore, it can be noticed that as the welding speed decreases the bottom length will increase.

4 Conclusion

Net shape butt welding of mild steel sheets has been demonstrated using a single mode fibre laser. A specific set of welding parameters were found to achieve the net shape welding (for either the top and the bottom welds) at different parameters of laser power, welding speed and focal point position. There is a linear correlation between the welding speed and top height; as the speed increases the top height changes from negative to positive. A negative fpp is found to improve surface quality in most circumstances.

Using a fibre laser for the welding process creates a very efficient use of the material components, and has the potential to minimize the total cost of the production. Further investigations are in-progress to understand the mechanical and physical properties of the welds and model the behaviour of weld bead.

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Reference

laser precision Microfabrication (LPM 2002).


Laser net shape welding

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Keywords:
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Welding
Geometry

ABSTRACT

Over the last 40 years of laser welding practice, weld bead geometry always experiences a section of the weld bead slightly above or below the parent material surface. In this paper, a new concept – net shape welding is introduced, whereby the weld joint fusion zone is flat to the parent material surface. Experimental work was carried out to demonstrate net shape laser square butt welded mild steel sheets. Tensile test results show that the net-shape welds well outperform those with traditional weld bead geometry. Computational fluid dynamic and finite element models have been used to assist in the understanding of net-shape weld geometry formation and the superior mechanical properties.

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1. Introduction

Laser welding is a well established joining technology and has been widely applied in the automotive, aerospace, energy, electronic and medical industries. The advantages of laser beam welding include precise energy control, low thermal distortion, small heat affected zones, high welding speed, deep penetration (high weld depth to width ratio) and the elimination of the need for a vacuum chamber. Laser welding is particularly suitable for joining 3D structures, complex assemblies, high precision components and very thin materials including metals, ceramics and polymers. Weld bead geometry is a critical quality factor that can significantly influence the final mechanical properties (e.g. tensile and fatigue properties) and microstructures.

A large volume of research work has been carried out to understand the effect of laser welding parameters (e.g. laser power, welding speed, focused beam spot size) on weld bead geometry and its effect on the mechanical properties. Murugan and Buvanasekaran [1] and Benyounis et al. [2] used design of experiment and a statistical modelling technique to develop experimental relationships between the laser welding parameters (laser power, welding speed, beam incident angle, focal plane position) and weld bead width, depth and heat affected zone size (HAZ) for welding 304 stainless steel and medium carbon steel sheets. Welding speed and focal plane position have been found to be the most significant factors affecting the weld bead width. Krasnoperov et al. [3] classified the welds into 3 stable modes (partial penetration, closed keyhole full penetration and open keyhole full penetration) and an unstable mode (oscillating between partial and full penetration). Open keyhole welding (weld bead width is similar on the upper and lower parts of the weld bead), although having lower energy efficiency than the closed keyhole full penetration welds (weld bead width is wider on the top than at the root) due to loss of energy through the open keyhole, was recommended as the choice of welding operations due to its operation stability. Karlsson et al. [4] classified weld bead geometry into a number of groups for corner joints using a matrix flow chart method. Weld beads with characteristics such as undercut, root cavity and root snagging have been recognised and the effect of laser welding parameters on the geometry formation was identified. Wei et al. [5] studied the effect of Prandtl and Marangoni (Ma) numbers on the laser weld bead geometry. They found that the weld bead root surface became convex for $10^5 < Ma < 10^7$. Arora et al. [6] studied the effect of Marangoni effect on laser conduction weld bead geometry. They found that a wavy weld pool fusion boundary can be formed when Ma is greater than 26,000. Rai and Debroy [7] developed a technique for weld bead geometry design by combing 3D modelling, generic algorithm optimisation and a small number of experiments. They recognised that the heat transfer in the upper part of the melt pool is dominated by convection due to vigorous circulation of molten material driven by the Marangoni effect. Rai et al. [8] developed a convective heat transfer model for determining the weld bead geometry in laser welding of structural steels. They found that a humped root surface could be formed due to recoil pressure and smaller weld area compared with the top surface. Robert and Debroy [9] used dimensionless parameters such as Marangoni and Peclet numbers to predict the weld geometry in stationary laser spot welding of a large range of engineering materials. Marangoni number was found to increase with the laser power. Alam et al. [10] studied the effect of smooth and rough weld bead surfaces on fatigue properties of the welds. They found that surface ripples in welds can reduce fatigue life and the root of the weld (compressive) is less important in influencing the fatigue properties than the top surface. Du et al. [11] examined the effect of weld bead geometry in laser lap welding on the tensile strengths of the joints. They found that welds with exact penetration (full penetration with zero weld width at the bottom) had highest tensile strengths than the partial penetration and over penetration (full penetration with weld bead width > zero at the bottom).

Despite the considerable effort made in predicting and understanding weld fusion zone profiles (particularly the weld...
penetration depth and width) and their effects on mechanical properties, little is understood on the characteristics of top and bottom weld bead surface formation which may have significant effects on the performances of the components joined. Over the last 40 years of laser welding research and applications, the weld bead geometry has been having a section either above and/or below the parent material surfaces. The commonly accepted good weld bead geometry is to have a section of the weld bead slightly above the parent material surface, although in some cases these are machined flat to the surface after the welding. For some applications, a flat weld bead surface may be desirable for precision assemblies, removal of surface stress raisers, application of surface coatings, lowering the resistance to fluid flows (for pipes and vessels), better corrosion protections and cosmetic effects etc. In this paper, a new concept in laser welding – net shape welding is introduced, whereby the weld bead is flat to the parent material surface (for both the face and the root) within the welding process. Experimental work was carried out using a 1 kW fibre laser to demonstrate net shape welds for square butt welds mild steels sheets. The tensile tests were carried out to compare the weld joint strengths for different weld geometry. Computational fluid dynamic modelling and finite element modelling have been used to assist in the understanding of the net-shape weld geometry formation and the superior mechanical properties achieved for the net shape welded parts.

2. Experimental procedure

Experimental samples were BS1449 (CR4, AISI 1018/EN 10130) cold rolled mild steel (0.25% C, 16.85% Cr, 10.08% Ni, 1.91% Mn, 2.086% Mo, 0.12% Cu, 0.62% Si, 0.03% Co, 0.029% P, 0.051% N, 0.001% S and balance Fe) sheets of 1.5 mm thickness. The edges for welding were machined to have vertical walls. Butt welding was performed using an IPG YLR-1000-SM 1 kW single mode fibre laser (1075 nm wavelength, \( M^2 = 1.1 \)) delivered through an optical fibre with a 14 \( \mu \)m core diameter. The fibre output assembly was connected to a z-axis Precitec processing head with a lens assembly and a coaxial gas nozzle. The laser beam was focused via a lens of 190.5 mm focal length to give a beam spot diameter of approximately 50 \( \mu \)m at focus. The conical coaxial gas nozzle had an exit diameter of 2 mm and the workpiece was placed at a standoff distance of 5 mm from the nozzle. An Ar shroud gas was used in the experiment at approximately 25 L/min flow rate to protect the weld surfaces from oxidation at high temperatures. The workpiece was mounted on a high speed linear motor CNC translation table. A Design Expert 7.0 software package was used for designing the experiments. An L47 orthogonal array, which composed of three columns and 47 rows, was applied. The experiment was designed based on three groups of welding parameters (laser power, welding speed and focal plane position) with five levels of each. A response surface method (RSM) was used to identify the significant processing factors affecting the key weld bead characteristics including the top height – TH, relative to the top surface of the parent material (positive is above the surface and negative is below the surface) and root length – RL (a displacement from the bottom surface (positive is above the surface and negative is below the surface)).

After the laser welding the weld fusion zone bead surface characteristics were examined using a Wyko white light interferometer. Weld bead cross sectional geometry characteristics were analyzed using optical microscopy. The samples were cross-sectioned, mounted in a resin, ground successively in 80, 180, 320, 600 and 1200 emery grits and polished with diamond slurry to 3 \( \mu \)m surface finish and finally etched with Krolls reagent (2 ml nitric acid and 18 ml methanol) for approximately 60 s before the optical microscopic examinations. Tensile tests were carried out for a range of laser butt welded samples based on EN1002-1 2001 standard.

3. Results

Fig. 1 shows typical weld bead cross sectional geometry at various welding conditions. At a low welding speed, a notched, concave top surface was developed (Fig. 1a); at a medium speed a net-shape weld was demonstrated (Fig. 1b) and at a high speed a raised-up weld bead above the parent material surface is shown (Fig. 1c). Typical weld bead widths are 145–276 \( \mu \)m at the root and 275–400 \( \mu \)m at the top surface. The root length varied between –75 \( \mu \)m and +75 \( \mu \)m.

Fig. 2 shows the variation of weld bead top face height with the welding speed. It clearly demonstrates that under low welding speeds notched surface weld beads were produced and at relatively high welding speeds, these can be avoided and a net shaped weld surface can be achieved. Fig. 3 shows the interactions between laser power and welding speed in affecting the weld bead top surface geometry. The net shape welds can be achieved at certain power and speed combinations. If the laser power increases, the net-shape welding speed needs to increase as well.
Fig. 4. Tensile test results for (a) a net shape weld – breaks at the parent material (b) other weld geometry – breaks at the weld joint.

Fig. 5. Ultimate tensile strengths of the test pieces for welds produced at 600 W laser power. – 2 mm Fpp.

Figs. 4 and 5 show the tensile test results which clearly demonstrate that net shaped welds have superior mechanical properties than other weld bead geometry. It is worth noting that at the net shape, the strength of the weld is stronger than the parent material. Therefore the measured values for the net shaped welds are in fact the parent material tensile strengths. For welds with other geometry the welds broke at the weld zones, despite the fact that the weld bead width was wider at lower welding speeds than for the net-shape welding conditions. These were tested repeatedly with at least 3 tests for each set of welding parameters. The yield strength showed similar trend.

4. Discussion

3D sequentially coupled computational fluid dynamic (CFD) modelling and finite element analysis (FEA) modelling were performed to understand the weld bead surface geometry formation and to predict the melt flow, solidification and stress characteristics at various laser welding parameters. The CFD and FEM analyses were performed using Fluent and Ansys commercial packages, respectively. In the CFD modelling, Navier–Stokes mass, energy and momentum balance equations were used. A Gaussian volumetric heat source was used to represent the laser heat source and convection with radiation heat loss was assumed on the surfaces. The fluid flow in the weld pool is primarily driven by the combination of surface tension and buoyancy force. On the top and bottom surfaces, the shear stress caused by the variation of surface tension due to temperature is given by

\[ \tau = \frac{\sigma_{0}}{\Delta T} \nabla \cdot T \]  

where \( \sigma_{0} \) is surface tension gradient and \( \nabla \cdot T \) is surface temperature gradient. During the computation, the values of surface tension gradient are expressed as a function of the surface temperature at any time. This surface tension gradient influences the direction of melt pool movement which eventually decides the change in surface geometry of the weld pool surface. The oxygen content was assumed as 0.01%. The escaping vapour exerts a recoil force on the weld pool surface and as a consequence, a key hole is formed. The vapour pressure, \( P_{v} \), depends on the evaporation enthalpy \( \Delta H_{v} \) and the temperature \( T \):

\[ P_{v}(T) = P_{o} \cdot e^{\Delta H_{v}/R \cdot (1/T_{v} - 1/T)} \]  

where \( P_{o} \) is the vapour pressure at the boiling temperature \( T_{v} \), and \( R \) the ideal gas constant.

Fig. 6 shows the weld bead profiles under three different welding speed conditions at a 600 W laser power. A transition of surface tension gradient takes place from negative at the lower welding speed (e.g. 75 mm/s) to positive at the high welding speed (e.g. 125 mm/s). For the net shape welds (i.e. at a 100 mm/s welding speed), the surface tension gradient is close to zero. At the lower welding speed (negative surface tension gradient) the weld pool molten material on the surface flows outwards causing a depression in the weld pool centre after solidification. At high welding speeds (positive surface tension gradient), the weld pool molten material flows inward causing a raised up or bulge weld bead above the surface after solidification. At a particular welding speed, there is minimum melt flow due to close to zero surface tension gradients. Similar phenomenon was observed by Zhao et al. [13] during the study of Marangoni flow in laser spot welding of stainless steel sheets. They found that as temperature increases, the surface tension gradient reduces and flips from positive to negative (if the oxygen content is greater than 0.005%). As the oxygen content increases, the surface tension gradient also increases. The FEM investigation makes use of the modified geometry and the temperature history predicted by the CFD analysis. Fig. 7 shows the calculated residual stress distribution on the surface after the laser welding at 600 W laser power. The net shape welds and bulge welds at high welding speeds have much smaller residual stresses due to reduced heat input to the material. Furthermore, the residual stress of the net shape welding shows smooth transitions, free from stress concentrations, which is not the case for other two weld bead geometries.

To understand the effect of weld bead geometry on the tensile strength characteristics of the welds, a non-linear finite element analysis incorporating multi-linear isotropic hardening was performed to predict the generated stress and distortion of the 3 typical geometries identical to the experimental pieces of the tensile tests: (1) a notched weld, (2) a net-shaped weld and...
(3) a bulge weld (Fig. 8). To focus on the geometry effect, the material properties were assumed uniform for the weld zones and identical to the parent material. A tensile load of 4500 N was applied to pull the weld apart, in line with the experimental tensile test conditions. The simulation (Fig. 9) shows that the mode of stress concentration and the displacements as a result of the load are quite different. For the net shaped weld, the stress concentration and high distortion are away from the welding zone while both the notched weld and bulge weld show stress concentrations and high distortion in the weld zone areas. The experimental micro-hardness and microstructures in the weld zones and heat affected areas are almost identical for the three weld geometry Thus the reason that the net shaped welding has superior mechanical properties would be largely because of its flat surface weld geometry which shifts and spreads the stress concentration to places away from the weld zones, in contrast to other weld bead geometry.

5. Conclusion

Net shape laser square butt welding of mild steel sheets has been demonstrated. The weld bead geometry on the top and bottom surfaces varies with laser power and welding speed. CFD modelling has shown the main reason for the different weld bead surface geometry formation as the Marangoni effect with flipping surface tension gradient signs as the melt pool temperature changes. The superior ultimate tensile strengths of the net-shape welds compared with conventional weld bead geometry are largely due to the lack of stress concentrators at the weld zones.

References

Weld bead characteristics of fibre laser butt welded 1 mm mild steel sheets and CFD modelling

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Abstract
This paper presents the effect of welding parameters on the butt welded 1 mm mild steel sheets using a 1 kW single mode fibre laser to achieve net shape welds (weld bead geometry flat to the parent surface). A series of experiments were performed using statistical design of experiments (DoE) techniques and analysis of variance (ANOVA) for the understanding of parameter interactions and optimizing the above selected welding parameters. Microstructure characteristics were analysed to understand the solidification behaviour. Computation Fluid Dynamic (CFD) modeling was used to understand the thermal history and weld beam formation. The work shows that development of the net shape butt welds using fibre laser is possible. Keywords: Fibre Laser welding, design of experiment (DoE), geometry, net-shape, Marangoni force, finite element, surface tension force, statistical modelling.

1 INTRODUCTION
The application of laser welding and joining techniques has increased steadily with the advent of high powered industrial laser systems. Attributes such as high energy density and accurate focusing allow high speed processing of precision assemblies [1]. Compared with other welding processes such as arc welding, induction welding, solid state welding it’s recognised that laser welding produces less heat into the workpiece. As a result, there is a smaller heat affected zone (HAZ) and smaller workpiece deformation [2]. Laser beam welding is a field of increasing significance in manufacturing due to lower dimensional and shape deformation of components and higher processing rate [3]. Because the laser has the ability to weld reproducibly at very a high speed using Computer Numerical Control (CNC) with competitive cost, it has made laser welding competitive in a variety of industrials applications [4]. It has been
successfully used where high welding speed, high laser power, high energy density and deep penetration are necessary. Laser welding now falls in the group of high-energy-density beam processing technology with the potential of producing welds of high aspect ratios and has the benefits of operating in atmospheric conditions, elimination of a need for a vacuum system [5]. For welding thin materials, strict requirement for workpiece fitup and thermal distortion control is recognized as a challenge that a laser beam would have an advantage over other heat sources [6]. For welding thicker materials smaller heat affected zone and low thermal distortion are important where laser beam welding would play an important role [7].

Studies over the last few years show that the availability of high power fibre lasers has enabled higher energy efficiency welding to take place [8, 9]. In the laser generated melt pool, a high temperature gradient is generated; rapid melt flow as a result of Marongoni effect takes place. As a result, rapid solidification of the weld can cause the weld bead to be above or below the parent material surfaces. Three forces drive the mechanisms of the fluid flow. These are friction force of the metal vapour abscending from the capillary (keyhole), which essentially contributes to kinetic energy in the weld pool, the movement of the capillary relative to the workpiece, the force from temperature-dependent surface tension and thermal expansion of the weld pool [10]. One of the important parameters determining the weld bead geometry is the Peclet number. Increasing the Peclet number, the cross section of the weld bead can vary from a rectangular to a triangular geometry [11]. Beam absorption coefficient, thermal diffusivity, melting and boiling points, among the range of physical properties have been found to be the major factors affecting the weld pool geometry [12].

Earlier work by the authors have shown that a net shape weld bead on the upper surface and at the root could be obtained and that welding speed is a critical parameter for weld bead geometry control [13-15]. This paper further understands the mechanism involved in the net shape weld bead formation supported by microstructure analysis and CFD modeling.
2 EXPERIMENTAL DESIGN AND PROCEDURES

2.1 Design of experiments and methodology

Design Expert (a commercial software tool for Design of Experiment and Statistical Modelling) was used in the experimental study to understand welding parameter interactions. The experiment was designed based on three groups of welding parameters with five levels of each. The selected welding parameters for this research are: laser power, welding speed and laser beam focal point position (positive means above the surface and negative means below the surface). Table 1 shows the design factors, input variables and experiments design levels. An L35 orthogonal array, with three columns and 35 rows, was applied.

<table>
<thead>
<tr>
<th>No</th>
<th>Variables</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laser Power (W)</td>
<td>350 375 400 425 450</td>
</tr>
<tr>
<td>2</td>
<td>Laser Welding (mm/s)</td>
<td>75 100 125 150 175</td>
</tr>
<tr>
<td>3</td>
<td>Focal Point Position (mm)</td>
<td>-3 -2 -1 0 1</td>
</tr>
</tbody>
</table>

2.2 Laser welding preparation and methodology

Laser welding was performed on AISI 1018 / EN 10130 mild steel plates with its composition shown in Table 2. The metal was cut into sheets of 25 mm x 50 mm x 1 mm thickness.

<table>
<thead>
<tr>
<th>%</th>
<th>C</th>
<th>CR</th>
<th>MN</th>
<th>MO</th>
<th>N</th>
<th>NI</th>
<th>P</th>
<th>S</th>
<th>SI</th>
<th>CO</th>
<th>CU</th>
</tr>
</thead>
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<td>EN10130</td>
<td>0.025</td>
<td>16.85</td>
<td>1.91</td>
<td>2.086</td>
<td>0.051</td>
<td>10.08</td>
<td>0.029</td>
<td>0.001</td>
<td>0.62</td>
<td>0.03</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Then the sheets were machined from one edge with a rectangular profile which were butt joined (parallel edges) using a 1 kW single mode fibre laser. The samples were fixed on a CNC motion system and clamped during the welding process as shown in Figure 1. The coaxial assist gas was Argon with a gas pressure of 100 kPa. The gap between the welding nozzle tip and the sample was 5 mm. The nozzle used for experimentation had an aperture of 2 mm.
2.3 Weld bead characterisation
After the welding experiments, the samples were cross-sectioned, perpendicular to the weld direction, mounted in a resin, polished with diamond slurry to 6 µm and 3 µm surface finish and finally etched with Krolls reagent (1ml Nitric Acid and 9 ml Methanol) for approximately 40 seconds for further examination. The microstructures were imaged using Polyvar optical microscopy. Finally, the weld bead cross section area was measured in terms of the TH = top height, TW = top width, RH = root height and RW = root width for each sample as shown in Figure 2.

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2.4 Response surface methodology
A response surface method (RSM) was used to understand parameter sensitivity and their interactions. The analysis of variance (ANOVA) performance was used to understand the importance of the input parameters and their correlation with the weld
characteristics. Six output parameters were examined: Top Height (TH) and Top Width (TW) signifying the top weld bead geometry features, Root Height (RH) and Root Width (RW) signifying bottom weld beam geometry characteristics. In addition, average weld width (Wavg) and taper (WT) were considered using the following equations

\[ W_{\text{avg}} = \frac{(TW + RW)}{2} \]  
(1) For calculate the average weld width

\[ W_T = \frac{(TW - RW)}{2} \]  
(2) For calculate the average weld taper

3 RESULTS AND DISCUSSIONS

3.1 Statistical modelling and analysis

Three models were built to relate the welding parameters with six responses, top height, root height, top width, root width, average, and taper model. All models were related to the two design factors, which are given in the Table 1. A complete analysis of variance (ANOVA) technique was used to classify the significance of the coefficients. The welding parameters A- Laser Power and C- Focal Point Position (Fpp) were found significant while B- Welding Speed was not significant. All of them are highlighted in Tables 3.
Table 3 ANOVA table of top height (TH) model

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob &gt; F</th>
<th>Effect</th>
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<td>970.42</td>
<td>2.48</td>
<td>0.0828</td>
<td>Significant</td>
</tr>
<tr>
<td>A-Power (w)</td>
<td>1236.69</td>
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<td>1236.69</td>
<td>3.16</td>
<td>0.0869</td>
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</tr>
<tr>
<td>B-Speed (mm/s)</td>
<td>96.12</td>
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<td>96.12</td>
<td>0.25</td>
<td>0.6244</td>
<td>Not Significant</td>
</tr>
<tr>
<td>C-fpp (µm)</td>
<td>1585.11</td>
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<td>1585.11</td>
<td>4.05</td>
<td>0.0544</td>
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<td>27</td>
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<td></td>
</tr>
<tr>
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<td>361.00</td>
<td>0.90</td>
<td>0.5277</td>
<td>Not significant</td>
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<td>402.54</td>
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<tr>
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<td></td>
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</tbody>
</table>

α≤0.01 = H significant, α≤0.1 = significant, A- Power and B-Speed C- Focal plane position.
Value of ‘Prob > F’ less than 0.1000 indicate model terms are significant. Where df is the Degrees of freedom for the selected model

From the ANOVA for response surface Quadratic Model Root Height (RH) model in Table 4, it can be seen that C2 (focal position) is significant while other parameters are not significant because their significance values are more than 0.1.
Table 4 ANOVA table of Root Height (RH) Model

<table>
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<td>0.2962</td>
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<tr>
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<td>0.34</td>
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<tr>
<td>C-fpp</td>
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<tr>
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<td>978.94</td>
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<td>B²</td>
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</table>

α≤0.01 = H significant, α≤0.1 = significant, A- Power and B-Speed C- Focal plane position.

Value of ‘Prob > F’ less than 0.1000 indicate model terms are significant.

During the analysis of variance (ANOVA) for the response surfaces, nine surface quadratic models were built to relate the six responses (top height, root height, top width, root width, average weld width, and taper) to the laser welding parameters. The significance of the variables was determined. From the analysis C- Fpp and B2 were found significant while B- Speed and A- Power were not significant for the top width highlighted in Tables 5.
Table 5 ANOVA table of Top width (TW) Model

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<th>Source</th>
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<th>Mean square</th>
<th>F value</th>
<th>Prob &gt; F</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
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<td>Not Significant</td>
</tr>
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<td>A-Power</td>
<td>1944.00</td>
<td>1</td>
<td>1944.00</td>
<td>2.48</td>
<td>0.1302</td>
<td>Not Significant</td>
</tr>
<tr>
<td>B-Speed</td>
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<td>1</td>
<td>2007.56</td>
<td>2.56</td>
<td>0.1244</td>
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</tr>
<tr>
<td>C-fpp</td>
<td>3736.17</td>
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<td>3736.17</td>
<td>4.77</td>
<td>0.0405</td>
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</tr>
<tr>
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<td>0.49</td>
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<tr>
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</tr>
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<td>0.0400</td>
<td>Not Significant</td>
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<tr>
<td>C²</td>
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<td>1072.37</td>
<td>1.37</td>
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</tr>
<tr>
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<tr>
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</tr>
</tbody>
</table>

α ≤ 0.01 = H significant, α ≤ 0.1 = significant, A- Power and B-Speed C- Focal plane position.

Value of ‘Prob > F’ less than 0.1000 indicate model terms are significant.

For the root width, the significant terms are A- Power and C2 while others were not significant as shown in Tables 6.
### Table 6 ANOVA table of Root Width (RW) Model

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob &gt; F</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
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<td>9</td>
<td>1446.57</td>
<td>2.57</td>
<td>0.0356</td>
<td>Not Significant</td>
</tr>
<tr>
<td>A-Power</td>
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<td>6666.67</td>
<td>11.87</td>
<td>0.0024</td>
<td>Not Significant</td>
</tr>
<tr>
<td>B-Speed</td>
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<td>1.03</td>
<td>0.3220</td>
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</tr>
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<td>C-fpp</td>
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</tr>
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<td>696.89</td>
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</tr>
</tbody>
</table>

\( \alpha \leq 0.01 = \) H significant, \( \alpha \leq 0.1 = \) significant, A- Power and B-Speed C- Focal plane position.

Value of ‘Prob > F’ less than 0.1000 indicate model terms are significant.

### 3.2 Weld bead profiles

Figure 3 shows the effect of welding parameters on the responses (top height, root height, top width, and root width). It is clear that, under this set of operating parameters the top weld bead surfaces are near net shape. Weld bead profiles were slightly above the parent material surface while the root weld beads were not in net shape. In addition, the cross sectional weld bead profiles were positively tapered. On the other hand, in Figure 4 near net shape welds were demonstrated for the root welds beads. Figure 5 shows near net shape welds for both the top and root. Figure 6 shows examples where neither the top nor the root has achieved the net shape or near net shape welds.
Fig. 3 Examples of near net shape from top side with welding parameters (11-30-35) P: 400 W, S: 125, and Fpp: 1 mm, (20-5-35) P: 425 W, S: 100 mm/s, and Fpp: 0 mm, and (33-14-35) P: 350 W, S: 125 mm/s, and Fpp: -1 mm.

Fig. 4 Examples of near net shape from root side with welding parameters: (19-7-35) P: 375 W, S: 150 mm/s, and Fpp: 0 mm, (9-3-35) P: 425 W, S: 150, and Fpp: -2.00 mm and (33-14-35) P: 350 W, S: 125 mm/s, and Fpp: -1 mm.

Fig. 5 Example of near net shape from top (cap) and root sides with welding parameters: (4-9-35) P: 375W, S: 150 mm/s & Fpp:0 mm, (26-1-35) P: 425 W, S: 150 mm/s, and Fpp: -2 mm. (22-26-35) P: 400W, S: 125 mm/s & Fpp: -3 mm.
Fig. 6 Example of not near net shape from top (cap) and nor root sides with welding parameters: (21-27-35) P: 400W, S: 75 mm/s & Fpp: -1 mm, (10-23-35) P: 400W, S: 175 mm/s & Fpp: -1 mm. and (8-25-35) P: 400W, S: 125 mm/s & Fpp: -3 mm.

3.3 Weld bead top surface quality

Figures 7 and Figure 8 show the effect of welding speed and laser power on the weld bead top surface displacement, at a focal plane position = -1.0 mm (below the sample surface). It is clear that at certain values of laser power, welding speed and focal point position, the top height can reach zero. According to the graph below, when the welding power increases the top height decreases. This has the similar effect of reducing welding speed. Both would result in an increase in surface temperature. This means that control of the welding parameters, commonly given in terms of either specific energy or line energy, is essential for the control of the top height geometry. The top height varied from -44 µm to 39 µm in this operating parameter range.

Fig. 7 Contour graph showing the effect of laser power and welding speed
3.4 **Weld bead root surface quality**

Figures 9 & Figure 10 show the effect of welding speed and laser power on the weld bead root surface characteristic. It’s clear that zero root height can be obtained under certain welding parameters. This net shape would be helpful for pipe welding where the machining will be more complicated for internal wall finishing. Undesirable, non-net shape welds would either affect the fluid flow or become the source of stress concentration or weaker points for corrosion/erosion attacks. It’s clear by increasing the laser power the root height changes from negative to positive, similar to the effect of reducing welding speed. Both would result in more material to be melted and higher temperatures in the welds. When gravity overcomes the surface tension the weld drop out phenomenon would occur. The root height varied from – 76 μm to 86 μm under this set of operating parameters.
Fig. 10 A 3D graph showing the effect of power and speed on the Bottom Length.

3.5 Top width TW
Laser power and welding speed are concurrent to the formation of the keyhole and its size. The inclination angle of the keyhole front wall would increase as the welding speed is increased to make up for the loss of absorbed laser power due to the shorter interaction time between the substrate and the laser beam [16]. Figure 11 shows the effect of the laser power, welding speed and focal point position on the top width. It can be noticed that the top width varied between 260 µm and 397 µm under this set of operating parameters.

Fig. 11 A contour graph showing the effect of laser power and welding speed on the weld bead top width
3.6 Root width RW
At a constant welding speed and varying the laser beam power, there would be an approximation of linear coupling between the weld pool length and weld pool depth [10]. Figure 12 shows that all the three welding parameters: laser power welding speed and focal point position would affect the root width. The root width changes from 60 µm to 217 µm under this set of welding parameters.

![Fig. 12 Contour graph showing the effect of laser power, welding speed and focal point position on the root width](image)

3.7 Average weld width
The depth and the length of the weld pool is linearly related to the laser power intensity [17]. Figure 13 shows the response of average weld width to variation of laser power, welding speed and focal point position. It can be noticed that by increasing the laser power, and reduce the welding speed, the average weld width will increase. The average weld width varied between 186 µm and 282.5 µm.

![Fig. 13 Contour graph showing the effect of laser power and welding speed on the average weld width](image)
3.8 Average weld taper

The keyhole in the laser welding is formed at the beam irradiation point. Deep penetration welding is realized by deeper absorption of the laser beam inside the keyhole. The keyhole shape is therefore affecting the weld bead geometry, particularly on the weld bead width, depth and taper [18]. Figure 14 shows the response of weld bead taper to changes in welding speed, laser power and focal point position. It is known that both laser power input and welding speed affect the size of the keyhole and its formation. It is clear from the figure that a combination of high welding speed and low laser power can produce more tapered weld bead with the former having a more significant effect. It’s also noticed that the value of the taper ranges from 59.5 µm to 163 µm. Weld bead taper would be expected to affect the joint strength.

![Fig.14 Contour graph showing the effect of laser power and welding speeds on weld bead cross section taper](image)

3.9 Mechanical properties

3.9.1 Micro-hardness test

1. Bulge weld

![Fig. 15 a Micro-hardness test scan lines at bulge weld produced at P: 450W, S: 150 mm/s and Fpp: -2mm](image)
2. Notch weld

Fig. 16 a Micro-hardness test scan lines at notch weld produced at P: 400W, S: 75 mm/s and Fpp: -1mm

3. Under cut weld and

Fig. 17 a Micro-hardness test scan lines at under cut weld produced at P: 350W, S: 125 mm/s and Fpp: -1mm

4. Net shape weld

Fig. 18 a Micro-hardness test scan lines at net shape weld produced at P: 375W, S: 150 mm/s and Fpp: 0 mm
Table 7 shows the values of the micro-hardness in 4 typical weld bead geometry at various locations from the centre of the fusion zone (zero location).

Table 7 value of the hardness test

<table>
<thead>
<tr>
<th>Dist.</th>
<th>Bulge weld</th>
<th>Notch weld</th>
<th>Under cut weld</th>
<th>Net shape weld</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hardness</td>
<td>Hardness</td>
<td>Hardness</td>
<td>Hardness</td>
</tr>
<tr>
<td>-0.715</td>
<td>106.2</td>
<td>103.7</td>
<td>105.3</td>
<td>108.3</td>
</tr>
<tr>
<td>-0.495</td>
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<td>106.2</td>
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<tr>
<td>-0.275</td>
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<tr>
<td>0.935</td>
<td>105.7</td>
<td>105.9</td>
<td>104.7</td>
<td>107</td>
</tr>
</tbody>
</table>

Fig. 19 Hardness distribution for 1 mm thick of mild steel laser welding
The micro-hardness values were measured under a load of 500 N with 10 s indentation time with 0.055 to 0.11 mm separation between the indentations. It can be seen as shown in Figure 19, that the highest hardness 379.4 Hv was for the net shape welding parameters and was higher than other types of the welds. The hardness profile of the net shape welding was narrower because the HAZ was less extensive in the net shape welding.

3.9.2 Microstructure
Parameters, which control the solidification of castings, also control the solidification and microstructure of welds. However, various physical processes that occur due to the interaction of the heat source with the metal through welding add a new dimension to the understanding of the weld pool solidification. Conventional theories of solidification over a broad range of conditions can be extended to understand weld pool solidification [19]. In the weld pool the heat flow and fluid flow can influence the cooling rates, temperature gradients solidification microstructure [20]. Optical microscopy was used for the examination of weld microstructure characteristics. Figure 20 shows the microstructures of a bulge weld (weld bead is above the top surface), typically achieved under low laser power and higher welding speed.

1 Bulge weld

Fig. 20 Microstructures of a bulge weld produced at
P: 450W, S: 150 mm/s and Fpp: -2mm
Fig. 21 The three areas of microstructures of a bulge weld

Fig. 21 (a) shows the microstructure of the parent material, showing equiaxed grains while in Fig 21 (b), the HAZ area, which was a combination of martensite and equiaxed grains in this transition area. In the locations close to the parent materialist is equiaxed whereas in locations close to the fusion area it is martensite. Fig 21 (c) shows the microstructure in the welding areas showing martensite because of rapid solidification due to rapid cooling after welding. When the properties of a polycrystalline material are under consideration, the grain size is often determined. In the resolidification areas and in some places of HAZ areas close to the welding areas, the needle shaped grains are the martensite phase while the white regions are residual austenite that fails to transform during the short time rapid quenching.

2 Notch weld

Fig. 22 Microstructure of a notch weld produced at 
P: 400W, S: 75 mm/s and Fpp: -1mm
Figure 23 shows the microstructure characteristics of a notch weld (typically achieved at low welding speed and high laser power). In this case, the heat affected zone is larger than that in the bulge welds and grain sizes are larger due to more energy input and slower cooling rates.

The grains are still in a relatively high strain energy state even after the recovery is complete. Recrystallization is the formation of a new set of strain-free and equiaxed grain (i.e., having approximately equal dimension in all directions) that have low dislocation densities and are characteristic of the precold-worked condition [21]. Both time and temperature will affect the process of the recrystallization as well as the degree (or fraction) of recrystallization [21]. The biggest grain size noted in this microstructure group was in the notch weld.

3 Under cut weld and

Fig. 24 Microstructure of a under cut weld produced at
P: 350W, S: 125 mm/s and Fpp: -1mm
Figure 25 shows the undercut welds are typically seen when the laser power is too low. Insufficient energy is input into the material. Heat affected zones are narrower and grain sizes are smaller and close to the grain size of net shape welding due to rapid cooling.

4 Net shape weld

Figure 26 Microstructures of a net shape weld produced at
P: 375W, S: 150 mm/s and Fpp: 0 mm

Figure 27 The three areas of Microstructure of a net shape weld
Figure 27 shows, Under this welding condition, due to high welding speed, longer weld pool along the laser scanning direction is expected. Surface tension gradient is expected to be close to zero at the solidification points on the weld surface to allow net shape welds to occur. The heat affected zone is smaller and the grain size is lightly smaller than the other three welding conditions.

Rapid solidification theories have been extended to welds solidified at very high cooling rates. However, microstructure development in the weld fusion zone (FZ) is more complicated because of physical processes that occur due to the interaction of the heat source with the metal during welding, including re-melting, heat and fluid flow, vaporization, dissolution of gasses, solidification, subsequent solid-state transformation, stresses, and distortion. These processes and their interactions profoundly affect weld pool solidification and microstructure.

The increase in hardness can be noted at a distance from the interface HAZ areas/ FZ areas. In the fusion zone the refinement of the grain was the result of remelting and rapid solidification of the material. According to Quan et al. (2008) and Coelho et al. (2008), the increase in hardness can be explained by the decrease of the grain size [22]. Referring to the abovementioned hardness test result and to the micrographs in Figure 27 (c) it is clear that the grain size is very small in comparison to other welding conditions. The transition zone in the HAZ areas is subjected to temperature and cooling rate less drastic than those found in the fusion zone (welding areas).

4 CFD MODELLING

In order to understand the effect of laser welding parameters on the fluid flow and solidification characteristics and causes of the different weld bead geometry formation, computational fluid dynamic (CFD) modeling was carried out. The three different typical weld bead geometry (net shape, bulge, and notch) were considered and compared in the modeling.

4.1 Model Formulation

The computational domain with a dimension: length, L = 2.5 mm, width, W = 4 mm and thickness B = 1 mm was considered for CFD computation. The ambient
temperature was set at 300°K. The analysis made use of material properties of BS1449 cold rolled mild steel adopted from Woolman [23].

The CFD analysis was performed to model the physical phenomena in the laser welding such as phase transition, heat transfer and fluid flow and is performed using finite volume based code, Fluent 13.0. The mathematical model used in this work is based on the Navier-Stokes equations with the Reynolds method of averaging the time-dependent equations (RANS). The governing equations [24] are composed of the conservation of mass, conservation of momentum, and conservation of energy, which are given by equations (3)–(5):

\[
\frac{\partial p}{\partial t} + \nabla (\rho \vec{v}) = 0 \tag{3}
\]

\[
\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla (\rho \vec{v} \vec{v}) = -\nabla p + \mu \nabla^2 \vec{v} + S_w \tag{4}
\]

where \( \rho \) is the density, \( \vec{v} \) is the melt pool velocity in respective directions, \( p \) is the pressure force, \( \mu \) is the viscosity and \( S_w \) is the momentum sink.

The energy equation is written in terms of the sensible enthalpy, and an appropriate formulation of the latent heat function play a pivotal role in ensuring that the results from the energy equation are consistent with phase-change considerations.

\[
\frac{\partial}{\partial t} (\rho H) + \nabla (\rho \vec{v} H) = \nabla (k \nabla T) + S \tag{5}
\]

where \( H \) is enthalpy, \( k \) is the thermal conductivity, \( T \) is the temperature and \( S \) is the volumetric heat source. Enthalpy of material is computed as the sum of sensible enthalpy (\( h \)) and latent heat (\( \Delta H \)).

\[
H = h + \Delta H \tag{6}
\]

\[
h = h_{\text{ref}} + \int_{T_{\text{ref}}}^{T} C_p \, dT \tag{7}
\]
where $h_{\text{ref}}$ is the reference enthalpy, $T_{\text{ref}}$ is the reference temperature and $C_p$ is the specific heat at constant pressure. Latent heat content ($H$) can be written in terms of latent heat of the material $L$:

$$\Delta H = \beta L$$

where $\beta$ is the liquid fraction, which is defined as

$$\beta = \begin{cases} 
1 & \text{if } T > T_l \\
(T - T_s)/(T_l - T_s) & \text{if } T_s \leq T \leq T_l \\
0 & \text{if } T < T_s 
\end{cases}$$

where $T_l$ is the liquidus temperature and $T_s$ is the solidus temperature. The values of $\beta$, ranges between 0 and 1 defining the extent of melting. The mushy zone is treated as a porous medium in momentum equations. A momentum sink is added to the momentum equation (Eq. 4) to extinguish velocities in the solid region. Momentum sink ($S_m$) due to reduced porosity in the mushy zone can be written as:

$$s_m = (1 - \beta)^2 \left( \frac{1}{\beta^3 + \xi} \right) A_m(w)$$

where $\xi$ is a small number (0.001) to avoid division by zero and $A_m$ is the mushy zone constant.

Heat loss due to convection and radiation is considered over all surfaces and a Gaussian volumetric heat source as proposed by Goldak [25] was used as the input laser heat source given by:

$$S = \frac{3P}{\pi abc} \exp\left( -\frac{3x^2}{a^2} \right) \exp\left( -\frac{3y^2}{b^2} \right) \exp\left( -\frac{3z^2}{c^2} \right)$$

where $P$ is the absorbed laser power. The parameters $a$ and $b$ are taken to be equal to the focal radius the laser beam and $c$ is the height of the volumetric heat source (same as the plate thickness). The heat source was added as a source term in energy equation (Eq. 5).

The fluid flow in the weld pool is primarily driven by the combination of surface tension, viscous force and buoyancy force. On the top and bottom surfaces, the shear stress caused by the variation of surface tension due to temperature is given by

$$\tau = \frac{\partial \sigma}{\partial T} \nabla T$$
\[ \frac{\partial \sigma}{\partial T} \] is surface tension gradient and \( \nabla T \) is surface temperature gradient. During the computation, the values of surface tension gradient are expressed as a function of the surface temperature [26], at any time. Shear stress given by equation (12) is applied to momentum equations (Eq. 4).

The weld bead surface changes in this model were incorporated due to the effect of two phenomena. The first one is the surface deformation produced by keyhole penetration velocity [27, 28]. The next one is due to the surface tension gradient, which influences the direction of melt pool movement, which eventually influences the weld bead surface profile.

In order to regulate the laser heat source and to track the weld bead surface profile, a compiled user defined function (UDF) file was introduced to the prepared FLUENT case file. The UDF are written in the C programming language and linked to the FLUENT solver.

4.2 CFD modeling results

In order to study the effects of the laser welding parameters on the temperature, weld bead profiles and weld bead structural characteristic, three sets of simulations are performed, with a speed of 75, 125, 175 mm/s and a constant laser power of 400 W. The CFD analysis was performed for 200 time steps of which 175 steps is for the laser welding phase (corresponds to the welding length) and rest is for cooling phase.

To highlight the thermal phenomena in the laser welding, first the results are prepared in the form of temperature contours with included modified weld bead surface profile. Part of the absorbed energy is being used to melt the metal and part of it is being conducted into the solid base metal. Heat conduction is the major mode of heat transfer in the initial stage. In the intermediate stage, the metal melts up and the subsequent fluid convection leads to a deformation of the free surface of the weld pool.
Figure 28 shows the temperature contour along the mid-cross section and the corresponding weld bead profile. The plots are generated after the temperature and weld bead profile reach a quasi-steady state. As can be seen from figure 28 (a), low speed (75 mm/s) results in relatively higher temperature due to the longer laser interaction time. The Figure 25 clearly shows the change in weld bead profile with speed. A low laser welding speed (75 mm/s) results in notched weld bead surface (figure 28 (a)), whereas high speed (175 mm/s) results in a bulge weld bead surface (figure 28 (c)), and for an optimal welding speed (125 mm/s) the weld bead surface was in line with the parent material (figure 28 (b)).

The velocity vector on the material top surface is shown in Figure 29. The forces, which influence the molten pool dynamics, are primarily the surface tension force, viscous force, and buoyancy force. Amongst all these forces, surface tension force is predominant, since it initiates the flow within the small molten pool. As can be seen from the Figure 29, high magnitude of velocity vector (0.16-2.37 m/s) is found for a speed of 75 mm/s and 175 mm/s and a relatively very low magnitude of velocity vectors

![Figure 28 Temperature contour (K) with weld bead profiles for 400 W laser power and speed: a) 75 mm/s, b) 125 mm/s, c) 175 mm/s](image1)

![Figure 29 Comparison of top surface velocity vector for 400 W laser power and speed: a) 75 mm/s, b) 125 mm/s, c) 175 mm/s](image2)
(0.02-0.16 m/s) is noticed for a welding speed of 125 mm/s. The velocity vector was highly influenced by the surface tension gradient of the material which again, depends upon the surface temperature. A transition of surface tension gradient takes place from negative at the lower welding speed (e.g. 75 mm/s) to positive at the high welding speed (e.g. 175 mm/s). For the net shape welds (i.e. at 125 mm/s welding speed), the surface tension gradient is close to zero. At the lower welding speed (negative surface tension gradient) the weld pool molten material on the surface flows outwards causing a depression in the weld pool centre after solidification. At high welding speeds (positive surface tension gradient), the weld pool molten material flows inward causing a humped weld after solidification. At a particular welding speed in the range of 125 mm/s, there is minimum melt flow due to close to zero surface tension gradients.

5 CONCLUSIONS
The weld bead geometry characteristics in fibre laser butt welding of 1 mm thick mild steel sheets have been examined and 4 different cases have been found: bulge weld (at low laser power and high welding speed), notch weld (at high power laser or low welding speed) under cut weld and net shape weld (certain laser power and welding speed and focal point position combination). Design of experiments and statistical modeling techniques have been used to identify the parameter interactions. Microstructure analysis shows little differences between the type of welds apart from slight changes in grain size and orientation.

From the CFD analysis, it is has been found that the main cause of different weld bead surface heights is the surface tension gradient which can be controlled by the surface temperature thus the welding parameters. A switching of surface tension gradient from negative to positive occurs at certain welding parameters. A net shape weld can be achieved if the surface tension gradient is zero.

REFERENCES


13. R. M. Eghlio, A. J. Pinkerton and L. Li, "Investigation of Net - Shape Welding of Mild Steel Sheets with a 1 kW Single Mode Fibre Laser" The 7th


