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The Use of Custom Beam Profiles in Laser Deposition, Observation of Microstructure and Melt Pool Flow

Ву

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Doctoral Thesis

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1 Abstract

The work presented in this thesis discovers that through the use of shaped laser beam profiles the microstructure of the deposition can be modified. It has been seen that though modifying the beam profile melt pool flow observed during the preposition process has altered.

A number of problems have been identified with current laser deposition processes, typically porosity, cracking and undesired deposition profile. The work identifies that thermal profiles are a major factor influencing both the microstructure and deposition. Methods for observing and measuring thermal profiles are explored.

A number of beam profiles are used in this study showing a number of effects on the thermal profiles present during the deposition on Inconel 625 onto mild steel substrate. EBSD and ESD analysis is used to examine the properties of the depositions. Further imaging and analysis of melt pool flow during the process is undertaken using high speed camera imaging, motion tracking and novel pyrometry techniques.

As was expected the use of modified beam profiles had an influence on the microstructure of the depositions formed, large variations in grain size an orientation were observed along with alloy element segregation. Through the melt pool imaging techniques developed it was observed that the material transport mechanisms were modified by the shaped laser beam dramatically reducing the material transport velocity, indicating a reduced thermal gradient.

This work shows that through modifying the laser beam profile factors influencing the quality of a resulting deposition can be changed. Through further work this principle can be expanded to use the laser beam profile as an input factor to allow the used design of deposition profiles.

1.1 Research Question

This work aims to investigate to answer the question, "Can the thermal profile in the deposition melt pool be controlled to improve that deposition?"

2 Introduction

Lasers can be a complicated and expensive option for many processes, as such need justification for their use. Some problems exist where there is simply no alternative available to solve the problem than to use the unique properties a laser possesses. Other justifications can be that the laser is able to do an existing job quicker, cheaper, more accurately or just better.

Laser deposition is a process developed in the late 1970's exploiting some of the properties of laser beams to accurately deposit metallic materials to improve the surface properties of components, this technique developed to replace tungsten inert gas welding to deposit material for aeronautical engine component repair following wear in use.

The high thermal energy required to fuse the material in place, along with the quick processing times, lead to deposits with reduced material properties when compared to the parent material. The mechanical propertied in the deposit are influenced by the thermal cycle during the processing. The thermal profile in the material will have a result on the cooling rates and temperatures reached, influencing the microstructure formed in the deposition.

Indirect influence on the thermal profile during a laser process can be achieved by a number of factors such as laser power, which will have an effect on the temperature reached and scan speed influencing the cooling rates. Direct influence on the thermal profile is much harder to achieve. To have direct influence on the thermal profile in the interaction region the intensity profile in the laser beam needs to be designed to suit the thermal profile required. This study looks at how altering the laser beam intensity profile affects the thermal profile at the interaction region in a laser deposition process.

The next chapter, Chapter 2, explores the process of laser deposition introducing the problems seen in the micro and macro structure. Problems with current deposition processes and laser beam intensity profiles are discussed along with the effects of modifying the beam profile into some simple shapes. It goes on to introduce the effect of the thermal profile on the macro scale, with the fluid flow mechanisms acting on a melt pool and the driving forces behind them. Visualization of the melt pool is important in understanding the material transport process in action, as well as any thermal profiles seen. The literature is examined to look at methods of in process monitoring and imaging particularly in a thermal domain.

Introduction

Chapters 3 and 4 look at formulation of experimental methodologies and application of those methodologies respectively. Experimental methods along with techniques for result analysis are discussed and trailed, with some alterations to methodologies introduced following the initial investigations in Chapter 4.

Chapter 5 explores the how the depositions have been modified by the thermal profile resulting from the modifications to the input laser beam. The alteration of the thermal profile leads to a modification in the solidified microstructures and surface profiles. Also explored are alloy element distributions within the deposition indicating a flow pattern was present during formation of the material.

The mechanism of melt pool flow is used as an indicator to the thermal state of the deposition melt pool. The melt pool flow is driven by thermal gradients in the liquid pool, therefore through observation of the flow in real time during the deposition process, the driving mechanism can be determined. Knowledge of the flow mechanism in action on the deposition pool allows the driving forces, and therefore the thermal gradients to be deduced. As observation inside the molten pool is beyond the current state of the art, surface flow and melt pool form are used as indicators to the melt pool transport mechanisms in action. The methods and findings are discussed further in Chapter 6.

The results of this study, discussed in Chapter 7, show that the laser beam intensity distribution is able to modify the thermal profile seen in the deposition pool. It has also been shown that the alterations to the thermal profile have affected the microstructure of the resulting deposition. Both the changes to microstructure and melt pool flow, follow the theoretical mechanisms explored in this study and the literature. This allows the work to be considered as a validation of theoretical concepts and models. The work contained in this study can be expanded to allow for the production of designed microstructures in laser deposition where the laser beam profile used is dictated by modelling of the process from microstructure formation backwards to find the energy profile required at the material surface.

2.1 Claims of Originality

The work detailed in this thesis compromises the following original work;

- Complex three dimensional laser beam profiles have shown to directly influence the microstructure and profile of depositions.
- Dramatic grain size reduction in laser deposition using shaped laser beam
- Depositions made using asymmetric beam intensity profile producing asymmetric microstructure in the deposition.
- Modified beam profiles have shown to alter the melt pool flow in laser depositions.
- Longitudinal laser beam shaping has resulted in stability improvements to laser process.
- High resolution, in-process, colour imaging of laser deposition.
- High resolution, high speed thermal profile analysis of laser deposition.
- Quantitative analysis of complex melt pool flow in laser deposition melt pools.

2.2 Publications Arising from This Work

- Grain size control in the weld pool and heat affected zone using holograms. 4th International Conference on Recrystallization and Grain Growth, ReX and GG IV, July 4, 2010 - July 9; 2010; Sheffield, United kingdom: Trans Tech Publications Ltd; 2012.
- Weld pool shaping and microstructural control using novel computer generated holographic optic laser welding of steel and stainless steel. 6th International Conference on Processing and Manufacturing of Advanced Materials -THERMEC'2009, August 25, 2009 - August 29; 2009; Berlin, Germany: Trans Tech Publications Ltd; 2010.
- Gibson MR, Tyrer JR, Higginson RL, Blackmur M. The control of grain size during welding and direct metal deposition using three dimensional time-temperature control provided by holographic beam shaping. ICALEO 2009 Congress Proceedings; LMP Conference 2009:653-659.

- Gibson MR, Tyrer JR, Higginson RL. Direct Metal Deposition Melt Pool Temperature Distribution Control Through Novel Holographic Beam Shaping, Allowing Improved Mechanical and Corrosion Properties. ICALEO 2009 Congress Proceedings; LMP Conference 2009:545-551.
- Gibson MR, Tyrer JR, Higginson RL. The use of customised beam profiles to control the overall physical cross section of direct metal deposition of Inconel 625. Proc ICALEO 2008, Temecula, CA 2008:57-63.
- Gibson MR, Tyrer JR, Higginson RL. Novel computer generated diffractive optics modifying beam characteristics to improve the microstructures of directly deposited Inconel 625. Proc ICALEO 2008, Temecula, CA 2008:7-13.

3 Literature and Technology Review

3.1 Laser Deposition

Laser deposition also known as laser cladding is the addition of a filler material to the surface of a base material through a welding operation. Usually the additive material is in the form of a powder, but some processes also used wires and pastes (1-6).

Laser deposition emerged out of academic institutions after the development of high power CO₂ lasers in the mid 1970's. The first process of using a laser to deposit wear resistant coatings is discussed by Steen in 1978 (7). The process described uses a laser to heat an area of substrate, the area is exposed to a chemical vapour, depositing material in the heated region. Steen introduced the idea of using beam shaping optics to control the shape of the laser induced deposition, and holographic mirrors in particular. Around the same time, in 1979, a paper was published by Belmondo and Castagna (8) from the FIAT Research Centre in Torino, reported the first use of laser surface coating using a pre-placed powder, melted under the heat of a 15kW CO₂ laser. The coatings were required to increase the wear resistance and tribological performance of automotive parts. The powder used was a selection of elements and carbides chosen for their known wear resistance. In their study an approximately uniform energy input was achieved by using two high frequency oscillating mirrors to provide a rectangular heating region of varying dimensions. The study reported that the coatings, up to 1mm thick, were similar in composition to plasma sprayed examples. However, porosity formed in the plasma sprayed deposition aided the retention of lubricant. Porosity, as seen in plasma spraying, could be created in the laser process by adding elements into the powder mix that would evaporate during the heating process forming gas inclusions in the remaining deposit. The laser had improved the bonding of the coating to substrate, where the plasma sprayed coatings had serious problems with adhesion of the coating to the base metal of the part. This paper was the first account of a laser deposition process that has the ability to compete with the existing thermal spray processes in terms of deposition rate, while improving the mechanical properties of the deposition adhesion.

The first reported industrial use of the process was by Rolls Royce in 1981 in the production of the RB-211 jet engine (9) shortly followed by Pratt and Whitney in 1983

with the JT8 and JT9 engines (10). In the case of the Rolls Royce blades, manual tungsten inert gas (TIG) welding was used to weld a cobalt-based alloy to the wearing surfaces of blade tip shroud interlocks. The welded coating was easily diluted by the base material of the blade, mainly nickel, with adverse effects on the wear resistance of the deposit. To control the dilution a number of stages were needed in the TIG deposition process. The blades needed to be machined before the welding operation; an initial weld was made and then partially ground back. A second weld was made before a finish grinding process made to form the final deposition geometry. The processes required a high level of operator skill to control the penetration depth of the weld. The delicate balance between the penetration of the weld to avoid excess dilution, while providing sufficient bonding of the deposition, was prone to fluctuations caused by operator fatigue and personnel changes. Another significant problem was cracking in the heat affected zone of the weld. The high alloying in the blade material coupled with the high heat input from the TIG process made the depositions prone to thermal stress cracking (9).

The small size of the blade interlock made the pre placed powder method developed by Belmondo and Castagna unsuitable, leading to the development of a blown powder technique, presented in 1983 by Weerasinghe and Steen (11). The laser deposited coatings were a significant improvement over the original TIG method. The deposits were made with dramatically reduced heat input to the blade, eliminating cracking problems. The penetration and therefore dilution of the deposition was reduced taking the double pass weld and grinding operation to a single laser deposit. Cost savings were made to both the welding process of 85% and a reduction in the hard-facing material usage of 50%.

Laser deposition would initially appear to be unable to compete with thermal, mechanical and explosive methods for the coating of large areas, making the process suitable for coating small precise areas. However the unique advantages of the laser process, of improved microstructures, dilution accuracy and bonding (11) will reduce material usage, component rejection and form a superior deposit, making the process economically competitive for coating large and small areas.

3.1.1 Process

There are two main categories for the laser deposition process, these categories relate to the method of addition of the raw material into the process

- a) Pre-placed Process, this is a two stage process, where the material is placed in position prior to the heating operation. The material is usually in powdered form, but this process can use pre-placed paste or wire (12).
- b) Fed Process, in this process the material added to the clad during the heating process. The material is usually fed as a powder in a gas stream (13,14), but can be laid down as a powder paste (15,15,16), fed into the clad as a wire (17-21) or a combination of these (2,4,22).

Pre-Placed Process

As mentioned above, this process was first shown following developments by the FIAT research centre in 1979 (8). A chemical binder is usually required to hold the powder in place, especially when a gas flow is present during the welding process. The evaporation of this binder causes porosity in the final clad (10). For some uses this is seen as an advantage, as the porous surface improves the lubrication retention properties.



Clad Direction

Figure 3-1: A schematic of the pre-placed deposition process using powder

In the second stage of the process the laser beam creates a melt pool on the surface of the pre-placed material, the melt pool travels through the material to the interface between the clad and base material, there the heat travels into the base material bonding the clad, a schematic of the process is shown in Figure 3-1. This process requires high control of the heat input to the clad. The heat input will have an effect on the dilution of the clad material by the base material. (10).

Material Feed Processes



There are three main methods of adding material during the deposition process.

Figure 3-2: Schematic of the fed deposition processes (a) paste feed, (b) wire feed and (c) powder feed.

Paste Feed

In this process a powder material is mixed with a binder to form a paste. The paste is deposited upon the substrate ahead of the laser beam. The binder is usually in the form of an alcohol, so it evaporates rapidly, leaving only the powder once the laser beam is incident on the deposition. If the binding material was to remain present during the heating process porosity will be present in the deposited material. The paste feed process is illustrated in Figure 3-2a.

Wire Feed

This process, shown in Figure 3-2b, has the advantage that material in the wire form is cheaper than powdered material, and that all the material fed into the clad will be melted in the melt pool. But in contrast the process causes low surface quality, poor bonding strength, porosity, cracks and drop transfer (10).

Powder Injection

In this process powdered material is fed into the melt pool, either carried by a gas stream or by gravity. An off axis powder delivery system is illustrated in Figure 3-2. Using powder delivered coaxially with the beam has the advantage of enabling material deposition to take place in any direction.

The powder feed needs to be carefully controlled to ensure a stable powder stream and feedrate is maintained (23). The powder is initially fed and measured by various means, typically gravity, mechanical wheel, fluidised or vibration (10), and then finally carried to the clad by an inert gas stream.

3.1.2 Laser Deposit Parameters

Deposit Profile

The profile parameters are used as a descriptive term for the dimensions of the deposited layer. The profile is represented as a ratio of the width of the deposit to its height, (*w/h*). A study by Qian et al. (24) shows that the profile ratio of the deposit increases with an increase in the deposition speed, or a decreasing of material feed rate. This observation is confirmed by a study by Liu and Li (25). A further indicator of the deposit profile is the angle the deposition makes with the substrate (α), Figure 3-3.



Figure 3-3: Deposit profile terms

Laser deposit profiles all possess a domed profile, Liu et al. (25) showed that the transverse cross section shape of the deposit is caused by the two dimensional shape of the beam incident on the work piece and the powder distribution caused by the powder delivery nozzle. This study however neglected the fluid flow forces acting on the weld pool caused by temperature gradients induced by the uneven intensity distribution within most laser beams. Weerasinghe and Steen in 1983 (11) found that deposits with a heavy level of dilution showed an almost uniform elemental composition. This shows that there is significant motion of material in the melt pool to mix the melted substrate and deposit material. A number of other authors have shown or observed a stirring effect in the weld pool (26) but these effects have been widely neglected in studies for the prediction of the deposition profile.

Liu (27) in a computer modelling study made the assumption that as the melting points of the deposition material and substrate are similar, the average temperature in the melt pool will be around the melting point of the materials. He concludes that the viscosity of the melt pool will therefore be high enough to allow the effects of melt pool flow to be neglected. Although it is stated that a 500W CO₂ laser, when using a focusing lens, the beam profile was quite possibly a Gaussian distribution and certainly circular in shape. Both these beam profiles will produce a temperature gradient across the transverse deposit profile, with hotter at the centre than at the edges of the deposit. Liu reports that the depositions produced are 0.3mm in width therefore required a weld pool also 0.3mm in width. The minimum temperature of this weld pool will be at the melting point of the material, but due to the centre of the beam being more intense than the outer edges, the centre of the weld pool will be significantly above the materials melting point. The statement from Liu, that the average weld pool temperature is just above the melting point is thought to be incorrect. The minimum temperature of the molton pool will be the melt point of the material, with the with the average temperature of the pool being above this figure. This therefore casts doubt into the validity of neglecting fluid motion in the pool, based on the pool temperature being of just above melting point. In this study and an earlier example by the same author along with Lijun Li (25), also neglecting flows in the molten material, the theoretical models produced are compared against experimental results. However the images in the reports are of insufficient quality to make a judgement as to the validity of the theoretical models and no quantitative measure is provided by the authors. In both these papers (25,27) the only factor influencing the shape of the deposition was the distribution of powder flow into the weld pool. This will form a Gaussian function due to

the nature of flow within a pipe. The function given for the mass distribution input to the weld pool is:

$$m(x, y) = \frac{2\dot{m}_p}{\pi R_p^2} \exp\left[\frac{-2(x^2 + y^2)}{R_p^2}\right]$$
(3-1)

Where, m(x,y), in grams, is the mass concentration at (x,y), mm, m_p is the mass flow rate at the peak of the flow, in g.min⁻¹, x and y represent the Cartesian coordinates, in mm, through a cross section if the powder flow and R_p represents the diameter of the powder stream, in mm, where the mass flow rate has dropped to a factor of e² to the peak flow.

A paper by Yang Xi-Chen et al. (28) showed that there is a significant level of stirring of the weld pool. They measured a velocity 0.8ms⁻¹ in the molten material. Their observations on the homogenous distribution of alloy elements in the pool supports those of Weerasinghe and Steen in 1983 (11). A statement of great interest to this study is made by Yang Xi-Chen et al., where the convection flows in the deposit are related to the laser beam shape. The observations show that the dilution of the deposit is heavily dependent on the convection flows in the pool. A convection flow from the bottom of the deposit towards the surface will increase the dilution of the deposit material within the substrate. The direction of fluid flow matches this case with a traditional unshaped beam. Where the centre of the weld pool is heated with a greater intensity, increasing the density causing material at the centre of the pool to rise.

Investigations by Woolf in 1988 (29) showed that a surface skin on a weld pool, caused by buoyant inclusions or impurities such as oxides, have an effect to reduce surface flows. This makes the dominating weld pool force the buoyancy flows caused by differential densities. The model by Woolf cannot be applied directly to laser deposition as it is rectangular and in the surface of the weld, as such the weight of the material above the substrate surface is not applied. Further discussion on the mechanisms involved in melt pool flow is covered in section 3.4.

Dilution

There are two methods for measuring the dilution of a deposit material by the base material. The physical method uses a ratio of how far the deposit has penetrated into the substrate against the deposit height

Dilution= Depth of Penetration (3-2) Clad Height+Depth of Penetration

The alternative and more widely used method is to express the dilution as a percentage of the volume of material at the surface of the deposit contributed by melting of the substrate:

Dilution

$$= \frac{\rho_c(X_{c+s} - X_c)}{\rho_s(X_s - X_{c+s}) + \rho_c(X_{c+s} - X_c)}$$

Where

 ho_c is density of melted deposition material, g.mm⁻³

 ρ_s is density of substrate material, g.mm⁻³

 X_{c+s} is weight percent of element X in total surface of deposition

 X_c is weight percent of element X in deposition

 X_s is weight percent of element X in substrate

Dilution of the deposit material by the substrate is considered detrimental to the quality of the deposit, degrading the mechanical properties (30). The mechanism for dilution of the deposit with parent material differs depending on the deposition process. Where the deposition material is pre-placed the dilution of the final deposit is dependent on the laser power used for the weld. This differs in a single step process, where the material is added during the weld, in this case material feed rate will depict the dilution levels in the deposition, this is shown in a study by Qian et al. (24) who show that the dilution in a deposit can be improved with a decrease in the deposition speed or an increase in material feed rate. This is shown not to be the case by a mathematical modelling for laser deposition with wire feeding. A study by Kim et al. (21) where their finite element model of deposition by wire feeding showed that the dilution of the

(3-3)

deposit is decreased with an increase in deposit speed. This study also shows preheating of the substrate has an effect to increase the dilution of the deposit layer.

In addition to the parameters of the laser, as discussed above a study by Yang Xi-Chen et al. (31) found that the weld pool flows, driven by the beam profile, had an effect on the deposit dilution. With an upward flow causing mixing of the substrate material into the deposition.

3.1.3 Laser Deposition Applications

Coating

In this process a thin layer of new material is deposited onto a part to change its surface properties. This gives the part properties that the bulk material cannot achieve alone, such as corrosion resistance and/or wear resistance.

Generally wear resistive coatings are required to perform three main tasks.

- 1. A strong bond to the parent part, which will not fracture under physical or thermal loading.
- 2. Optimum properties from both the coating and parent materials, for this to be achieved there should be no mixing between the coating and base materials.
- 3. Thick enough to provide wear resistance throughout the lifetime of the part, but still able to resist delimitation from the parent part.

Coating by laser processes has numerous advantages over other processes, such as thermal spraying, explosion coating, plasma coating, Metal Inert Gas and Tungsten Inert Gas welding.

- 1. Thin layers can be achieved.
- 2. A wide variety of materials can be used for both the substrate and deposit material.
- 3. Fully dense coatings can easily be achieved.
- 4. Good control of the dilution of the deposit by the substrate material, reducing the thickness of deposit needed to achieve the desired surface qualities.

- 5. The heat input to the part is low and localised, reducing deformation in the coated part.
- 6. The laser can be controlled to heat a small localised area, allowing coatings to be placed exactly where needed with minimal wastage.
- 7. The process is easily automated.
- 8. The very fast quenching rate achieved with laser processes allows a very fine microstructure to be formed in the deposited coatings when compared to competing processes.

Laser Deposition for Component Repair

The high cost of repairing components by welding needs to outweigh the cost of new parts. The process is therefore reserved for the repairing high value parts such as turbine components (32,33), machine tooling (26) and steam turbine blades used in the nuclear industry (34,35).

In steam turbines with the blade tips approaching supersonic speeds, condensing water causes erosion to the leading edges of the blade aerofoils. Traditionally repair of this damage has been undertaken using TIG welding to deposit material onto the damaged area of the blade. The blade is then machined back to the original dimensions. A study on power station blades in Australia by P. Bendeich et al. (32) showed that the laser weld repair of turbine blades left residual stresses in the component. In this case the blades were repaired with a cobalt based Stellite 6. Test deposits were made onto stainless steel 420 plate as a comparison to the blades, of presumably, although not stated, the same material. Residual stresses in the blades and test welds have been caused by a combination of the differing thermal expansion of the materials with a difference in heating/cooling rates at varying locations throughout the repair. A maximum residual stress was measured in the turbine blade in excess of the yield point of 420 stainless steel, indicating that repair of blades in this way is likely to result in mechanical failure at the repaired region. Recommendations by Hollingworth and Ortolano (33) state that initial repairs in 1977 made by manually welding Stellite onto the high chromium (12%) content blades caused cracking at the weld interface. This is due to the difference in thermal expansion between the two materials. These findings agree with the measurements of P. Bendeich et al. (32) where the residual stress in the repairs was above the yield of the blade material. The solution found was to weld in place a wrought Stellite shield using a nickel-based filler

material. In addition to chromium Grezev and Safonov (36) found that increases in boride phases in a material increased cracking on welding.

A mechanism for deformation in the components produced through laser deposition has been proposed by Kruth et al. (37) as the temperature gradient mechanism (TGM) used for laser bending. The rapid heating of the surface layer and the relative slow conduction of heat lead to differential expansion and material strengths. The combination of these factors leads to a deformation of the material. Control of the heating rate in the material could be of use to reduce the deformation by this mechanism.

Machine tools, although not manufactured from expensive materials have a large amount of machining cost invested in them. Repair of the components may be required after manufacturing errors, wear or fractures in service. There are some special considerations with the repairing of mould tool (38), where any imperfection in the surface of the mould will be transferred to the parts produced. Any porosity present, and, where the part is to be polished, any variations in hardness will lead to a contour where the repair was made. The process is further complicated when texturing is to be applied to the mould. In this operation the surface of the tool is exposed to an acid attack. The chemical composition of the filler material used will have a significant effect on the depth of acid attack. The composition of the repair material will also have an effect on the microstructure formed in the deposit, this coupled with the differing microstructure formed under the welding process to that of the machined tool body will also affect the depth of acid attack. Failure in die tools can be attributed to a number of mechanisms (39). On die casting of metals the most common failure is cracking at the mould surface due to thermal fatigue, or erosion from the molten material injected into the cavity. For injection moulding of polymers the high pressures cycles will cause fatique. To reduce their failures, the dies surfaces are often treated by nitriding or chromium plating. A study by Vedani et al. (26) investigated the problems of weld repairing tool steel dies with such coatings applied. The welds were made using a Nd-YAG laser with the filler material in theform of a 0.5mm wire. The depositions made on uncoated 1.2738 tool steel showed microcracks when a deposition material rich in carbon and chromium was used. When the depositions were made onto chromium plated samples of the tool steel they always showed cracking in the heat affected zone. The melting of the chromium plating had significantly enriched the deposition causing cracking as the deposition solidified. Depositions made onto a nitrided sample of the tool steel showed a very large level of porosity formation. There are also levels of cracking origination from the pores. On examining the surface of the deposits, pores

breaking the surface are located towards the outer edges of the track. Separation in this way can be explained by either a transportation of the molten material towards the edges of the pool, or the intense beam centre reducing the formation of the gas inclusions at the deposition centre. There is no information in the article about the beam delivery system and therefore the energy distribution at the work piece, so only speculation regarding the effect of beam distribution can be made

3.2 Materials and Material Behaviour

3.2.1 Microstructure

The thermal cycle during the laser process will affect the microstructure, residual stress and distortion of a deposition (37,40,41) consequently the properties of the material produced by laser deposition may be quite different from the wrought state (42,43). The laser deposition process adds further complications where material is re-melted and heat treated during the deposition of subsequent layers (44) when depositions are made side by side to cover large areas or the deposition of additional layers to build a thicker coating.

In the previous section difficulties in the weld repair of components were identified. This review will concentrate on the materials used for the manufacture and repair of high cost components, suitable for repair welding with a laser. The difficult operating conditions of the parts require them to be made from special materials. These usually heavily alloyed materials have shown problems with cracking at the fusion zone or within the deposit, attributed to differences in thermal expansion rates between the deposit material and the substrate, (32), the increase in crack promoting elements through alloying of the base and filler materials (33,39) or surface treatments of the parent part (39). Another important factor on the influence of mechanical failure is the microstructure left by the laser processing itself. The very rapid cooling rates given by laser processing will give a microstructure differing from that of the parent material. Any uneven heat input from the laser beam will also have an effect on the temperature reached and cooling rates for the material leading to variations in the microstructure of the solidified deposit. These changes in the microstructure might be beneficial, for example, the rapidly quenched microstructure will give coatings with good wear

properties. However for welding for the repair of parts require a deposit with similar mechanical properties.

Dinda et al. (43) found depositions of Inconel 625 to have columnar dendrites growing epitaxial from the substrate. The dendrite growth direction was seen to be with the direction of the laser scanning. This would indicate that the slowest rate of cooling is along the laser traverse path. Ganesh et al. (42) found that the deposition of austenitic stainless steel 316L developed a typical cast microstructure associated with segregation and directional solidification. Many of the problems seen in the repair of structures is the cracking due to residual stresses caused in the welding process. The microstructure promoted in the deposits due to thermal gradients present in the molten material will have a reduced resistance to the crack propagation. According to Saxena (45) weld locations form the point for the majority of failures in elevated temperature service components. An investigation into the microstructures produced in the conduction laser welding of 316L stainless steel by Kell et al. (46) showed that the energy distribution input to the weld from the laser beam has an effect on the resulting microstructure in the solidified deposit. Kell compared the welds produced using a Gaussian energy distribution and a rectangular beam of uniform distribution. The initial observation found was that the fine microstructure observed in the weld was segregation of the alloy constituents, and not grain boundaries as have might have been assumed previously with laser melting processes. In this case using a uniform beam distribution had no observed effect on the grain size, remaining at 200µm, although the segregation of the alloy elements was decreased. In a continuation Kell et al. (47) used modified beam profiles to control the microstructure and weld pool forces to produced weld with superior appearance and microstructure. Using thermal modelling Kell was able to predict the heat flow from the laser into the material. An ideal thermal profile is chosen to give near uniform heating across the width of the weld pool. Using a holographic optical element to reconstruct this profile, welds were made with a more consistent microstructure across the weld region. The modified beam distribution produced a weld with smaller grains than the Gaussian distribution, with an improvement in the boundary angles between neighbouring grains in the weld.

The grain boundary characteristics of the deposition are important in the resistance to intergranular cracking, an issue identified as a problem for the weld repair of components. Controlling the grain boundary properties is of *"critical importance"* (48) and controls a number of intergranular decay processes, fracture, corrosion, stress corrosion cracking, sliding and creep cavitation, embrittlement and sensitisation (42). found that the resistance to pitting corrosion in laser deposited 316L stainless steel

was lower than that of the same material in wrought condition. The repeat exposure at the sensitisation temperature range caused by heating during subsequent layer deposition coupled with the slow rate of cooling seen in the depositions lead, to sensitization of the material. Post annealing of the material was able to improve the pitting corrosion resistance. The authors noted that there was a wide variation in the corrosion resistance performance in the laser deposited samples.

The grain size and geometry also play a role in the properties of the bulk material. Particularly important in the repair of high temperature machinery if the resistance to creep at high temperature offered by a large average grain size.

Crystal boundaries fall into three categories, low angle, Coincidence Site Lattice (CSL) and random high angle. Of special interest is the coherent twin boundary known to enhance bulk material properties. Twinning is a property when neighbouring grains have crystal orientations that are a mirror image of each other. The formation of this improved microstructure usually requires cold working followed by an annealing operation (48).

3.3 Thermal Profiles

3.3.1 Thermal Profiles in Laser Materials Processing

Han and Liou (49) found through thermal modelling that the thermal profiles present during a static welding process influenced the shape of the molten pool. A number of other authors have made reference to the influence on microstructures resulting from the laser beam profile (50).

Yong (51) talked of the desire to have a non-circular beam for a number of processes. The effect of two laser beam profiles on laser surface treatment were modelled by Maier et al. (52) in a modelling study on the influence of Gaussian and uniform rectangular beam although no comparison was made between the two differing beam profiles.

3.3.2 Measurement of Laser Induced Thermal Profile

Measurement of surface thermal profiles during laser material processing is difficult requiring specialist equipment (40,41,44,50,53,54). The conditions seen in laser machining are extreme even for non-contact pyrometry techniques. Ignatiev et al. (41) stated that care must be taken when using indirect measurement techniques, such as total intensity of radiation from a processing region. This measurement can be made up of a number of contributing factors, for example emission due to surface temperature and the emission from plasma plume. The two influences on the measurement are not easily separated leading to incorrect reading of the process conditions.

Pyrometry

A number of authors have described the problems when using optical temperature reading methods during laser materials processing due to the similarity in the wavelengths used in the processing and measurement. Doubenskaia et al. (53,55) discussed the complications of using optical pyrometers during processing with a Nd:YAG laser as the 1064nm laser wavelength is within the damage threshold of the majority of commercial pyrometers. In their study notch filters are used to protect the pyrometer. Similar problems have been described by Adams et al. (56) during the measurement of laser surface annealing using a diode laser at 810nm. The authors found that the use of filters alone was not sufficient to remove the influence of the laser source and further compensation was required in software.

The high speed of acquisition for pyrometry signals has been used to allow the thermal evolution of an interaction region during pulsed laser processing. Doubenskaia et al. (55) used a pyrometer to analyse material temperature during deposition with 20ms pulses of a Nd:YAG laser.

Single Colour

A single colour pyrometer, also known as a single wavelength pyrometer, measures the amount of a narrow wavelength band emitted by a surface. The single wavelength pyrometer will only read the true temperature of an ideal black body, non-ideal surfaces known as grey bodies will emit at a value lower than the black body (57), this reading is known as the brightness temperature. The ratio between the emission of the grey-body being observed and the ideal black-body is known at the spectral emissivity and must be known to increase the reliability of the temperature readings. The relationship for single wavelength pyrometry is: (58).

$$J_{\lambda}(T) = \epsilon_{\lambda} J_{\lambda}^{bb}(T)$$
(3-4)

Where

 $J_{\lambda}(T)$, W.m⁻² is the measured single wavelength emission at temperatur

 ϵ_{λ} is the material emissivity

 $J_{\lambda}^{bb}(T)$, W.m⁻² is the emission of a black body at temperature T

Ignatiev et al. (54) discussed the construction of a single colour pyrometer suitable for use for the monitoring of laser materials processing. It consists of a photo lens and pinhole diaphragm connected to an InGaAs photodetector by an optical fibre. The detector is filtered at a wavelength of 1.5µm. The photodetector signal is amplified before interfacing to a computer with custom written software. It is claimed this system will can measure temperatures in the range of 800-4700K.

Shakeel et al. (59) used a single colour pyrometer to measure the surface temperature of a molten pool during laser melting of metal powders. Optics on the pyrometer allow it to measure a spot region of 300µm, in the cited study the authors were using the pyrometer at an angle, although they acknowledge this will expand the measurement region. In the study the pyrometer spot is "significantly" smaller than the melt pool, leading to a localised temperature reading being taken at a discrete region of the melt pool. A very similar setup was used by Safdar et al. (60) to again form comparison between a thermal model and experimental results. However the pyrometer was used alongside a thermal image camera with a discrepancy between the values recorded. The author notes that the pyrometer readings are more consistent with the thermal modelling. The time temperature plots obtained also differ from the thermal model, this was attributed to a lag in the pyrometer, no information as to the sampling rate was given and no indication of a lag has been seen in any other literature.

Doubenskaia et al. (53) used an array of single wavelength (860nm) photodiodes to give a 2D image of the thermal profile during laser deposition. The array was able to give two dimensional information on how the thermal profile varied within the melt pool.

Although an accuracy of ±1% is quoted for a CCD based monochromatic pyrometer (53), A major drawback for the use of single colour pyrometry for the measurement of molten metals is that the emissivity of the material changes with temperature (61). The changes in emissivity with temperature makes the grey body approximation invalid. This will lead to errors in the temperature measurement requiring a carefully calibrated compensation curve.

Two Colour Pyrometer

To overcome the problems of single colour pyrometry the two colour, also known as, two wavelength pyrometer was developed. The two colour pyrometer measures the amount of energy emitted in two narrow wavelength bands, with a grey-body the emissivity at these two bands can be approximated as constant and cancelled when a ratio of the two readings is taken (41,57).

An online process monitoring system for selective laser melting was proposed by Chivel and Smurov (62) using a two wavelength pyrometer to give a spot temperature reading and a video camera to give feedback as to the melt pool thermal distribution.

A pyrometer system was used by Smurov et al. (50) consisting of an imaging lens collecting light onto a mirror with a pin hole diaphragm. Following the diaphragm was a diffraction grating. This separates the light into a spectrum by wavelength. Two photodiodes are placed at locations on the spectrum to capture the intensity of two different wavelengths, the output signals were computed using analogue circuitry to give a direct reading of temperature as a voltage level signal. This method was able to give a linear response to the temperature up to 2350K. It was found that during welding of mild steel there was a level of "intensive" noise that was attributed to the splatter emitted from the melt pool. The reading varied depending on whether a particle of splatter crossed the field of view of the pyrometer at the beginning of its trajectory, when it was still hot, or at the end, when it had cooled, or indeed not at all. It is noted that temporal filtering may be able to reduce this effect. The authors also note that the level of this noise seen in the signal may indeed be a useful process measurement of how the level of splatter is affected by the processing parameters.

Pavlov et al. (63) used a two wavelength pyrometer developed by the authors for online monitoring of a selective laser melting process (SLM). The pyrometer had a measurement spot of 560µm. This is a large measurement region relative to the laser interaction spot of 70µm leading to an underestimate of temperature as some unprocessed substrate was in the measurement window. This is acknowledged by the authors who use the pyrometer to give relative readings as to the surface conditions and not to give readings of temperature. The much larger pyrometer spot was used by the authors to characterise how the heat from previous tracks remained in the substrate and contributed to the following processes. It was seen that the temperatures reached in the tracks increased with the number of tracks deposited.

In an extension to the two colour pyrometry technique Doubenskaia and Smurov (64) discussed the use of a pyrometer that reads at 12 wavelengths although only 4 were used by the authors to calculate the temperature.

Jenkins and Hanson (58) calculate that the errors in the two colour pyrometry process used are ±50 K on measurements of approximately 1600 K. Estimation as to the accuracy of a two colour pyrometry system by Ignatiev et al {{315 Ignatiev,M. 1994;}} gave errors of less than 10 K on reading of up to 5000 K.

Ignatiev et al. (54) investigate the errors in two colour pyrometry when an erosion plume is ejected from the melt pool. As the plume only emits in certain wavelengths dictated by the material chemistry the reading of the ratio between wavelengths is distorted leading to inaccurate thermal readings.

Imaging Systems

The use of imaging systems allows for a two dimensional measurement of the deposition pool. This is an advantage over the single point pyrometers that are only able to record the average temperature in the measurement spot. The emission spectrum of many metals at the temperatures used in welding and deposition sit in the sensitive regions of standard silicon based imaging sensors allowing low cost thermal measurement of molten metals (61)

Doubenskaia et al. (53) used a non-intensified CCD camera system to visualize a powder stream in laser deposition. The camera was filtered to image in a band of 800-960nm. Although the camera was not used in the study to image the melt pool it is described as being able to image a brightness temperature range of 1200-3500°C and could be suitable for melt pool imaging, although the wide band of wavelengths images

would affect the accuracy of temperature readings, this has been estimated by Zhao et al (65), who analysed the errors of this technique to 1.5% - 3%.

Chivel and Smurov (62) use a CCD based system alongside a pyrometer to get 2D thermal profiles of laser melting and sintering processes. They use a beam splitting prism to get two images at different wavelengths. The relative intensity between the two images was then used to calculate the temperatures of the object.

Jenkins and Hanson (58) discussed the use of visible wavelengths for the collection of emission levels in a study on two colour pyrometry of soot particles in flames. A similar process was used by Bardin et al. (61) to give real time temperature monitoring during laser conduction welding. The system was chosen as it was able to give readings in the 2000 -3100K range outside most commercial pyrometers and could give the 2-D temperature profile required. Bardin discussed the use of various camera setups to form a ration between two wavelength bands. The authors chose to use a colour CMOS camera with built in Bayer filter giving three band pass filter options of 450nm, 550nm, 650nm ±70nm. Custom software was able to extract the red/green channels from the image to form a ratio to be multiplied by a scale factor to give the temperature the pixel is imaging. The system was able to provide closed loop control of the laser spot size at a rate of 10Hz.

3.4 Melt Pool Flow

Shakeel et al. (59) stated that experimental measurement of melt pool flow is a major challenge, adopting numerical modelling for calculating convective heat flow.

The dominating mechanism of weld melt pool flow is regarded to be the Marangoni flow (59,66-68). Buoyancy flow is a second mechanism discussed in the literature (40). Kou and Wang (69) showed that the surface tension flow was approximately 300 times faster than that of the buoyancy flow mechanism.

As the main melt pool forces are driven by temperature gradients the melt pool flow can be altered by controlling the thermal profile in interaction region (66,70)

3.4.1 Marangoni Flow

The forces creating Marangoni flow was first discussed in relation to weld penetration depth variations in robotic tungsten inert gas (TIG) welding in the 1960's (66). Similar effects were also seen in laser welding.

Marrangoni flow is driven by surface tension gradients within the liquid melt pool. Where variations exist a flow is induced from areas of low viscosity to areas where the viscosity is higher.



Figure 3-4: Schematic showing Marangoni flow in relation to surface tension gradient

In the case of weld pool flow, high thermal gradients are seen from the centre of the melt pool to the edge, in the region of 500K.mm⁻¹ (66). The elevations in temperature at the centre of the melt pool cause a drop in the surface tension. This thermal gradient produces low surface tension at the centre to high surface tension at the edges of the pool (66). The corresponding material transport effect is to drive the low viscosity material from the centre of the melt pool to the edges, recirculating within the pool. This effect is illustrated in the schematic in Figure 3-4. The mechanism of Marangoni flow has been simulated by a number or authors. Limmaneevichitr and Kou (68) described a study by Ishizaki et al. (71) where a soldering iron was used to locally heat the surface of a thin slice of molten paraffin. In their study Limmaneevichitr and Kou use a transparent pool of NaNO₃ heated with a defocused CO₂ laser. NaNO₃ was chosen as it exhibited similar surface properties to those seen in metal welding. In the study laser light sheet illumination was used to give visualization of a single 2D plane in the melt pool. It was found that increasing the power of the laser heating source led to an increase in the melt pool flow speed. The flow patterns seen were two counter-rotating pools flowing across the surface from the centre to the edges then returning up the

centre of the melt pool. This flow is of the same mechanism proposed by other authors (66)

3.4.2 Melt Pool Flow Modelling

Safdar et al. (59) compare thermal models based on both heat transfer and fluid flow mechanisms. In a heat transfer mechanism the maximum temperature reached in the melt pool is significantly higher than that seen with a fluid flow model. The uniform circular beam profile leads to a 600K higher peak temperature. In the study an experimental measurement is made showing the peak temperature predicted by the fluid flow model to be much closer to the measured value. Using the same model the heat transfer model leads to melt pool depth prediction five times that of the experimental measurement. These observations give evidence to the melt pool being fluid and of low viscosity enabling fluid flow mechanism to be the overriding heat transport mechanism. Further investigation by the author (72) shows good correlation between modelled and experimental results when a numerical model designed to account for Marangoni and buoyancy flow forces is used.

Numerical modelling on melt pool flow by Safdar et al. (59) indicated surface flow velocities to a maximum of 0.712m.s⁻¹ for a 3.34mm uniform circular beam induced melt pool of EN-42A mild steel. In the same study this model was used to simulate the melt pool for rectangular beams, a rectangle of 2.5x3.5mm with the short side parallel to the scanning direction gave a surface flow prediction of 0.656m.s⁻¹. Other studies have computed higher velocities in the melt pool during welding of aluminium of 3m.s⁻¹ when a small melt pool is present, 0.6mm wide by 0.15mm deep (73). A study by He et al. (44) found the fluid flow velocity in a tool steel melt pool to be 1.7m.s⁻¹ when using a circular Gaussian beam. This higher velocity than seen by Safdar et al. (59), who used a uniform circular beam, is easily explained by the higher thermal gradient induced by the Gaussian intensity distribution.

Han and Liou (49) used computer modelling to investigate the effect of the melt pool flow mechanism on the shape of the melt pool. A number of circular beams with different intensity modes were used to make static melt pools in 304 stainless steel. It was found that the laser beam mode altered the melt pool flow. The melt pool flow in turn played an apparent role on the melt pool shape. Safdar et al. (59) in thermal modelling of laser melting of metals showed the possibility of a small melt pool preceding the main melt pool when using uniform circular beam geometry. The authors point out this is undesirable as it may lead to inconsistencies in the resulting microstructure including concentration of alloy elements or porosities.

3.4.3 Melt Pool Flow Observation

Zhao et al. (40) discussed a study by Heiple and Roper (74)who used a high speed camera to visualize the surface flow of a gas tungsten arc (GTA) weld pool. Flow velocities were found to be in the region of 0.5-1.4 m.s⁻¹ with an average value of 0.94 m.s⁻¹. A similar visualization technique was used by Ecer et al. (75)

3.5 Laser Beam Distribution

3.5.1 Laser beam profiles in Laser Materials Processing

The majority or laser materials processing uses circular or possibly rectangular beams (59,60). The laser beam geometry is considered to be a viable tool to alter the melt pool characteristics (59). Varying the laser beam geometry enables a control of the melt pool thermal profile without alteration to the power, feed rate or scanning speed, giving added flexibility to the process control. In conduction processes, without melting, the shape of the beam alters the energy absorbed across the width of a scanning beam. A circular beam when scanned will absorb more energy at the centre of the track than at the edges where the energy per unit area will be lower, this leads to variation in the depth of penetration of the heating effect of the laser. Penetration will be hemispherical when using a circular beam and more uniform when a rectangular beam is used (60).

The shape of the laser beam has the ability to alter the maximum temperature reached. Safdar et al. (60) investigated the temperatures reached in a number of beam profiles without melting. It was found that beams longer than wider in relation to the scanning direction gave higher temperatures; the beams compared had the same power density and scanning parameters.

Safdar et al. (59) found that, through thermal modelling, when uniform intensity beams of differing shapes are used, a constant power density in the beam will lead to similar maximum temperatures. The authors comment that beams with a longer dimension in the scanning region tend to show a slight elevation in the maximum temperature. Importantly, when the beam shape was varied the heating and cooling rates seen from the model differ with the change in beam shape. Of the shapes studied, a rectangular beam with the long dimension in the scanning direction gave the highest heating rate, closely followed by a circular beam, with a diamond (square rotated 45°) beam giving the slowest heating rate. It is noted a slow heating rate is preferable when undertaking processes involving diffusion such as transformation hardening and conduction welding. The cooling rates output from the model showed a reversal from the heating rates, with the diamond beam shape having the largest cooling rate of those studied. Importantly the second fastest cooling rate was seen with a circular beam. The circular beam also has the highest cooling rate at the transition temperatures between solid to liquid phase. A similar effect was seen in a study by Safdar et al. (60) in a laser heating study.

3.5.2 Methods of Modifying Beam Energy Distribution

The Gaussian distribution intensity profile produced by many lasers (51) can be altered in a number of ways.

Masking

A mask can be used to only allow the shape of beam desired to be incident on the material surface. This method has been used for surface heating of metals (60)

Beam Splitting

Lu (51) modeled the thermal profile in material after the splitting a Gaussian beam into quadrants about the centre point of the beam. Lu arranged the quadrant beams with the peak at the corners of a square with the Gaussian curve internal to the square. In practice this would be achieved through the use of a four faceted prism. This intensity

profile although non uniform has shown through modelling to give a uniform square heated region. It is noted that the uniform region is achieved when the distance between the peaks of the re-arranged beams is equal to the diameter of the original Gaussian beam.

Diffractive Optical Elements

Diffractive optical elements (DOE) are computer generated kinoforms, a complex diffractive structure that can take the output laser beam and transform the beam shape and intensity distribution into any desired profile. Controlling the intensity distribution of the beam allows a tailored energy distribution to develop in the material being processed.



Figure 3-5: Schematic of phase shifting due to DOE stepped surface

Figure 3-5 illustrates how the stepped surface of a DOE induces phase shifts in the reflected beam, at a value of twice the step height. The elements surface is divided into an array of cells, with each cell's height carefully machined. When a coherent light beam is incident on the element, each cell reflects a spherical wave front. With the phase of the wave shifted relative to the step height of the surface. The reflected wave fronts interfere, reconstructing the desired intensity profile at a given working distance.

Optic elements for high power CO_2 lasers, as used in this study, are a reflective surface with a stepped relief. Figure 3-6 shows an image of a DOE for use in a high power CO_2 laser, along with an SEM image of the elements stepped surface. The pattern of steps

on the DOE surface is generated by a computer algorithm. The stable beam profile of the laser is input to the software, this then calculates the DOE pattern required to produce the desired beam intensity distribution. The pattern is designed by dividing the incident beam width into a grid of 256 x 256 pixels. The user is then able to define the relative intensity level at that pixel.



Figure 3-6 Holographic Optical Element (HOE) for use in high power CO₂ laser (a) and (b) an SEM image of the elements stepped surface.

Manufacture of the DOE's uses a photo lithography process, similar to the manufacture of integrated circuits. The process, as shown in Figure 3-7, uses a film writer to create a grey scale mask for the optic design. The mask is used to selectively expose a photoresist coating applied to the optic. The grey levels in the mask result in variations of the photoresist curing, darker areas in the mask lead to les curing of the resit. The final step is to use a plasma etcher to translate the photoresist pattern into the body of the optic. Where the photoresist was strongly exposed the etcher penetrates less resulting in a higher step on the optic surface.



Figure 3-7: Processing steps to create DOE from computer generated mask

DOE's have been used in a number of studies on the influence of three dimensional beam shaping in laser materials processing (46,47,76-79).

3.6 Summary

The literature shows that there are a number of problems with the laser deposition of metallic materials. Problems such as residual stress, cracking and distortion are caused by the microstructure formed by the laser process (37,40,41). Laser produced depositions typically exhibit a cast microstructure associated with segregation and directional solidification (42).

It has been seen from a number of authors that the thermal cycle throughout the deposition process influences the formation of the microstructure (42,43). The thermal profile in the melt pool has been seen to be influenced by the laser beam shape, in turn altering the deposition microstructure (50).

Through the use of numerical modelling, alterations in thermal profile of the melt pool have been seen when shaped laser beams are used. It therefore leads to the conclusion that the laser beam shape has a role in the alteration of the thermal profile and therefore the microstructure formed in laser depositions.

As well as a modification in the microstructure seen due to the laser beam shape, a number or authors have investigated the role laser beam shape has on the material transport taking place during the deposition process. The review of literature shows direct measurement of melt pool flow to be very difficult, leading to numerical modelling used to simulate the process (59). The mechanisms of melt pool flow have been identified as thermal profile dependant (59,66-68). The melt pool flow has been seen to alter with changes in the laser beam profile. Numerical modelling has shown alterations to both speed and direction of the flow mechanisms.

Thermal profiles in the melt pool has been identified as a driving factor for both the microstructure and profiles of the resulting deposition, however measurement of the thermal profile has been identified as being difficult to achieve (40,41,44,50,53,54). Ignatiev (41) identifies that the use of indirect measurement, where a number of factors
contribute to the measured value, such as surface temperature and plasma plume, as problematic, introducing errors to the measurement. Pyrometry is able to produce direct readings of the thermal profile in the deposition pool, however the extreme operating conditions during the laser process make measurements complex, limiting the operational window of parameters for which the measurements are suitable.

3.7 Conclusions

The literature has shown that the beam shape is able to alter the microstructure of a laser deposition. The thermal profile in the deposition pool is a driving factor on both the microstructure formed and the melt pool flow. It is therefore expected that the melt pool flow can be used as an indicator as to the microstructure formation in the deposition.

As the laser shape and intensity profile has been seen to directly modify the thermal distribution it is expected that the use of modified beam profiles will alter the microstructure and physical profile of laser produced depositions.

In this study Diffractive Optical Elements will be used to modify the laser beam used to depositions. It is expected that the microstructure in the formations will alter in line with the expected changes to the thermal distributions. To further understand the thermal distributions present in the melt pool, the surface flow will be observed as an indicator to the thermal profile. It will the aim of this study to show that through the modification of a laser beam intensity profile the thermal profiles in the melt pool will also be altered. This will be then observed through the metallurgy of the depositions and in process factors such as material transport and thermal profiles.

The literature has shown that through thermal modelling the properties of the deposition are altered by detailed observation during the process have not been undertaken to validate the modelling. This work aims to meet this requirement. Once a thorough understanding of the mechanisms at work is gained, the use of customised beam profiles will allow greater control of the material properties present in laser depositions.

This chapter details the materials, techniques and procedures used in this study. The literature review identified a number of suitable materials that are to be used.

A number of studies have identified beam intensity distributions that have shown influence on the material transport. This section identifies the beam intensity profiles that will be used in the study, along with the laser and optical setups that will be used to produce them.

This section also details the analytical techniques used to compare the depositions made with the different beam intensity profiles. The preparation methods and materials used to enable the analysis procedures are detailed. This information is important for any possible recreation of the results throughout this study.

4.1 Substrate Materials

Two substrate materials have been used, mild steel and 316L stainless steel. Both materials have been used in sheet form at thicknesses between 0.8mm – 2mm. The chemical composition of the substrates is shown in Table 4-1.

Element % Weight	С	Cr	Mn	Мо	Ti	Ni	Ρ	S	Si	Fe
316L Stainless Steel	0.02	17.00	1.26	2.45	0.01	10.40	0.029	0.003	0.037	Bal
Mild Steel	0.15- 0.20	-	0.60- 0.90	-	-	-	0.04 max	0.05 max	-	Bal

Table 4-1: Che	emical compos	sitions of su	ubstrate materials
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The samples were initially cut into sheets 210mm x 60mm, using a metal shear. This enabled the sheets to fit into the clamping device shown in Section 4.3.3.

4.2 Deposition Materials

Initial studies used stainless steel 316L as a deposition material. The composition of this deposition is shown in Table 4-2.

Element Ρ С Fe Cr Si Ni S Мо Mn % Weight 316L stainless Bal 17.7 2.6 1.3 0.58 10.40 0.021 0.018 0.006 steel

Table 4-2: Chemical composition of 316L deposition material

Following the review of literature, it has been chosen that the focus of the investigations detailed here will concentrate on using high nickel alloys. These alloys are used to make high value components for use in harsh environments, including high temperature applications in gas turbine engines, nuclear reactors and in sea water environments.

Table 4-3: Chemical compositi	ions of nickel based deposition materials
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	Element (% by weight)														
	Ni	Cr	Co	Мо	Ti	Fe	AI	Si	Mn	Cu	С	S	Zr	Nb	К
Waspalloy UNSN7001	Bal	18.0 - 21.0	12.0 - 15.0	3.5 - 5.0	2.6 - 3.25	2.0 Max	1.0 - 1.5	0.75 Max	0.50 Max	0.10 Max	0.02 - 0.12	0.02 Max	0.02 - 0.12	-	-
Inconel 625	58.0	20.0	1.0	8.0-	0.40	5.0	0.40	0.50	0.50	-	0.10	0.01	-	3.15	0.01
	Min	-	Max	10.0	Max	Max	Max	Max	Max		Max	5		-	5
UNSN06625		23.0										Max		4.15	Max

These alloys contain a high number of alloy elements making the weldability of the alloys poor, this coupled with a high level of chromium leads to a high rate of cracking in the depositions. Two materials have been chosen based on availability, Waspalloy and Inconel 625 (IN625). The composition of both materials along with the American Society for Testing and Materials Unified Numbering System (UNS) are shown in

Table 4-3. The materials are used in a powdered form.

4.3 Laser Procedures

4.3.1 Optical Setups

All the experiments have been undertaken using a Coherent Everlase S48. The laser uses carbon dioxide as a medium with a slow flow gas system, outputting a stable TEM₀₀ mode 10.6µm wavelength beam. The laser has maximum practical output of 1000W, as measured by the internal power meter. For this investigation the powers referred to are those given by the internal power meter, before the losses due to optic inefficiencies. Using the internal power meter allows comparisons between depositions made with the same optical setup, however there are a number of inefficiencies in the system that will lead to the power at the workpiece being lower than that indicated by the internal power meter.

To estimate the internal losses in the optical system a value of 5% loss per surface will be used, this loss is calculated by taking this loss in power at each surface as a compound calculation. Two optical setups are used, and detailed below, the gaussuan cutting head has 6 surfaces between the power meter and workpiece. This will lead to a estimated reduction in power by 26%. The DOE setup has an increase in the number of surface to 10 but also includes losses in the efficiency of the DOE element, this inefficiency is approximately 20%. The estimated power loss at the workpiece from that indicated by the power meter is 50%

The laser system has an optics train where two processing heads are fitted, this allows the direct comparison between the Gaussian beam from a traditional refractive optic cutting head and the customised beam profiles provided by the DOE. The laser beam

is emitted from the laser aperture and circularly polarised to allow multiple directional processing. The beam passes through ZnSe window, mounted at 45° to the optical axis allowing a He-Ne visible wavelength laser to be added along the same beam alignment as the CO_2 beam. The aligned visible beam of the HeNe laser is used for aligning the laser optics onto the work piece. A 45° gold mirror turns the beam into a manually movable mirror. This mirror can be removed to send the beam into a cutting head fitted with a single final focus lens. This head provided the irradiance distribution required for the Gaussian distribution comparison experiments. The final focus lens fitted was 29mm in diameter with a focal length of 63.5mm. With the manual mirror left in place the beam is sent through a 2x beam expander and a final 45° mirror to send the beam into a custom housing in which the DOE optical setup is mounted. A beam expander is required to increase the 15mm raw beam up to 30mm, this allow full illumination of the DOE surface, designed for a 30mm beam.



Figure 4-1: Schematic of the refractive optics system used for Gaussian beam irradiance distribution

A schematic of the cutting head used to achieve the Gaussian energy distributions is shown in Figure 4-1. The cutting head has a bezel that will raise and lower the final

focus optic. This allows the point of focus to be moved respective to the workpiece, allowing the dimension of the beam irradiating the workpiece to be changed.

Provision for an assist gas is provided for when the system is used for cutting, in the case of these experiments the flow is used at very low flow rates (<10I/min) to prevent contamination of the optical system.

To maximise the efficiency of the DOE the laser needs to illuminate the surface as close to its normal as possible. To accomplish this with the dimensions of the optics a mounting system is used to hold the optics at 5.5° to the beam axis. A plane mirror, also mounted at 5.5° is used to illuminate the optic. The beam passes through a ZnSe window upon exiting the housing, this reduces the contaminants entering the housing while processing. A schematic of this arrangement is shown in Figure 4-2.

To protect the ZnSe window and add a shield gas to the deposit as required, a custom nozzle has been built and fitted to the DOE housing. The designed nozzle holds a ZnSe window to keep processing debris from entering the optics housing. The nozzle has three points to feed processing gas, allowing an even flow of gas out of the nozzle to minimise powder loss during the depositing process. The cone nozzle shown in Figure 4-3 has a 10mm aperture, this is however easily changed to allow different flow characteristics in the gas stream. An assembled and exploded view of the nozzle is shown below in Figure 4-3, and installed in Figure 4-4. The collar shown in Figure 4-3 fixes to the base of the DOE housing, this allows the height of the nozzle to be adjusted to change the working distance of the system without affecting the workpiece distance relative to the DOE focal plane. Technical drawings of the nozzle components are given in Annex A.



Figure 4-2: Schematic of the DOE mounting Arrangement



Figure 4-3: Assembled and exploded views of the DOE housing shield gas nozzle



Figure 4-4: Gas shield nozzle installed

4.3.2 Laser Operation

The deposit lines were programmed using the CAD package AlphaCAM 2000. This software allows the geometries and speed of the traverse to be programmed along with switching on and off the laser and process gasses. The CAD data was converted to Numerical Control (NC) using AlphaEDIT and a custom written post processor. This package converts the NC code to the specific format required by the laser control system. The data was transferred via an RS232 link to the laser control system.

The workpiece is fixed to an Anorad 2000 positioning table and controlled through a PC interface. The PC is able to automatically control the switching of the laser's shutter and the solenoids controlling the gas flow.

Shield Gas

The shield gasses used on the laser system are controlled by solenoid valves attached to the controller as described in Section 0. When the valves are opened there is a delay in the regulator reducing the pressure of the gas to the set value, this results in the powder placed for the experiment being blown from the substrate. To control the excess pressure a silencer has been added to the gas line to absorb the excess pressure long enough for the regulator diaphragm to compensate the flow. In addition the deposit program turns the gas on when the nozzle is clear from the edge of the workpiece to avoid further removal of the placed powder.

4.3.3 Deposition Process

The substrates are clamped onto a 15mm thick Duratec insulation board in a custom built clamping frame as used in previous DOE depositing investigations (46, 47,78).



Figure 4-5: Assembled and exploded view of the substrate clamping arrangement

The clamping arrangement is shown in Figure 4-5. Once the substrate was clamped onto the insulating board it was cleaned in-situ using Iso-Propanol to remove any surface grease. For the depositing process the powder was pre-placed on the substrate before installation under the laser head. This allows the removal of complications caused by the powder delivery process. The powder was placed in a

layer of even thickness on the substrate surface using an aluminium block with an adjustable blade.



Figure 4-6: Method of spreading powder track onto substrate, and illustration of the resulting track

The thickness of the powder layer was adjusted by setting the blade height on the aluminium block using feeler gauges. A small amount of powder was placed in front of the bock, which when drawn across the substrate left a track the desired thickness.

During the laser operation the workpiece is moved under the beam as shown in Figure 4-7. The laser starts at the base of the powder layer, the then traverses away from the deposit area to avoid blowing of the powder when the gas solenoid is opened. The workpiece returns to the start point where the laser shutter is opened. After the deposit has been made the gas valve and shutter are closed and the table indexes ready for the next deposit.



Figure 4-7: Diagram showing the traverse or the workpiece in relation to the laser and gas operation

4.4 Beam Irradiance Distributions

4.4.1 Gaussian Irradiance Distribution

The Gaussian energy distribution, Figure 4-8, is the energy intensity produced by the majority of industrial lasers and their optics systems. In this study deposits have been created using this distribution to form a comparison between the effect of the differing beam shape and irradiance distributions.



Figure 4-8: Intensity plot of a Gaussian beam irradiance distribution

The Gaussian distribution shows a concentration of the intensity at the centre of the beam and in circular in shape. The optical setup on the cutting head uses a 29mm lens with a focal length of 63.5 mm. The input beam to the lens is 15mm. Using equation 4-1 (79) this gives the waist of the beam to be approximately 100µm.

$$W_o = \frac{2.44 f\lambda}{D}$$

Where W_o is Beam waist (mm) f is Focal length of lens (mm) λ is wavelegnth of light (nm) D is diameter of beam at lens (mm)

To achieve deposits at a similar energy density to that given by the DOE, the Gaussian beam will need to be used out of focus, giving a larger spot size. This is illustrated in Figure 4-9 The cutting head has been set up with the focal point 1mm below the nozzle. The cutting head is lowered until the cutting head is touching the substrate, then raised the amount required out of focus, plus the 1mm set working distance.



Figure 4-9: Out of focus setup to allow larger Gaussian beam size.



4.4.2 Uniform Pedestal Irradiance Distribution

Figure 4-10: Intensity plot of Uniform Pedestal irradiance distribution, as designed

A DOE has been used to reconstruct the Gaussian beam into a rectangular pedestal with a uniform irradiance distribution, Figure 4-10. This distribution has been used in previous studies as well as some of the initial investigations for this study. The profile is rectangular with a spot 3mm by 5mm. This distribution was used with the 5mm axis running parallel to the traverse direction, giving a deposition nominally 3mm wide.

This profile was chosen as it will put an even intensity distribution at the surface of the workpiece. By providing a uniform heating profile the thermal profile at the workpiece is expected to also be more uniform. The profile has been chosen to be rectangular, not a uniform "top hat", as this study uses moving beams. When a circular beam is scanned, uneven heating is induced due to the different chord lengths of the beam exposed across the interaction width.



4.4.3 Rugby Posts Irradiance Distribution

Figure 4-11: Intensity plot of Rugby Posts distribution, as designed

The first customised beam profile used in this study will be referred to as rugby posts due to the front elevation profile. The intensity profile is used in two forms, the first rectangular 3mm x 5mm and second square measuring 2mm by 2mm. The central section is cut away; with the intensity in this section a third that of the side extremities. The profile is shown in Figure 4-11.

This profile is a modification to the uniform rectangular pedestal described above. It is anticipated that although the uniform pedestal will have an even heating profile, the induced thermal profile in the material will not be uniform. Conduction at the edges of the melt pool will have an effect to induce a gradient from the centre out. This optic has been designed to increase the energy input at the edges of the beam to balance conduction losses.



4.4.4 Half Pipe Irradiance Distribution

Figure 4-12: Intensity plot of Half Pipe irradiance distribution, as designed

The half pipe distribution is once again named due to the appearance of the front elevation. The irradiance distribution is similar to that of the Rugby Posts, although straight cut out in the centre is replaced with a radiuses section with minimum intensity at a third of the maximum at the edges, shown in Figure 4-12. The shape of this optic is square with a spot 2mm by 2mm. The distribution was used with the trough running parallel to the traverse direction, giving a deposition nominally 2mm wide.

The half pipe distribution is a modification of the Rugby Posts beam profile. With the step changes in the heating profile in the rugby posts distribution there is a possibility of inducing steep thermal gradients within the melt pool, counteracting to intended

uniform heating profile. The half pipe wedge provides similar increased energy at the edges of the beam to balance conduction losses, but with smoother transition to the low intensity sections of the beam. This will mimic the smoother thermal gradients expected due the conduction losses.

4.4.5 Half Pipe Wedge



Figure 4-13: Half Pipe Wedge beam intensity distribution, as designed

The Half Pipe Wedge beam intensity profile is a variation on the Half Pipe profile. It adds a section to the leading edge of the profile that ramps up to the full intensity profile. The ramp section is 1/3 of the final beam profile making the beam spot 2mm in width and 3mm in length, the intensity profile is shown in Figure 4-14. Provision of the ramp is intended to stabilize the leading edge of the melt pool. As the laser beam scans there will be a sudden increase in heating as the laser is incident on the workpiece. This sudden increase in temperature will lead to a high thermal gradient at the leading edge. Providing the ramp seen in the half pipe wedge the inclusion of material into the melt pool is anticipated to be smoother.

4.4.6 Offset Rugby Posts



Figure 4-14: Offset Rugby Posts beam intensity profile, as designed.

The Offset Rugby Posts beam intensity profile, Figure 4-14, is a variation on the standard Rugby Post profile illustrated earlier. This variation has one of the side flanks at a lower level. The two sides are therefore at maximum intensity and 2/3 maximum with the centre section at 1/3 the intensity of the maximum peak.

This profile has been chosen to deliberately induce a non-uniform thermal gradient in the deposition profile. It is anticipated that this profile will produce a deposit with one side close to melt point while the other receives a greater than required heating inducing evidence of overheating.

4.5 Energy Density

Where deposits were made with differing energy distributions the energy densities used to produce them are not matched. The distance the workpiece was below focus was set so the diameter of the Gaussian beam matched the width of the DOE used. This would ideally produce tracks with a similar nominal width. Due to the difference in area between the beam profiles the energy densities used to create the deposition would not match. However the physical dimensions of deposition width would be comparative, allowing simpler comparisons to be made when the depositions are analysed.

The specific energy density provided a useful measure of both the speed and power the deposit was produced with. Where the mean energy density is used, it has been calculated using the following formula,

$$E = \frac{P}{VD}$$

where:

E = Mean Energy Density(Jm⁻²) P = Mean LaserPower(W) V = Velocity (ms⁻¹)D = Beam Diameter(m)

As equation 4- uses the beam diameter, non circular irradiance distributions have been converted into an equivalent diameter based on their area.

4.6 Deposition Analysis

4.6.1 Deposit Axis Definitions

Figure 4-15 below defines the axis referred to for the analysis of the deposits.



Figure 4-15: Deposit sectioning orientations

Deposition Profile Measurement

During initial investigations the surface profile of the depositions has been measured. A Talysurf instrument was used to measure the surface profile of the depositons. The Talysurf laser stylus is able to detect when a laser beam is in focus on the surface of the workpiece, providing the height measurement recorded by the system. On the settings used, the laser stylus had a full scale reading of 300µm and a resolution of 200nm in the vertical axis.

Analysis

The point data from the Talysurf was input into the analysis software Talymap Gold Version 4.1. This software was used to convert the data into a series of transverse cross section plots relating to each scan made across the deposit. A mean cross section was found from all the transverse scans taken. The Talymap software was used to level the data, to take out any error due to substrate deformation left by the laser process.

A number of measurements were taken from the averaged and levelled data. This included, the area of the deposition above the substrate, the width and maximum height of the deposition. From the information gathered a measure of the depositions squareness can be calculated. The squareness value is a ratio between the deposition area and the area of a rectangle of the same width and height as the deposition. This value is illustrated in Figure 4-16 and calculated using equation 4-3.



4-3

Figure 4-16: Dimensions of deposit used for squareness calculation

Squareness =
$$\frac{A}{a \times b}$$

4.6.2 Optical Microscopy

The deposit samples were cut using an abrasive saw. The cuts were made in the transverse axis to the deposit direction, as shown in Figure 4-15. The deposits were sectioned towards the end of the laser traverse, when the temperatures in the process will have stabilised. The samples were all mounted in conductive Bakelite, this allows the option of analysing any of the samples in an electron microscope. The cut samples were held upright with mild steel or polymer clips. A Struers Prontopress was used to mount the samples at 180°C for 8 minutes with a load of 20kN.

The samples were ground with successive grades of silicon carbide paper (80 - 4000 grit) and further polished using a 1µm diamond suspension. Samples were cleaned with detergent and rinsed with methanol prior to etching.

A number of different etchants were used for the different deposition materials, there compositions are given in Table 4-4, along with the time exposed. Inconel samples where electrolitically etched using an 80% solution of Phosphoric Acid with 5V for 20-30s.

Material Etched	Common Name	Time (s)					
Stainless Steel	Kallings Reagent	4	Compound	Water	HCI	CuCl ₂	Ethanol
			Amount	40ml	40ml	2g	40ml-80ml
Waspalloy	-	30	Compound	FeCl ₃	HCI	Water	HNO ₃
			Amount	5g	50ml	100ml	Few Drops

Table 4-4: Composition of acid etchants used

Once etched the depositions were imaged using a Reichert-Jung MeF3 fitted with a Fujifilm Fujix HC300Z digital camera to capture the images. An Olympus manufactured graticule was used to obtain a scaled micron marker on the images.

4.6.3 Electron Backscatter Diffraction (EBSD)

Electron Backscatter Diffration (EBSD) is an analysis technique able to identify the crystallographic orientation. It is used in this study to examine crystal orientations, grain size and shape.

EBSD uses an adaption to a standard Scanning Electron Microscope, where a phosphor screen and high sensitivity CCD camera have been installed. Samples were prepared as detailed for optical microscopy samples, but without etching of the material. An additional polishing preparation is required for EBSD. The surface has to be very flat to allow the crystal structure to be observes, variations in the surface flatness, or defects, such as scratches, will lead to inaccuracies in the analysis. To achieve this flatness the samples a further polished with colloidal silica for approximately 30 minutes using large volumes of water as a lubricant.



Figure 4-17: Schematic layout to EBSD components

EBSD works by placing the polished, flat sample in the SEM, mounted at an angle of 60° from the base plate (30° to the beam), pointing towards the phosphor screen. As electrons from the beam enter the sample some will backscatter, being released from

the sample. The electrons scattered will exit the crystal lattice under the Bragg condition, causing them to diffract. The electrons will fall on the phosphor screen will cause it to fluoresce. It is this fluorescence that means the diffraction pattern is captured by the CCD camera. The system layout is shown in Figure 4-17. A number of diffraction patterns are coincident on the phosphor screen caused by diffraction form a number of crystal lattices within the material. The EBSD pattern, an example is given in Figure 4-18, is a series of bands, relating to the crystal lattices that formed the pattern. A computer is used to find the bands, measuring their position and spacing. A look-up table is used to match the band geometry to a crystalline structure.



Figure 4-18: Electron Backscatter Diffraction pattern from 316L Stainless Steel

EBSD is used in this study to produce grain orientation maps. To provide this information the electron beam is scanned in a grid pattern across the sample area. The diffraction patterns are captured and analysed at every point in the scan grid. This process typically takes over 6 hours for the scan sizes needed for a whole deposition region. With information of grain orientations over the whole area allows the grain boundaries to be found, where the grain orientations change. This provides the ability to produce grain size maps along with statistical data on the distribution of grain sizes in the deposition analysed.

EBSD is a slow process requiring a large amount of preparation, the cost of the technique is also very high.

4.6.4 Energy Dispersive Spectroscopy (EDS)

When the electrons hit the deposit sample energy is transferred to the atoms in the sample. These atoms release this energy as an X-ray. The wavelength of the X-ray is specific to the material from which it originated. X-rays falling on a detector can have the energy transferred calculated and converted to a wavelength allowing the material data to be captured. This data collection can be synchronized with the EBSD scan allowing chemical composition to be mapped. Quantitative data on the composition of a specific area of the sample can also be measured.

5 Initial Investigations

This section details initial experiments undertaken to decide the materials and procedures used throughout the study. This section looks initially at the modifications to deposition profile seen through the depositing of 316L stainless steel, it shows that the modification in profile is significant and warrants further investigation. The use of two high nickel alloys is investigated with Inconel 625 showing much higher deposit ability, prompting the use of this material for further investigations.

Problems with retained heat within the substrates between depositions are examined and solutions sought. This solution will be retained in depositions made in the later sections of the work

5.1 Deposition Profile

A number of deposits were made using 316L stainless steel powder onto a substrate of the same material, to see the possibility of metal powder deposition with the laser setup available.

Figure 5-1 shows a deposition made using the out of focus beam from conventional refractive optics. This deposition shows a characteristic domed profile, caused by a combination of convection flows and surface tension forces, driven by the uneven heat input from the laser beam and conduction from the deposit area into the substrate.



Figure 5-1 Single deposition made using a unmodified Gaussian distribution, 400W 3mm.s⁻¹

Figure 5-2 shows the deposition resulting from the uniform energy distribution provided by the uniform rectangular DOE. The effect has been to produce a deposition with reduced doming of the surface. The DOE has removed the uneven heat input from the laser beam contributing to deposit pool flows. The characteristic domed shape still matches that of the Gaussian deposit, although in this case the aspect of the deposition has increased. This is due to the same mechanisms existing to form the deposit, however, in this case the deposit pool flows are reduced, with only conduction through to the substrate forming the temperature gradients which drive the molten material.



Figure 5-2 Deposition made using uniform intensity rectangular beam, 800W 3mm.s⁻¹

Both depositions were scanned with a Rodenstock RM 600 Laser Stylus to give measurements of the deposition profile. Profiles for the deposits shown in Figure 5-1 and Figure 5-2 are shown in Figure 5-3 and Figure 5-4 respectively.



Figure 5-3: Relative transverse Profile of Gaussian beam deposition, 400W 3mm.s⁻¹



Figure 5-4: Transverse Profile of Uniform Pedestal beam deposition, 800W 3mm.s⁻¹

The data from the scan can be used to calculate the area of the deposition above the substrate surface. Taking a ratio of this area against the area of a rectangle of the same height and width of the deposition will give a measure of the squareness of the deposition. A value closest 1 will indicate the best profile for minimising overlap between tracks and building vertical walled structures. A number of scans were taken at different longitudinal positions along the deposit, giving a total of 5 squareness values for each deposition. The values for these scans are tabulated in Table 5-1 and plotted in Figure 5-5.

Beam	Transverse Scan									
Irradiance										
Distribution	1	2	3	4	5					
3x5 Uniform	0.65	0.67	0.69	0.71	0.71					
Gaussian	0.53	0.60	0.68	0.64	0.66					

Table 5-1: Squareness ratios for Gaussian and Uniform Pedestal Deposits





The scans made of the two beam distributions show that the uniform pedestal is producing a deposition with a consistently higher squareness. This is due to the reduction in temperature gradient driving the formation of the deposition profile.

5.2 Deposition Profile Design

A uniform intensity distribution during powder melting has been seen to produce a deposition with reduced doming of the surface. However, due to conduction losses through the substrate a completely uniform temperature across the molten pool is not produced. By using the ability of a DOE to reconstruct the beam intensity into any 3D structure, an energy distribution has been created to reduce the thermal gradient caused by conduction through the substrate. This is achieved by having the majority of energy at the outside edges of the deposit pool. Any excess heat will act to oppose the deposit pool flows seen when using conventional beam distributions.

5.2.1 DOE Design Reproduction

A plot of the designed output of the DOE is shown in Figure 5-6, along with a perspex print of the actual laser output.



Figure 5-6 a), Designed Rugby Posts output laser beam intensity distribution and b) Perspex beam print.

A variation between the designed output in Figure 5-6a, and the measured profile b exists. There will always be a variation between the designed profile and the actual one due to errors in a number of factors. These include variation in the real input beam profile from the profile used in the calculation, approximations used in the computer algorithm, and errors in the manufacturing of the stepped DOE surface. A combination of these errors has led to the profile present in the Perspex print differing from the ideal beam intensity distribution. Material properties of the Perspex will also reduce the sharp edges present in the ideal designed profile, leading to smoother edges shown in the burn print.

As can be seen in Figure 5-6b the squared edges of the transverse profile have been reduced to give a curved profile to the inside section of the profile. The intense regions at the extremities of the profile have a sharp point, instead of the flat top in the designed profile. It is likely this sharp point is partly due to errors in the reconstruction of the designed profile along with affects of the deep burn print into the Perspex.

In the transverse profile the sides designed to be walls of uniform height have been reproduced as points at the corners of the beam, dropping towards the centre. It is estimated that the beam has been reproduced with a variation of approximately 25% from the designed profile

Although the beam is reproducing a slightly different profile from the designed vales once the beam is absorbed into the material, where conduction will reduce the sharpens of intensity changes, and once the longitudinal profile is scanned, the time averaged profile in the material with me closer to the desired, designed profile. The modified distribution has been used to produce a deposition in the same way as previous energy distributions. The resulting deposition has a significantly improved transverse profile, with a flatter top and angled sides. This deposition is shown in Figure 5-7.



Figure 5-7 Deposition made using a modified beam distribution, showing improved transverse profile, 700W 3mm.s⁻¹

A surface scan was used to measure the area of the deposit above the substrate in the same way as the Gaussian and uniform pedestal distributions above. The results are shown in Table 5-2.

Beam Irradiance	Transverse Scan									
Distribution	1	2	3	4	5					
3x5 Half Pipe	0.65	0.64	0.63	0.73	0.63					

Table 5-2: Squareness rations for Half Pipe Deposit

5.3 Multiple Layer Depositions

A double layer deposition was produced using the Uniform Pedestal. As can be seen from Figure 5-8 the squared profile has been retained after a second layer has been fused. The deposition is fully dense and exhibits a continuous microstructure between the two deposits.



Figure 5-8 Double layer deposition produced using DOE, 750W, 3 mm.s⁻¹

5.4 Weldability Investigations

5.4.1 Waspaloy Deposition

Using a substrate of 2mm plate mild steel the laser was unable to produce a deposition on the surface. Figure 5-9 shows the unsuccessful depositions of Waspaloy on 2mm mild steel. Figure 5-9a shows the pass made at a laser power of 700W and 3.3mm.s⁻¹, representing an energy density of 48MJ.m⁻², parameters that would have produced a successful deposit when depositing stainless steel to a substrate of the same material. Figure 5-9a is a deposit at the same speed but at the highest power used of 900W, 62MJ.m⁻².



Figure 5-9: Unsuccessful depositions of Waspaloy on 2mm mild steel at a) 48 MJm⁻² and b) 62 MJm⁻²

The lack of fusion to the substrate is thought to be due to the high thermal conductivity of the mild steel and the large volume of material in the 2mm thick plate. For the waspaloy to fuse to the substrate sufficient heat must be transmitted through the powder to melt the surface of the steel. Any heat transferred from the melt pool into the substrate is conducted away into the body of the steel.

The austenitic 316L stainless steel used in previous experiments has a low thermal conductivity, the heat sink effect will therefore be reduced. Using 316L as a substrate successful deposits were made at powers in excess of 750W, 51MJ.m⁻², higher than that needed when using stainless steel as the deposition material. A deposition made at 55 MJ.⁻², shows a complete deposition across the width of the powder track, although there is oxidisation at the surface of the deposit and the longitudinal cross section is uneven, Figure 5-10.

Initial Investigations



Figure 5-10: Deposition of Waspaloy on stainless steel made at 55 MJm⁻²

As well as the low thermal conductivity of the stainless steel that made it possible to deposit the Waspaloy, there is a high coefficient of thermal expansion leading to significant distortion in the substrates. The distortion of the stainless steel substrates is likely to affect later deposits made on the substrate, as it will lift away from the insulating board, moving out of the focal plane of the laser system and will induce stresses in the substrate.

Using thinner gauge mild steel as a substrate will reduce the volume of the substrate, this will reduce the heat sink effect. A series of deposits were made using a substrate 0.8mm thick. Again in these experiments satisfactory depositions could not be made. Although the deposition shown in Figure 5-11a has formed on the surface of the steel substrate. There is significant penetration through the underside of the substrate, shown in Figure 5-11a. Penetration through the underside of the substrate will have dramatic effects on the deposition profile, as a volume of material is pushed through to form the penetration out from the substrate underside.



Figure 5-11: Waspaloy deposition, at 49 MJm⁻², a) Surface, b) Underside

The processing window for depositing Waspaloy on steel in this way seems very narrow, decreasing the laser power from that used for the deposition above by 10W, the smallest resolution possible from the laser's power meter, produces the deposition shown in Figure 5-12, where the deposition has not formed on the surface.



Figure 5-12: Deposit images of Waspaloy on steel made at 48 MJm⁻² a) Surface, b) Underside

In an attempt to form depositions on steel without penetration the same 0.8mm steel sheet was used but to counteract the heat sink effects the substrate was heated before the laser operation. Heating the substrate will require less laser power to be used to overcome the substrate conduction losses, reducing the possibility of penetration. A Carbolite oven was used to heat the whole clamping arrangement, insulation and substrate to 300°C for 20 minutes. Just heating the substrate will have caused

difficulties when clamping and rapid cooling of the substrate upon contact with a cool clamp and insulation. For the first experiment the powder track was spread after the substrate was heated. Placing the powder on the heated substrate caused the powder to absorb moisture from the atmosphere, making spreading a uniform track impossible. It was therefore decided that the powder will be pre-placed before heating.

Heating the substrate had a limited effect on the deposition of Waspaloy. However depositions were successfully made at 48 MJm⁻² with deposition forming on the surface and no penetration through the underside of the substrate, the deposition of the deposit is shown in Figure 5-13.



Figure 5-13: Deposition of Waspaloy on mild steel, preheated to 300°C and made at a laser power of 48 MJm⁻²

To avoid the complications of heating the substrate, further initial investigations are to revert back to using 1mm 316L stainless steel as a substrate.

Multiple Layer Waspaloy Depositions

In this experiment the deposits were made parallel to the track direction, this aided the re-depositing of the powder track. The first depositions were made using a powder depth of 0.5mm, this shrinks to a deposition of approximately 0.3mm in height, so with the second powder track laid 0.8mm thick, there is 0.5mm of powder available for each deposition. 10 minutes was left between deposits to allow the deposition and substrate to cool.



Figure 5-14: Double layer deposit of Waspaloy onto stainless steel

The deposition in Figure 5-14 shows the result of a two layer deposit. Most notable is the increase in oxidation causing the yellowish surface to the deposition. It is also clear that the longitudinal deposition profile varies considerably over the deposition length. There is noticeably greater penetration through the substrate with the double pass deposits, this could be due to heat remaining in the substrate after the first deposit affecting the second.



Figure 5-15: Four layer deposition of waspaloy onto 316L stainless steel

Initial Investigations

Following the two layer deposits, four layers of waspaloy were deposited under the same conditions. In this case penetration through the substrate could not be avoided. Figure 5-15 shows the micrograph image of the four depositions. As can clearly be seen there has been an amount of material penetrated through the substrate, most likely due to the build up of heat from subsequent runs. There are areas of the deposit that show up darker, indicated by red arrow, due to the difference in resistance to the acidic etch. This is likely to be oxide inclusions formed on the surface of deposits, trapped in the deposit when subsequent layers were deposited on top.

5.4.2 Inconel 625

Inconel 625 is another high nickel alloy used specifically in the manufacture of turbine components. The material used was supplied by a turbine repair company, TRT Limited who repair components for RB211, Tay and Trent civil aviation engines (80).

Weldability Investigations

A series of depositions were produced to find the most suitable parameters for deposition of Inconel 625. In the same way as with the Waspaloy deposition, the Inconel was spread in a track 20mm wide and 0.5mm thick. The deposits were conducted using the same beam intensity distribution as the Waspaloy deposition, a 3mm by 5mm Uniform Pedestal.

The depositability of the Inconel was much better than the waspaloy, depositions could be made directly onto 0.8mm sheet, without the need for preheating and 2mm plate mild steel, if the substrate was heated.


Figure 5-16: Deposition of Inconel 625 on 2mm mild steel, made at 950W and a lower speed of 2.5mm/s, 87 MJm⁻².

Using a preheated 2mm substrate, a deposit was made at 950W, however the speed needed to be dropped to 2.5mm/s. This will have an affect to increase the energy input to the deposit area. As can be seen from Figure 5-16 the deposition is dull in appearance owing to an oxide layer, the composition of which is likely to differ from that of the Waspaloy due to the difference in colour. The deposition formed has a uniform longitudinal profile, this could be due to the properties of the Inconel or the lower speed used for this deposition. The scan speed of 2.5mm/s was maintained for successful depositions onto the thinner 0.8 mm substrates.

Using the Inconel on 0.8mm substrates, successful depositions could be made using a variety of power levels. This prompted a study to find the power range leading to successful depositions. A deposition was made using 700W (64 MJm⁻²), in the middle of the expected range of powers. The power was then increased at increments of 10W until the deposit penetrated through the substrate. Then the power was decreased from 700W to find the point where insufficient heat was input to form a deposition track. The maximum power found was 800W with a minimum at 500W, representing a range of 27.5 MJm⁻². This shows a massive improvement over the deposits with Waspaloy, where the window of operation was seen to be less than 0.9 MJm⁻².

5.5 Substrate residual heat

When comparing two deposits, sometimes the one produced with a higher power would show greater balling of the powder and lack of fusion to the substrate, characteristics of a reduced energy input to the system. The characteristics of the deposit showed to be dependent on the order they were made on the substrate and not the energy density used to make them, i.e. depositions that appeared to have less energy input were made first on the substrate. The errors can therefore be explained by the residual heat in the substrate was having a greater effect on the deposition than a reduction in energy input. This can be seen in Figure 5-17. This residual heating affect will mean that results will be dependent on the location within the substrate as well as the parameters used, greatly confusing the process.



Figure 5-17: Deposition made first with 54 MJm⁻² (a) shows greater balling and lack of fusion when compared to the lower energy deposition (b) at 51 MJm⁻².

A thermal image camera was used to visualise the heat being transferred through the substrate. Figure 5-18 shows the heat conducting through the substrate after each deposit. The images show a front of approximately 55°C to 85°C at the site the next deposit will be made.

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Figure 5-18: Thermal images of heat transferring through substrate after each deposit

Figure 5-19 below shows the temperature gradient in the substrate after the 3rd deposition had been made. The depositions are being made right to left. The cooling of the substrate can clearly be seen to the right of the central peak, where the deposition positions show as peaks on the curve. The heating in the substrate can be seen by the curve to the left of the peak. This shows that the next deposit position will be made where the temperature is already elevated.



Figure 5-19: Temperature gradient in substrate after 3rd deposition, a) Thermal Image, b) Line profile L1

Figure 5-20 shows the thermal profile of a substrate after all the depositions are complete. The profile shows a smooth cooling curve with peaks at each deposition location.



Figure 5-20: Thermal profile over substrate after all depositions are complete, a) Thermal Image, b) Line profile L1

A solution to the problem of heat transfer across the substrate between depositions, was found by cutting the substrates into discrete sections. The substrates were cut using a laser into 6 sections, held in place by two 1mm tabs at the top of each section. Cutting the sections has two benefits, it stops the transfer of heat across the substrate by removing the conduction mechanism and it allows easy removal of individual depositions for analysis. Figure 5-21 shows a CAD model of how the substrates are cut.



Figure 5-21: CAD model of laser cut for substrate sheets



Figure 5-22 shows the thermal images of the cut substrates after each of the depositions. It can be seen that the heat produced by the depositing process is contained within the section of the substrate. There is very little heat transferred in front of the deposition (to the left on the images).





As before a temperature profile was taken across the substrate after the 3rd deposition was made. The thermal profile is shown in Figure 5-23 which shows sharp temperature drops when travelling back from the latest deposition. Forward to the deposition there is a sharp temperature drop at the boundary to the new substrate section, showing very little of the heat is transferred forward to the next deposit.



Figure 5-23: Temperature profile in the substrate after the 3rd deposition



Figure 5-24: Thermal profile across the substrate with all depositions completed

A thermal profile taken across the completed substrate, Figure 5-24, shows there to be discrete temperature drops between neighbouring sections. The profile also shows there to be an even temperature across the individual sections. This even temperature will cause an even cooling rate on the section so as not to affect the microstructure formed in the deposition.



Figure 5-25: Two depositions in neighbouring sections of substrate, made with no delay between runs, the same parameters and showing visibly the same deposition, 64MJ⁻².

Figure 5-25 shows the result of two depositions made on neighbouring sections of the substrate. The deposits were made using the same power, 700W and same speed 2.5mm/s, 64MJm⁻². In this case there was no delay left between the laser operations, previously left to allow the substrate to cool between runs. The only delay between runs was for the traverse of the CNC table, approximately 17 seconds. The two depositions visually show very similar depositions. This shows the effect of residual heat from the first deposit in the second section was not enough to affect the resulting deposition.

5.6 Multiple Pass Inconel 625 Depositions

With successful single depositions in Inconel, and the ease of depositing straight onto steel substrates, deposits of multiple layers have been investigated.

As with previous multiple layer depositions, the first deposition was made with a track thickness of 0.5mm, reducing to approximately 0.3mm of deposited material. The subsequent tracks were therefore laid 0.8mm and 1.1mm thick. A maximum of three layers of deposition could be achieved before the maximum track height was reached. This differs from the waspaloy deposits, where the penetration through the surface of the deposit meant that the height of the deposition dropped as material was pushed through the substrate, allowing four layers to be deposited in the same track height range.

From previous runs it was known that, although depositions could be made down to 46MJm⁻², 64 MJm⁻² was the lowest power that produced a deposition with a good visual appearance. This power was therefore chosen for the multiple layer depositions to minimise the heat input to the process. It is known that a single layer deposit at 64 MJm⁻² will have no penetration through the substrate as a number of these have been made. To find the effect of multiple layer depositions on the penetration into the substrate, depositions were made with 2 and 3 layers and compared to single deposition. All the tracks were made at 64 MJm⁻².



Figure 5-26: Single layer deposition of Inconel 625 onto 0.8mm mild steel at 700W and 2.5mm/s, 64 MJm⁻².

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Figure 5-26, Figure 5-27 and Figure 5-28 show that multiple layer Inconel deposits can be achieved. In the case illustrated there has been an increase in the doming of the transverse section profile from that seen in the single layer deposit, Figure 5-26. This is expected to be due to the increase in molten material volume, causing increased deposit pool flows. This effect can also be seen in the longitudinal direction as shown in Figure 5-29. Addition of the third layer has increased the penetration into the substrate, however the magnitude in the case of the Inconel is greatly reduced from the Waspaloy where the deposition material penetrated the underside of the substrate.



Figure 5-27: Two layer deposition of Inconel 625 onto mild steel.



Figure 5-28: Three layers of deposition, Inconel 625 on 0.8mm mild steel. Showing an increase in penetration



Figure 5-29: Surface of two layers of Inconel 625 on mild steel showing uneven surface

5.7 Inconel 625 Deposition Profiles

Depositions have been produced using a Gaussian distribution provided by conventional refractive optics. This will show if the same improvements are offered by the modified beam distribution shown to improve the transverse cross section in laser deposition of 316L stainless steel.

As described in Section 4.3.1 a focusing head was used, fitted on an identical laser as the DOE experiments. The substrate was positioned below the focal point to produce a beam diameter of 3mm to match the DOE beam's width.

The range of powers producing successful deposits with a Gaussian beam was much narrower than that for the DOE modified beam. At 150mm/min a laser power of 300W, representing 40 MJm⁻², was found to produce a deposit with comparable penetration into the substrate. The lower average energy required in the Gaussian depositions is due to the uneven distribution of the energy in the beam. The centre of the beam has a much higher energy density that the average, melting the material more easily.

When comparing the depositions from the Gaussian distribution, Figure 5-30 and the DOE distribution, Figure 5-31, the intensity distribution of the Gaussian beam has formed a deposition with a characteristic domed profile. The modified distribution provided by the DOE is thought to overcome the temperature gradient induced by the laser beam and conduction losses to the substrate. This profile was thought to reversing the deposit pool flows, and has produced a deposit with a significantly flatter top surface.



Figure 5-30: Gaussian distribution deposit of Inconel 625 on mild steel



Figure 5-31: DOE modified beam deposit of Inconel 625 on mild steel

Measurements taken from the micrographs, shown in Table 5-3, give the height, width and penetration of the deposition. In a similar result with the multiple layer deposits, the height of deposition for the Gaussian distribution deposition is greater than the depth of powder track in which it was produced. This shows there is a mechanism raising the domed profile of the deposition.

	Deposition Height (µm)	Deposition Width (mm)	Penetration into substrate (µm)
Gaussian Distribution	660	1.9	90
Modified DOE Distribution	340	2.8	160

Table J-J. Approximate measurements of Gaussian and DOL deposition prome	Table 5-3: A	pproximate	measurements o	f Gaussian	and DOE of	deposition	profiles
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The measurements of the depositions show the width of the deposition left by the Gaussian distribution is only 63% of the beam diameter, while the DOE deposition is 93% of the beam width. This forms a dramatic improvement for the depositing of large areas, where fewer scans will need to be made, making the process quicker. With the DOE the laser power per millimetre of deposition width is greater at 250W/mm compared to the Gaussian distribution's 160W/mm, but the reduction in overlapping between tracks needed with the improved profile may also make the process more cost effective in terms of laser power as well as speed.

5.8 Deposition onto Turbine Blade Surfaces

In an approximation to repair welding of worn turbine blades, DOE depositions were made to the trailing edge of an aeronautical turbine engine low pressure compressor blade. The blade supplied by TRT Limited is repaired using Inconel 625 and is believed to be of the same material. As explained in Chapter 2 repair of highly alloyed nickel components often results in cracking in the deposits or fusion region.



Figure 5-32: Depositions of Inconel 625 onto trailing edge of turbine blade.

The depositions were made at 64 MJm⁻² and using the modified beam distribution from the 3x5mm Half Pipe DOE. The depositions, in Figure 5-32, show a uniform longitudinal profile, the transverse profile appears to have a flattened surface. A small crack is present at the end of the top deposit (as indicated by a red arrow). This crack is located at the end of the laser pass, and is believed to be due to an excess of heat in the material caused by the delay from the CNC table falling stationary at the end of the run to the closing of the laser shutter.

A series of laser surface scans were taken of the deposits. A plot of the average surface profile from 100 measurements over a 2mm length of deposition is shown in Figure 5-33. The profile shows a slope due to the curved surface of the blade.



Figure 5-33: Average surface profile of Inconel 625 deposition onto trailing edge of turbine blade

The average surface scan shows a deposition with a very flat top surface. The scan data has been reconstructed as an image of the surface, Figure 5-34. As can be seen from the reconstruction the surface profile of the deposition is maintained along the whole 2mm measurement range.



Figure 5-34: Image of turbine blade deposition surface constructed from surface scan data

5.9 Shield Gas Investigations

The depositions made for the initial investigations have all been made using air as an assist gas. The only role served by the assist gas is to maintain a positive pressure in the optics systems to prevent splatter from the deposition process contaminating the optics.

The addition of air, as well as the ambient atmosphere will cause an oxide layer to form on the surface of the deposition. This has been seen so far as a dark surface to the Inconel depositions and a yellow/green coating on the Waspaloy. The air is set to a low flow rate to minimize the effect on the deposition.

EDS carried out on a sample shows the chemical composition of an oxide at the edge of a DOE Inconel 625 deposition. The EDS map indicates that the oxide is formed from oxygen and chromium as shown in Figure 5-35.

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Figure 5-35: EDS scan on oxide on the surface of the deposition

During these initial investigations, trials using Argon as an assist gas have been undertaken. Argon is used in industry as an assist gas for deposition as its inert properties shield the melt pool form oxidation. The initial trials showed that the laser available for use in this study was not able to produce depositions using an inert shield gas, whereas depositions made with a minimal flow of air were possible. As further laser power was not available it was decided that the depositions will be made using air at the lowest flow rates possible. The use of no assist gas is not possible as the assist gas also acts as a shield to keep contaminations away from the optics.

It is anticipated that the cause for the lack of depositions when using Argon is due to the removal of the oxide layer. Although the removal of the oxide layer is highly desirable for the quality of the deposition, it also reduces the absorption of the laser beam in to the molten material. Using the shield gas, the molten pool will have a shiny, highly reflective surface, reducing the amount of laser energy absorbed in to the deposition material. Depositions in air have been successful as the oxide that forms absorbs the laser energy, improving the efficiency of the process.

In industry, where more laser power is available, the use of air as an assist gas is likely to produce depositions with undesirable properties. A oxide laser will form on the surface of the deposition, that when layers are built up will trap the inclusions within the depositions. Although the use of air as an assist gas in undesirable, this study looks to investigate the difference between the differing beam shapes, as the oxide inclusion in present in all cases the observations to be made will still be valid.

To avoid the oxide layer on the surface of the depositions causing errors in their analysis it will be removed by sand blasting the surface of the depositions after the depositing process. This will remove the brittle oxide layer with little effect on chemical composition of the deposition underneath.

5.10 Conclusions

Successful depositions have been made of stainless steel powder using both a Gaussian and reconstructed energy distribution, showing the basic laser setup is suitable for the investigations. When analysing the surface profiles a significant alteration in the transverse profile has been shown.

Changing to a more challenging high nickel alloy, Waspaloy showed difficulties in achieving acceptable depositions. The production of depositions in this material required high energy input and pre-heating of the substrates, along with a very narrow process window. A different high nickel alloy, Inconel 625, has shown a greater weldability than the Waspaloy. Deposits could be produced at much greater range of input energies and showed favourable results in terms of penetration with multiple layer depositions.

An important problem encountered was the transfer of heat forward of deposition into the substrate. The raised temperature present in the substrate prior to the deposition being made was causing significant errors in the results. With the main factor influencing the deposition being the position it was made on the substrate. Thermal images were used to visualise how the heat was flowing through the substrate after each of deposition. The images showed significant pre-heating of the substrate and an uneven cooling rate across the depositions, that could influence the microstructures in the depositions. A solution has been found by laser cutting the substrates into sections, stopping the conduction mechanism. Thermal images have shown that the temperatures within the sections are even and that heat in no longer transferred into the site of the next deposition.

Argon has been rejected as a possible shield gas due to the loss of laser power at the workpiece.

5.11 Changes to Methodology

- 1. All depositions will be made on the sectioned substrates. This removes the errors caused by transfer of heat into neighbouring depositions
- 2. Inconel 625 will be taken forward as the main material in this investigation. It has shown to have a much greater weldability than Waspaloy
- 3. The depositions will be sand blasted prior to analysis to remove the brittle surface oxide.

6 Effect of Beam Irradiance Distribution on Deposition Microstructure

This chapter looks at how modifications to the beam profile alter the microstructure present in the deposition. In all cases the use of customised DOE beam profiles has shown difference to both the growth orientation and size of the grain structure seen in the depositions. The use of EBSD and EDS techniques has been able to highlight the alteration in the microstructure due to the use of customised laser beam profiles.

6.1 Introduction

It is expected that depositions produced using different beam profiles will have different microstructure compositions. Both the shape and irradiance profile of a scanning beam will have a driving effect on the temperature distribution present during the deposition process. These two effects are illustrated in Figure 6-1. Figure 6-1(A) shows the effect of scanning a circular beam. A point on the centreline of the beam traverse (B) will be irradiated for a time proportional to the beam diameter, a point towards the edge of the beam will be irradiated for a time proportional to the chord length at this point.



Figure 6-1: Effect of beam shape and intensity distribution on induced thermal gradients



Figure 6-2: Percentage of exposure at the transverse centre line of beam at different locations across the beam diameter

Figure 6-2 shows the time of exposure to the scanning beam at different locations across a beam of unity diameter, the exposure is expressed as a percentage of the peak at the centre of the beam. The plot shows the exposure varying from a maximum at the centreline of the beam, with a sharp drop off towards the edges.

Figure 6-1(b) shows the affect the beam intensity distribution will have on the temperature profile induced in the deposition. The Gaussian beam illustrated has a concentration of the beam's power in the centre. Inducing a temperature profile significantly hotter in the centre than the extremities. The power across a Gaussian beam expressed as a percentage of the peak power is shown in Figure 6-3.



Figure 6-3: Plot of the Gaussian beam energy distribution as a percentage of the peak energy

The round Gaussian beam, used for a majority of CO_2 laser processing, represents a combination of these two effects. The combined effect is plotted in Figure 6-4.



Figure 6-4: Combined effect of the beam power distribution and shape

The temperature profile produced will influence the microstructure formation, as temperature gradients present during the process will cause uneven cooling rates and different maximum temperatures reached. The uneven cooling rates will lead to changes in the solidifying crystal growth and orientation. Differing maximum temperatures along with different cooling rates will influence the phase formations in the solidified material.

The uneven temperature profile will cause excessive heating in the deposition. With a much greater heat input being present at the centre of the deposition than at the edges. For the deposition to have formed the laser must have induced heating to a minimum of the melt temperature of the deposition material. This would make the central region of the deposition, where irradiance is far greater than the edges, reach temperatures far in excess of the material melt point. Excessive temperatures in these regions can induce porosity and alloy degradation due to the boiling of alloy constituents, an overall increase of the deposition grain size and directional solidification to the grain structure may also be seen.

6.2 Stainless Steel Deposition

Two depositions have been analysed using EBSD. The grain size and crystal orientation data is analysed in the following sections. The two depositions were produced with a Gaussian and Uniform Pedestal irradiance distributions. The depositions were made using the experimental procedures described in Chapter 3. The parameters used for each weld are shown in Table 6-1.

		Gaussian Intensity	Uniform Pedestal
		Distribution	Intensity Distribution
Substrate		0.8mm Mild Steel	0.8mm Mild Steel
Beam Size	(mm)	3 Ø	3 x 5
Speed	(mms⁻¹)	3.33	3.33
Power	(W)	400	800
Energy Density	(MJm ⁻²)	27	55
Powder Track Depth	(mm)	0.5	0.5

Table 6-1: Parameters used for production of depositions

The parameters used for each the two EBSD scans are shown in Table 6-2.

		Gaussian Intensity	Uniform Pedestal
		Distribution	Intensity Distribution
SEM Magnification		121	90
Scan Mode		Hexagonal Grid	Hexagonal Grid
Step Size (µm)		5	8
Working Distance (mm))	16	17
Binning		8x8	8x8

Table 6-2: EBSD scan parameters

6.2.1 Grain Orientation

The EBSD scan is able to identify crystal orientations within the laser depositions. By comparing electron back-scatter patterns to a material database the system is able to identify the orientation of the crystal the pattern originated from. When the system indexes across the sample, any changes in the pattern indicates a change in the crystal orientation, and therefore a new grain and a grain boundary. By examining the orientations between the grains within depositions made using different laser beam profiles any influence on the crystal orientation structure caused by the heating pattern can be seen.

The plot of misorientation angles for substrate 316L is shown in Figure 6-5. The plot shows the misorientation angles between 10° and 60°. Grain misorientation angles below 10° are not shown at these can be inaccurate due sample preparation artefacts. The data for the plot was taken from the EBSD scan of the DOE uniform deposition, with the scan area cropped down to remove the deposition and heat affected zone, leaving only unmodified substrate microstructure. The plot shows a peak at an angle of 60°. This angle relates to a coherent twin boundary, formed during the growth of a crystal. As stated in the literature review, coherent twin boundaries are known improved resistance to intergranular corrosion and cracking.



Figure 6-5 Misorientation angle between neighbouring grains of substrate

Figure 6-6 shows the crystal orientation within a deposition made using the uneven Gaussian intensity distribution. The large difference in grain size between the substrate and deposition can be seen.



Figure 6-6 Inverse pole figure orientation map of Gaussian deposition showing grain orientation

Producing the same plot for the Gaussian distribution deposition, shown in Figure 6-7. The plot shows the misorientation angles between 10° and 60°. It can be seen that the deposition process has had an effect to reduce the proportion of twin 60° boundaries.



Figure 6-7 Misorientation angle between grains in a Gaussian distribution deposition



Figure 6-8 Inverse pole figure orientation map of grain orientation for Uniform Pedestal deposition

The same scans were taken of a deposition made using the uniform rectangular beam from a DOE. As can be immediately seen from the crystal orientation plot shown in Figure 6-8 the grains are shown with colours more evenly distributed over the pole map key, when compared to the large region of blue/purple colours in the centre of the Gaussian deposition in Figure 6-6. This indicates a more random distribution of grain orientations than seen in the Gaussian deposition. A plot of the angle between crystal orientations in neighbouring grains is shown in





Figure 6-9 Misorientation angle between neighbouring grains in a DOE deposition of uniform intensity

The number of twin boundaries at 60° has decreased from the levels seen in the unprocessed substrate, but has not fallen to the levels seen in the Gaussian deposition. The higher proportion of high angle boundaries in the uniform intensity deposition will produce a microstructure with superior mechanical properties, compared to the Gaussian distribution. The deposition will have a greater resistance to intergrannular cracking and corrosion.

The MacKenzie distribution (80) describes the random orientations of cubes. Plotting this distribution against the misorientation data gained from the EBSD scans will show any manipulation of the crystal orientations during the deposition. Figure 6-10 shows that all the misorientation profiles are similar to the Mackenzie distribution apart from an increased proportion of the 60° coherent twin boundaries and a higher proportion of low angle boundaries.



Figure 6-10: Misorientation angle distributions in comparison to the Mackenzie Distribution

6.2.2 Grain Size

The same EBSD data was used to measure the grain sizes in the depositions produced. The distribution of grain size, measured as the grain area, is shown in Figure 6-11.



Figure 6-11: Distribution of grain sizes in welds produced using Gaussian and Uniform Pedestal

To simplify the comparison between grain size in the two depositions a plot of accumulated deposition area percentage against grain area is given in Figure 6-12. This plot indicates the percentage of the deposition below a certain grain size, for example, reading across the plot at the 50% line, will give about $25,000 \mu m^2$ for the Uniform Pedestal distribution and $50,000 \mu m^2$ for the Gaussian deposition. This indicates that half the area of the sample of the uniform pedestal is made of grains $25,000 \mu m^2$ or smaller, with half the Gaussian deposition being made of grains up to twice this size. The uniform pedestal line has a greater gradient than the Gaussian distribution, indicating a greater percentage of the deposition area is made up of smaller grains than the Gaussian distribution.



Figure 6-12: Plot of accumulated deposition area percentage against grain area.

Table 6-3 shows information read from the accumulated percentage curve, giving an indication of the grain size composition.

Table 6-3: Grain Size Distributions in Depositions Made Using Gaussian and UniformPedestal Profiles

Percentage of Deposition	Grain Area (μm²)

	Gaussian Distribution	Uniform Pedestal Distribution	
50%	<50,000	<20,000	
90%	<180,000	<80,000	
100%	<400,000	<280,000	
Mean	115,943	69,892	

A colour map of the deposition region has been produced showing the grain diameters, (the largest dimension across a grain). The map for the Gaussian deposition is shown in Figure 6-13a. The map shows a dominating proportion of large red and orange grains, relating to a grain diameter of 224µm to 896µm.

Comparing the Gaussian distribution map to the one for the uniform pedestal deposition, Figure 6-13b, shows a reduction in the number of large grains shown in orange and red, with the dominant grain sizes being reduced to those indicated in yellow, in the 112µm to 224µm range.



Figure 6-13: Comparison between grain size distribution maps, a) Gaussian distribution B) Uniform Pedestal

6.3 Inconel 625 Deposition

Inconel 625 is used in a number of industries due to its corrosion resistance and mechanical properties at elevated temperatures. It was used in this study as Inconel 625 is deposited in the laser repair of aircraft engine turbine blades.

A number of different beam shapes have been analysed, each time comparison has been made to an unmodified Gaussian beam intensity distribution.

All depositions were made using the experimental procedure described in Chapter 3. The Inconel 625 depositions have been analysed using EBSD. Two depositions were scanned, one made using a square Half Pipe irradiance and a Gaussian irradiance distribution as a comparison. The depositions where produced using the parameters in Table 6-4. Although the beam sizes have been set to both present a 2mm wide beam, the depositions formed have a difference in the widths formed. This is due to the Gaussian beam reducing in intensity towards its edges. The minimum intensity required to form the deposition, i.e.melt the material, might therefor not be found all the way to the outside edges of the beam.

		Gaussian Intensity	Half Pipe
		Distribution	Intensity Distribution
Substrate		0.8mm Mild Steel	0.8mm Mild Steel
Beam Size	(mm)	2 Ø	2 x 2
Speed	(mms⁻¹)	5	2.5
Power	(W)	500	500
Energy Density	(MJm⁻²)	50	89
Powder Track Depth	(mm)	0.25	0.25

Table 6-4: Parameters used in Inconel 625 depositions for EBSD analysis

The EBSD scans were made using the parameters in Table 6-5

Table 6-5: Inconel Deposition EBSD Scan Parameters

		Gaussian Intensity Distribution	Half Pipe Intensity Distribution
Scan Mode		Hexagonal Grid	Hexagonal Grid
Step Size	(µm)	2	2
Working Distance	(mm)	15	15
Binning		8x8	8x8

6.3.1 Grain Orientation

As with the previous EBSD scans maps of the deposition showing the orientation of the crystal structure within them have been produced. The Inverse pole figure map for the Gaussian irradiance distribution deposition is shown in Figure 6-14, along with the misorientation plot for the deposition in Figure 6-15. The misorientation angle plot shows the expected random distribution except the extra peaks at 60° and low angle boundaries. The 60° peak indicates a proportion of coherent twin boundaries as seen in the stainless steel depositions discussed earlier. The peak of low angle boundaries is likely to come from errors caused by sample preparation and the oxide layer present on the surface of the deposition. These low angle boundaries were omitted from further analysis.



Figure 6-14: Inverse pole figure map Inconel 625 deposition made using Gaussian irradiance distribution



Figure 6-15: Misorientation angle distribution in Gaussian Irradiance deposition in Inconel 625



Figure 6-16: Inverse pole figure map of deposition using Half Pipe irradiance distribution

The inverse pole figure map for the Half Pipe deposition is shown in Figure 6-16. The map shows a deposition with a slight bias to a crystal orientation of 111. This is confirmed by the inverse pole figure in Figure 6-17.



Figure 6-17: Inverse pole figure for Half Pipe distribution deposition

A plot of the misorientation angle distribution over the deposition area shows the same random distribution as seen in the Gaussian irradiance profile. The large proportion of low angle boundaries are again present. These boundaries will also be excluded from further analysis. The peak at 60° has reduced in this case to within the random orientation distribution. The misorientation distributions of both depositions along with the Mackenzie random orientation distribution are shown in Figure 6-19. The depositions show a profile comparable with the Mackenzie distribution with an extra peak in the Gaussian irradiance distribution at 60°.


Figure 6-18: Misorientation angle distribution in IN625 deposition using in Half Pipe irradiance distribution



Figure 6-19: Misorientation distributions of the depositions and Mackenzie random orientation distribution

6.3.2 Grain Size

As with the stainless steel depositions in Figure 6-11, the grain size data from the depositions has been taken from the EBSD scan. Figure 6-22 shows the distribution, with the grain size given as the grain area in square microns.



Figure 6-20: Distribution of grain area in depositions made with Gaussian and Half Pipe distributions

A plot of the grain area distribution as an accumulated percentage of the deposition, shows a similar result as with stainless steel depositions. The greater proportion of the deposition is made up of smaller grains than an equivalent proportion of the Gaussian beam distribution deposition.



Figure 6-21: Grain area distribution as an accumulated proportion of the deposition

Numerical values read from the Figure 6-21 are given in Table 6-6, this gives a numerical comparison on the distribution of the grain size. Also in the table is the average grain size calculated as part of the EBSD scan.

Percentage of Deposition	Grain Area (µm²)		
	Gaussian Distribution	Half Pipe Distribution	
50%	<1,600	<800	
90%	<6,900	<2,900	
100%	<7,000	<6,100	
Mean	3,069	1,502	

Table 6-6: Grain Size Distributions in Depositions Made Using Gaussian and Half PipeProfiles

A grain size distribution map of the Gaussian irradiance profile deposition is shown in Figure 6-22. The map shows a number of large grains, shown in red, occupying the central volume of the deposition.

By contrast only a few grains in the Half Pipe distribution deposition have fallen in to the largest size category, shown in Figure 6-23. With those that have, appearing to be from the lower end of the size range. The overall texture to the deposition is much finer than the Gaussian deposition.



Figure 6-22: Grain size map of Gaussian irradiance distribution deposition



Figure 6-23: Grain area distribution map of Half Pipe deposition

6.3.3 EDS Maps

The EDS data has been used to produce maps showing the distribution throughout the weld of the four main alloying elements, nickel, chromium, iron and molybdenum. Figure 6-24 shows the element distributions for the deposition made using the Gaussian irradiance beam. All of the maps show a segregation of the respective elements within the deposition, with the pattern being most noticeable for iron. This pattern in contrasted with the DOE produced Half Pipe distribution deposition, Figure 6-25. In this case there is a much greater evenness to the distribution of alloy elements throughout the deposition, with only a slight concentration of some elements in the left hand side of the images.



Figure 6-24: EDS maps of the four main alloy elements for Gaussian distribution deposition



Figure 6-25: EDS maps of the four main alloy elements for Half Pipe distribution deposition

6.4 Uneven Beam Intensity distribution

In the depositions analysed so far there has been a notable difference in the grain size and alloy segregation in the solidified material, when comparing a deposition made with a modified beam intensity distribution to a deposition produced with a Gaussian beam. In this section depositions made using the offset rugby posts distribution that has been created intentionally to produce a non-uniform heating pattern to see that effects on material properties. Using this beam intensity profile to make Inconel 625 depositions it was expected that the edge with a high intensity will lead to an overheating of the melt pool and the side with a lower intensity will lead to a melt pool with a lower temperature and therefore a reduction in the cooling times upon solidification.

Figure 6-26 shows a grain size distribution map for a deposition made using a Gaussian beam distribution.

The grain size map for the Offset Rugby Posts is shown in Figure 6-27. As can be seen from the two figures the grain size distribution is different between the two deposits. The Gaussian deposition has mainly grains in the largest size category, with, as would be expected, the largest grains at the centre where cooling will be slowest. In the Gaussian deposition the grains are very columnar, stretching from the interface at the bottom of the deposition towards the surface. The columnar grains signify slow directional cooling and provide a route for intergranular cracking and corrosion into the deposition. The Offset Rugby Posts deposition is showing a distribution of grain sizes that varies across the deposition. The grain size in the deposition is decreasing from left to right, matching the decreased intensity on the right hand side of the beam distribution. The differing intensities at the side edges of the Offset Rugby Posts beam distribution have been able to manipulate the cooling rates in the deposition to give a graded microstructure across the width of the deposition. An improvement in the grain aspect ratio, a measure of how columnar the grains are, is seen in the DOE modified deposition 50% of the Gaussian deposition has a grain aspect ratio of 3.85 or more, this figure falls to 3.23 for the high intensity side of the Offset Rugby Posts deposition and decreases further to 2.99 for the low intensity side. The lower figures indicate a reduction in the formation of columnar grains.



Figure 6-26: Grain size and grain boundary map of the deposition of Inconel 625 using a standard Gaussian Beam.





Figure 6-28 shows a plot of the grain area distribution for the two depositions, separating the high and low intensity sides of the Offset Rugby Posts. The plot shows the grain area against the accumulated fraction of the whole deposition area. The plot shows that the low intensity side of the deposition contains the smallest grains, this is shown by the red line with the steepest gradient, this is followed by the Gaussian distribution in blue. The largest grain area distribution is in the high intensity side of the Offset Rugby Posts where the higher intensity in the beam has modified the cooling rate allowing the growth of larger grains.



Figure 6-28: Accumulated grain size plot for the deposited material by Gaussian and ORP-DOE with the high and low energy intensities in the ORP-DOE plotted individually.



Figure 6-29: Gaussian deposition EDS map for iron



Figure 6-30: Offset Rugby Posts EDS map for iron.

EDX maps for the levels of iron in the depositions are shown in Figure 6-29, for the Gaussian deposition, and Figure 6-30 for the Offset Rugby Posts. This gives patterns for the distribution for iron within the deposit. Iron has been chosen as it has shown the largest segregation of any element analysed in previous scans. As can be seen, the levels of iron varies within the depositions. It is thought this is due to iron from within the Inconel alloy which is drawn up from the mild steel substrate. The Gaussian deposition shows two circular features, in the Offset Rugby Posts deposition a single central feature is seen. The Offset Rugby Posts deposition also shows lower levels of iron present at the side of the deposition where the highest intensity of laser energy was present.

The pattern for the mixing of alloy constituents could be an indicator of internal material transport flow.

6.5 Alloy Segregation

As has been seen in previous sections, scans of a deposition composition have shown that the concentration of certain elements varies throughout the volume of the deposition. This segregation of alloy elements is most noticeable for the element iron. The segregation seems to follow patterns that would appear similar to the theoretical internal material transport mechanisms. By comparing the flow patterns of a number of beam profiles, it is hoped some indication of the internal flow mechanism can be found.



Figure 6-31: EDS maps of iron concentrations in a) Gaussian b) Rugby Posts c) Half Pipe d) Offset Rugby Posts beam intensity distributions.

Figure 6-31 shows the EDS map of iron in depositions made with a) Gaussian, b) Rugby Posts, c) Half Pipe, and d) Offset Rugby Posts beam intensity profiles. The colour maps show the relative intensity of iron within a deposition, the intensity levels shown are not comparable between maps, only the patterns of segregation can be compared.

6.6 Discussion

6.6.1 Energy Profiles

It has been shown that when a circular beam of uniform intensity is scanned it induces differential levels of laser energy on the substrate. This effect is increased when an uneven intensity distribution is present in the beam. This affect can be reduced by shaping the beam to compensate for the increased energy at the centre, this however uses the movement of the beam to induce a thermal profile in the workpiece. By using the motion of the laser beam to control the thermal profile, any time control, for preheat etc. is lost. The DOE's shape the laser beam in two axis as well as intensity to control the thermal profile in the material. This can be used to give a time-temperature profile in the material.

When compared to the Gaussian beam distribution all of the DOE modified beam profiles have shown a difference in the microstructure properties of the depositions. The Gaussian deposition used as a comparison for the modified beam profile produces a predictable heating pattern at the work piece. The effect of this heating is seen in the microstructure formed in the depositions. All the Gaussian depositions made have formed with a domed profile. The doming of the profile fits the accepted theory, (59,65-67) that the melt pool transport affects combine to make material flow up the centre of the melt pool, causing the raised doming of the melt pool.

6.6.2 Grain Orientation

The differing beam intensity profiles have had an effect on the grain growth orientations. Observing the solidification directions of the grains, gives an indication on the solidification regime in the deposition. Two indications on the growth directions are given in the Sections 6.2.1,6.3.1 and 6.6.2, a map of the grain orientations and a plot of the angle between neighbouring grain orientations.

The grain orientation maps give an indication of locations of any areas of the deposition with a similar grain orientation, indicating low angles between the grains.

These are seen in the maps as an area of similar colours, this is particularly evident at the centre of the stainless steel Gaussian deposition in Figure 6-6. From the scan data taken from the Uniform Pedestal DOE deposition an area away from the HAZ was analysed to find the grain orientation data for the raw substrate. This scan showed an elevated proportion of grain boundary angles of 60°. This angle indicates a twinning boundary, where a crystal has formed from within another during the growth phase. A number of studies have found that the promotion of these twinning boundaries has a positive effect on the mechanical properties of the deposition.

When similar investigations were undertaken with depositions of Inconel 625 made onto mild steel substrates a greater number of twinning boundaries were seen with the unmodified Gaussian beam. Other than a rise in the twinning boundaries in the Gaussian, all Inconel depositions showed a grain orientation distribution that fitted that expected from a Mackenzie distribution. This shows that there was little external influence of the growth direction of the grains in any beam distribution. It is likely that there were a greater number of twinning boundaries seen in the Gaussian Inconel deposition over the DOE because in the Gaussian case it is believed the grains are growing for a longer time than the DOE depositions. As twinning boundaries are formed from grains during the growth phase this would lead to a greater opportunity for twinning boundaries to form within grains from the Gaussian depositions.

6.6.3 Grain Size

Further indication of the elevated heating at the centreline of the deposition is seen when observing the grain size distribution throughout a Gaussian deposition. All the Gaussian depositions shown have an distribution of grains within the deposition, with the largest grains at the centre of the deposition. The elevated heating at the centre of the melt pool, combined with the lowest heat losses at the centre of the deposition have led to the growth of grains increasing the grain size. A further effect of the elevated temperature is seen in the shape of the grains in the deposition. The Gaussian depositions are showing columnar grain formations, these are grains with a high aspect ratio. Columnar grains will grow along the axis of cooling within the deposition. In the Gaussian depositions shown here, these grains are arranged vertically, indicating a slow cooling rate through conduction into the substrate and losses at the surface. Long columnar grains, as seen in these depositions are, characteristic of fusion welds, where the heat losses upon solidification have led to a directional grain structure. A consequence of a directionally solidified grain structure is a reduced resistance to intergranular cracking and corrosion along with a directionality to the mechanical strength of the deposition.

In all cases the use of a modified beam intensity profile has led a change in the resulting deposition microstructure. The change in the beam intensity profile also had an effect on the general deposition parameters. All the modified beam intensity distributions required an increase in laser power and a decrease in the transverse velocity to achieve welds of a similar appearance. This is due to a decrease in the maximum energy density within the beam, the intense centre of the Gaussian beam is able to reach the melting point of the deposition material while the average power of the whole beam is still relatively low. This low volume of molten material at the centre of the weld will then have a greater absorption of the laser beam as well as being stirred by material transport effects, conducting to the surrounding material aiding in melting. As previously mentioned it was decided in this study to use parameters that gave comparable deposition results, not to match the deposition parameters between beam profiles.

Where the DOE has been used to provide a more uniform heating to the deposition process, dramatic reductions in the average grain size. The average grain size in the stainless steel deposition shown reduced by 39.7% and the Inconel 625 deposition decreased by 51%. The other characteristic signs of the uneven heating seen in the Gaussian deposition have been affected. The shape of the deposition has lost some of the characteristic doming. The aspect ratio of the grains in the deposition has decreased, indicating less directionality in the solidification due to a greater uniformity to cooling mechanisms. The grain size data does not indicate the heating of the deposition pool, but rather the cooling profile. This cooling profile can be used to work back to an understanding of the heating that had been applied to the deposition. In the Gaussian deposition the central region is assumed to have reached the highest temperatures in the deposition driven by the increased thermal input at the centre of the Gaussian beam. The increased thermal energy input and reduced cooling due to the thermal mass at the centre led to grain growth. In the cases of the DOE modified beams, the thermal mass affect still existed but the excessive heating by the beam will have been reduced. This has lead to a decrease in the time available for the grains to

grow, resulting in a smaller average grain size. The grains have also decreased in aspect ratio, it is thought this is due to the reduction in an overall direction of cooling and grain growth.

The plots of the accumulated grain size distribution throughout the whole depositions show that the DOE modified beams have produced depositions with reduced grain sizes throughout the whole grain size range. This indicates that the whole deposition has cooled at a faster rate, not just a reduction in the larger grains seen at the centre of the deposition where cooling is slowest in all cases.

When looking at the grain size distribution maps in Figure 6-13b and Figure 6-23 for DOE modified beams there is still a small collection of large grains at the centre of the depositions. This is due to the reduced cooling rate at the centre where the thermal mass is greatest. As this effect is similar between the modified and unmodified they will have an equal effect on the cooling of the two depositions, any difference in the grain size distributions is therefore due to the beam profile changes.

The depth into the substrate over which grain modification has taken place in the stainless steel depositions is far greater than that seen when the substrate and deposition materials differ. This is likely to be due to the matching of melting point between the stainless steel substrate and the powder of the same material. When sufficient energy was input to the powder to form a good melting and fusion of the deposition, it was sufficient to have microstructure changes over a much greater depth than was seen when depositing the dissimilar materials. With the Inconel 625 depositions made onto steel, the substrate is of a higher melting point than that of the material being deposited onto it.

6.6.4 Alloy Element Segregation

EDS maps have been successful in identifying the distributions of alloying elements within the depositions. The maps have shown that there is a non-uniform distribution of individual elements within the depositions. Different elements appear to show differing

levels of segregation within the depositions and the levels of segregation between differing beam intensity profiles also varies.

The EDS maps shown in this study are illustrations of the number of counts seen at a detector during the scan process. The data therefore can be used for direct comparison between scans of different depositions. The patterns created during the segregation can, and have been interpreted to give indications of the internal material transport patterns.

The deposition produced by the different beam intensity profiles all show different distributions of iron within them. The Gaussian distribution EDS map shows a circular band of low iron concentration below the surface of the deposition. Below this band of high concentration following the shape of the band above. The centre of the deposition shows a region of low intensity rising towards the deposition centre. The concentration patterns are symmetrical about the centreline of the deposition. It is possible that the circular band and central region are following the theoretical material transport mechanism as shown in Figure 6-32. If the iron concentration is indicating the internal material transport flow pattern within the deposition dominated by the convective buoyancy force, a low concentration of iron would indicate a region of elevated temperature. This may be due to the low concentration of iron occurring where the material transport is rising through the deposition.



Figure 6-32: EDS map of iron concentrations in Gaussian Inconel 625 deposition with possible flow pattern illustrated.

The half pipe beam intensity distribution is, in transverse cross section, similar to the reverse of a Gaussian profile, in that it has a maximum intensity at the edges and a minimum at the centre. Looking at the EDS map for the half pipe beam intensity

distribution the concentration of iron is an approximate reverse of the Gaussian map. The map shown in Figure 6-31c shows a central region of increased concentration with two areas either side with lower iron content. If conduction losses through the substrate were not balanced with the beam input then there would be an excess of heat the edges of the melt pool and a region of lower temperature at the centre. This heat profile would oppose that expected from a melt pool heated with a Gaussian beam. The regions of high and low iron intensity in the EDS map are opposite to those seen in the Gaussian deposition, therefore agreeing with the theory that the regions of lower iron concentrations are occurring in the deposition where more heating has occurred. Using the iron concentrations the material transport expected in the half pipe deposition are illustrated in Figure 6-33.



Figure 6-33: EDS map of iron concentrations in Half Pipe Inconel 625 deposition with possible flow pattern illustrated.

Segregation of iron in the remaining depositions does not show a pattern as clear as those seen in the examples above. Patterns in the remaining deposition profiles shows single circular bands of iron concentrations centred in the deposition. This is possibly due to the reduction in thermal gradients removing overriding material transport leading to the stirring of the melt pool as indicated by the alloy segregation.

6.7 Conclusions

Through the use of modified beam intensity profiles the microstructure of the resulting depositions has been influenced. Circular Gaussian laser beams have been seen to increase the energy at the centreline of the deposition. This uneven energy input has led to a region of high temperature at the centre of the deposition, with a cooler region at the edges.

A number of techniques have been used to look at the microstructures left in depositions made with different beam profiles.

Depositions made with a modified beam distribution have shown changes in the deposition transverse profile. It is considered that this is due to the modified beam profile changing the material transport mechanisms on the molten pool during the deposition process. The material transport is driven by the temperature gradient in the molten pool. The modified beam profiles have changed or reduced the thermal gradients leading to changed material transport and therefore a different physical profile to the deposition. These observations will be investigated further in Chapter 6

In Inconel 625 depositions the grain orientations have been formed in line with the Mackenzie random distribution. Some elevation in the number of coherent twin boundaries is seen in the depositions made using a Gaussian distribution. This is seen as an indicator that grain growth has occurred in these depositions. The higher number of coherent twin boundaries is seen in the DOE modified depositions when in stainless steel. The stainless steel used, 316L, is known to promote twinning boundaries, as such direct comparison to the Inconel depositions has not been made.

Significant grain size reductions have been seen when DOEs were been used to provide uniform heating at the deposition. By modifying the heat input the cooling rates have been modified to reduce the growth of grains during solidification. Grain sizes have been reduced throughout the whole range as shown in Figure 6-12 and Figure 6-21 for the stainless steel and Inconel depositions respectively. The average grain size in the stainless steel was reduced by using the Uniform Pedestal DOE by 40% and 51% for the Inconel depositors made using a Half Pipe modified beam. In a further investigation to see the extent of influence of grain size caused by a modified beam an optic was used to raise the grain size on one side of the deposition and reduce on the other.

EDS maps have been produced showing the segregation of alloying elements within the deposition. The maps have shown variation in the element Iron that falls in line with the accepted theories of material flow.

7 Effect of Beam Irradiance Distribution on Melt Pool

7.1 Introduction

In this chapter a number of different visualisation methods have been utilised to gain a closer understanding of the thermal profiles present in the melt pool during the deposition process. The driving factor on the quality of a deposition is the thermal profiles present during the process. The thermal profiles in the melt pool are very difficult to observe, however there are a number of indirect factors driven by the thermal profile that are more easily observable.

Two melt pool flow regimes dominate material transport in the melt pool. Buoyancy flows are driven by differential densities of molten metal within the pool. Surface tension flows, otherwise known as marrangoni flow, over the surface of the melt pool are driven by differences in the viscosity of the molten material. Both these dominating material transport effects are temperature driven. Through the observation of the melt pool flow mechanisms an understanding of the thermal profiles of the melt pool can be gained. Although it is very difficult to observe material transport within the melt pool itself, the flows seen over the surface of the melt pool are more easily visualised. Two visualisation methods have been undertaken and detailed in this chapter:

Initially high speed video has been used to capture the melt flow patterns; this was initially a monochrome system with a limited optical setup. The optical setup, and low resolution camera used for the monochrome high speed video limited the resolution of the final images. Although differences in the melt pool shape and motion could be seen these were not conclusive results.

To obtain images with a higher resolution, high magnification still frame photography has been carried out on different beam intensity profiles. Still photography has been able to produce images of the melt pool shape, showing how the melt pool leading edge takes in powder, a function of the laser beam shape. The melt pool surface shape can also be seen using still photography. This gives an indication on how the material transport mechanisms have deformed the melt pool under thermal gradients induced by the laser beam intensity distribution. Using the optical setup developed during the still frame photography, further high speed videos were taken using a colour high speed camera system. The higher magnification achieved in this setup allowed the surface flow patterns and melt pool shaped to be seen. By tracing the flow paths over the melt pool surface information as to the direction and velocity of the surface flow has been obtained.

Further analysis has been undertaken to look at the thermal profiles on the surface of the deposition. By taking the colour information from the recorded frames the intensity of the images can be separated from the recorded colour. The colour information obtained can then be used to give an indication of surface temperature profiles.

Editing the high resolution video files to only show the difference between frames highlighted the motion of the melt pool flow. Motion tracking algorithms were used in custom software to track and quantify the flow over the melt pool surface.

7.2 Monochrome High Speed Video

7.2.1 Camera setup

A monochrome high speed camera was used to image any material transport on the surface of the melt pools, and to what extent this varied between beam intensity profiles.

The melt pool was imaged during the deposition process with a Photron FASTCAM APX RS. The camera has a monochrome CMOS sensor at a maximum resolution of 1024 x 1024 pixels. This resolution was maintained at the 1000 frames per second used. The camera position is fixed using a custom camera mount suspended from the roof of the laser safety enclosure. Mounting the camera in this way gave a stable mounting isolated from the table motion. The mounting platform could be mounted on either side of the cabinet, to allow both laser heads, Gaussian and DOE, to imaged. The images captured by the camera would therefore by static relative to the laser head, looking along the axis of the work piece traverse. The camera mounting method is shown in the photograph, Figure 7-1. A video frame taken by the camera showing the deposition process under external lighting is shown in Figure 7-2. The final videos were taken using only the self illumination of the melt pool.



Figure 7-1: High speed camera set up to film DOE beam deposition



Figure 7-2: Frame of deposition using a cutting head under externally lit conditions showing the camera view relative to the work piece.

The self illumination of the melt pool provided an excess of light which the camera would be unable to record, and could possibly damage the CMOS sensor. This necessitated the need to fit a number of neutral density filters to the front of the lens. The neutral density filters attenuate the light levels passing through them evenly over visible wavelengths, therefore not affecting the colour of the recorded image. The filters were removed in turn, gradually increasing the light levels, until a suitable image was recorded by the camera.

As with other depositions the tracks imaged were made of Inconel 625 powder fused onto a substrate of 1mm mild steel. The substrates were laser cut into discrete sections to allow multiple welds to be made on each substrate without residual heat conducting through the substrate affecting later depositions. To remove the influence of injected powder mass flow profiles the powder was pre-placed onto the substrate. Prior to spreading of the deposition material the substrate was cleaned with Isopropanol. To allow a clear view of the melt pool the top clamping plate was not used in these experiments, the substrate was simply placed on the duretec insulation. All depositions were made using a Coherent S48 slow flow CO_2 laser producing a maximum output of 1.2kW, with all power measurements taken on an internal power meter. The laser is fitted with a twin optical setup. A conventional refractive cutting head is fitted, giving a TEM₀₀ beam, or the laser can be used to illuminate the DOE mirror to provide custom beam outputs. The work piece was set at different depths below the focal point of the cutting head to give a beam diameter matching the width of the customised beam. The beam widths were matched by making burns into Perspex. The work piece was traversed beneath the beam using an Anorad CNC-2000 two axis table.

To remove any affects of gas assist on the melt pool motion, air at a very minimal flow rate was used, purely to keep a positive pressure inside the laser head to prevent entry of fume.

Different welding parameters were used between the beam intensity profiles. This is due to the two intensity distributions affecting the melting mechanism differently. The parameters used are given in Table 7-1.

		Half Pipe
Beam Size	3mm	3 x 5mm
Powder Track Thickness (mm)	0.5	0.5
Power (W)	500	900
Traverse Speed (mm/s)	4	2.5

Table 7-1: Laser parameters for high speed videoed depositions

7.2.2 Results

The region of interest only forms a small part of the frame captured. This is due the limitations in magnification achieved with the optical setup used. In further investigations in Section 7.3 the optical setup has been improved to give a higher magnification of the melt pool to allow a higher resolution and detail. To allow further analysis of the captured images they will be shown cropped to the region of interest around the melt pool.



Figure 7-3: Cropped screenshot of melt pool formed with Gaussian beam

A cropped screen shot of a melt pool formed with a Gaussian beam is shown in Figure 7-3. To illustrate the variation in material transport between the melt pool formed with the Gaussian and the half pipe beam, a sequence of screen shots have been captured at 5ms intervals, shown in Figure 7-4. To enhance the visibility of the melt pool surface patterns the contrast in the images has been increased. A corresponding sequence of the Half Pipe deposition is given at the same time intervals in Figure 7-5.

0 ms	5 ms	10 ms
15 ms	20 ms	25 ms
30 ms	35 ms	40 ms

Figure 7-4: Screen shot sequence of Gaussian melt pool at 5ms intervals



Figure 7-5: Screenshot sequence of half pipe melt pool at 5ms intervals

To further visualise the material transport in the melt pool a threshold algorithm has been applied to the melt pool videos. Applying the threshold allows easier identification of the melt pool flow regimes. The video sequences were imported into the video manipulation software package Virtual Dub version 1.9.8. A threshold filter was applied to the Gaussian video at a value of 55 and at 150 to the Half Pipe video. The difference in the threshold values if due to differences in brightness of the melt pool in the videos. The threshold will output a video with, in the case of the Gaussian deposition, any pixel value of between 55 and 255 will be shown at white, any pixels with a value of 54 or lower would be shown at black. As no frame to frame consistency is seen in the images in the Gaussian deposition, Figure 7-4, the time interval between the frames for both depositions has been decreased to 1ms. A still frame sequence for the Gaussian and Half Pipe distributions is shown in FiguresFigure 7-6 andFigure 7-7 respectively.



Figure 7-6: Thresholded screenshots of Gaussian beam profile deposition, screenshots at 1ms intervals.





Figure 7-7: Thresholded screenshots of Half Pipe deposition pool. Frames taken at 1ms intervals to illustrate material transport patterns

The deposition pool of the two beam shapes in Figure 7-4 and Figure 7-5 for the Gaussian and half pipe distributions differ considerably. The Gaussian distribution is showing no frame to frame consistency, whereas there is little change in consecutive frames in the half pipe distribution.



Figure 7-8: Thresholded screenshots of Half Pipe deposition pool at 5ms intervals

Increasing the time interval between the frames more movement in the melt pool can be observed. This gives a greater movement of the material between the camera frames. Figure 7-8 shows a screenshot sequence detailing the motion of the melt pool at 5ms intervals. The images show a region of high intensity at the centre of the melt pool, highlighted in red. As the sequence progresses the region at the centre grows laterally. This area of high intensity could be due to a region of increased temperature or the development of a surface oxide, with different emission properties. The lateral growth of this region could be an indicator of the material transport directions. As seen with the Gaussian deposit in Figure 7-6 the growth of the central region, highlighted in red is laterally from the centre to the edges. This mechanism fits the accepted theory of material with elevated temperature rising through the body of the molten material on a buoyancy driven flow, then viscosity forces pulling the material over the surface to the edges. Although the same mechanism for growth of intense regions is seen in the videos the velocity of the growth is very different. This high speed video clearly shows that there is a difference between the surface flow resulting from the Gaussian and Half Pipe beam distributions. Expansion of this analysis is required to enable more conclusive observations to be drawn on the modifications to melt pool flow resulting from a modified beam profile.

7.3 Still Photography

The previous section details the technique used and post analysis of high speed video taken of the melt pool during the deposition process. The images gained have been able to show the main melt pool transport mechanisms and gain a comparison of the velocities present in the material transport mechanism. The ability to gain conclusion from the black and white high speed imaging was hampered by the poor magnification and broadband self-illumination. In an attempt to find a better setup for imaging the melt pools, images were taken of the melt pool using a much higher optical magnification and improved sensor resolution. This exercise allowed for the formation of an optical setup that was taken forward to a further round of high speed video discussed later in Section 7.4. The high resolution images of the two melt pools are taken using a three colour sensor. The three colour sensor allows for a number of new analysis techniques shown later in this section.

A Nikon D50 digital single lens reflex camera was used along with a Sigma 105mm macro lens. To provide a high magnification image of the melt pool a number of extension rings were fitted to increase the image size at the sensor. With the camera being used in close proximity the melt pool an infra-red cut off filter was fitted to the front of the lens to block radiation that would not be imaged by the camera, but could damage the sensor. The camera was mounted on a platform suspended from the roof of the laser safety cabinet. This isolated the camera system from the machine table vibration. The melt pool was imaged from a mirror mounted behind the deposition. The mirror is mounted to an optical mount with a twin axis tilt adjustment. This enabled the framing of the melt pool to be precisely positioned in the camera. Both the mirror and camera were fixed relative to the laser head, with the work piece traversed by the machine tables. This enabled a static view of the melt pool. The camera was connected via USB to a laptop and controlled using Nikon Camera Control Pro software. This enabled the camera to be remotely triggered from outside the laser

safety cabinet. A schematic diagram of the camera and laser setup is shown in Figure 7-9.

To produce images with a maximum possible depth of focus the smallest available aperture of f32 was used. This limited the maximum shutter speed to 1/250s. To ensure consistency across the range of beam profiles the camera was used in a fully manual mode using the same settings throughout. The camera was only triggered once the laser was approximately half way along the deposition track. This ensured the melt pool was imaged only once it had reached a steady state condition. A series of images was taken of each laser beam intensity profile.



Figure 7-9: Still photography camera setup.

7.3.1 Gaussian



Figure 7-10: Still Photography image of melt pool created using Gaussian beam irradiance distribution – Nikon D50, 1/250s, f32

The image in Figure 7-10 shows an example of the melt pool during a Gaussian beam deposition, with the weld direction into the page. The characteristic domed profile of the deposition can be clearly seen, both at the leading edge and the solidified deposition in the foreground. At the leading edge of the deposition there are a number of spheres of molten material. It is anticipated this is due to the leading edge of the laser beam having sufficient energy to melt the material but the surface tension is too strong for the material to flow into the main deposition, if the material has not had contact with the main body to allow the incorporation of the spheres. At the centre of the image above the deposition is a region of plasma. This indicates that the melt pool is reaching a very high temperature, greatly elevated from the material boiling point.

7.3.2 Half Pipe





An example image of a melt pool formed during a deposition using a DOE modified half pipe beam is shown in Figure 7-11. This image is taken with the weld direction the same as the Gaussian deposition in Figure 7-10. The melt pool in this deposition is thin and flat, clearly showing the leading edge of the melt pool. There is a slight slope across the deposition, with an increase in material visible along the left hand side of the image. Spheres of molten material are clearly seen at the leading edge of the melt pool. In this case there are also a number of spheres of molten material at the edges of the deposition track. This is likely to be due to the increased thermal input caused by the increased intensity at the edges of the beam. On examination after the deposition process these spheres of molten material have not reached sufficient temperature to wet onto the substrate and so not adhered upon solidification.

Centrally above the deposition track is a region of intensity. This feature is small and elongated in shape. This indicates that it is a small amount of molten material being ejected from the melt pool, the elongated shape indicates the material in moving during the frame.

7.3.3 Discussion

The still images in Figure 7-10 and

Figure 7-11 show dramatic differences between the shapes of the two deposition pools. The deposition formed with a Gaussian distribution shows significant doming of the solidified deposition. The shape of the half pipe DOE deposition shows a melt pool with far greater flatness. The difference in melt pool shapes fits in with the expected theory that the DOE deposition will have reduced thermal gradients compared to those present in the Gaussian deposition. The image of the DOE deposition shows an increase in the pixel intensity at the edges of the melt pool. This fits with the expected thermal profile where there is an increased level of laser intensity at the edges of the pool. The extra intensity at the edges of the melt pool is an element of the DOE design where the extra intensity at the edges the beam compensates for conduction losses in the substrate.

The quality of the images obtained in these SLR photographs shows that the optical setup is suitable for investigations with high speed filming equipment.

7.4 Optical Pyrometry

Electromagnetic radiation is given off all by all matter above absolute zero. As the temperature of the matter varies the spectrum of the emission changes. The emitted spectrum varies according to Planks law for the electromagnetic radiation of a black body. A black body is the theoretical ideal radiator of thermal radiation, also a body that absorbs all thermal radiation reaching the surface.



Figure 7-12: Plank's law curves for a black body at varying temperatures, spectral radiance against wavelength (1).

As can be seen from Figure 7-12 the level of emission increases with an increase in the object temperature. An increase in temperature also results in a shift in the spectrum towards a higher frequency. Although a black body is only a theoretical surface and not achievable in practice, the emissivity property of a material indicates the ability of a body to behave as the theoretical case. The emissivity (ϵ) of a surface is a ratio between the energy radiated by that body to the energy radiated by the theoretical black body.

A number of instruments exist to measure the thermal radiation given from a substance in order to determine its temperature. The simplest method measures the intensity of a narrow wavelength band. As the temperature of the material varies the proportion of the measure band varies giving an indication of the temperature. As only a single intensity is measured this method is easily effected by volume of material measured, standoff distance, incident angle of detector, measurement time and background conditions. The intensity measured by the instrument is compared to Plank's law to find the intensity at the measured wavelength band, giving the temperature of the body. A value for emissivity is required to relate the real surface to the theoretical plank's law curve, this is a point of further errors in the temperature measurement.

A second method of optical temperature measurement is known as a two colour pyrometer. This method uses two detectors each measuring separate narrow wavelength bands. By taking the intensity of the two readings a ratio is formed. The ratio between the two readings allows the position on the plank's law curves to be found independent on the actual intensity of the readings. This removes the complications of emissivity scaling, providing the assumption of the emissivity at the two measured wavelengths, known as the grey body approximation, remains valid. If the instrument is designed so that the measurements are taken at the same angle and over the same area complication in the measurement setup are also greatly reduced.

The temperatures reached during the welding of many metals is sufficient to emit thermal radiation of short enough wavelength to be in the visible spectrum. When the material emits in the visible spectrum shifts in the emitted spectrum are seen by the eye as colour changes in the molten material. This affect has been used to characterise the temperature of hot metals for manual working and has formed a scale for incandescent lighting colours.

As the deposition pools emit visible light during the deposition a standard colour camera can be used to extract the temperature profiles in the melt pool. A colour digital imaging sensor uses a Bayer filter, Figure 7-13, to record the colour information from the image. A checker pattern of band pass filters are arranged over the individual pixels on the sensor surface. When the image is captured the intensity at each pixel is recorded, an algorithm in the camera controller overlays the colour information onto the image using the ratio of intensities captured from the red, green and blue filtered pixels. A digital file for a Bayer filtered colour image therefore contains intensity information for every pixel and colour information for each group of 4 neighbouring pixels. By processing the image file to extract the colour information for the pixels the ratios between the red, green and blue pixels can be extracted. The extracted colour information can be to form a two colour pyrometer.


Figure 7-13: Schematic of Bayer filter for image sensor chip (2)

It is not the intention to use this process to give temperature readings of the melt pool. The measurements will be used to see the relative thermal distribution within the deposition pools not absolute readings. Although a similar process can be used to give readings of surface temperature there are a number of limitations in the technique used in this study. The filters used in the Bayer are transmissive to a wide band of wavelengths with the exact parameters on the transmission properties not known. The in camera algorithm used to add the colour information is not fully known, as such scaling may be added to the ratios making absolute temperature readings unreliable. A further possible introduction of was that some of the camera systems used provide compression of the image files on-board the camera, the pixel maps produced cannot be relied on to be a true indications of the pixel values recorded. Although these factors have led to the decision to not attempt to extract individual temperature readings from the images recorded, it is felt that very useful information on the nature of the thermal profiles present in the melt pools can be extracted from colour images taken during the depositing process.

7.4.1 Pyrometry Processing



Figure 7-14: Flow diagram of thermal profile extraction process.

RGB pixel maps were extracted from the image files. These files contain a value at each pixel for the red, green and blue level. The first stage of the algorithm finds the scaling factor required making the red value for a pixel equal to 1, this scaling factor is then applied to both the green and blue values for that pixel. The scaling is calculated for the next pixel and applied to the corresponding green and blue. By allying this process to every pixel in the image the resultant pixel map contains purely colour information, with the intensity information removed. This image is referred to in this study as the normalized image.

By scaling of all three channels in this way, the green channel becomes a ratio of the Red : Green information and the blue channel becomes a ratio of Red : Blue. By plotting one of these channels we get an image of the output of a two colour pyrometry process. This process is illustrated in Figure 7-14: Flow diagram of thermal profile extraction process.

7.4.2 Still Images

Intensity Normalization

The following figures show the pyrometry process applied to the still images taken during the deposition process. Figure 7-15 shows the raw pixel maps for the two deposition images before any analysis. In both cases the deposition direction is into the page. Differing light levels given off during the deposition process and slightly different camera orientations has resulted in images of differing brightness. Figure 7-16 shows the same pixel maps with the intensity element of the pixel values removed. This leaves the ratio between the red/green/blue channels showing only the colour in the image. It can be seen that the intensity differences between the two images has been removed.



Figure 7-15: Full colour bitmap image from camera of a) Gaussian Deposition b) Half Pipe DOE



Figure 7-16: Normalized images showing colour information only, intensity of each channel has been removed leaving only the ratio between the colour channels

The normalized images showing only the colour information in the image enable a clearer comparison to be made between the two deposition profiles.

Thermal Mapping





Figure 7-17 has isolated the ratio between the red/blue channel. This gives a clearer indication of the thermal profile present in the deposition. The scale assigned to the images is only a relative intensity, it should not be related to an absolute temperature.

The process applied to the images shows the technique adds value to the analysis of melt pool formation. When the pyrometry information is extracted to form the images in Figure 7-17 a region of elevated temperature can clearly be seen above the surface of the Gaussian deposition. It is believed this a region of plasma. This region is formed by the overheating of the deposition material. Other than the region of plasma above the melt pool, no regions of elevated temperature are seen. It is anticipated that the regions of highest temperature in the Gaussian deposition will be at the leading edge along the centreline, in the images this region is shadowed by the humped melt pool. In the DOE deposition there are a number of regions indicating an elevated temperature.

7.5 Colour High Speed Video

Using the optical setup developed for high magnification still image capture of the deposition process, high frame rate video has been used to investigate the dynamics on the surface of the deposition pool during the laser process. The theory of melt pool flow shows that there is a proportion of the material transport over the surface of the melt pool. It was hoped that by using high frame rate video the mechanisms of the melt pol surface flows could be investigated.

Using a high frame rate colour camera images have been captured for visualisation in their raw state and for processing using pyrometry techniques as used in the still images in Section 7.4.2

A number of laser beam profiles were used to form depositions of Inconel powder onto mild steel substrates.

7.5.1 Experimental Setup

Figure 7-18 shows the viewing setup for the high speed video process. A mirror has been used in the setup to allow a close in view of the deposition without exposing the camera lens to the melt pool, where heat and splatter can damage the front lens element. The use of a mirror also allows for positioning of the field of view to look as close as possible to give the clearest view of the melt pool in process.



Figure 7-18: Viewing orientation for colour high speed video of deposition process

The camera position is fixed relative to the laser head looking along the axis of the work piece traverse, shown in Figure 7-19. This allows a static view of the deposition forming relative to the laser beam.



Figure 7-19: High speed camera set up to film DOE beam deposition

The videos use the self illumination of the molten weld pool, with an infra red blocking filter in place to protect the camera CCD. The iSpeed 3 camera uses a Bayer filter arrangement to get red, green and blue signals on one sensor, with a built in algorithm to convert the signal from each pixel on the sensor into a RGB value for each pixel in the image. The camera was used to output an uncompressed bitmap image for each frame in 24 bit colour. This gives 256 possible values for each of the red green and blue channel of the image.

Videos of depositions made with the parameters in Table 7-2 have been taken. The diameter of the Gaussian beam has been expanded to 2mm, this gives all the depositions the same nominal width. Differing parameters are needed for the beam distributions, this is due to the abilities of the shapes to initiate melting of the materials. The high intensity "spike" in the center of the Gaussian beam means this distribution is able to induce melting at a lower power and higher speed.

	TEM ₀₀	Half Pipe	Half Pipe Wedge
Beam Size (mm)	2Ø	2 x 2	2x3
Powder Track Thickness (mm)	0.5	0.5	0.5
Power (W)	750	850	1000
Traverse Speed (mm/s)	5	3.5	3

Table 7-2: Laser parameters for high speed videoed depositions

7.5.2 Imaging



Figure 7-20: Gaussian distribution deposition high speed video frames



Figure 7-21: Half Pipe deposition high speed video frames

Screen shots of the deposition melt pool from a Gaussian beam profile and a Half Pipe DOE profile are shown in Figure 7-20 and Figure 7-21. Four frames of each of the depositions are given to show any slow material flow seen over the period of the video. As can be seen from the figures the shape of the melt pools is different for the beam intensity distributions. The image of the melt pool formed by the Gaussian beam intensity distribution shows circular leading and trailing edges. Linear flow patterns are seen at the leading edge of the deposition continuing over the surface of the pool. These are particularly evident in frames 100 and 200. Preceding the leading edge of the deposition pool are a number of spheres of molten deposition material. It is likely that the laser beam is preheating the powder ahead of the melt pool. Where the temperature is only a little over melt point the material will have a high viscosity and surface tension, leading it to form spheres. As the laser traverses and the temperature of the material in the spheres increases they will wet to the substrate and be incorporated into the melt pool.

The square half pipe beam shape in Figure 7-21 has altered the resulting deposition pool shape. The flat front of the beam profile has resulted in a flat front to the melt pool. The apparent curvature of the trailing edge of the melt pool has also reduced. This is likely to be a compounded effect of the square edge of the laser beam and a reduced curvature of the solidified material. Flow lines are seen in the half pipe deposition as in the Gaussian, in this case the flow is straight over the pool surface, whereas in the Gaussian distribution the flow was deflected towards the outer edges of the pool. Balling of material preceding the leading edge of the deposition pool is still seen. The number of the spheres appears to be reduced, with no gap apparent between the formation of the spheres and the leading edge of the deposition pool.

Through observation of the for the two deposition profiles the mechanism for how material is incorporated into the melt pool can be seen;

- Powder is heated by the very leading edge of the laser beam. As the beam traverses the powder heats to melting point, but due to the high viscosity of the just molten material spheres are formed.
- 2. The laser beam continues to heat the sphere of material incorporating newly melted powder.
- 3. As the temperature, and volume of the sphere increases a point is reached where the surface tension is unable to hold the sphere intact and the material is incorporated into the main deposition melt pool.

Following the 3rd phase where the material is incorporated into the melt pool there is a period of instability caused by the sudden addition of the molten material. Screenshots of this phase are shown in Figure 7-22. The destabilizing effect of this process is likely to affect the profile of the solidified deposition and possibly the resulting microstructure.



Figure 7-22: Screenshots of Half Pipe deposition showing incorporation of molten sphere

A third laser beam profile has been used that has been designed to reduce the effect of balling in material preceding the deposition melt pool. The Half Pipe Wedge is a beam profile similar to the Half Pipe but incorporating a graduated leading edge. It is expected that the slow uniform heating of the powder bed preceding the melt pool will stabilize the incorporation of the powder into the molten deposition. Screenshots of the deposition process using the Half Pipe Wedge energy distribution are shown in Figure 7-23.



Figure 7-23: High speed imaging frames of Half Pipe Wedge deposition at 100ms intervals

The effect of gradual heating at the leading edge of the deposition pool appears to have had a limited effect on the levels of balling and associated melt pool destabilization. The first two screenshots in Figure 7-23 are showing the formation of spheres of material. Observations of the videos has shown that the flow of material from front to the back of the melt pool has reduced through the inclusion of preheating in the beam profile.

7.5.3 Pyrometry Analysis

A pyrometry technique applied to colour still images was shown in Section 7.4.1. Using the raw colour images from the high speed video camera the same analytical steps have been taken to remove the intensity distribution and be left with colour information. As was shown in the still frame analysis this colour information can be used to give an indication of the thermal profiles present on the surface of the deposition.

The three stages to the pyrometry analysis are shown in Figure 7-24. The image produced when the intensity term is removed from the Gaussian distribution shows the extent to which the powder bed is preheated, as indicated in Figure 7-25. The extent of

any preheat zone in the DOE profiles are to be too small to be easily distinguished from the rest of the melt pool.



Figure 7-24: Stages of pyrometry analysis of colour high speed video

There is little or no difference in the size of any preheating zone prior to melt pool between the Half Pipe and Half Pipe Wedge profiles. The incorporation of the slower heating to the front of the intensity profile has had no observable effect on any preheating zone at the leading edge of the melt pool.



Figure 7-25: illustration of melt pool and pre-heating boundaries in Gaussian deposition

Figure 7-26 shows a sequence of frames for the scaled colour channel images for each of the analysed deposition pools. As has been seen in previous analysis of the images the shape of the melt pool is different particularly the straightening of the leading edge of the DOE depositions. The isolation of a single colour ratio in these images has highlighted any flow pattern to the surface. This is particularly evident in the Gaussian deposition frames 100 and 200. No overall flow system is evident in the DOE frames. The patterns shows a distribution of small regions of higher values over the whole surface of the DOE melt pools. Some balling of material is present at the leading edge of the DOE deposition pool but this is at a lower frequency and number to that seen in the Gaussian deposit. An interesting effect is seen in the Half Pipe deposition frame 100, where a large region of elevated temperature is seen at the trailing edge of the deposition pool. This region is a plasma plume that is seen above the surface of the melt pool during the formation of the melt pool. The formation of these plasma pools are seen more often, and are larger in size in the Gaussian deposition than with a DOE. Examples of frames showing plasma formation in the Gaussian deposition are shown in Figure 7-27



Figure 7-26: False Colour Red/Blue ratio images of the three deposition pools at frames 0, 100, 200 and 300 representing 100ms intervals



Figure 7-27: Plasma event examples during Gaussian deposition with corresponding frame number



Figure 7-28: Chart showing relative occurrence of plasma formation during deposition

The images produced from the pyrometry analysis contain a lot of detail of the surface features. This is in part due to the surface temperatures as well as the surface composition, i.e. oxide formation. Surface material transport effects can be seen in the still frame images but to gain an understanding of the thermal profile over a longer time period a total of the intensity imaged over a number of frames has been calculated for each deposition profile.

The images in Figure 7-29 give the total intensity for a sum of 5, 10, 100, 200 or 400 frames. The same scaling factor is applied to all three images on each row of Figure 7-29. The scaling factor is calculated by taking the summed images for all beam profiles for each frame number multiple. The largest value for any of the three summed images is then divided into all of images before they are all multiplied by 255. This

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results in all the images with the same number of frames totaled having the same scaling factor. This allows the final intensity values of the images can be compared. Figure 7-29 shows a number of different quantities of frames summed. In the 5 to 10 frame summation the flow patterns seen in a small timeframe are still visible, with contrast between the flow lines shown in red against the yellow background. As the number of summed frames increases the number of pixels at a higher intensity after scaling is increasing, shown by the increasing level of red in the images. This would be an indicator that the flow over the surface is not completely dominated a single pattern, but rather a combination of flow over the whole surface. The flow pattern seen in the Gaussian deposition remains visible as the number of summed frames increases. This shows that these patterns must be dominating. Summations of 100 frames show the detail of the dominating flow patterns and so have been expanded in Figure 7-30.



Figure 7-29: Total image intensity for 5, 10, 100, 200 and 400 frames

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Figure 7-30: Scaled total intensity figures showing 100 frames.

7.6 Flow Tracing

To aid in the visualisation of the melt pool surface a number of image processing techniques have been utilized. The video frames were initially processed using a commercial motion tracing module in Image Pro, image processing software. Traces were not able to be made due to the complexity in the images confusing the algorithm used in the software. To enhance the material transport flows seen on the surface of the melt pools, to allow motion tracing, the videos have been edited to show the differences between consecutive frames. The resulting frame shows only parts of the melt pool surface that have altered in between the frames.

Using custom software written in National Instruments LabView the first two frames of the video are read into memory. To form the frame of the new edited video the absolute difference between the first and second frame has been taken. By taking the absolute difference a change from light to dark is captured as well as a dark to light change. As only the change in pixel value is captured the videos are of a much lower intensity than the original frames. To enable visualisation of the process seen the resulting frames are therefore multiplied by a factor of 10. This process in repeated for the rest of the video file, where the next difference frame will be made from the absolute difference between frames 2 and 3 and so on.

The difference videos have been useful in isolating the motion seen in the high speed videos. Clear patterns of flow are seen on the surface of the deposition pools. In the figures below a series of frames are shown to see the typical flow patterns for each of the deposition beam profiles. Figures Figure 7-31, Figure 7-32 and Figure 7-33 give a series of difference images for the Gaussian, Half Pipe and Half Pipe Wedge respectively.



Figure 7-31: Image sequence showing frame to frame difference in colour high speed video with Gaussian distribution, frames at 2ms intervals



Figure 7-32: Image sequence showing frame to frame difference in colour high speed video with Half Pipe distribution, frames at 2ms intervals



Figure 7-33: Image sequence showing frame to frame difference in colour high speed video with Half Pipe Wedge distribution, frames at 2ms intervals

Using the difference videos the flow patterns on the deposition pools can be observed. However firm conclusions as to the pattern of flow are open to interpretation. To investigate further the nature of material transport software has been written to trace the path of features in the deposition pool image over a number of frames. The software takes a number of user defined points on the image in the first frame and tracks the features at those points between frames. The locations of the points are recorded for each frame allowing traces of the flow to be illustrated along with measurements of the speed and direction. Feature tracking utilises the Lucas-Kanade for optical flow tracing, the input parameters are given in Table 7-3.

Level	4
Max Iterations	5
Window Size	15
Displacement Threshold	0.01

Table 7-3: Lucas-Kanade a	Igorithm input parameters.
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It is worth noting at this point that the software is only able to record the motion of the features relative to the flat image plane. This is not a true measurement of the flow

over the more complex three dimensional form of the melt pool. The errors involved between the surface of the pool and the image plane are considered to be small and the overall comparison between the speeds seen in different melt pools to be valid.

The software outputs a number of images.

- The first output is an image of the starting frame with the initial measurement points overlaid. These points were user input to the software. The change in the location of the features at these points will be tracked to form the movement trace.
- 2. The next output image shows a point-to-point trace of each measurement through the video frames. This trace is overlaid on the final frame of the video sequence. The individual traces overlaid on to the image are assigned random colours; the colour has no indication as to properties of the trace. The plot gives an indication of the total distance travelled by each of the measurement points over all the frames. This gives an indication of the absolute velocity of the material transport.
- 3. The third image shows a vector of the flow by drawing a line between the initial user defined point and the final point in the trace. This overlay gives an indication into the distance covered between the first and last frames analysed, therefore giving the mean displacement for the flow over the measurement period. As all the frames between the differing videos are taken over the same time period this plot gives an indication of the average velocity of the flow.
- 4. The final image output from the analysis software give a line of best fit to all the points in an individual trace. This gives an indication as to the overall direction of flow that feature took.

As well as the image outputs from the software the coordinates of the measured points is output. This will be used to calculate speed and relative motions of the points on the surface of the deposition pools.

7.7 Flow Analysis of Colour High Speed Video

A number of 10 frame sections of the deposition pool difference videos have been extracted to analyse the flow patterns on the melt pool surface. The sections chosen have been taken at approximately 100 frame intervals. The exact positions of the frames varies between deposition pools as the frames have been chosen to show the

clearest flow patterns without flaring from plasma or splatter ejection from the depositions. The frames extracted for the motion trace analysis are given in Table 7-4.

Figure 7-34 to Figure 7-45 show the resulting images from the flow analysis for the second section of 10 frames.

Deposition	Section 1 Frames	Section 2 Frames	Section 3 Frames	Section 4 Frames
Gaussian	70-79	158-167	272-281	350-359
HP	6-15	113-122	200-209	265-274
HPW	5-14	105-114	204-213	322-331

Table 7-4: Difference video fame number for flow analysis sections

7.7.1 Gaussian





Figure 7-34 shows the staring locations of the user input start locations for the flow tracing process. These 15 points have been equally spaced at the front half of the deposition pool.



Figure 7-35: Section 2 point to point trace of flow over the analysed 10 frames for the Gaussian deposition.

Figure 7-35 shows the point to point trace for the motion flow over the analysed 10 frames. As can be seen the different points are traces with a unique colour. With the exception of the pink trace all the points input have flown to the back of the melt pool. The majority of the flow lines show that the material is flowing around the edges of the melt pool with a lower influence of flow over the top of the melt pool. All the trace lines show motion of a consistent direction, with no major direction changes within the measurement period.



Figure 7-36: Flow vector image for section 2 of Gaussian deposition analysis.

Figure 7-36 shows the flow vector for the TEM00 deposition. This image shows a line drawn between the position of each measurement point at the start of the sequence and the corresponding measurement point in the last frame. The length of the line in this plot gives the total distance covered between the first and last frames. The lines can also give an indication of the flow direction, although this can be misleading where the flow is curved, as is the case in this deposition.





Figure 7-37 shows the final frame in section 2 with an overlay of the line of best fit of the coordinates of a tracked point in each frame of the sequence. This plot gives an indication of the direction of flow but the length of the line does not give any indication as to the distance travelled. As can be seen by this plot the overriding flow direction is around the sides of the deposition pool.

7.7.2 Half Pipe



Figure 7-38: First frame of section 2 of Half Pipe video showing trace point initial locations

Figure 7-38 shows the initial frame of a section of the Half Pipe deposit being analysed. Marked as an overlay are the initial measurement coordinates. These points are traced frame by frame to give the motion of the deposition.



Figure 7-39: Half Pipe section 2 point to point trace of flow over the analysed 10 frames

Figure 7-39 shows the resulting point to point data for each of the 15 measurement locations. The traces show the flow to be variable with no overall direction. All of the traces show there is significant changes in the direction of the flow throughout the measurement period. All traces have remained in the first half of the deposition where the initial points were located.





Figure 7-40 shows the vector plot for the calculated flow. This overlay indicates the distance covered between the first and last frames measured. The vector lines show that the distances covered by the 15 locations are uniform indicating that there is a stable velocity to the flow.



Figure 7-41: Half Pipe line of best fit plot showing overall direction of flow

Figure 7-41 shows a line of best fit for each of the measurement points. The majority of the lines show flow across the deposition perpendicular to the deposition. There is however, no overall pattern to the flow shown over these 10 frames.

7.7.3 Half Pipe Wedge

The initial measurement point locations for the Half Pipe Wedge deposition are shown in Figure 7-42.

Figure 7-43 shows the analysed point to point traces for the Half Pipe Wedge intensity profile. As with the half pipe deposition the traces show that the flow has been in a number of directions, with individual measurement traces showing variation in the flow direction throughout the measurement period.



Figure 7-42: First frame of section 2 of Half Pipe Wedge video showing trace point initial locations



Figure 7-43: Half Pipe Wedge point to point trace of flow over the analysed 10 frames



Figure 7-44: Flow vectors for Half Pipe Wedge deposition, showing distance covered by the measurement points in 10 frames

The distance covered by the trace points between the first and last frames is shown in Figure 7-44. These vectors show that there is a greater level of consistency to the distance travelled by all the measurement points than seen in the previous depositions.



Figure 7-45: Line of best fit between the trace points for Half Pipe Wedge Deposition showing direction of flow

The direction of flow indicated by the lines of best fit in Figure 7-45 shows there is a possible flow pattern in the Half Pipe Wedge deposition. Clockwise flow in the right hand side of the deposition can be seen. As seen from the previous figures the

distance covered by this flow structure and therefore the speed is much lower than the flow seen in the Gaussian deposition.

7.7.4 Comparison

As a direct comparison between the flow patterns seen with the three beam intensity profiles, point to point flow trace diagrams are given for the three intensity profile distributions in Figure 7-46.





Figure 7-46: Comparison between flow patterns seen with Gaussian, Half Pipe, and Half Pipe Wedge beam intensity profiles.

7.7.5 Analysis

Point to point data captured by the motion tracing software, this allows for further analysis into the speed and directions of the melt pool flow. Two measures of the surface flow are taken from this data.

1. Distance Travelled

The distance travelled is calculated by taking the sum of all the distances between frames, regardless of direction. This measure shows the distance covered by a feature over the number of frames used. If the time for the frames is included this measure gives the speed of movement, without any direction information

 The distance covered is calculated by taking the distance between the location of the feature in the first frame and it's location in the last frame. This measure gives more information on the overall flow patterns, and allows a mean direction of flow to be calculated.

A schematic illustrating these two flow measurements id given in Figure 7-47.





The speed of the melt pool flow has been calculated by calculating the straight line distance between successive points in the trace and dividing by the time between

frames. This give a speed travelled in numbers of image pixels. To convert to a real world unit the calibration images taken with the videos are used to measure the number of pixels covering 1mm. this gives a scale factor to convert the speed into real world mm/s. The calibration marker gives a scaling factor of 86 pixels per mm in real world.





Figure 7-48 shows the mean speed of the flow in each of the 4 sections of video analysed. The speed is calculated by taking the distance moved between consecutive frames in the tracing videos and dividing by the time between frames of 0.667ms. The TEM₀₀ profile shows a lower speed of flow in the first section, around 130mm/s. It should be noted that the video was only captured at the midpoint of the deposition process, this lower speed is therefore unlikely to be the melt pool flow "getting up to speed". Following the first section the speed is more stable varying between 180mm/s and 218mm/s. The Half Pipe deposition has shown a stable speed across the video sections varying between 180mm/s and 198mm/s. The Half Pipe Wedge profile has shown to give a larger variation in the deposition surface flow speeds, varying between 97mm/s and 240mm/s, with 240mm/s being the largest average speed of all the video sections.

These results suggest that the point to point, or speed of travel is largely even between the beam profiles. This result would at first appear to contradict the results seen from the images of flow patterns in the previous section. This result shows that the speed of flow between frames is largely similar, but that the direction of motion varies between frames of the DOE depositions, leading to an overall lack of flow patterns and velocity.

An average surface flow speed for each deposition over all the sections of the videos is given in Figure 7-49. This chart shows that although the Half Pipe Wedge profile had the maximum mean value for a section average it has overall the slowest surface flow. Both the Half Pipe and Gaussian depositions show similar flow speeds, with the Half pipe showing the maximum average speed.



Figure 7-49: Mean surface flow speed for each deposition profile

The plots in Figure 7-48 and Figure 7-49 give the average speed of the flow, measured from the point to point data. This gives a misleading story when we consider the direction of flow is very different between the Gaussian and DOE beams. It was clear from the images of flow lines that the distance covered in the Gaussian deposition was much greater than the distance covered by either of the DOE depositions. The average

speed data would appear to conflict with this, where the fastest moving deposition flow showing at the DOE Half Pipe. We therefore need to distinguish between the speed of the flow on a point to point measurement and the speed of flow over a larger scale. The direction of flow in the DOE deposition was seen to be very variable when compared to the Gaussian, even if a flow of this type has a high speed it will not contribute to a material transport mechanism over the whole deposition profile.

The distance covered during each section of the video, i.e. the distance between the point selected in frame 1 and the tracked position reached in frame 10 has been calculated. This distance shows the material transport on a larger time scale than seen by the point by point distance data. The two measures of distance used, the distance travelled and distance covered are illustrated in Figure 7-47.



Figure 7-50: Chart showing the mean distance covered for each section of the analysed videos

Figure 7-50 shows this calculated distance covered as a mean value for each of the analysed video sections. All but one of the Gaussian distances is larger than any of those from the DOE modified beam distributions. This shows that the flow in the Gaussian distribution is having a greater material transport effect than seen in the DOE beams. We can also clearly see there is a large variation in the speed of the flow during the deposition process. To look at why there is a large variation in the speed of flow between sections of the Gaussian deposition plots of all sections analysed are
given in Figure 7-51. The two sectors with lower than expected values are the first and third. A number of measurement points at the front of the deposition have not remained within a small area over the tracking of the flow. It appears as if there has been insufficient texture at this part of the image to allow the algorithm to form a successful trace. In the third section of the video a number of points located at the centre of the domed deposition surface have produced traces with a random motion. As can be seen from the frame shown there are no features in this section of the image for the tracing to have used to find the flow pattern.





The half pipe deposition shows a more consistency in the distance covered in the sections. This therefore shows a more consistent speed of melt pool flow. The distances covered show a steady increase from one section to another. This shows acceleration in the flow over the deposition process.





Figure 7-52 illustrates the mean distance covered by all the traces over the four sections for each of the depositions. The predicted result of a drop in material transport speed has been shown to be valid with a reduction of \approx 47% from the Gaussian to Half Pipe and \approx 52% reduction from the Gaussian to TFW distributions.

The analysis of material transport flow tracing so far has looked at the point to point travel between frames and the overall distance travelled over the set of 10 frames analysed in each section of the videos. By combining these two measurements the linearity of the flow patterns can be quantified. If the flow pattern in each frame was in exactly the same direction then the sum of all the point to point distances will be equal to the distance between the first and last point. If however there was to be a large variation in the direction of the flow, either due to a turbulent flow or a circular vortex pattern, then the ratio between the two measurements would decrease away from a unity value.



Figure 7-53: Mean ratio of distance travelled to distance covered for all analysed frames

Figure 7-53 shows a decrease in the linearity of the flow when using the DOE modified beam profiles. In the Gaussian deposition the ratio of distance travelled to distance covered is higher showing that the direction of motion of the individual frames is contributing towards material transportation the deposition. This result is consistent with that seen in the motion trace images where the traces in the Gaussian distribution show long flow lines with the flow in a consistent direction. The lower ratio in the two DOE depositions is due to the inconsistent directions of flow seen during the video sections. Flow directions between frames have been in different directions leading to a reduced overall material transport.

8.1 Laser Beam Profiles

This study has shown that when compared to a standard Gaussian distribution beam the shaped beams have altered the process to result in a modified deposition. All the modified beam profiles used showed that the modified heating provided by the beams has resulted in significant changes at both the physical and microstructure levels. The changes in physical profile seen in this study will form a basis for further optimisation to control the shape of the deposition to match the end use of the process such as, coatings being laid down in a rectangular uniform thickness deposition. Changes to the microstructure have also shown improvements, decrease in the average grain size can lead to depositions with improved material properties and lack of segregation, improving corrosion performance.

The most dramatic modifications to the microstructure in the depositions have been through the use of a deliberately asymmetrical deposition. The analysis of a deposition made using the offset rugby posts beam profile shows dramatic changes to the grain size across the width of the deposition. This is an indication of how the heat flow into the material can influence the solidified material.

The correlation between the surface flow patterns seen during the deposition process and the microstructures resulting from them gives a clear indication that the thermal profiles observed driving the melt pool are also a direct controller on the microstructure formation. From this study it is known that the thermal profiles have an influence on the alloy element segregation but it is not known if this is a direct result of the thermal profile or caused indirectly through the material transport mechanisms.

The beams chosen have shaping in only the axis perpendicular with the laser scanning direction, with exception of the Half Pipe Wedge that has an additional ramp up function. It was felt that shaping in this direction would have the most significant effect on the material transport. This has been shown to be a reasonable assumption, with the only profile with longitudinal shaped profile, Half Pipe Wedge, having a limited effect over the profile without the ramp. The dramatic profile seen from the Offset Rugby Posts further indicates that the transverse shape of the laser beam has a strong influence. The initial conclusion drawn from observing the effect of introducing the

wedge to the Half Pipe was that the transverse laser transverse profile influences the properties of the process, with the longitudinal profile controlling the stability. The beam shapes used in this study have only limited shaping in the longitudinal axis as such further investigation is encouraged. When linear shaping requires a two dimensional laser scan the beam shaping method can be rotated as required to maintain a liner motion relative to the beam shape axes.

The work undertaken during the initial investigations has revealed that the use of single substrates for multiple depositions introduced significant errors to the process. The conduction between depositions has been imaged using thermal imagery to see the extent of preheating at the deposit sites. The resulting segmented substrates, laser cut to remove the conduction mechanism, have removed the introduced errors and increased the productivity of sample preparation. This method of substrate preparation has been adopted by others at Loughborough University during laser materials processing research.

8.2 Microstructure

There is no doubt, as illustrated in Figure 5-13, that through shaping the beam the grain size in the deposition is reduced. The beam shape used was expected to reduce the thermal gradients and therefore the growth of grains. With the result following the expectation it shows that the beam shape can be used to give a user defined influence to the microstructure. The results seen in this study can be used to provide the foundation to further modelling and investigation with the ultimate aim of providing a process where the process is modelled in reverse to take the desired microstructure as an input to a computer model to output the beam profile required to manufacture that desired microstructure.

The change in the microstructure from a circular Gaussian profile to a rectangular beam has shown to reduce the average grain size by 41% while still maintaining the growth orientations seen in the substrate, when compared to the Gaussian deposit. The use of a more complex beam shaping profile provided by the Rugby Posts distribution has further reduced the thermal profile to provide a deposition with a further reduction in grain size from the Gaussian beam by 51%. From Figures 5-24 and 5-25 it can be seen that the modified beam profile provided by the half pipe distribution has reduced the alloy element segregation seen in the cross sections. It is considered most likely that the alloy element segregation is caused by the material transport in the melt pool. The high cost of the analysis and lengthy preparation time required have limited further investigation in this study. Alloy element segregation patterns in line with the material flow patterns seen during surface flow visualization. This possible correlation leads to the use of material transport visualisation in process to give a feedback mechanism to control the alloy element segregation taking place.

The use of an unbalanced, asymmetric beam profile in the form of the Offset Rugby Posts distribution has given a significant alteration to the material properties across the deposition width. The non-symmetrical beam has resulted in a non-symmetrical microstructure in the deposition, it is thought that this result is the first produced with a induced grain size gradient across such a small deposition, and has led to publication of the work (1). The results have since been repeated by an undergraduate study using the same equipment and beam profile. Although no immediate practical use if foreseen as to the use of the profile, it demonstrates that the microstructure in a laser process can be designed through the intuitive use of the laser beam energy profile. This process can be expanded through the use of computer modelling to provide more complex control of the deposition microstructures to provide user designed material properties.

8.3 Melt Pool Imaging

It has been seen in the broadband black and white high speed video that the melt pool flow is similar to the expected mechanism. The more uniform heating profile provided by the Half Pipe beam distribution was shown to reduce the speed of material transport at the surface of the pool. The low resolution and broadband self-illumination of the material during the process prevented clear conclusions being drawn from the images captured.

The material transport flow seen in the low resolution frames indicated a transport mechanism in line with the resulting solidified depositions, where the Gaussian showed a flow pattern of brighter sections growing at the centre of the deposit. This flow from

the centre out, is in line with the theory of surface tension driven flow from the hot centre to the cooler edges. This indicates that the thermal profiles shaping the depositions are also driving the flow, that the flow directly forms the surface profile of the deposition or a combination both effects.

The production of colour images at a higher resolution has given a much greater clarity to the melt pool flow over the images seen in just black and white. Higher resolution images have enabled the flow patterns to be observed in more detail and further analysis undertaken.

The videos taken during the process show a clear difference between the flow in the Gaussian deposition and the Half Pipe. The flow in the Gaussian deposition streams around the centre of the melt pool, whereas flow in the Half Pipe deposition melt pool is straighter, over the top of the pool. The variation in the flow illustrates that the change in thermal profile has altered the temperature gradients in the material, in turn this has altered the viscosity in the molten material leading to a change in the flow. By introducing the Half Pipe distribution over the Gaussian the melt pool has gained obvious stability and a more linear flow, seen to have also reduced the segregation left in the solidified deposition. The dramatic alteration in the surface flow pattern, through alteration of the energy input, illustrates further that the surface flow is a temperature driven process and that through careful design of the thermal input the flow can be influenced leading to control of the profile shape and segregation.

The video frames clearly show that the change in the laser beam profile from the Gaussian deposition, non-inform in two axis, to the half pipe that is only shaped in a single axis has had dramatic results on the direction and velocity of the material transport flows. The introduction of a third shaped beam that incorporates a lead in ramp has had only a small influence on the deposition pool over that already achieved by the Half Pipe without the ramp. This gives further indication that in a liner process as seen here the transverse section, perpendicular with the line on traverse has the largest effect on the flow patterns seen in the melt pool. The ramp provided by the Half Pipe Wedge has had a stabilising effect on the deposition pool.

The thermal analysis of the images using techniques, adapted from those used to analyse combustion temperatures, have successfully been used to illustrate the thermal gradients present in the melt pool. On single frame images pyrometry analysis has highlighted the surface flow patterns as seen in Figure 6-30. As the analysis is undertaken in a number of integrated frames the texture of the flow patterns is removed to reveal the underlying thermal profiles. When the results are integrated over

100 frames the thermal profiles are seen. The thermal profile illustrating the Gaussian deposition can be seen with areas of high intensity in a ring around the melt pool, where heated material from the leading edge of the pool flows around the central region. In contrast the integrated images for the Half Pipe depositions shows no overall patterns to the images leading to the conclusion that the thermal profile present at the surface of the molten pool is significantly more uniform.

A further indication of the thermal profiles in the melt pool has been gained by observing the plasma formation during the deposition process. Instances of plasma plume formation indicate elevated temperatures are present in the melt pool. The number of occurrences of plasma formation has been shown to be greatly elevated in the Gaussian deposition in comparison to both the DOE depositions. This indicates that the melt pool is generating higher temperatures, far in excess of those required to melt and form the deposition. This is likely to cause grain size growth and could be a contributing factor into the segregation of alloy elements seen in the EDS analysis. The plasma plume will absorb the laser beam energy causing a shadowing of the melt pool. The reduction in absorption in the deposition material while the plasma formation is present will lead to instability in the process. A number of health issues have also been identified due to the presence of plasma in laser materials processing.

Gaining quantitative data from the high speed videos was seen as, and has been a challenge. Commercial software designed for particle tracing was unable to use the complex features seen in the high speed video frames. The use of custom software to extract the difference between neighbouring frames and to use this information to form the patterns for tracing has enabled the formation of quantitative date about the surface flows produced by the different beam intensity profiles. This technique could be applied to a number of different motion tracking situations to remove complicated scenes in the images that do not add any information to the motion to be analysed.

Flow traces produced by the analysis show there are two differing flow patterns between the Gaussian deposition and the two DOE shaped profiles. The Gaussian deposition produces a directional 'streaming' flow, from the centre of the leading edge to the back of the deposition, whereas the DOE beams produce a flow that 'meanders' from the leading edge over the top of the melt pool. The driven flow seen in the Gaussian deposit indicates that the force driving the flow is greater than that in the DOE depositions. The increased driving force is a direct result in the modification of the thermal profile induced by the laser beam, a greater temperature gradient in the melt pool has led to an increase in the driving mechanism on the material flow. As the two

dimensional images are formed looking at a compound effect of a scene in three axis the real distances covered will be different from those calculated. The Gaussian deposition that flows from the base of the melt pool, over the sides of the deposition moves in three planes and therefor is likely to have travelled a greater distance than indicated in the images. The DOE flows are more liner onto the top of the melt pool, travel in a more planar manner.

The Gaussian deposits have a surface flow shown to cover a greater distance in the 10 frames when compared to the DOE depositions. The observations show that for the flow to be faster the driving force must be greater. This leads to an increased thermal gradient across the melt pool. The lowest temperature in the melt pool must be the point at which the material is no longer able to flow, this will be consistent between all the melt pools. The maximum temperature in the deposition pool must therefore be the driving factor to differentiate the two types of melt pool flow. It is therefore concluded that the maximum temperature reached in the Gaussian deposition to be significantly higher causing an increase in the thermal gradient driving the flow. This conclusion that the Gaussian melt pool has a higher maximum temperature is further supported by the occurrence of plasma being higher.

The observations of surface flow made in this study agree with the accepted theory for the mechanisms of melt pool flow seen in the literature survey. While the observed material transport speed are lower than those predicted in the literature, where a prediction of 0.625 m.s⁻¹ was made for tool steel with a rectangular beam (2), the observed mean value of approximately 0.2 m.s⁻¹ for the half pipe beam is of the same order of magnitude. A variation in these values would always be expected as the beam profiles do not match nor the materials. All the modelling results literature showed that a modification to the material transport would be expected, this has been shown to be accurate.

The literature also stated that material flow from GTAW welding had been observed between 0.5 to 1.4 m.s⁻¹, This figure is again higher than the observations here, but of the same order of magnitude.

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9 Recommendations for Further Work

9.1 Microstructure

This study has shown that the microstructure and surface profile of a laser produced deposition can be altered through the use of customised beam profiles. Through the use of numerical modelling of the thermal profiles induced by the custom beam profiles the microstructure in the deposits can be predicted. A numerical model can therefore be used to take, as the input, the desired microstructure in the deposition to form the laser beam intensity profile required to produce that microstructure.

The extent of the complex crystallography analysis in this study has been limited by time and funding. An upgrade to the equipment used will allow the gathering of EBSD and EDS date much faster reducing the cost of the process. More extensive testing of a number of complex asymmetrical beam intensity profiles is required to measure the extent of how the microstructure of depositions can be altered.

This study concentrated on the deposition if high value metallic materials using the uniform heating provided by the beam profiles to give uniform heating for microstructural influence. The use of customised beam profiles is likely to have great advantages in the processing of materials with narrow processing windows, such as polymers.

9.2 In Process Imaging

The techniques used and developed in this study have produced detailed quantitative melt pool flow patterns. This data would ideally be used to validate a numerical model built to predict the microstructure and melt pool flow.

Imaging of the thermal profiles of the melt pool surface has been constrained to relative measurement of the profiles not absolute measurement of temperature, with indirect indicators as to the temperatures reached have been used, such as the ejection of plasma. Extending the techniques used in still and high speed in process imaging is recommended to allow absolute measurement of the surface thermal

profiles. Knowing the temperatures reached would allow thermal profiles to be tailored to control the microstructure of formations as well as process efficiency improvements. Absolute measurements of temperature would be valuable for calibrating thermal models of many laser processes.

It has been seen in that the introduction of longitudinal shaping has had a stabilising effect on the melt pool. Further work is recommended to investigate if the stability can be increased further, and what effect it has on the microstructures formed. The use of longitudinal shaping should be extended to investigate whether the microstructure can be influenced by modifying the time-temperature profile induced in the processed material, for example using the beam to perform post heating annealing processes on the tail end of a deposition.

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A. Annex A







