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Using black PMMA to investigate losses in fibre laser cutting

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Abstract

Fibre laser cutting technology has become interestingly prevalent. There is an associated interest in ensuring the process is efficient. This can be done by investigating how much laser light passes through the cut without being absorbed. Beam prints can be useful in terms of quantifying how much light is lost from the process, as well as indicating the nature of the reflections taking place in the cut zone. Beam prints in poly-methyl methacrylate (PMMA) has previously been shown to be useful as a cheap analytical tool for CO₂ cutting. However, transparent PMMA cannot be used in fibre laser cutting as it does not absorb the fibre laser wavelength of 1.06µm. Previous work with fibre lasers has established that certain black grades of acrylic are highly absorptive of 1 micron wavelength [1, 2]. Previous attempts to use black PMMA in quantitative work have reported that the energy required to evaporate a one unit volume depended on scanning speed [1, 3]. This would require an, inconvenient, calibration exercise to be carried out for any specific experimental set up.

This thesis investigates how Carbon Filled Black Acrylic (CFBA) can be used to quantify losses in fibre laser cutting. A series of experiments are carried out and determine a specific evaporation energy of 3.4J/mm³ for black PMMA. However, this figure is only applicable when two key conditions are met: 1. The laser beam is intense enough not to be affected by the threshold effect and 2. There is effective flushing of the plume of vapour which contains the monomer and carbon dust cloud which can otherwise absorb the laser irradiation. When these two conditions are met, CFBA can be used as a cheap analytical tool for fibre laser cutting.

Quantitative results reported in this thesis confirm that the energy lost from the cut front decreases with increases cutting speed. This means that the efficiency of the cutting process increases with increasing cutting speed.

A novel laser cutting set up is developed where the CFBA remains stationary with respect to the cutting head. This produces distinct “leaf” prints which can provide quantitative and qualitative information about the transmission and reflection of light in the cutting zone. Comparison with some basic modelling work confirm that key dimensions of the leaf prints can be linked to the cut front inclination and kerf walls. Further modelling work is required to fully understand all the information contained in.

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List of symbols

Symbol	Unit	Nomenclature
w_o	mm	The beam waist
θ	radians	The Beam divergence
λ	μm	The Wavelength
Z_R	mm	The Rayleigh range
w_z	mm	The radius at a point along the z-axis
Z	mm	The distance along the z-axis
Θ	radians	The divergence angle of the actual laser beam
r_T	mm	Beam radius at the top surface of the sheet
φ_{In}	$^\circ$	Inclination angle
r_B	mm	Beam radius at the bottom surface of the sheet
n		The refractive index
k		The extinction coefficient
R_p		The parallel reflective
R_s		The perpendicular reflective
A_{Ave}		The averaged absorptivity
P	W	A laser power
b	W	Laser power transmitted without interaction with the cut front
t	s	Time
r_f	%	Reflectivity of the cut zone as a percentage
H	W	The power of the oxidation
E_{cut}	J	Specific energy needed to melt
L, l	mm	Length of sample and length of cut line
d	mm	Material thickness
k	mm	Kerf width
A	W	Conductive loss function
B	W	Radiative loss function
C	W	Convective loss function
ρ	g/cm^3	The density
T_m	$^\circ\text{C}$	Melting temperature
C_p	J/g.K	Specific heat capacity
K	W/m.K	Thermal conductivity
R	mm	Large radius
r	mm	Small radius
H	mm	Height of a circular truncated
a	mm	The radius of the base of the spherical cap
h	mm	Height of spherical cap
m	g	The mass of sample
$m_{initial}$	g	The initial mass
m_{final}	g	The final mass
$V_{mode\ print, V}$	mm^3	The evaporated volume
A	mm^2	The area removed per second
M	mm^2	The bulging area per second
R	mm^2	The heat affected zone per second
C_s	mm/s	The cutting speed
l_c	mm	The length of cutting line

Symbol	Unit	Nomenclature
P_{surplus}	W	The power surplus
T_g	°C	The glass transition temperature
T_{DS}	°C	The decomposition temperature started
T_{DF}	°C	The decomposition temperature finished
W, w	mm	The width of sample

Abbreviation

Symbol	Nomenclature
CFBA	Carbon filled black acrylic
Nd:YAG	Neodymium-doped yttrium aluminium garnet laser
CO ₂	Carbon dioxide laser
PMMA	Poly methyl methacrylate
CNC	Computer Numerical Control
C.W.	Continuous Wave mode
P.W.	Pulse Wave mode
BBP	Beam Parameter Product
SEM	Scanning Electron Microscope
TEM _{xy}	Transverse Electromagnetic Mode
HAZ	Heat Affected Zone
FVM	Focus-variation microscopy
DSC	Differential Scanning Calorimetry
TGA	Thermogravimetric analysis
TMA	Thermomechanical analysis
MMA	Monomer
HSI	High speed image
Cr ₂ O ₃	Chromium Oxide
FeO	Iron Oxide
PZT	Type of ceramic
M ²	M squared
MF	Melamine Formadelhyde
PE	Polyethylene
PC	Polycarbonate
(C ₅ O ₂ H ₈) _n	Methyl methacrylate
BLSP	Boundary layer separation point

1 Introduction

1.1 General background

Since the early 1970s the laser has been employed as a cutting device and it has undergone many improvements [4, 5]. This technology provides industry with high cutting speeds and high precision that can be easily achieved with low cost [6]. To achieve this goal, computer numerical control (CNC) technology is used in laser systems [7]. The laser machines are an alternative solution to traditional mechanical processes and are suitable for a wide range of materials [4]. The applications of this technology depend on factors such as thickness of metal, assist gas and other cutting parameters [8]. Development in optical methods give the potential for even greater efficiency [9].

Laser cutting is a non-contact process which utilizes light to cut materials so no mechanical force is applied to the work piece except the force that come from the assist gas. Therefore, these systems have demonstrated ability to cut delicate or thin materials [4, 5].

Fibre and CO₂ laser systems are most commonly employed in industry. Both these technologies have high intensity beams of infrared light. The solid state laser with 1.06µm wavelength and CO₂ laser with 10.6µm wavelength, sharing the same general principle of cutting [10].

1.2 Aims and objectives

This work attempts to analyse various aspects of the interactions between the fibre lasers and Carbon Filled Black Acrylic (CFBA). This interaction is of interest because clear acrylic has been a useful tool for obtaining information (position of the beam, energy distribution within the beam etc.) for CO₂ lasers – but clear acrylic is transparent at the wavelength of fibre lasers (1.06 microns) and so cannot be used with fibre lasers. Adding carbon dust to acrylic makes the material black – and makes it absorptive to fibre lasers – this makes it possible to use CFBA to make quantitative and qualitative measurements of fibre laser beams in the same way as clear acrylic can be used with CO₂ laser beams.

This work reveals for the first time a specific evaporation energy for carbon filled black acrylic (CFBA) when the material is exposed to a high intensity (focussed or near-focussed) fibre laser beam.

Particular interest is also focused on the beam print produced below the laser cutting process by energy reflected out of the cut zone and energy which passes through the cut zone without being absorbed. This gives qualitative and quantitative information about the behaviour of the laser beam inside the cutting zone [1, 3, 4].

The questions addressed in this thesis are the following;

1. What is the specific ablation energy of carbon filled black acrylic (CFBA) irradiated with a fibre laser beam? Previous attempts to use the black acrylic to quantify energy losses of one micron 1 μ m wavelength light have reported a

speed dependency [1, 3], the energy required to remove unit volume was observed to increase with increasing speed. However, it must be noted that such a calibration exercise would have to be carried out for any specific experimental set up. The volume of the evaporated material is measured for various power/exposure time combinations, with or without an assist gas and at different stand-off distances for a stationary laser beam.

2. What information can be gained from the beam prints in CBFA? The beam print craters were created below the cutting zone which can provide information about the nature of the reflection taking place in the cut zone. Theoretical models have been investigated in order to understand the laser density distribution and the additional factors that effect on the profile of the beam print.
3. How does the ablation threshold vary? The threshold is not a simple function of the power density and the interaction time (the interaction time is a function of the movement speed) how it depends on the characteristics of the beam and the properties of the material.

1.3 Thesis synopsis

In order to begin the investigations into the fibre laser cutting and using black PMMA to collecting the losses energy during cutting process. The methodology was taken through various stages before arriving at the completion stage as show in Figure 1.1.

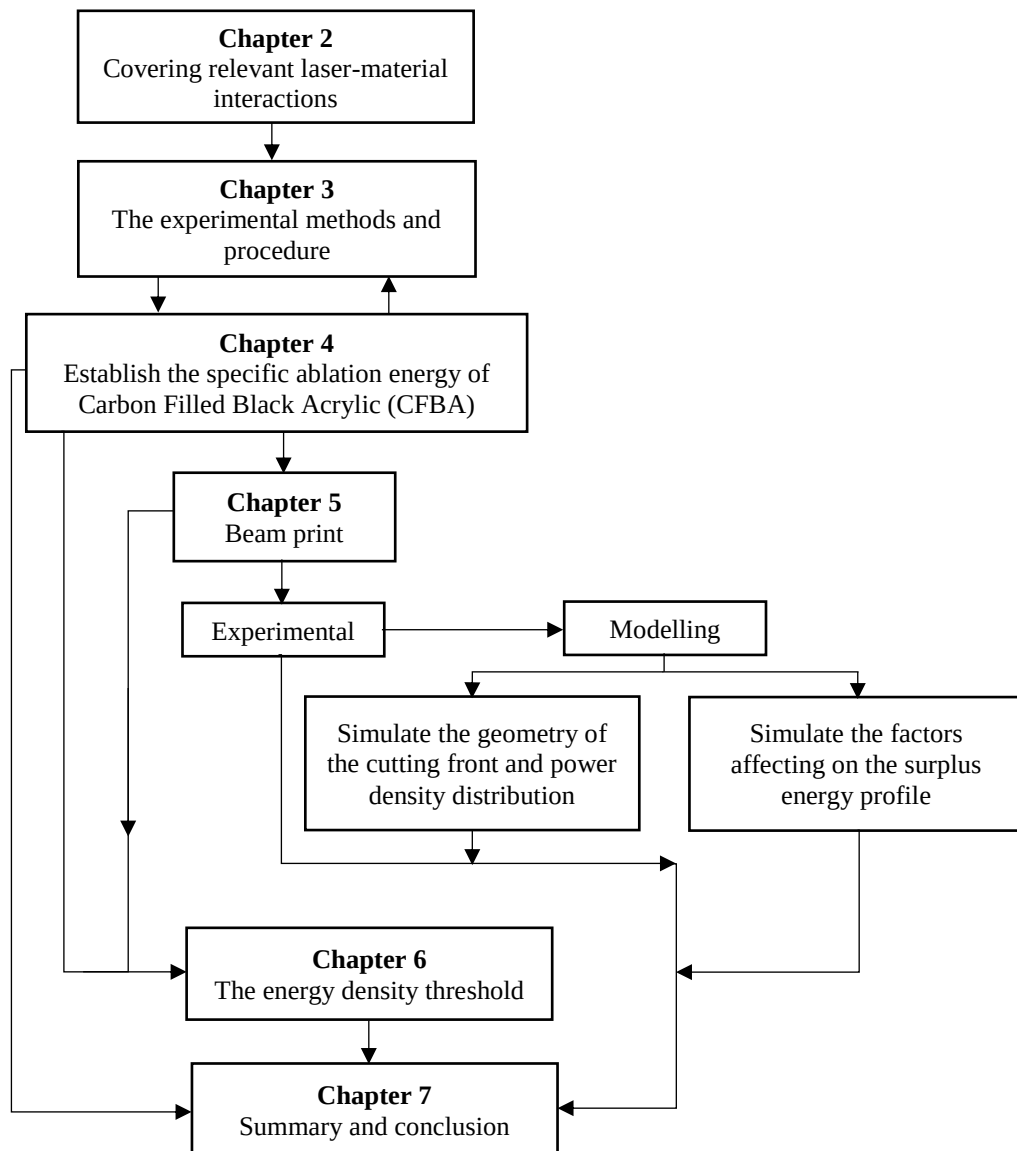


Figure 1.1-Methodology of the thesis

2 Literature review

2.1 Characteristics of laser beam

2.1.1 Laser beam absorption

When the laser beam strikes a surface at an incidence angle, some radiation is reflected while the rest is refracted and/or absorbed into the matter (Figure 2.1) [5].

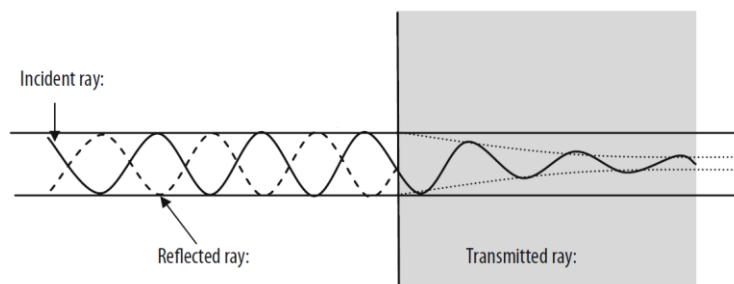


Figure 2.1- The electromagnetic ray striking an air-solid interface and undergoing reflection and transmission [5].

In the laser processing application, absorption and reflection significantly effect on the process quality, depending on a number of different parameters are listed in Table 2.1 [11].

Table 2.1-Effect of absorption parameters for laser and matter [11].

Parameters	
Laser	Metal
Wavelength	Chemical composition
Polarisation	Temperature
Incidence angle	Roughness/topography
Intensity	Oxide layers & contamination

Mahrle and Beyer [12] reported that the absorptivity quantity of steel at elevated temperatures shows differences value which has been calculated corresponding to the wavelengths as a function of the incidence angle for both fibre and CO₂ laser sources. The study based on Fresnel's equations for directional reflectivity, the results are shown in Figure 2.2. They concluded, the initial absorptivity quantity is varies with angle of incidence, reaching to a maximum of absorptivity at the Brewster angle.

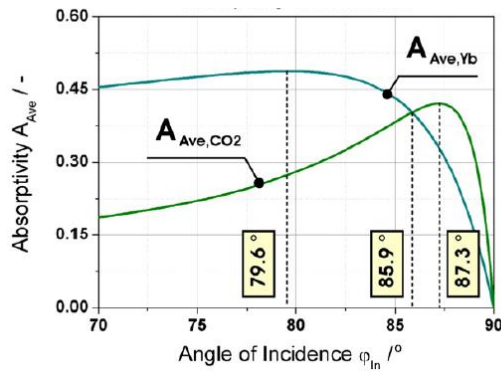


Figure 2.2-The absorptivity of molten steel at elevated temperature [12].

Also, a study [13] reported experimental evidences for the maximum 1 μ m laser absorptivity being at an angle between 8° to 14° which close to the Brewster angle of the cut front. Work described by Kaplan [14] investigated the Fresnel absorptivity which depends on the angle of inclination. The results shows the maximum absorptivity of laser occurred at the Brewster angle of 10.8° for 1 μ m and 2.7° for 10 μ m respectively. While, the laser absorbed stability at normal incident angle is 90° when the keyhole is created (Figure 2.3).

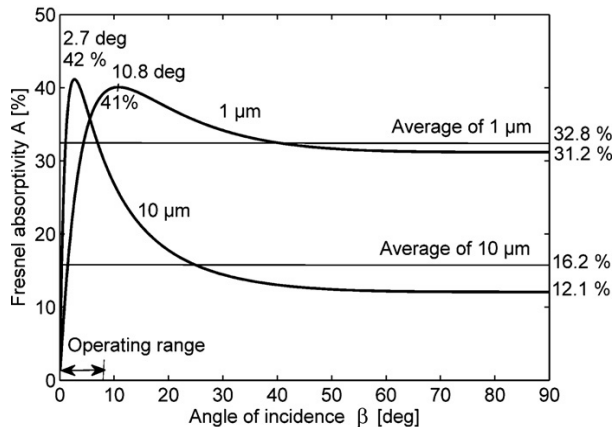


Figure 2.3-Fresnel absorptivity as a function of the incidence angle [14].

2.1.2 Modes of laser beam (Pulse and Continues Wave)

Laser cutting is a thermal process based on absorbed light energy converted to heat then producing molten material that can be easily removed by assist gas pressure. Cut quality is related to amount of energy used with faster cutting speeds needing more laser power [4, 15]. However, straight and curve cutting path demand a higher power continuous wave mode (C.W.), round and sharp corners involves a reduction in cutting speed and average power so pulsed mode is more appropriate [4, 16].

In a study [16] comparing cutting 1.2mm stainless steel by Pulse Wave (P.W.) and Continues Wave (C.W.). Nd:YAG laser beam with nitrogen or oxygen as assist gasses, the results showed, best cut quality is found for continuous wave mode with cutting speed of 8m/min, and a lower cutting speed of 2m/min for pulsed wave mode. Additionally, a C.W. laser beam is preferred for good quality with high cutting rate applications but P.W. beam is preferred for accurate cutting of fine components due to the laser energy input of P.W. cutting [17].

2.1.3 Laser beam quality

The laser beam quality produced by a laser oscillator (optical resonator), is a critical parameter in the practical performance of laser applications. This section covers the beam propagation and the various factors used to describe beam quality: the Beam Parameter Product (BPP)/ and M squared (M^2).

2.1.3.1 Beam propagation-Gaussian beam

To understand the laser beam propagation more deeply some terms should be defined. First of all, it is interesting to propagate the laser beam intensity along the z axis. However, there is also some intensity distribution along the x and y axis in the plane perpendicular to the propagation direction z (Figure 2.4) [18].

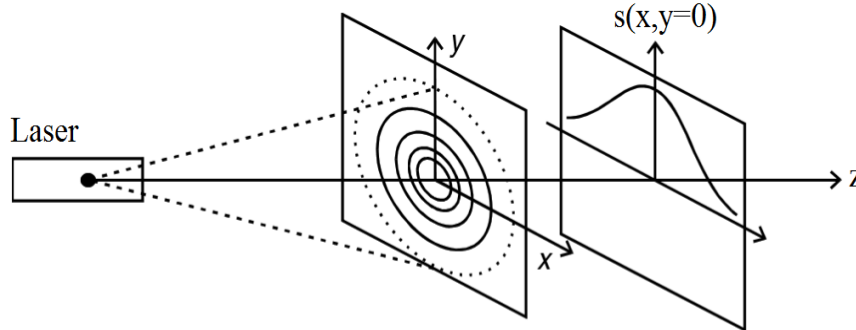


Figure 2.4- Intensity propagation in the x , y plane and z direction [18].

The energy density distribution of the laser beam characterised by transverse electromagnetic mode (TEM_{xy}) is mathematically described by a Gaussian profile and it has symmetrical propagation [4]. Because, the TEM_{00} function extends to infinity in the radial direction and diffraction causes spreading of it, the Gaussian shape is usually regarded as being truncated at some diameter at which the beam intensity has dropped to $1/e^2$ (13.5%) of its peak (Figure 2.5) [5].

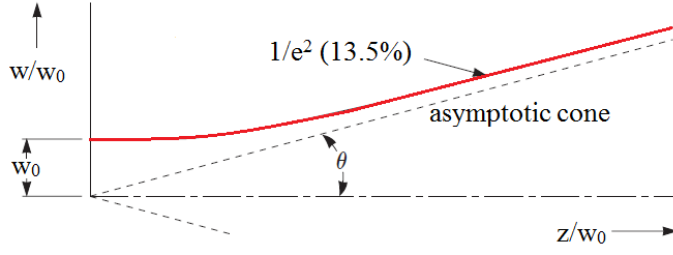


Figure 2.5- laser beam diameter as a function of distance [5].

From the above figure can observed a minimum spot size of the Gaussian beam at the waist is called the beam waist (w_0). For, a Gaussian beam single transverse mode, the value ($1/e^2$) of the waist radius-divergence product is represented in Equation 2.1:-

$$w_0 \theta = \frac{\lambda}{\pi} \quad 2.1$$

Where, w_0 is the beam waist radius (μm), θ is beam divergence angle between the central axis of the beam and a straight line (radians) and λ is the wavelength of the light (μm).

Hence, the beam intensity can be efficiently collected on a small area related with the beam divergence angles that directly with collimation degree. Moreover, highest collimation should have a divergence angle of zero. However, this is impossible in the physical limits due to the diffraction phenomenon (Figure 2.6) [18, 19].

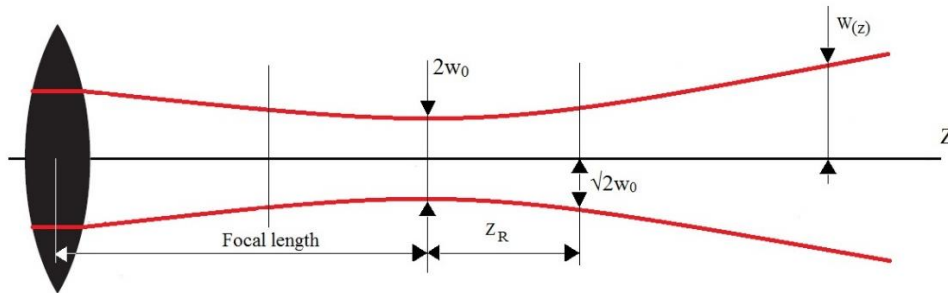


Figure 2.6- Schematic of the centre of the beam.

The distance from the focal point that have minimum diameter (w_0) to a point along the z axis that measures twice the width of the focal point in either direction by factor of $\sqrt{2}$ is called the Rayleigh range (Z_R) and it represented in Equation 2.2 [17].

$$Z_R = \frac{\pi w_0^2}{\lambda} \quad 2.2$$

Note that if the beam has a smaller waist, the shorter the Rayleigh range is. To calculate the spreading of a Gaussian beam at distance z accordance with Equation 2.3 is used [20].

$$w_{(z)} = w_0 \left[1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2 \right]^{1/2} \quad 2.3$$

Where $w_{(z)}$ is radius of beam at z distance (mm), and z the distance of the beam propagating (mm).

2.1.3.2 Beam propagation-non-Gaussian beam

The non-Gaussian beam may be have many local variations of the energy density (Figure 2.7). A Gaussian beam is considered having the maximum beam quality (TEM_{00}) and a single dense of energy [21, 22].

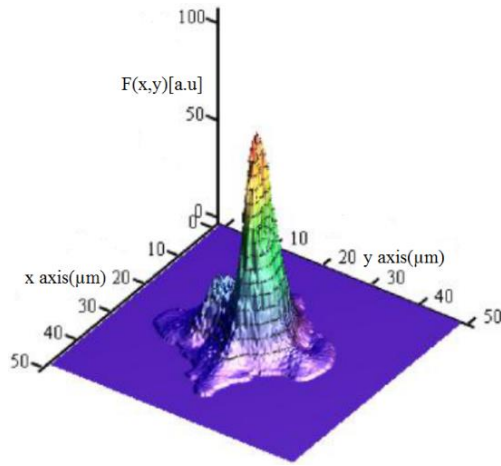


Figure 2.7- A non-Gaussian beam profile made as imprint on PMMA [22].

The degree of variation is represented by the beam quality factor. A perfect Gaussian beam ($M^2=1$) angular size smaller than a non-Gaussian beam ($M^2>1$) in the far field as shown in Figure 2.8 [5]. The value of M^2 shows how far from a true Gaussian any given beam is.

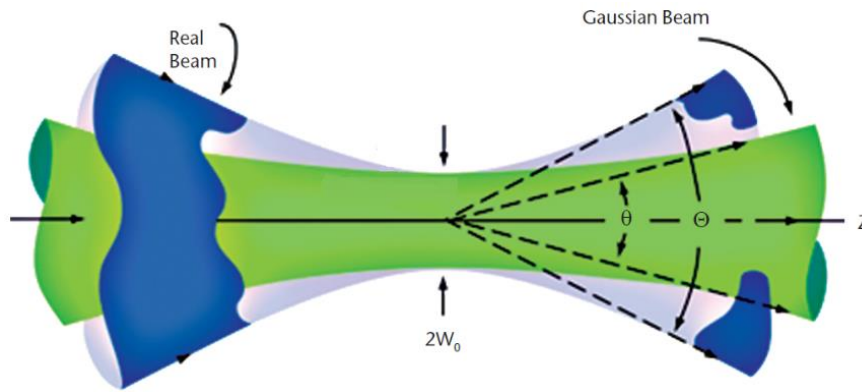


Figure 2.8- The ration of actual beam divergence to a perfect Gaussian beam having the same waist size and location [23].

This property of a particular laser beam relatively to a perfect beam is represented in Equation 2.4:-

$$M^2 = \frac{\pi w_0 \theta}{4\lambda} \quad 2.4$$

Also, as can be observed in Figure 2.8, M^2 can also be written as [23]:

$$M^2 = \frac{\Theta}{\theta} \quad 2.5$$

Where Θ is the divergence angle of the actual laser beam (radians).

Gaussian beam propagation is represented by Equation 2.6 and Equation 2.7 [17]:-

$$w_0 \theta = M^2 \frac{\lambda}{\pi} \quad 2.6$$

$$w_{(z)} = w_0 \left[1 + \left(\frac{M^2 \lambda z}{\pi w_0^2} \right)^2 \right]^{1/2} \quad 2.7$$

The M^2 is the product of the minimum beam diameter and divergence angle and it corresponds to a diffraction limited beam. The beam quality can also be described in terms of Beam Parameter Product (BPP), the beam radius measured at waist and the beam divergence half angle measured in the far field corresponding to a diffraction-limited Gaussian beam.

$$BPP = M^2 \frac{\lambda}{\pi} \quad 2.8$$

The type of study determines which of BPP or M^2 is employed: BPP is considered for lasers with different wavelength, M^2 for lasers with equal wavelength [24].

A study [3] that compared between CO₂ and Yb:YAG disk lasers indicated that the intensity propagation is different for two lasers because the quality factor (M^2) of these sources is different. Experimental results of the beam intensity propagation by micro

spot monitor were also reported. In the CO₂ case, the intensity profile was approximately a Gaussian distribution with maximum power reached to 42.99MW/cm² and 24.67MW/cm² for disk laser (Figure 2.9).

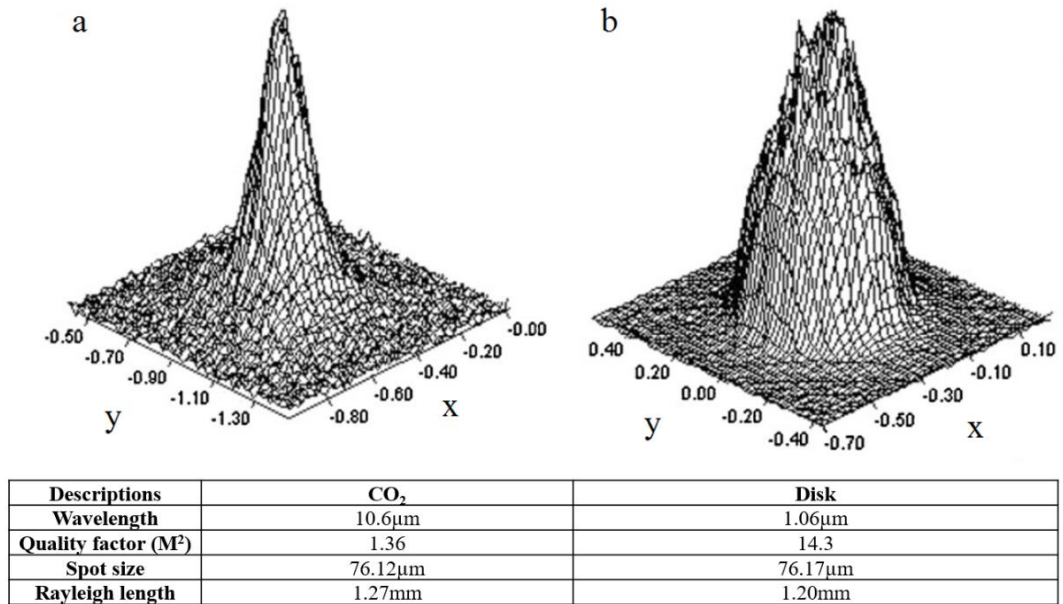


Figure 2.9- Measured of the beam intensity propagation for lasers. a) CO₂. b) Disk [3].

It should be noted that for very high power laser systems considering beam size and divergence angle that refer to BPP and M² is not suitable for analysing the laser beam and alternative parameters are used. However, this is very different to the lasers used in this work, for which BPP and M² are appropriate. super-Gaussian types is usually used for the output laser nearfield intensity propagation system [25].

2.1.4 Laser power

The intensity (J/m^2) of the laser power is described by the rate of power divided by the area over which the power is focused, this is also referred to as power density (W/cm^2). Also, it determines the thickness of work piece that can be cut and the interaction time [8, 26]. However, the value of the laser intensity can be changed by either power or spot size or time or all.

The rate of the energy which is emitted from a laser beam focused on a specific area for heating and melting of the work piece material is the laser power. Also, the quality and performance of cutting depend on it [19]. Laser power may be insufficient to cut through the entire thickness of the material [27]. Overall, high power intensity lasers depended on spot size with maximum output power that emitted from the laser system. However, this factors strongly dependent on the brightness sources [17, 28]. Bright sources is defined as the power emitted per the beam quality per wavelength as represented in Equation 2.9.

$$\text{Brightness} = \frac{\text{Laser power}}{\text{beam quality} * \text{wavelength}} \quad 2.9$$

The brightness of a laser source is a characteristic which given a laser particular importance property in cutting processing. Ozaki et al. [29] reported that in laser cutting of Austenitic stainless steel without assist gas, increasing laser power led to increase of the critical cutting speed and the shapes of kerf were almost the same resulted (Figure 2.10). Also, in a study [30] when cut of zinc-coated steel results showed in less power and attained higher speed in short wavelength than longest lasers.

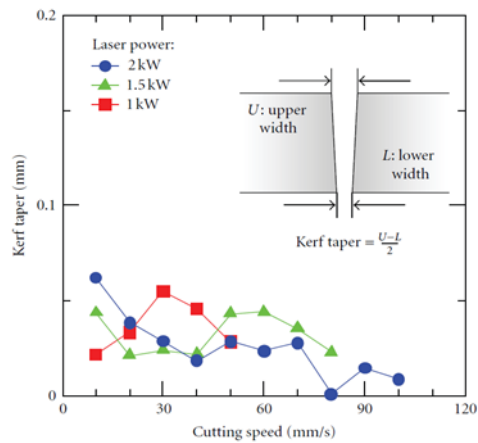


Figure 2.10- Effect of different laser power when cut SUS304 plate [29].

2.1.5 Beam threshold

A critical parameter in the laser materials interactions of performance is the beam threshold, of which there is no generally agreed definition, but it explains aspects of melting, damage and ablation for the laser processes. These aspects will materialise in the different forms such as heat affected zone (HAZ), recast layer, micro cracks and debris from ejected material [31]. The area above threshold has a smaller diameter than the spot size, due to the lack of energy diffusion out of the affected volume [32]. In another words, a small portion of the focused laser beam size is above the ablation threshold (Figure 2.11).

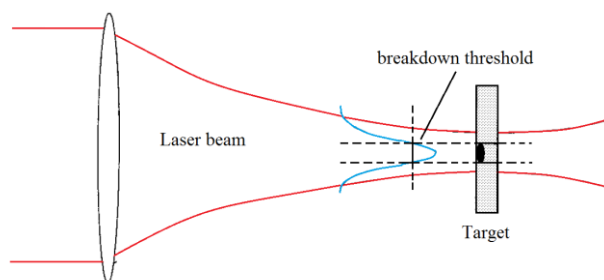


Figure 2.11- Laser beam focused at target and small portion near the centre is above the breakdown threshold [32].

The ablation threshold rate increases with laser power density up until a specific point before decreasing. This certain point is graded between power density and ablation rate changes is dependent on the materials [33].

Menéndez-Manjón et.al [34] investigated the influencing of laser intensity profile (flat-top and Gaussian) on the ablation rate during infrared femtosecond of silver targets in air. The results showed that homogeneously distributed for laser flat-top intensity profile but in Gaussian intensity implies the presences two ablation zones because the beam energy required to reach a determined peak fluence is much lower than the flat-top profile. Also, the intersection line between inner and outer ablated diameters represented threshold in silver as shown in Figure 2.12.

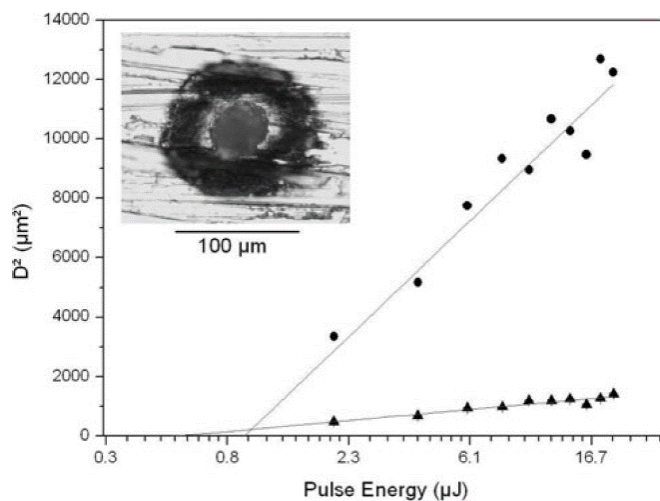


Figure 2.12- Determination of the threshold on the target (the ablated patterns on silver :inner, triangle; outer, circle) [34].

In the study [35] determined volume of the ablation rates for different materials (stainless steel, PZT, and PMMA) by performed grooves machining with femtosecond laser pulses (150fs, 800nm, and 5kHz). They found that the results were similar, differences correlated to the inhomogeneity of the groove profile. Also, PMMA has a higher threshold value of $0.76\text{J}/\text{cm}^3$ while both SS and PZT have lower volume

ablation rates of $0.13\text{J}/\text{cm}^3$ and $0.26\text{J}/\text{cm}^3$ respectively (Figure 2.13). Because the laser intensity has to be high enough to generate non-linear absorptions in the PMMA.

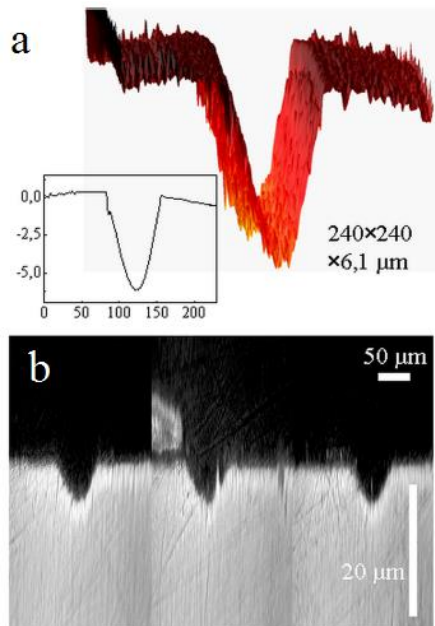


Figure 2.13-Comparison of the cross sections of ablated volume. (a)Confocal microscopy for stainless steel $0.8\text{J}/\text{cm}^2$. (b)Cross-sections for three samples observed by optical microscopy [35].

2.2 Laser cutting process

The basic general concept in laser cutting of metals for both CO_2 and Nd:YAG lasers is the same [10]. A high intensity beam of infrared light is focused onto the surface of work piece. The focused beam heats the exposure area and creates a melting zone throughout the depth of the sheet. The molten material is expelled from the localised area by assist gas pressure. Relative motion moves the cutting front through the material by moving the laser cutting head, the material or both [4, 36]. The key features relevant to laser fusion cutting are shown in Figure 2.14.

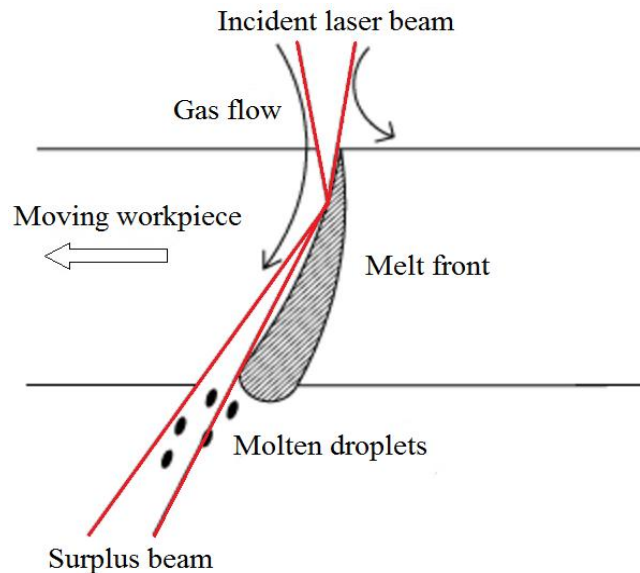


Figure 2.14- Schematics of the laser cutting process. Adopted from [37].

2.3 Laser cutting considerations

2.3.1 Cutting gas and pressure

The cutting gas type and pressure are selected depending on the material and the desired quality cut [19]. The role of assist gas during the laser cutting process is not restricted only to material removal through the bottom of the kerf. It has several additional functions such as suppressing the formation of plasma when cutting thin sections, protecting the focusing lens from spatter and cooling the cut edge [4, 17]. Inert and active gases are chosen based on the work piece material. Inert gas like nitrogen has been often employed when cutting alloy steel (stainless steel) and aluminium to achieve a clean cut edge without oxidation [4]. However, oxygen may also be used as an assist gas during cutting, it is capable of reacting with the molten material and releasing additional heat to the cutting zone (exothermic reaction). The pressure of nitrogen is generally higher than oxygen pressure and is directly proportional to thickness of work piece as shown in Table 2.2.

Table 2.2- Typical gas for laser cutting parameters stainless steel sheets with various cutting speeds and assist gas.

Thickness	Cutting speed/ (gas pressure)	
mm	m min ⁻¹ / (bar)	
	Oxygen	Nitrogen
1	11.0/ (4.0-6.0)	7.0/ (6.0)
2	7.0/ (4.0-6.0)	4.0/ (9.0)
4	3.0/ (4.0-5.0)	3.0/ (13.0)
6	0.6/ (3.5-5.0)	1.5/ (14.0)

Powell and Menzies [38] reported that when laser cutting stainless steel using oxygen assist gas, the chromium is oxidised as a layer of Cr₂O₃ on the surface of the cut front. The layer has a higher melting point than the base material. Therefore, it inhibits melt removal and results in residual melt or “dross” on the lower kerf surface, and a poor edge quality [4]. So, an inert gas is utilised to inhibit the oxides which have higher melting point and freezes more rapidly, causing dross problem [5].

In a study from Abdel Ghany and Newishy [16] when comparing oxygen with nitrogen as assist gases for 1.2mm austenitic stainless steel cut using the fibre laser, the results show that nitrogen gave good quality of cut edge and smaller kerf width than oxygen. While, increasing gas pressure increased the kerf width as shown in Figure 2.15. This is simply due to the higher gas pressure being more efficient at removing melt. It was also reported that cut edge roughness increased with increasing gas pressure.

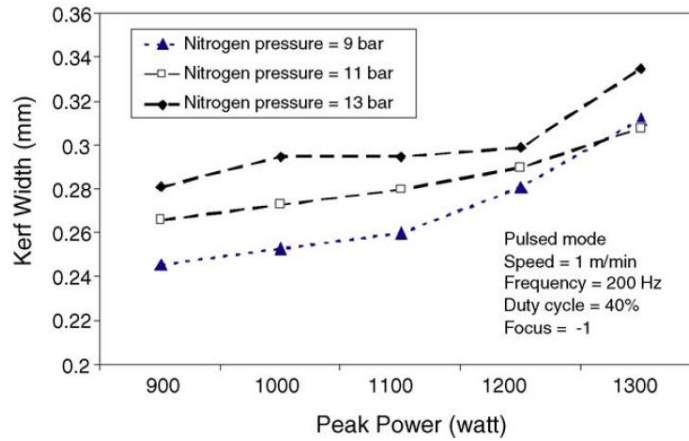


Figure 2.15- Effect of gas pressure on kerf width [16].

2.3.2 Cutting speed

The cutting speed mean that the stability of the energy provided to the cutting zone to the energy spent to generating a cut and the energy lost from it. The energy taken to generate the cut is independent of time but the energy loss is proportion to the time taken. Therefore, the energy lost decreases with increasing cutting speed due to increase in the efficiency of the cutting process [17, 39]. Additionally, the cutting speeds related to many factors such as the laser power, type of assist gas and pressure.

A study by Wandera, Kujanpaa and Salminen [40, 41] compared cuts of 10mm stainless steel by higher-power lasers for CO₂ and fibre. The results showed, at a specific cutting speed the laser power required to cut with a fibre laser was lower than that for CO₂ laser because higher the absorptivity of the fibre beam by the material. Also, nozzle diameter and gas pressure affect the rate of material melting and material removal from the cut kerf, and speed (Figure 2.16).

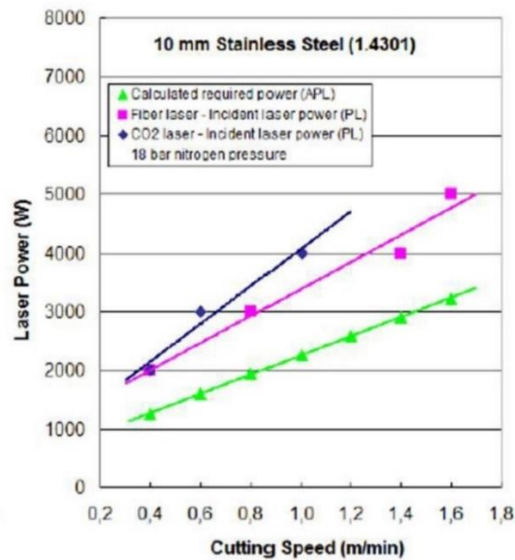


Figure 2.16- Fibre and CO₂ lasers compared when cut 10mm stainless steel [41].

In a study to improve laser cuttings cut 1-6mm the stainless steel with different types of lasers [42], results show that for all thicknesses, the fibre laser cutting speeds were highest compared to the disk and CO₂ lasers. High beam quality and shorter wavelength for fibre and disk laser enable focused to a smaller spot size resulting into higher power densities and cutting speed. Generally, decreasing the cutting speed for a material is inversely proportional to work piece thickness (Figure 2.17). The work piece thickness determines the relationship of interaction time between laser and material [17].

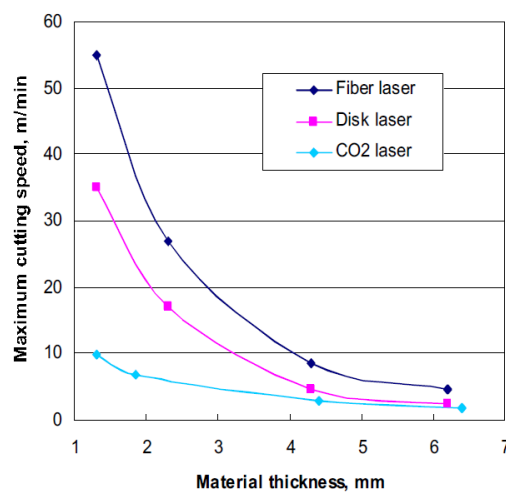


Figure 2.17- Maximum cutting speed for different types of lasers [42].

The cutting speed can affect the surface roughness. Hilton [43] reported that when comparing a series of experiments on cutting of 0.6-6mm stainless steel, employing the same parameters for both a disc laser and a CO₂ laser using nitrogen as assist gas, the surface roughness measurements show that in the 0.6 and 1.2mm cuts, the disc laser produced a better cut quality than the CO₂ laser. Otherwise, in the thicker plates 3 and 6mm, the CO₂ laser got a much better cut quality as shown in Figure 2.18.

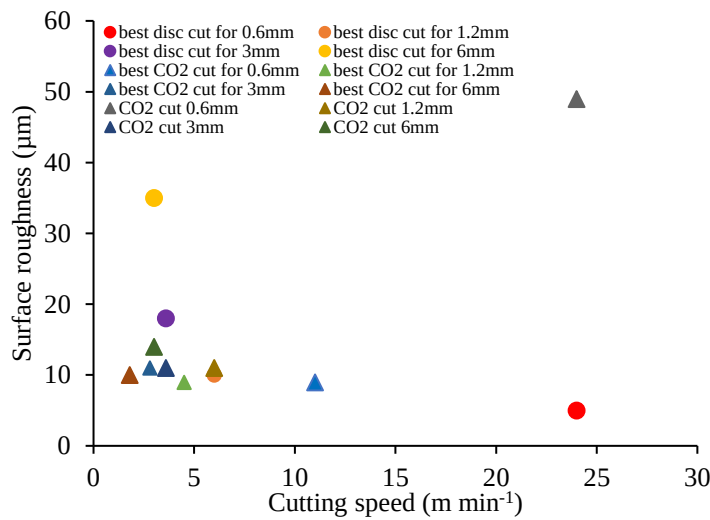


Figure 2.18- The surface roughness of cutting stainless steel with different laser type [43].

2.3.3 Cutting kerf

Kerf width is described as the width of material that is removed by a cutting process [17]. The width of the kerf larger is typically than the focused laser beam diameter and it refers to the distance between two the kerf walls. One can consider two values of the cutting kerf: upper and lower kerf which are measured on the top and bottom surfaces of cut sheet (Figure 2.19).

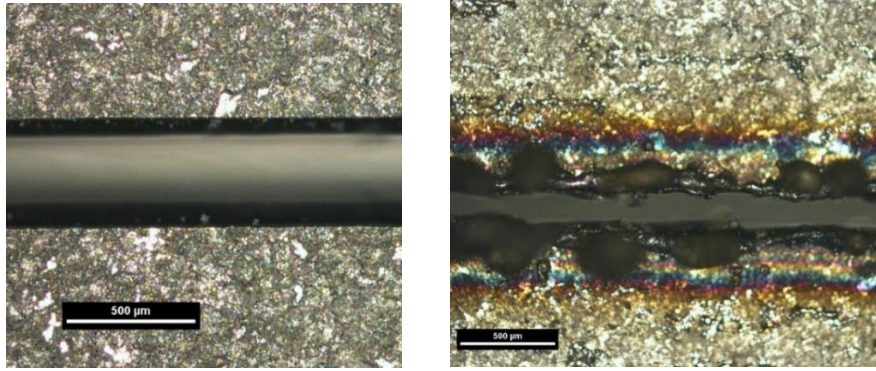


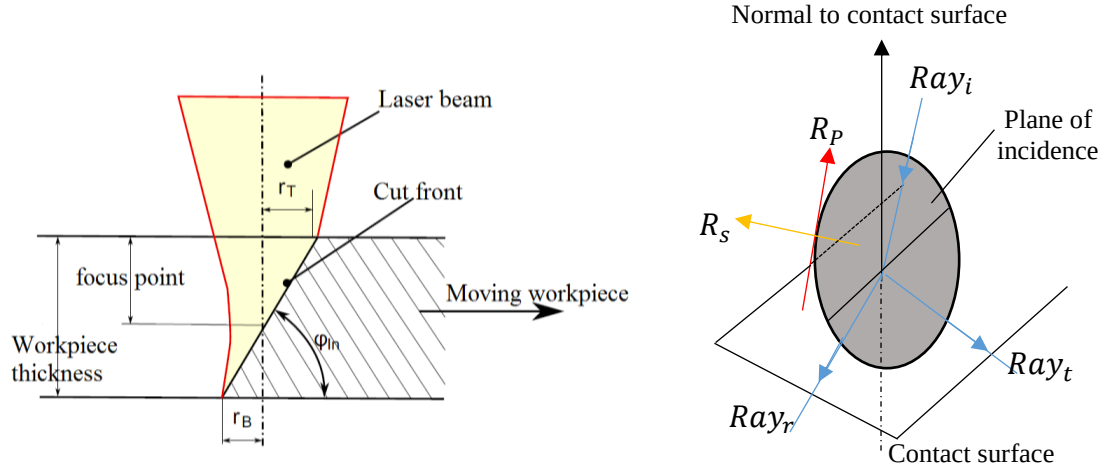
Figure 2.19- Showing the kerf width. Left) upper cutting kerf. Right) lower cutting kerf at (Laser power 4kW, 6.2m/min, N₂ 10bar and 4mm stainless steel thickness).

The volume of cutting kerf represents the amount of material removed from it. The geometry of the kerf depends on a number of cutting process parameters that affect the melt removal process and manipulate the resultant cut edge quality [17, 40]. Yilbas, Shaukat and Ashraf [44] reported that for CO₂ laser cutting when cutting steel 304, the kerf width size significantly increases with laser output power or decreases with laser cutting speed. In the case of fibre laser cutting, [45] reported that when cutting stainless steel, the kerf size is strongly influence by beam geometry.

2.3.4 Shape of cut front

During laser fusion cutting, a cutting front is created by Fresnel absorption of energy coming from the impinging high intensity beam which melts the metal throughout the thickness of material [19, 46]. In the study of Mahrle, Lütke and Beyer [47] a 2D model of the cut front related the absorptivity of the laser beam as a function of the incident angle as presented in (Figure 2.20). The results show that, under inert fusion cutting conditions for both fibre and CO₂ regimes, the maximum cutting rate is attained when the beam is coupled more efficiently into the work piece.

To explain that, an increased cutting speed results in increase of contact area and interaction time between the incident laser beam and melt layer in cut front [48].



$$R_p = \frac{(n \cos \varphi_{In} - 1)^2 + (k \cos \varphi_{In})^2}{(n \cos \varphi_{In} + 1)^2 + (k \cos \varphi_{In})^2} \quad R_s = \frac{(n - \cos \varphi_{In})^2 + k^2}{(n + \cos \varphi_{In})^2 + k^2} \quad A_{Ave} = \frac{R_p + R_s}{2}$$

Figure 2.20- Schematic of 2D geometrical model of cut front [49].

Where φ_{In} is the angle of incidence, n is the refractive index, k is the extinction coefficient, R_p is the parallel reflective, R_s is the perpendicular reflective and A_{Ave} the reflectivity of unpolarized radiation; Ray_i is Incident ray, Ray_r is Reflected ray and Ray_t is Refracted ray.

The absorptivity of the laser beam is increased as less is being lost through the cut kerf as the cut rate is increased (Figure 2.21) [5].

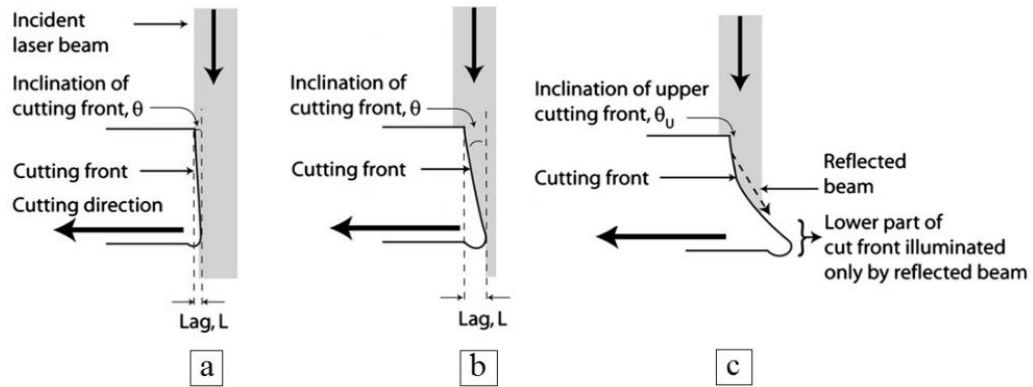


Figure 2.21- Effect of cutting speeds on the cut front geometry at the same cutting conditions; (a) slow cutting speeds,(b)moderate cutting speeds,(c)higher cutting speeds [13].

The study by Pocorni et al. [50], focused on the fluidity and cut front morphology for 10mm stainless steel cut with fibre regime and nitrogen as an assist gas. High speed imaging (HSI) has been employed to observe the melt flow properties influence on the cut quality (roughness and dross) during laser cutting. The results show the cut front as covered in bumps which themselves are covered in a thin layer of molten liquid (Figure 2.22).

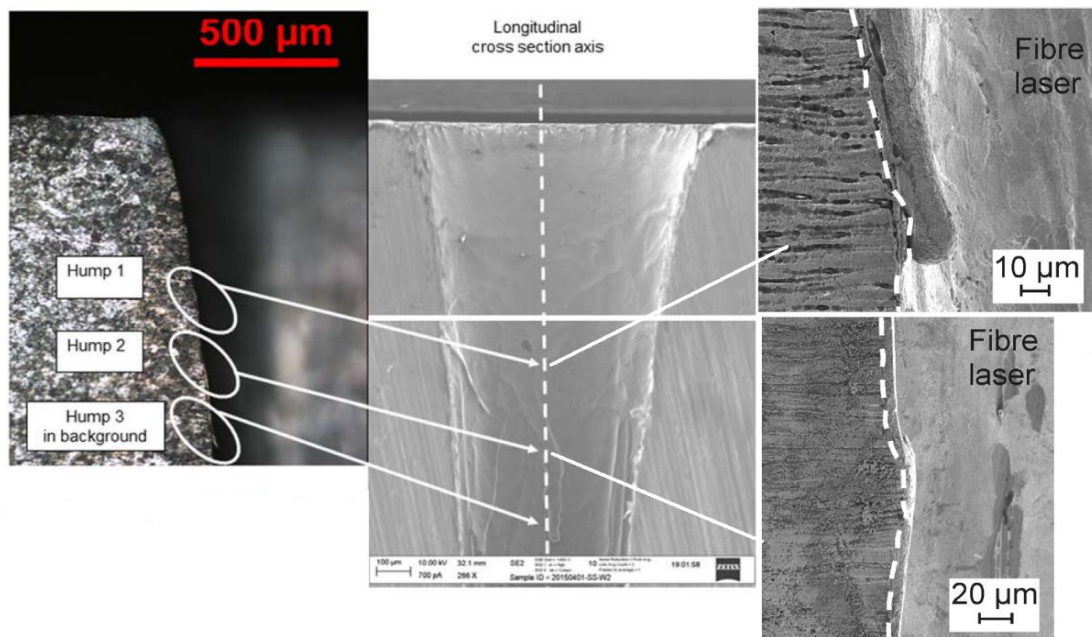


Figure 2.22- Longitudinal cross section of the cut front-cut by fibre laser regime at laser power 6kW, 1.8m/min and N₂ 16bar [50, 51].

In addition, bumps move down the cut front at an average speed of nearly 0.4m/s and are covered with molten flow layer with a velocity of approximately 1.1m/s. The average melt depth at the bottom of cut front has been measured to be approximately 0.17mm [50, 51].

In the study of Ermolaev et.al [52] a technique was used to visualise the laser cutting process, built on the trim cut method. A high speed camera has been used to simultaneously observe the molten material the cut front. A transparent sheet has been placed on one wall of the cutting kerf and it moved in the opposite direction to the work piece. The materials used in this study were cutting stainless steel and mild steel by fibre and CO₂ lasers. The general results in the case of the cutting stainless steel with nitrogen were that the laser wavelength has been greatly affected on the fluidity of metal (Figure 2.23). In CO₂ cutting case, the molten material constricted and located close to the cut front with surface forces inhibiting of melt to splitting. While, in fibre cutting the molten material flow is very unstable with several melt ejections on the side wall.

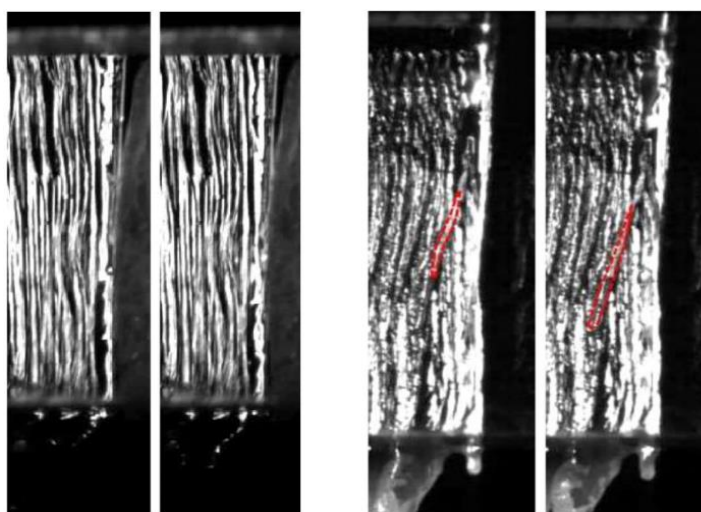


Figure 2.23- Comparison cutting of 6mm stainless steel at cutting speed 0.8m/min and N₂ 14bar with two 2kW laser machines. Left) 2kW CO₂ laser. Right) 2kW fibre laser [52].

In the study of Scintilla et al. [46, 53] a series of cutting experiments in inert gas with CO₂ and disk lasers regimes studied the geometric shape of the cutting front. The results show the absorptivity of the incident laser beam was determined by the local inclination angle of the cutting front and it changed with the cutting speed in order to satisfy the higher energy requirements. The lower section of the cut front becomes curved and extended in the cutting direction as can see in Figure 2.24.

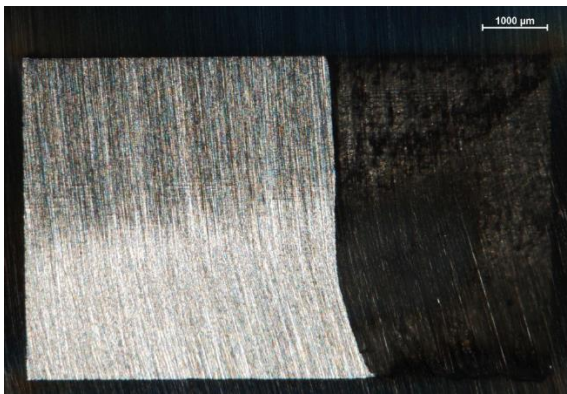


Figure 2.24- Longitudinal section of the cut front for 5mm tool steel cut of CO₂ laser and cutting speed 1.2m/min [46].

They concluded that, the lower position of the cutting front has been formed by interactions of the proportion of the laser beam with cut front and it increase with cutting speed. They attributed this to the effect of multiple reflection. Also, the effects of the laser beam regimes on the cutting front profiles are conformed; similar geometries are shown in Figure 2.25 and 2.26. Additionally, they observed the precise region of the cut front is inclined to angles close to the Brewster angle and absorptivity value are equal in disk laser (0.388°) and CO₂ laser (0.409°).

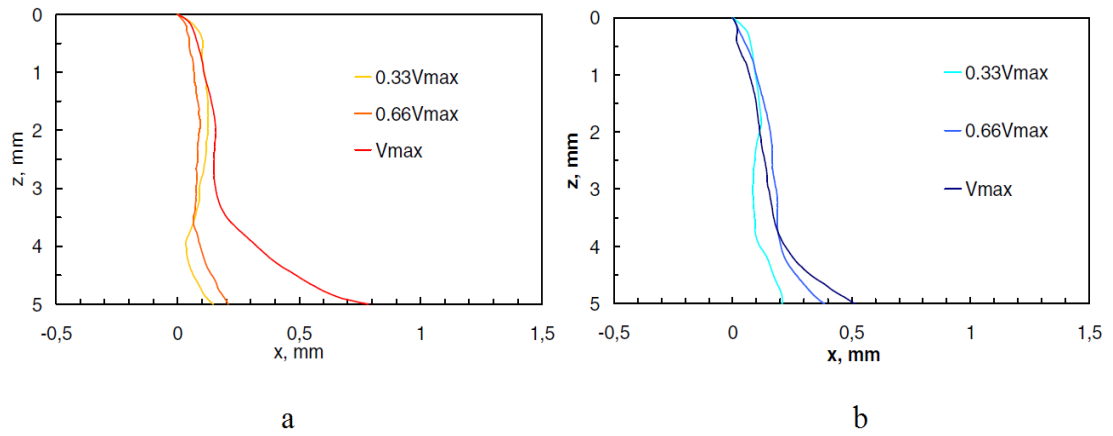


Figure 2.25- Effect of cutting on the cut front geometry (side view) for relative focal position $f/t = -0.33$, $t = 5$ mm. (a) CO₂ and (b) disk lasers cuts [46].

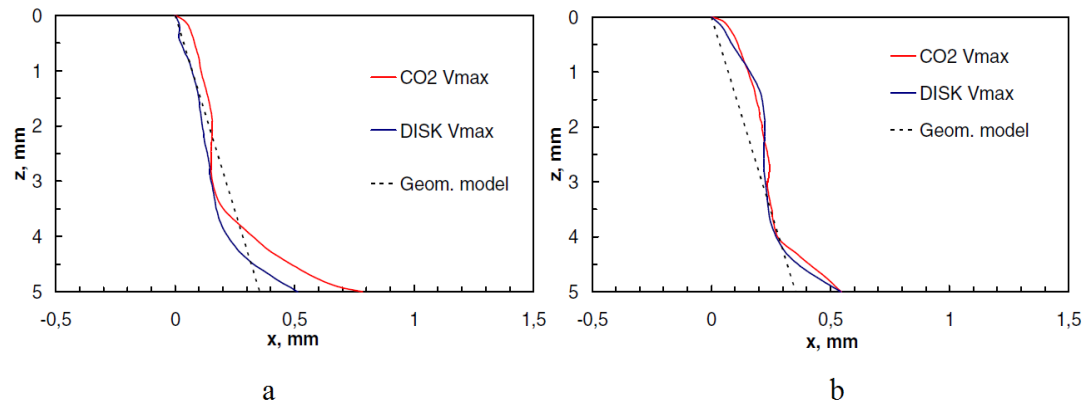


Figure 2.26- Effect of laser types on formed the cut front geometry at maximum cutting speed at $t = 5$ mm. (a) $f/t = -0.33$ and (b) $f/t = -0.66$ [46].

This phenomenon is described by Powell et al. [13] they explained that the cut front at slow cutting speed is approximately vertical and the laser beam travels straight through the cut zone without interaction with material (Figure 2.21a). As cutting speed increased, the curvature will be gradually extended at the bottom of the cut with deceleration of melt and increase of turbulence leading to roughness in the cut edge (Figure 2.21c). They reported that the optimal absorption of fibre laser happened at an angle between 8° and 14° , corresponding to the Brewster angle from $2-4^\circ$.

2.3.5 Laser beam behaviour inside the cut zone

The laser beam behaviour inside the cut zone can be investigated by following the evidence left behind. In the scientific articles there is ongoing discusses about the beam behaviour for fibre and CO₂ lasers. A study [54] reported that the rate of absorption during cutting process for two regimes are difference according to wavelength. The fibre laser beam at one micron wavelength has greater absorption than CO₂ laser. The fibre laser beam therefore has multiple reflection, with the cut zone (Figure 2.27).

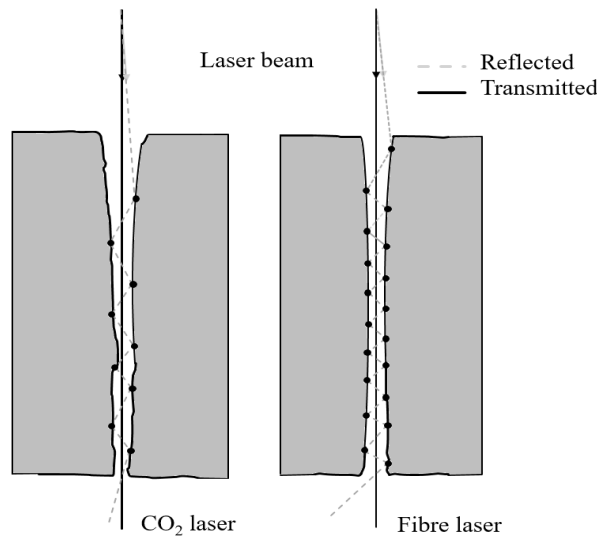


Figure 2.27-A schematic of laser beam behaviour inside the kerf geometry. The kerf geometry adopted from [55].

The investigation of Scintilla et al. [56] found the melted material by CO₂ has low viscosity because the energy absorbed in the cut front is used to increase the melt temperature. While, in the fibre laser the amount of melting material and viscosity has higher because the energy absorbed used to melt with lower average temperature. Also, it was [46, 53] reported that the multiple reflections by CO₂ in the lower of cut front zone significantly interact with reflected beam (as mentioned earlier in section 2.3.4).

A study [57] investigated the ray-tracing model by simulation of 6mm stainless steel cut by fibre laser then comparing the results with experimental. They concluded there are additional factors that affect the profile of the surplus energy exiting from cut zone such as dross, kerf wall roughness, cut front, and the bump (Figure 2.28).

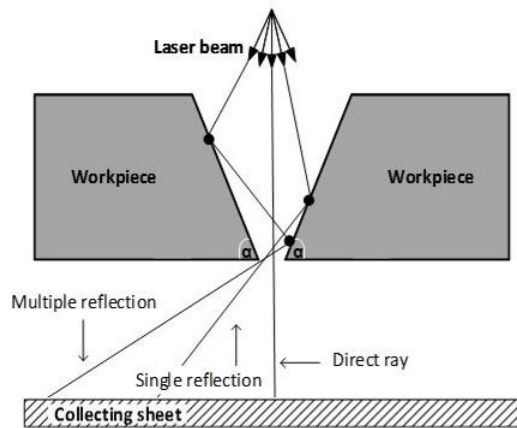


Figure 2.28- Schematic of the 2D ray tracing model of the kerf walls [57].

To understand the cutting process based on systematic calculations of simulation tool beside experimental work, CALCut tool takes into account many fundamental aspects such as the material and thickness, cutting speed and all aspect of laser beam (wavelength, quality, power, power density distribution, raw diameter) as well as the cutting gas type and pressure (Figure 2.29) [58].

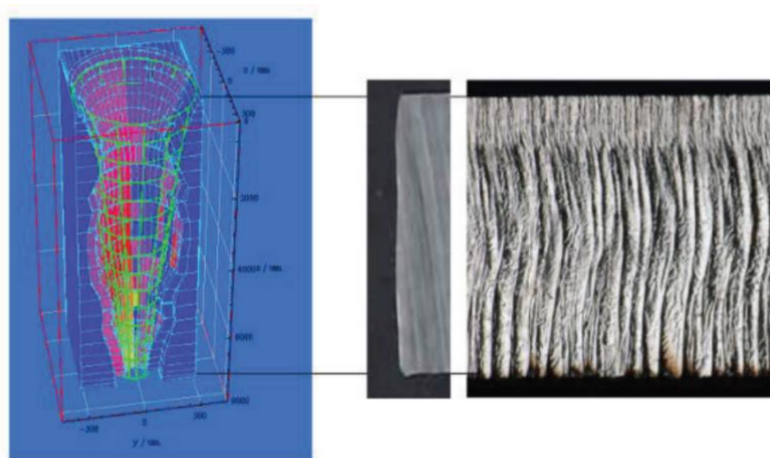


Figure 2.29- Theoretical and experimental of cutting 8mm steel, cutting speed 2.4m/min and nitrogen as assist gas. Left) CALCut calculation. Right) The cutting front [58].

2.3.6 Depth of cut

The depth of cut in the laser cutting process is directly proportional to the density of the laser beam and the cutting velocity. Also, it influenced by the material and thickness. The overall, laser cutting is a steady state thermal process and when work piece thickness is equal to the depth of cut the cut will happen [4].

Cutting of 10mm stainless steel with a higher fibre laser machine has been investigated, they found at maximum cutting speed 1.5m/min used high pressure nitrogen as assist gas can obtained good quality cutting [59]. It has been investigated to improve the cut quality based on tilting the cutting head. The study used 4mm stainless steel with fibre lasers with $1.07\mu\text{m}$ wavelength and it revealed an improvement in quality of nearly 25% when the position of cutting head was opposite direction of work piece moved [60].

2.3.7 Cut edge quality

The qualities of cut edge quality can be categorised as striations and dross attachment. These ray with different combinations of laser cutting parameters such as laser power, cutting speed used gas type and pressure, also optic system, specific laser source and work piece [4, 5].

2.3.7.1 Striations

Striations are of interest for many researchers and there are several possible explanations. Overall, the cutting speed and gas flux have significantly effect on the

cut edge patterns. At very low cutting speed, most of the laser power travels straight through the cut zone without interaction with material. The low speed also increases the time for assist gas interaction [13]. At higher cutting speeds, the change in cut front geometry produces multiple reflection resulting to higher temperatures decreases the viscosity of the molten, melting removal easier [61].

The study of Ivarson et al. [62], supported with earlier studies of same authors, explains that, the oxidation reaction is significant in changing the geometry of the striation profiles (Figure 2.30).

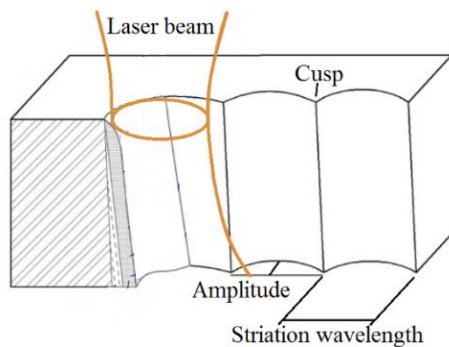


Figure 2.30- A schematic of this striation phenomenon. Adopted from [63].

They reported that, any increase in cutting speed produces a rise of striation wavelength and decrease in the kerf width. Moreover, the cusp is not made from re-solidified molten material or shock of gas dynamic waves but represents the interface between the solid sheet and the cut zone. Also, the type of gas determines the amount of heat added for cutting and its pressure depends primarily on the work piece thickness [19]. For example, oxygen is typically used in cut mild steel and reacts with the iron in an exothermic reaction (Additional heat generating) and the molten oxides do not adhere in the cut zone (clean cut edge) [17, 64]. The oxide layer is formed and is blown from top of the cut edge to the bottom. This layer will slow the chemical

reaction (The oxidisation of iron) which leads to a temperature drop. The combination of the laser and oxygen flux have contributed to removal of the oxide layer resulting in the temperature increase again. Therefore, this fluctuations in temperatures due to regularly spaced ripples “striations” (Figure 2.31) [4, 19].



Figure 2.31-Typical of mild steel cut edge produced by CO₂/ oxygen cutting [13].

2.3.7.2 Dross

The term dross is related with incomplete ejection of the molten metal layer from the bottom of the cutting zone and its formation depends upon the various materials and laser cutting parameters [19]. Moreover, the molten metal layer thickness is significantly affected by laser power intensity and the assist gas intensity (using an inert gas) [65]. A good cutting edge (dross-free) can be obtained in mild steel while stainless steel tends to form clinging dross of the bottom of cut edge. In the case of stainless steels, the assist gas reacts with the iron, chromium and any other alloying elements [4]. The adherent dross has been greatly influenced by the melting/flowing conditions of material on the cutting front and the cutting speed(Figure 2.32) [66].

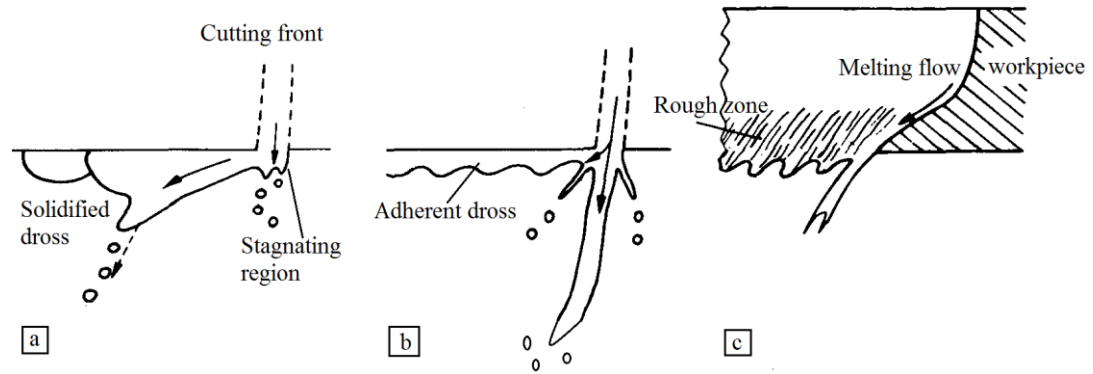


Figure 2.32- Schematics of the adherent dross at different cutting speed when cutting 2mm stainless steel with laser power 1kW used oxygen as assist gas. (a) 1.4m/min, (b) 3m/min, (c) 5m/min [66].

In the study of Wandera and Kujanpaa [67] an optimisation of the cut edge quality and inhibition of dross clinging on the lower of cut edge when cutting 10mm stainless steel by fibre laser and nitrogen as assist gas, It was reported that, to prevent any dross clinging in lower cut edge used high pressures of inert gas were applied and formed large kerf widths.

Oxygen assisted gas cutting of stainless steel gives high cutting speed compared with inert gas cutting because of the additional heat added to cutting process. Chromium oxide (Cr_2O_3) has been formed with a high melting temperature. These oxides forms a blanket inhibiting the oxygen from passing through to molten material. Therefore, the oxygen jet needs to rupture the oxide blanket to allow continued reaction. In other words, the active gas plays two important roles. First, a drag force is generated to blow the molten material out of the cut kerf. Secondly, the oxidation reaction provides extra heat added to the cutting process [4, 40].

The study of Yilbas and Aleem [65] compared the results of prediction and experiment on the dross formation during CO_2 laser when cutting 1.5mm mild steel with oxygen assist gas. They reported that the liquid layer thickness increased with laser power and

decreased with increasing assist gas velocity. Consequently, the iron oxide (FeO) produced in this process will be decomposed when heated to high temperature, this is an endothermic process which consumes much energy and could lead to a slump of the cutting process [13].

2.3.8 Energy losses in laser cutting process

During the cutting process, the laser power is not all absorbed by the cut front and there are always some losses. A portion of the laser beam may pass straight through the cut zone without interacting with the cut front while some may be reflected off the cut zone (Figure 2.33).

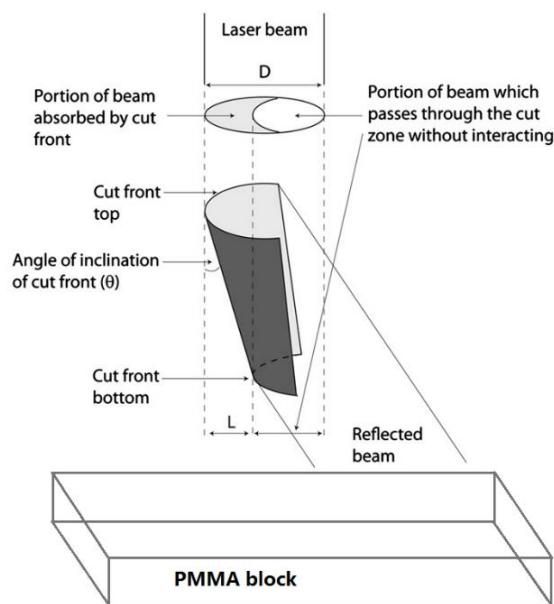


Figure 2.33- The laser beam loss during cutting process. Adopted from [13].

The laser beam absorption depends on the laser parameters (wavelength, power density and mode of operation) and interaction time as well as material properties (type, thickness) in addition to the Fresnel absorption coefficient and the incidence angle of the laser beam [3, 15, 68].

Generally, the energy supplied to the cut zone can be regarded as a dynamic equilibrium between energy used in generating a cut simultaneously with energy losses. Powell et al. described formula expression various components of the energy balance in the cutting zone.

$$\text{Energy supplied} = \text{Energy used in cutting} + \text{Energy losses from cut zone} \quad 2.10$$

They regarded that, the reflected and transmitted beam from the cut zone are the most important losses during laser cutting process [69]. One of the inexpensive techniques to determine the extent of such losses is by using a PMMA (Poly methyl methacrylate) block. Exposure of the PMMA to the laser irradiation then leaves an imprint related to the spatial distribution the beam energy [4]. An acrylic block placed underneath the cut zone can be used to collect any surplus beam and collect it as an imprint. Movement of the PMMA block has been selected according to the study of laser beam behaviour during cutting process.

In the study of Powell et al. [4, 69] analytical and experimental methods were used to study the thermal losses from the cut zone when mild and stainless steel were cut by CO₂ laser using oxygen as assist gas. They observed that losses rise rapidly when the thickness of the material increased. The laser beam absorption increased with temperature and shallow angles of incidence. Single and multiple reflections can take place in the cut zone and the results can be observed in the acrylic sheet as interference fringes (Figure 2.34b).

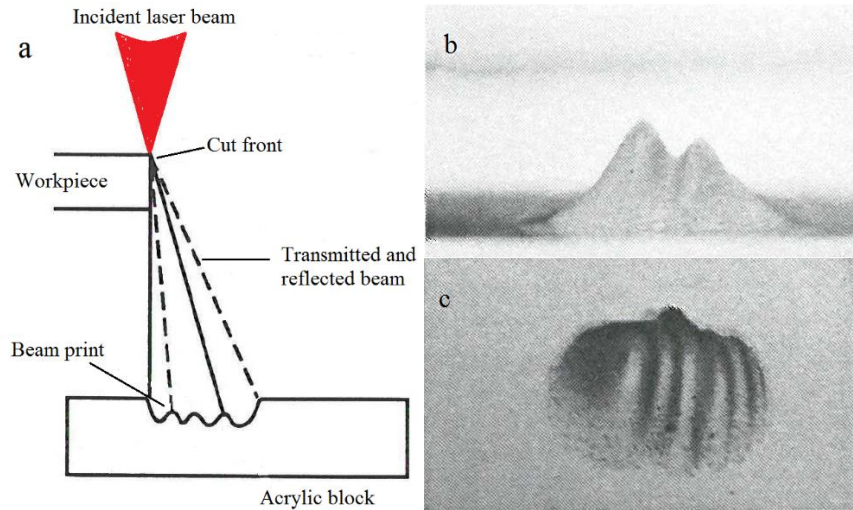


Figure 2.34- The beam print of the surplus energy was collected on transparent acrylic [69]. a) The generated of interference fringes. b) Cross section. c) Top view of the mode print.

Also, describing the general equation of energy supplied to cut zone.

$$(P - b) * t * \left[\frac{(100 - r_f)}{100} \right] + H = (E_{cut} * l * d * k) + \left[\left(\frac{t * \pi * d * k}{2} \right) * (A + B + C) \right] \quad 2.11$$

Where $(P - b) * t * \left[\frac{(100 - r_f)}{100} \right]$ = Energy supplied to cut zone, H = the power of the oxidation (W), $(E_{cut} * l * d * k)$ = Energy used in cutting and $\left[\left(\frac{t * \pi * d * k}{2} \right) * (A + B + C) \right]$ = Energy losses from cut zone.

Ivarson, Powell and Magnusson [70] studied the particles ejected from the cutting zone when cutting mild and stainless steel by CO₂ laser, finding optimum speed over a range of material thicknesses employing a laser power of 900W. The results showed that in the case of mild steel about 50% of the molten material is converted to FeO, the oxidation reaction contributes about 40% of the required energy input. But, stainless steel about 30% of the molten steel is converted to Fe₂O₃, this oxidation reaction contributes about 60% of the required energy to cutting zone.

Scintilla et al. [3] performed cutting experiments on cold worked steel with different sheet thicknesses to evaluate the primary energy losses through the cut kerf, comparing the results between CO₂ and disk laser regimes. The degradation of PMMA has been investigated in the range of cutting parameters for both transparent and black types. They found values of the degradation were 2.817 and 14.584J/mm³ for transparent and black PMMA respectively. The results of the study revealed that in case of disk laser, the primary energy losses, which consisted of transmitted and reflected powers were lower than those in the CO₂ laser cutting for the same values of relative cutting speed as can see in Figure 2.35.

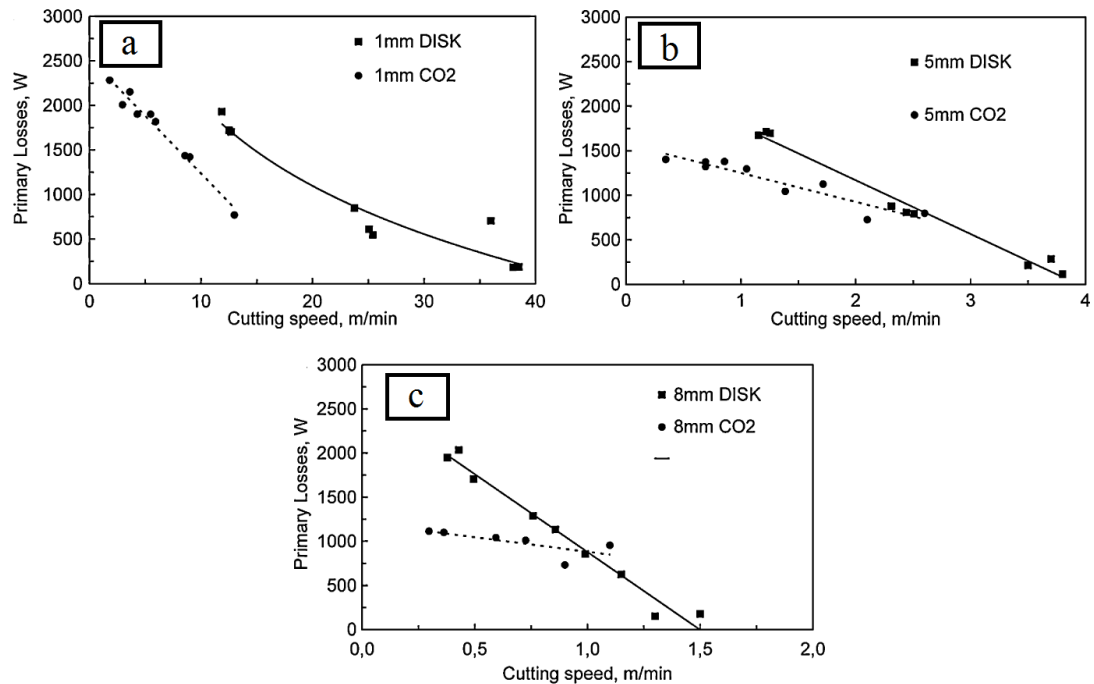


Figure 2.35- The primary losses of different lasers regimes with different sheet thickness. A)1mm, b)5mm and c)8mm [3].

A study [71] that investigated and calculated the process temperatures in fusion cutting based on the energy balance equation for cutting of 1, 5 and 8mm thick of cold work tool steel plates carried out on disk and CO₂ lasers, reported that, higher values of the maximum cutting speeds were obtained in disk laser and compared results with CO₂

lasers. For example, 1mm of maximum cutting speed was about 36 but 13m/min in CO₂ laser and for 5 and 8mm sheet thicknesses cutting speeds are still high comparable with same order. Temperatures of the cutting process for both regimes were calculated and these found for disk laser were lower values, corresponding to an increase in the melt viscosity leading to the worse cut quality.

Harris and Brandt [1] used the black PMMA to determine the specific heat of evaporation of it by focused a Nd:YAG a 1.064 μ m wavelength at various powers and cutting speed (Figure 2.36). The results shown that the value of heat evaporation energy of black PMMA between 4.5 to 5.5kJ/cm³ which is dependence on cutting speed.

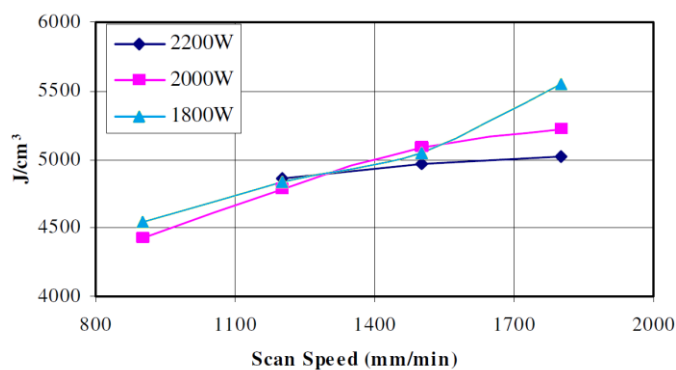


Figure 2.36- The specific heat of evaporation of black PMMA [1].

Also, they concluded can using black PMMA as a tool to qualitative and quantitative visualisation of a 1.064 μ m. However, work with Nd:YAG laser beams has established that certain black grades of PMMA are highly absorbing of 1 μ m wavelength light [72].

2.4 Polymers

Polymers are large molecules composed of repeating units. They are structured from a simple repeating portion called a monomer. These monomer molecules link together forming chains with a molecular weight of at least several thousand atomic mass units. Moreover, the monomer units are contain carbon and hydrogen atoms as main components besides other molecules like oxygen, nitrogen and sulphur. The type of elements, proportion and arranging in the monomer unit gives the base for producing different plastic [73]. Polymeric synthesis change the monomeric substance naturally as a liquid or even gaseous to become a solid or a viscous liquid as a polymer. However, the polymer chains become entangled with each other and the molecular forces are compounded greatly. The atomic composition of polymers have been participated to specific properties that are common of all polymers.

1. Low electric conductance.
2. Low thermal conductance and resistance, will easily irrevocably thermally degrade.
3. Lower density which between 0.8 to 2.2g.cm^{-3} .

The general features of polymers can be described here, such as crystallinity, glass transition and melting temperature which are determined by the structure and types of polymer [74, 75]. Individual properties vary with specific polymers such as melting viscosity, density, impact strength and yield strength and modulus.

2.4.1 Glass transition temperature

The glass transition position determines the polymer of flow at a specific temperature. Below this temperature the polymer is hard and brittle because the molecular rotation of chain segments are restricted. Above the transition temperature, the chains have gained mobility with more free rotation while increased thermal energy sets them moving more free. The glass transition temperature is affected by the structure of polymer, such as in PMMA polymer, it is approximated 104°C of amorphous, 115°C of syndiotactic and 45°C of isotactic [74, 76, 77].

2.4.2 Melting temperature

The crystalline melting point is about 1.5 times the glass transition temperature when measured in K (Figure 2.37). The melting point tends to decrease with the number of methylene groups in the repeat unit with reduction in the concentration of polar bonds (linkages such as esters or amides) [74, 78].

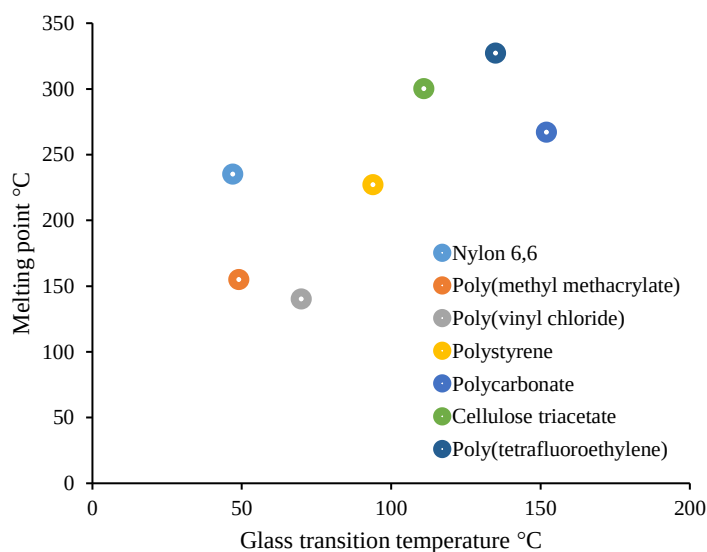


Figure 2.37- Relationship between glass transition temperature and melting point for different polymers [78].

2.4.3 Crystallinity in polymer

The crystallisation in polymer is determined by the arrangement of its molecular structure and the cooling rate, it is divided into three possible forms [75, 78].

1. Amorphous polymer, the structure of chains form a randomly ordered (mess).
2. Crystalline polymer, the structure of chains form a regularly ordered structure.
3. Semi crystalline polymer, the structure of chains form a mixture between amorphous and crystalline.

This regularity in structure of polymer makes a denser material, and more resistant to solvents. Also, the mechanical properties are affected by its crystallinity and the glass transition temperature [74].

Poly-methyl methacrylate, commonly known as PMMA is a good example where the structure of individual polymer chains determines the crystallinity of its structure. For many years PMMA was considered as an atactic structure, the chains in PMMA structure lacked the side groups which would inhibit them packing together successfully. Alternatively in isotactic PMMA, the more ordered allows better packing together into crystallites. It is now, understood that PMMA is defined as syndiotactic in structure (Figure 2.38) [74, 79].

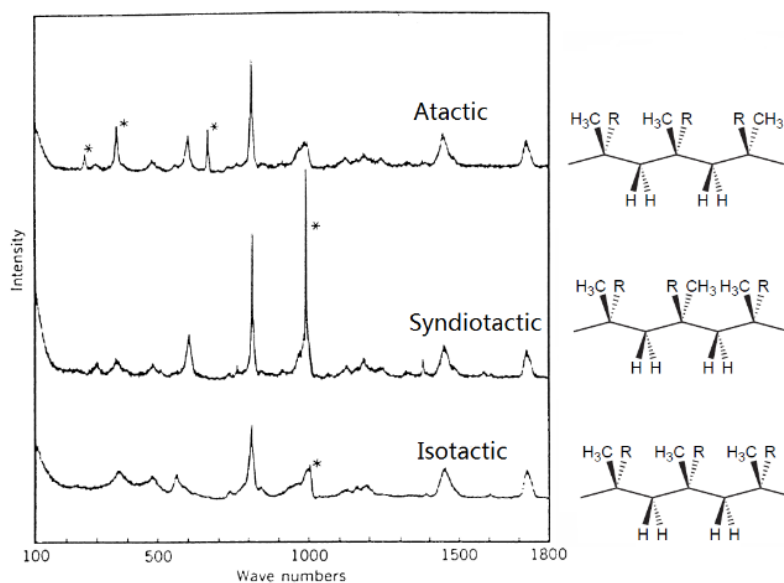


Figure 2.38- Various tacticities of PMMA. Left) Raman Spectroscopy. Right) Possibility of chemical compound for PMMA [74].

2.5 Poly-methyl methacrylate (PMMA)

Poly (methyl methacrylate) (PMMA) is the most important member of the wide range of acrylic polymers which may be considered structurally syndiotactic and it is a derivative of acrylic acid and its homologues as shown in Figure 2.39 [74, 80]. PMMA established most stable polymers structure with respect to laser process [81].

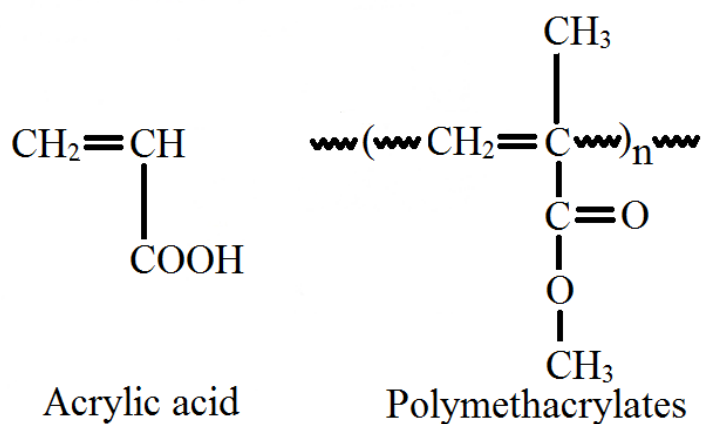


Figure 2.39- Chemical formula. Left) Acrylic acid. Right) Poly methacrylate [74].

PMMA may be considered as a linear polymer, the mechanical and thermal properties of it are mostly determined by the number of carbon atoms in the side chain, the length of side chain propagation and type of alcohol which it is prepared from [80]. The polymer becomes rubbery when the length of the side chain increases and the number of carbon atoms in chain does not exceed 12. On the other hand, increasing elastoplastic nature and wear resistance of PMMA, which is mostly a brittle materials can be manipulated with additives in the synthesis [80, 82]. For PMMA simple repeat unit, the monomer is methylene.

2.6 Characteristic of PMMA

In general PMMA is brittle with high strength and high surface hardness [75]. In the study of Kurkcu, Andena and Pavan [83] hardness and surface hardness behaviours of several polymers (PMMA, PC, PE and MF) was investigated. The results showed the surface hardness is dominated by the yield stress and it is independent of the loading conditions. PMMA is suitable for use in lighting purposes because it has little absorption of incident light, as shown in Figure 2.40 [75]. It can be coloured to a degree of saturation according to applications by additives [84].

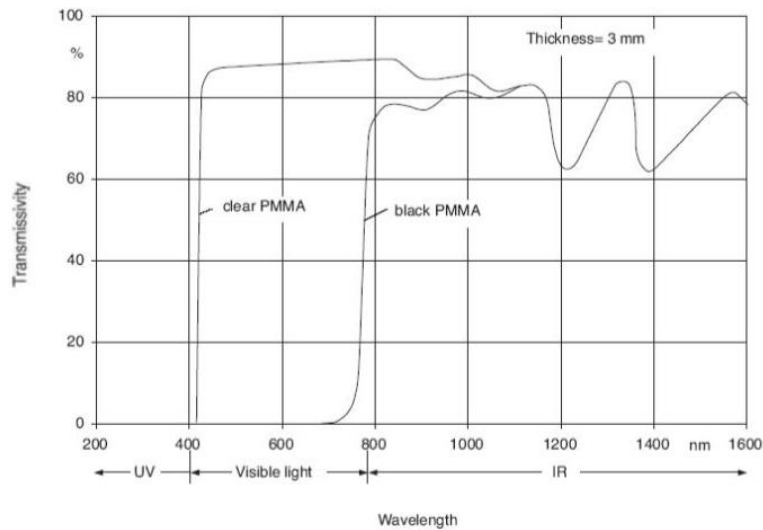


Figure 2.40- Light transmission during 3mm thickness of transparent and black PMMA in spectrums visible and IR.

A Second property of PMMA is good weathering resistance when compared with other thermoplastic materials [85]. While the PMMA exhibits a semi-crystalline structure that has great influence on thermal properties [86].

2.7 Degradation of PMMA

Degradation of polymer includes all aspects of changes in the chemical structure and physical properties due to external chemical or physical stresses. The physical factors involved mechanical forces, heat, radiation and ablation then focusing on one aspect which is heat. Measuring the decomposition in polymers material is crucial to understand relationships between thermal properties and polymer chain structure. Thermogravimetric analysis provides a useful tool to study this features [87]. The thermal decomposition of a PMMA refers to exposure at elevated temperature as it undergoes chemical changes without the simultaneous participation of another compound [88].

The general mechanism common in PMMA decomposition involves the breaking of bonds in the main chain into smaller ones [89]. The process heats up the PMMA which remains in the solid glassy state until it reaches the glass transition temperature. Then, supplying more energy to polymer, it undergoes scission to form unsaturated small molecules and propagate to free radical on the PMMA backbone [90, 91]. More specifically, via the depolymerisation mechanism the PMMA has been degraded to volatile monomers (MMA) and carbon dioxide [92].

In the study of Acosta, Gross and Perran [2] investigated the thermal degradation of black PMMA irradiated with $1.064\mu\text{m}$ laser in air. They observed in the central exposure region bubbles are generated by subsurface vapour formation. The carbon black pigmentation in PMMA has enabled absorption of the Nd:YAG laser beam throughout some depth of the sample, leading to localised heating and subsurface boiling (Figure 2.41). They concluded that the initial heating rate was dominated by absorption of the incident laser radiation followed by conduction into the rest of the material.

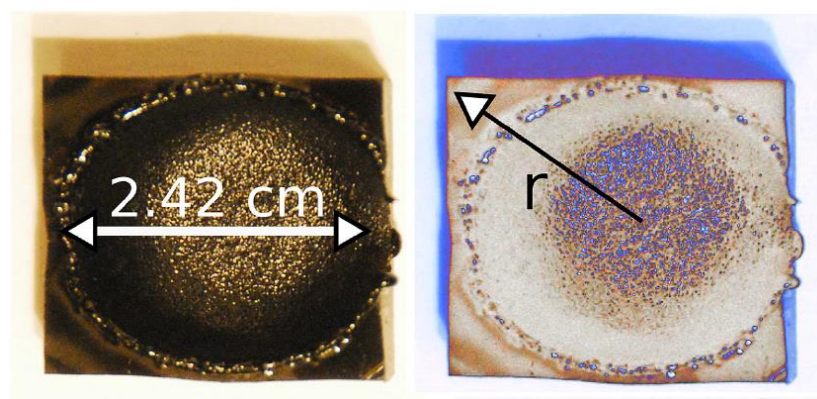


Figure 2.41-Black PMMA sample exposed to Nd:YAG beam. Left) the sample. Right) contrast filter [2].

Also in the study of infrared radiation absorption aspect, Linteris et al. [93]. The results show most of incident energy is absorbed, 80% of it in depth at the first 0.5mm, the apparent absorption coefficient for that thickness is fairly large.

Jiang, Ris and Khan [94] developed a technique to quantify the absorption of thermal energy in black PMMA by employing infrared heater source a 1.15 μm wavelength. They results show that at higher heating rates the radiation is deeper because of delayed ignition time for black PMMA samples, the transmissivity of it has linear relationship over a range the sample thicknesses from 1 to 4mm with a constant slop.

2.8 Summary

This chapter studies the literature related to the laser cutting of metals, in particular, the laser cutting of stainless steel work piece using nitrogen as assist gas and employing the black-PMMA to give details of qualitative information on laser absorptivity behaviour inside cut zone. The solid state fibre (1.06 μm) and CO₂ (10.6 μm) laser sources with different wavelengths were compared as the laser most widely used in the cutting process. The comparison of two lasers regime shows that the performance of cutting is different between them. The main conclusion that can be drawn from the comparison is that several factors can influence the analysis of laser-materials interactions. This work concentrates on the fibre laser because cutting work with a fibre laser has demonstrated better focusing properties and absorptivity, therefore higher quality cutting in terms of the kerf width, heat affected zone (HAZ) and the cut edge are achieved. An interesting complication with fibre lasers is the multiple reflections of the laser beam when absorbed on the cut front.

Using cheap material with a low thermal conductivity and high absorptivity, in this case poly-methyl methacrylate, it is possible to identify the primary energy losses (reflected and transmitted) from cutting process. The ablation pattern produced by the absorption of the laser energy in this material provides quantitative and qualitative information about the primary losses of light in the cutting zone.

A transparent PMMA material has been used to analysis the behaviour of CO₂ laser beam by capture the beam print at the cutting zone. However, this diagnosis tool is not suitable for solid state lasers as transparent PMMA has very low absorptivity to this wavelength. However, carbon-filled opaque grades of PMMA are highly absorbing of fibre wavelength. Finally, it is also observed that published studies on using carbon filled black acrylic (CFBA) with fibre lasers do not fully consider to the specific ablation energy of the black acrylic which is required to quantify lost energy.

This review of the relevant literature indicates there are question remaining on the reflection and transmission of the fibre laser beam in the cut zone.

3 Equipment and experimental procedures

3.1 Introduction

This chapter introduces the equipment and experimental procedures used in this research. The first sections concern the materials used and a study of the physical properties of PMMA. The following sections cover the laser machines and discuss the laser material interactions. Finally there is a description of using PMMA to investigate the surplus energy during laser cutting and the equipment which was used for observation.

3.2 Materials

It is well known that lasers generate part of the electromagnetic spectrum. Laser materials interactions may be affected by the surface quality of work piece. Sheets with shiny or reflective surfaces can reflect the beam. Dirty, rusty or processed surfaces may respond unpredictably in melting of the material. Thus, the surface roughness of sheet may affect incident laser light. Hence the surface of the material was inspected for any damage before experiments. The surfaces of the samples of black PMMA and stainless steel were covered with a protective polythene layer and this was removed before the experiments. Throughout this work all samples were obtained from the same suppliers.

3.2.1 Stainless steel 304L

AISI 304L stainless steel work pieces with thicknesses of 3, 4 and 6mm were utilised. The chemical compositions of the material is presented in Table 3.1. Optical emission spectrometry analysis (spectrometry-foundry master) was used to collect these results.

Table 3.1- The average composition of stainless steel measured by spark emission.

Wt. %	C	Si	Mn	P	S	Cr	Mo	Fe	Ni	Al	Co	Cu
3 mm	0.0448	0.555	1.56	0.0386	0.0094	18.7	0.259	69.6	8.43	0.0031	0.138	0.457
4mm	0.0351	0.656	2.13	0.0252	0.005	19.4	0.0466	67.5	9.35	0.0266	0.191	0.0308
6 mm	0.0439	0.554	1.50	0.0287	0.0085	19.0	0.264	69.3	8.68	0.0074	0.158	0.278

3.2.2 Black PMMA

Plastics are divided generally into two groups according to their chemical bonding: thermoplastics and thermosets [95]. The main physical difference in the thermoplastics can be re-melt back into liquid, whereas thermosets always remain in a permanent solid state. Poly methyl-methacrylate (also known as Acrylic or acrylic glass, PMMA, Perspex or Plexiglas) is one of the most common of the thermoplastic and when exposed to heat will degrade to the monomer methyl methacrylate [96, 97].

The general properties of acrylic are dependent strongly on temperature, testing ‘rate’ and humidity [74]. However, at room temperature it is hard, rigid and has good weathering resistance compared with other thermoplastics, some of its physical properties are illustrated in Table 3.2. Pigments and dyes are often blended with poly methyl methacrylate as additives to improve properties [74, 95]. The samples used here were sheets made from Poly-methyl Methacrylate (PMMA) with carbon filler

laser cut 1m x 2m sheets with thicknesses from 2 to 3.5mm. All samples were obtained from the same company; ASTARI.

Table 3.2- Material properties of carbon filled black PMMA.

Parameters	Symbol	Value	Range	Reference
Density(g/cm ³)	ρ	1.19	[1.18-1.19]	[98]
Melting temperature(°C)	T _m	160	[130-160]	[99]
Specific heat capacity(J/(g.K))	C _p	1.465	[1.42-2.09]	[2, 98]
Thermal conductivity(W/(m.K))	K	0.21	[0.19-0.24]	[98]
Hardness, Rockwell M	-	97	[85-105]	[100]
Weather Resistance		High		[100]

3.2.2.1 SEM examination of black PMMA

Black-PMMA is non-conductive, therefore a layer of a conductive material is applied to the surface of black PMMA samples for scanning electron microscopy (SEM) to enable or improve the imaging of it. A carbon coating in a vacuum system is created from a carbon rod between high-current terminals. On heating the carbon rod reaches its evaporation temperature, and a fine stream of carbon is accumulated onto the black PMMA sample.

3.2.2.2 Density of black PMMA (ASTM D792)

The mass of three black PMMA samples was measured by laboratory balance (Sartorius analytical ENTRIS 224-1S) and the volume was measured by immersion in water in a graduated container. The accuracy of this method is about $\pm 0.002\text{g/cm}^3$. The density of the carbon filled black acrylic was found to be 1.188g/cm^3 which is within

the range (1.17-1.20g/cm³) for standard clear acrylic. This demonstrates that the carbon filler does not have a big effect on the density of the material.

3.2.2.3 Thermal decomposition of black PMMA

In order to understand the thermal decomposition process of the black PMMA (Poly methyl Methacrylate) the properties of the material were monitored against time or temperature. A series of measurements were performed on the samples, including dimensions, energy, differential temperature, matter status and weight. Thermal decomposition experiments included differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), and Thermomechanical analysis (TMA). In order to increase the measuring accuracy of the results, each test was repeated three time at the same conditions and the average reported.

3.2.2.3.1 The differential scanning calorimetry (ASTEM D 3417-3418)

Differential scanning calorimetry (DSC), was used to measure the heat flow rate for a sample made from PMMA (Poly methyl Methacrylate). The difference in temperatures between the DSC samples and the reference junctions of a thermocouple is proportional to the differential heat flow to the sample [100], as shown in Figure 3.1. In this work a Differential scanning calorimetry instrument model (TA-DSC 2500) was used with programmable tray positions.

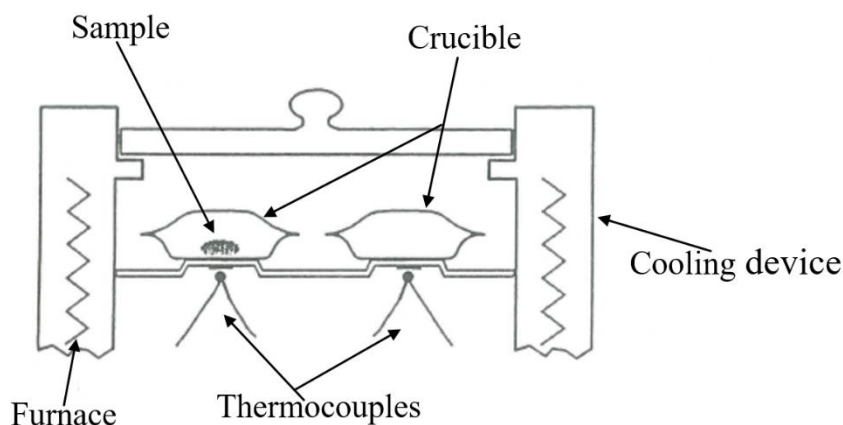


Figure 3.1- Schematic of the DSC instrument employed to find the thermal properties of PMMA.

To test the thermal behaviour of PMMA, a small portion of transparent and black PMMA samples were weighed accurately. The masses were 9.3 and 8mg respectively, by using the electronic laboratory balance (Sartorius analytical ENTRIS 224-1S) after first cleaning with alcohol to eliminate any contamination. Appropriate pans and hermetic lids (t-zero) were selected with a flat bottom for optimum contact between pan and sensor, also to minimise the contact resistance and to improve resolution. Before loading onto the calorimeter the weights of DSC samples were measured (Transparent, black PMMA with pan and lid) which were 52.1 and 51.8mg respectively. The runs are implemented in an inert (nitrogen) atmosphere with a heating rate of 2°C/min over a range of 20-490°C.

3.2.2.3.2 The thermogravimetric analysis TGA

The thermogravimetric analysis (TGA) is a test related to changes in the weight of sample, monitored as a function of temperature or time. The weight of sample is continuously monitored as the temperature is raised. Thermal decomposition of polymers can lead to weight losses as volatile monomers are released [100] as show in

Figure 3.2. Thermogravimetric analysis equipment model SDT-Q600 was used in this work.

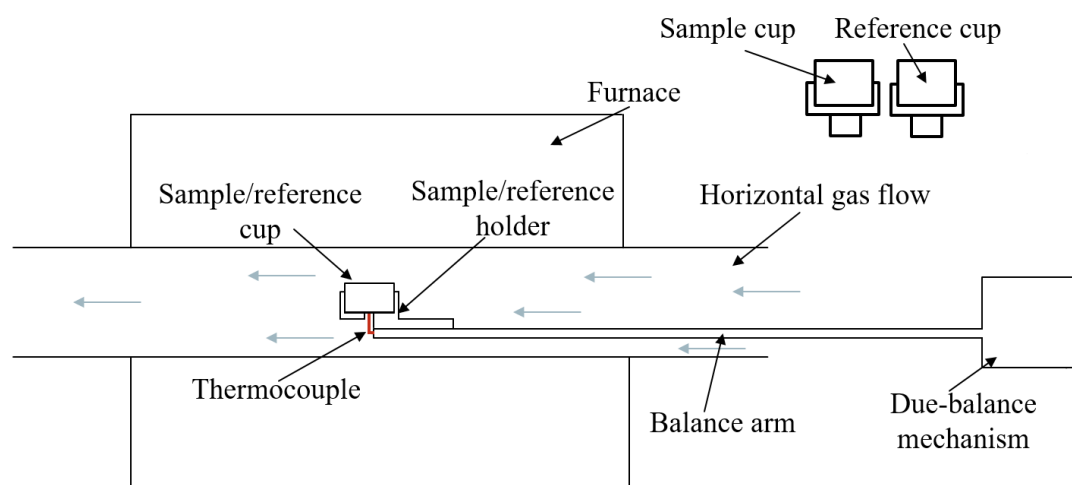


Figure 3.2- Schematic of The Thermogravimetric Analysis equipment used.

To calibrate the TGA, an empty alumina pan is used to determine baseline performance in the appropriate heating ranges to find any variance of weight. The test was performed with a heating rate of $5^{\circ}\text{C}/\text{min}$ between $20\text{--}500^{\circ}\text{C}$. The transparent and black PMMA (PMMA) were cleaned with alcohol then left to dry. The sample is placed individually into the alumina crucible and allowed to stabilise. The processes underlying the degradation of poly-methyl methacrylate were examined under inert gas (Argon) conditions. The mass of the transparent and black acrylic samples were 4.992 and 3.827mg respectively before turning on the heating.

3.2.2.3.3 Thermomechanical Analysis TMA

Thermomechanical Analysis TMA measures the properties of materials using a constant force applied on a sample under different thermal conditions. The measurements included the softening or glass temperatures, compression modulus, the

thermal expansion and melting point as show in Figure 3.3. The sample dimensions change in the vertical direction under an imposed temperature control. In this work the thermomechanical analysis model (TMA-Q400) was used.

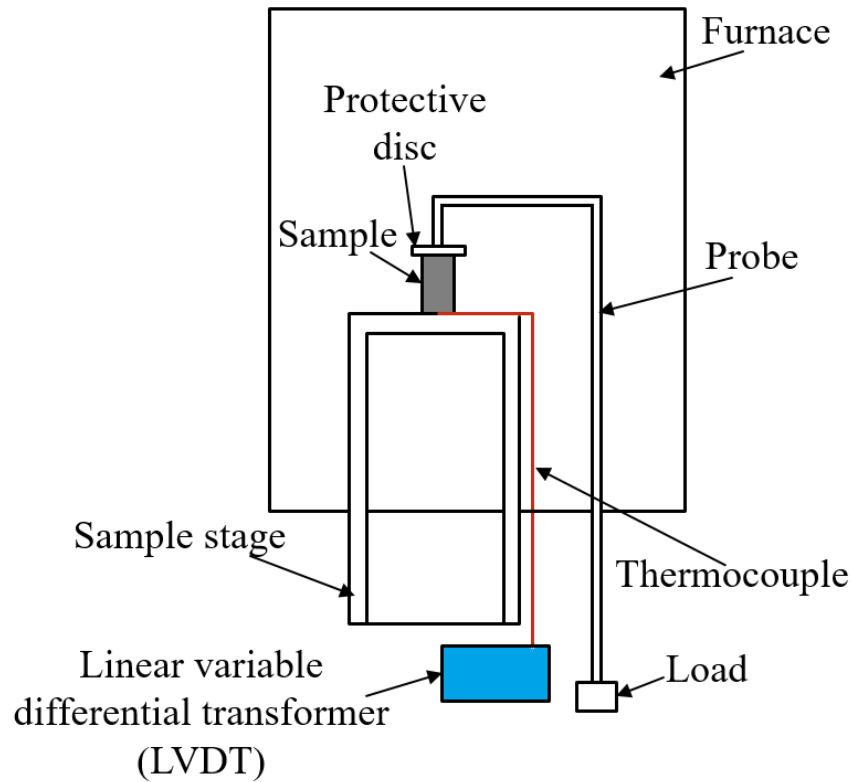


Figure 3.3- Schematic of The Thermomechanical Analysis equipment employed.

Preparation of samples for TMA: the black PMMA sample is chopped to a defined geometry ($4.74 \times 4 \times 3 \text{ mm}^3$) with parallel surfaces. The sample is cleaned with alcohol before testing and left to dry. Baseline calibration is performed on a quartz disc before testing to determine the variation of expansion. A heating rate of $5^\circ\text{C}/\text{min}$ was used between 20 - 500°C . A thin disc of quartz was placed between the top of the black PMMA sample and the probe. A force of 0.02N is applied to the sample and testing has been done under Argon gas conditions. Sample length taken from instrument screen controller after stabilisation was 4.7393mm .

3.3 Fibre laser system

The experiments were performed with two fibre lasers which are described below.

3.3.1 2kW laser machine

An IPG YLR-2000 fibre laser with a $1.07\mu\text{m}$ wavelength and maximum power of 2000W was used in the continuous wave mode. The optical fibre was delivered to a cutting head housing a 125mm focal length collimating lens, forming a $200\mu\text{m}$ diameter focused spot. The beam left the cutting head through a 1mm diameter nozzle used to deliver the assist gas coaxially with the laser beam. The focal position was on the surface of the work piece, 1mm below the end of the nozzle, the sample position was checked with a stand-off gauge to check the 1mm stand-off. Some features of the equipment are shown in Table 3.3.

Table 3.3- General characteristics of the IPG YLR-2000 (2kW) fibre laser cutting machine.

Contents	Values
Model	YLR-2000
Laser source	Ytterbium
Maximum set power	2000W
Number of module	4+1 reserve
3 delivery fibres(diameter)	200,400,600 μm
Wavelength	1070nm
Polarisation	Random
Laser mode	CW
Beam intensity distribution	TEM00
Feeding fibre length	5m
Cooling system	Chiller+ water cooling

3.3.2 4kW laser machine

The 4kW fibre laser was a Bystronic Bysprint Fibre 3015 with the following specifications: 4kW maximum output power type IPG 4kW, 1.06 μ m wavelength. This industrial cutting machine employs a moving head over stationary material.

3.4 Finding the specific evaporation energy of black PMMA

The main aim of this experiment is to find if it is possible to identify a specific evaporation energy for black PMMA evaporated by a fibre laser beam. For this experiment different laser powers, exposure times, beam sizes and atmospheric conditions were used.

3.4.1 Experimental parameters

The sheets of Poly-methyl Methacrylate (PMMA) with carbon filler were cut into 95x95mm² squares 3mm thick. Stacks of these squares were used as target material because this allowed accurate measurement of the drilled holes. Clamping was designed to avoid any split, displaced molten and bulges during laser irradiation, as shown in Figure 3.4. As the laser beam irradiates the acrylic it is rapidly evaporated at rates specified by the local energy density. The laser beam was delivered through a 600 μ m delivery fibre. Powers in the range of 400W to 1000W were used and for the majority of this work the focal plane was positioned 6mm above the acrylic, using Nitrogen as an assist (flushing) gas.

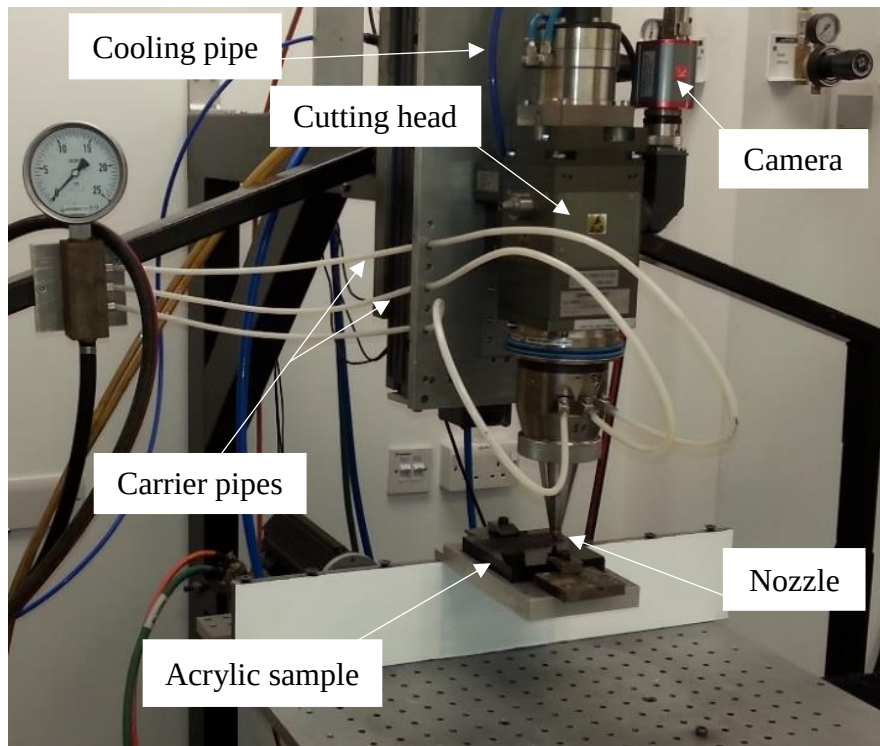


Figure 3.4- Shown new design of holding black PMMA sample.

Table 3.4 shows the parameters which were used. It should be noted that the laser was only on for the times stated, however the assist gas continued to flow for some time before and after the laser exposure. In each case five drilled holes were made and the results presented are the average values. All holes were observed and measured under an optical microscope (Nikon ECLIPSE LV100ND), 10X and 20X lens were used.

Table 3.4- Briefly shows the laser powers, irradiation time used.

Laser power	Irradiation times									
W	ms									
400*	100	200	300	400	500	600	700	800	900	1000
600*	100	200	300	400	500	600	700	800	900	1000
800**	100	200	300	400	500	600	700	800	900	1000
1000	100	200	300	400	500	600	700	800	900	1000

* Used only in the effect of air jet flow on evaporated volume experiment.

**Used on the effect of gas pressure and stand-off on evaporated volume experiments.

3.4.1.1 Calculation of evaporated volume

The volume evaporated from each 3mm thick layer was calculated separately by using the standard equation for the volume of a truncated cone as in Equation 3.1.

$$\text{Volume of truncated cone} = \frac{1}{3} \cdot \pi(R^2 + R \cdot r + r^2) \cdot H \quad 3.1$$

Where R is larger hole radius (mm), r is smaller hole radius (mm), and H is height of circular truncated cone (mm) as shown in Figure 3.5.

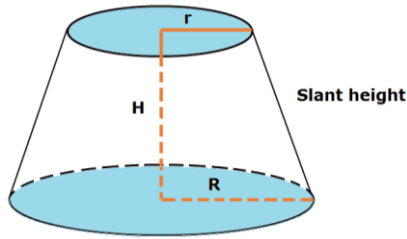


Figure 3.5- The Truncated cone.

The total volume of material removed per hole was then determined by summing the volume removed per layer, and with the final, incompletely pierced, layer being treated as a spherical cap. To determine the volume of the spherical cap used Equation 3.2, a Figure 3.6 shown the whole hole in the black PMMA.

$$\text{Volume of spherical cap} = \left(\frac{\pi \cdot h}{6}\right) \cdot (3 \cdot a^2 + h^2) \quad 3.2$$

Where h is the height of spherical cap (mm), and a is the radius of the base of the spherical cap (mm).

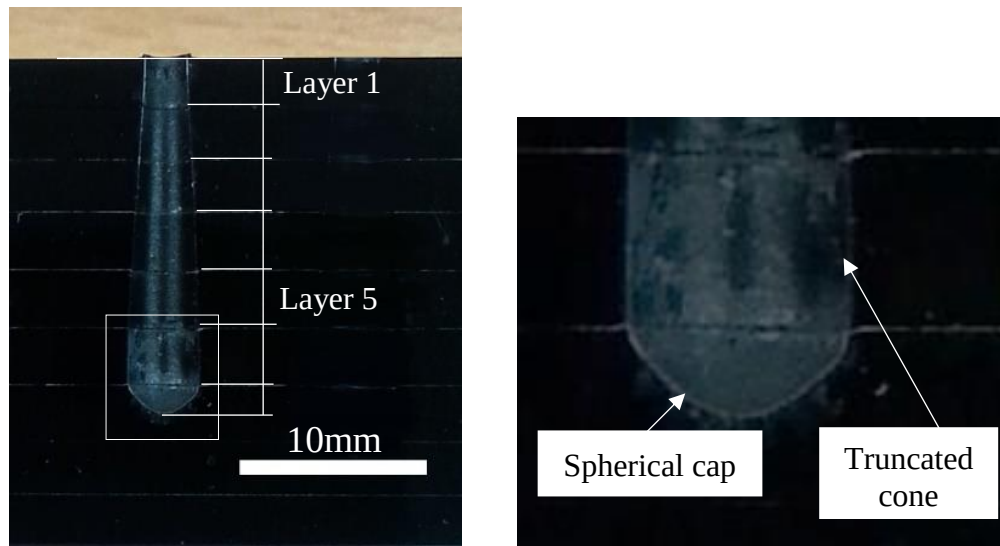


Figure 3.6- Cross section of the hole was made by used 1000W and 500 ms.

In this way the volume of the evaporated material was measured for each power and exposure time combination in Table 3.4.

3.4.2 Study of gas pressure effect on evaporation volume

The main aim of this experiment is to confirm that gas flow in the laser-material interaction zone influences the evaporated volume of black PMMA. The second aim is to find out how the evaporated volume changes with respect to gas pressure and irradiative time and laser power. Only direct irradiation of black PMMA was investigated, no stainless steel was cut in these experiment. Finally, an analysis of the effect of carbon smoke in blocking the beam will be carried out, by comparing the results for various gas pressures.

3.4.2.1 Experimental parameters

The experimental parameters are shown in the Tables 3.4 and 3.5. A nozzle aperture of 1mm with 6mm stand-off distance from the black PMMA (below the end of the

nozzle) and 800W laser power was used. The employed fibre diameter was 600 μ m with a lens with a focal length of 120mm. The evaporated volumes are calculated as mention in section 3.4.1.1 and duplicated for times of irradiation between 100 and 1000ms.

Table 3.5- Experimental parameters to study effect of gas pressure.

Laser power	Gas pressure								
W	bar								
800	0	1	2	4	6	8	10	12	14

3.4.3 Study of stand-off effect on evaporate volume

The aim of this experiment is to investigate if the stand-off distance influenced the evaporated volume of the black PMMA. The second aim is to find out if the evaporate volume changed with respect to stand-off and time irradiated at a given laser power and assist gas pressure.

3.4.3.1 Experimental parameters

The experimental parameters are shown in Tables 3.4 and 3.6. An 800W laser power was used with a nozzle aperture of 1mm and different stand-off distances. The employed fibre diameter was 600 μ m used with a lens with a focal length of 120mm. The evaporated volumes are calculated and duplicated for each time of irradiation.

Table 3.6- Experimental parameters to study effect of stand-off distance.

Laser power	Stand-off distance				
W	mm				
800	2	4	6	8	10

3.4.4 Study effect of air jet on evaporated volume

The aim of this experiment is to study the effect of air jet on the evaporated volume of black PMMA. The second aim is to find out how the evaporated volume removed changes with respect to air jet pressure and time irradiated using the same drilling parameters.

3.4.4.1 Experimental parameters

The experiment parameters are shown in the Table 3.7. The air jet aperture with a 5mm diameter was put close to the surface of the black PMMA sample. The employed fibre diameter was 600 μ m, used with a lens with a focal length of 120mm. The evaporated volumes are calculated with the same technique indicated in section 3.4.1.1 and duplicated for each irradiation time.

Table 3.7- Experimental parameters to study effect of air jet.

Laser power	Air jet pressure
W	bar
400	2
600	

3.4.5 Qualitative print

The main aim of this experiment is to confirm if the evaporated shape will be a good first order approximation of the energy distribution of the beam at any given distance. The second aim is an experimental investigation into convenient qualitative prints on the surface of a black PMMA block with respect to vertical distance from the focal point. Finally, an analysis of evaporated volume will be carried out.

3.4.5.1 Experimental procedure

A piece of wire was inserted into the beam path close to the surface of the focusing lens. The beam print is replicated with difference vertical distances z between the focal point and the surface of sample. Nitrogen assist gas was used with pressure of 2 bar to protect the focussing lens from fumes as shown in Figure 3.7.

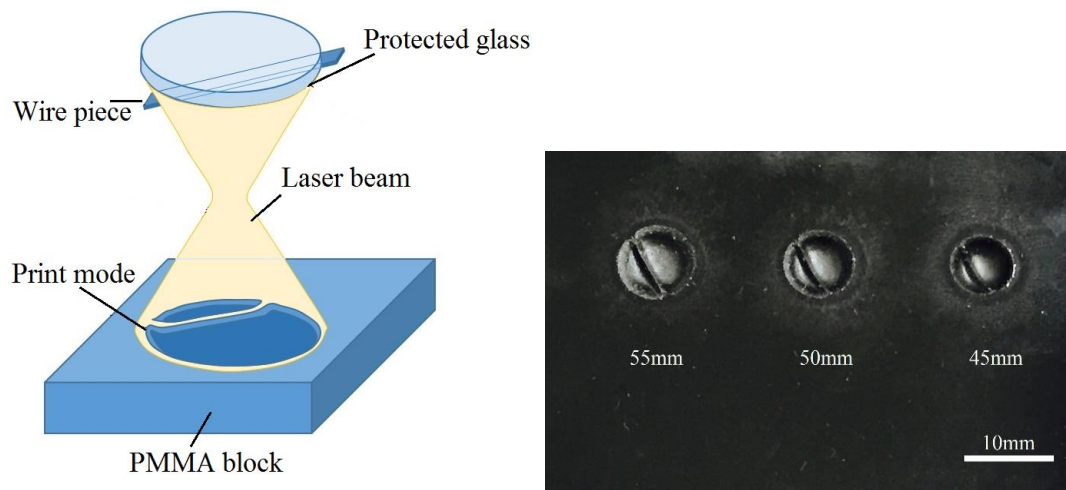


Figure 3.7- Schematic of experiment and mode print.

An Alicona G5 infinite focus variation optical profilometry (OP) was used to scan the mode prints and a Mat lab programme (Appendix 2) was used to calculate the volumes evaporated for each print, Table 3.8 shows the parameters used in this experiment.

Table 3.8- Experimental parameters of the qualitative print.

Laser power	Irradiation time	Vertical distance(z)		
W	ms	mm		
400	500	45	50	55

3.4.6 Profile and propagation of laser beam

To understand the laser beam propagation and energy profile, there are many devices which have so far been invented. The simple method under investigation here involves making mode prints on the black PMMA surface at known distances from the focus of a lens to investigate the propagation and profile of laser beam. Calculating the specific size and the depth of the focus needs reference to Gaussian optics and diffraction theory.

The main aim of this experiment was to determine the range over which quantitative results can be obtained using black PMMA. The second aim is to investigate the threshold effect as a function of distance. The employed fibre diameter was 200 μm used with a lens with a focal length of 120mm. Nitrogen was used as an assist gas with these experiments, delivered through a 1mm diameter nozzle.

3.4.6.1 Experimental procedure

The parameters of this experiment are shown in Table 3.9. This experiment is separated into two procedures. The first method is to make an imprint of a beam profile on the black PMMA at different vertical distances 'z' from the focal point to the surface of the sample, then replicated with the same conditions at different distances. The methodology is as follows:

1. Measure the diameter of the top of the evaporated blind hole.
2. Grind in cross section until the diameter of the top hole matches the original diameter measurement. This is done using a reference baseline on the sample surface as shown in Figure 3.8 Right.

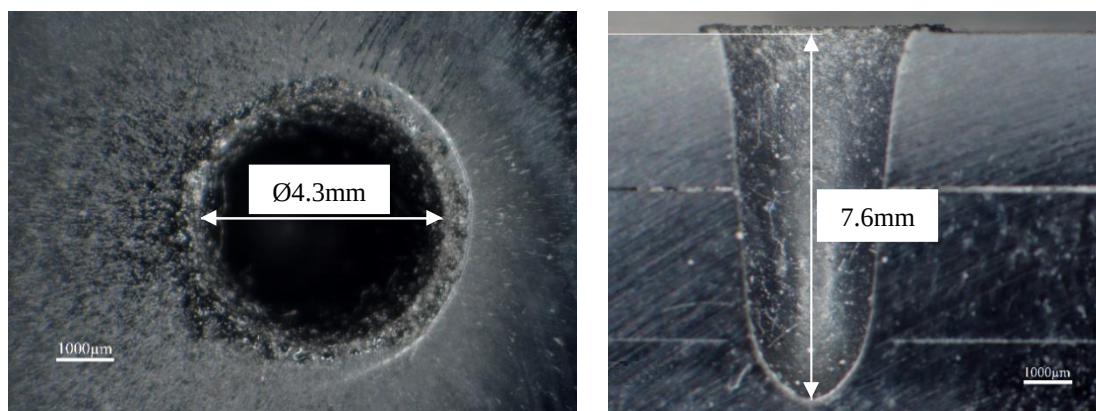


Figure 3.8- Experiment of beam profile print at 400W, 21mm vertical distance and 500ms time exposed. Left) The diameter. Right) Cross-section.

It can then be assumed that the ground surface reveals the centre plane of the hole as shown in the right of Figure 3.8.

Mass difference was used to determine the amount of material removed. The results achieved had a precision of about $\pm 0.006\text{g}$ for all measurements. The evaporated volume of the mode print is calculated by using Equations 3.3 and 3.4.

$$m = m_{\text{initial}} - m_{\text{final}} \quad 3.3$$

Where m_{initial} is the initial mass for black PMMA (g) and m_{final} is the final mass after hole evaporation (g).

$$V_{\text{mode print}} = \frac{m}{\rho} \quad 3.4$$

Hence, $V_{\text{mode print}}$ is the evaporated volume (mm^3); ρ is the density of black PMMA (1.188g/cm^3) and m is the mass difference before and after beam imprinting(g).

In a second method of estimating the evaporated volume the volume was calculated by use of PTC Creo 3 software as shown in the right of Figure 3.9 by assuming axial symmetry and generating a volume of rotation.

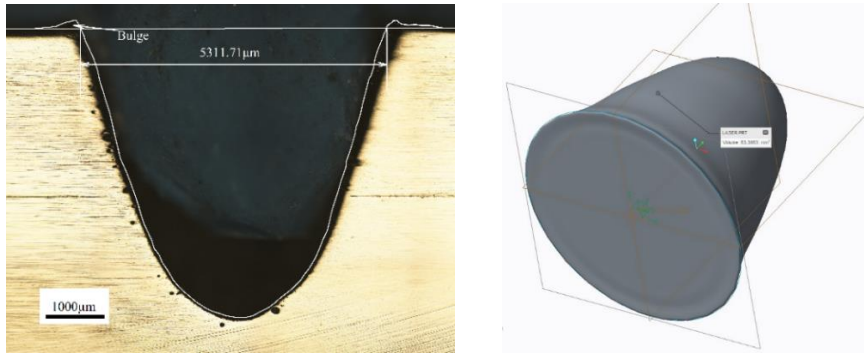


Figure 3.9- Cross-section and volume of beam print at 400W, 500ms and 30mm vertical distance between the end of nozzle to surface of CFBA. Left) Cross-section of beam print. Right) Volume of the same beam print calculated by PTC Creo 3 is 53.37mm³.

Table 3.9-Experimental parameter of profile and propagation of beam.

Laser power	Irradiation time	Assis gas and pressure (N ₂)	Vertical distance(z)									
			mm									
400	500	5	21	30*	40	59	78	97	116	135	154	

*Evaporated volume is calculated by using a PTC Creo 3 software.

3.4.6.2 Threshold experimental procedure

The parameters used in the experiment are shown in Table 3.10. Experimental activity consisted of making beam prints on black PMMA with three different laser powers and irradiation times. Beam profiles were recorded using a PRIMES beam analyser at different distances from the focal point. The experimental ablation diameter and laser beam analyser data are compared to determine the intensity that matched the diameter of hole. This provided information about the threshold for evaporation.

Table 3.10- The threshold experimental parameters.

Laser power	Irritation time					Assist gas and pressure (N ₂)	Vertical distance
W	ms					bar	mm
500	1	2	3	4	5	5	15
1200							
1800							

3.5 Using black PMMA to investigate surplus energy in laser cutting

To investigate the surplus energy in laser cutting, two different types of experiments will be used. Firstly quantifying surplus energy (grooves). Secondly, surplus energy distribution (stationary set up).

3.5.1 Quantification of surplus energy (Grooves)

The aim of this experiment is to quantify the surplus energy during fibre laser cutting of black PMMA.

3.5.1.1 Experimental parameters

The parameters used in this experiment are shown in Table 3.11 and Figure 3.11 shows the experimental set up. The sample is made of black PMMA with dimensions of 95x95x2.79mm³. The location of the cross-section of the evaporated grooves was 30mm from the start of the groove in order to avoid the region generated during table acceleration. The sample is fixed on the cutting table to avoid bending and movement through cutting. Liquid resin and hardener were mixed together then poured over the sample. The mixed will be hardened over time to give a hard casting. An optical microscope was used to take picture of the cross-section with details as shown in Figure 3.10b. The same conditions for cutting such as gas pressure, laser power, cutting speed and vertical distance (focus point to sample surface) were used with both the IPG YLR-2000 (2kW) and Bystronic Bysprint (4kW) laser systems. The area removed (A) is determined after establishing a baseline on the surface of sample. The bulging area (M) on the surface for both sides of the groove and, the HAZ layer area (R) are also measured for all samples as shown in Figure 3.10c.

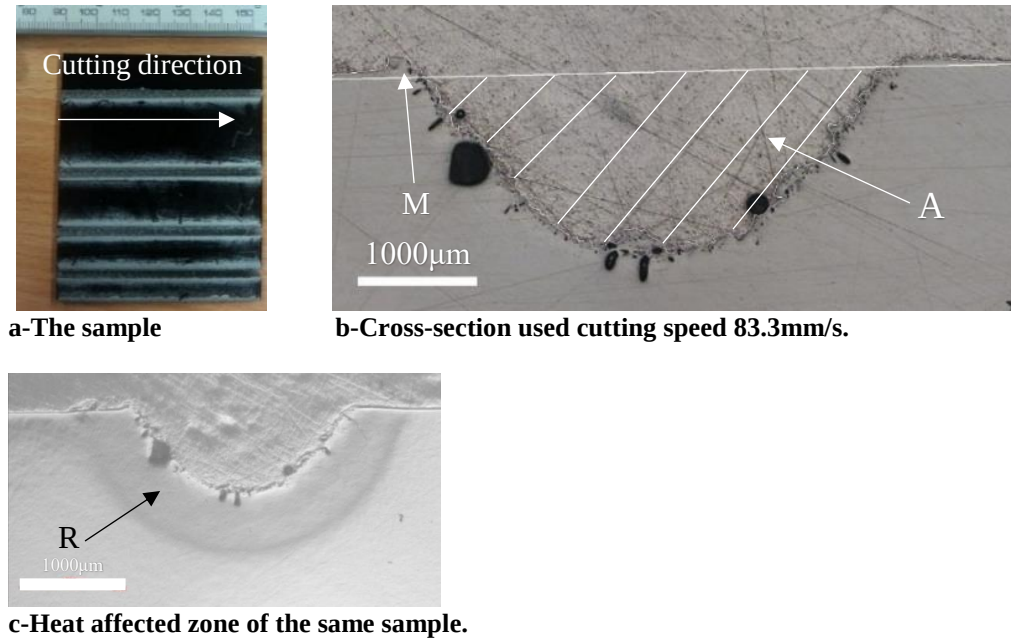


Figure 3.10- The sample of black PMMA cut by 400W.

The HAZ layer on the black PMMA samples was observed by the change in appearance. The phenomenon is dependent on the amount of light reflected off the surface of the sample. The micro-roughness of the surface of the sample scattered light in all directions and the HAZ therefore appears cloudy [100]. Finally, applying Equation 3.5 to calculate the power consumption during cutting of black PMMA.

$$P_{consumption} = (A * c_s) * 3.4 + ((M + R) * c_s) * (\rho * 60) \quad 3.5$$

Where $P_{consumption}$ is power consumption during process (W); A is a cross-section of the evaporated area (mm^2); c_s is cutting speed (mm/s); 3.4 is specific energy of evaporation of black PMMA (kJ/cm^3); M is a cross-section of bulge area (mm^2); R is a cross-sectional of HAZ area (mm^2); 60 is a specific energy of melting of black PMMA (J/g) according to DSC and ρ is the density of PMMA $1.188(g/cm^3)$.

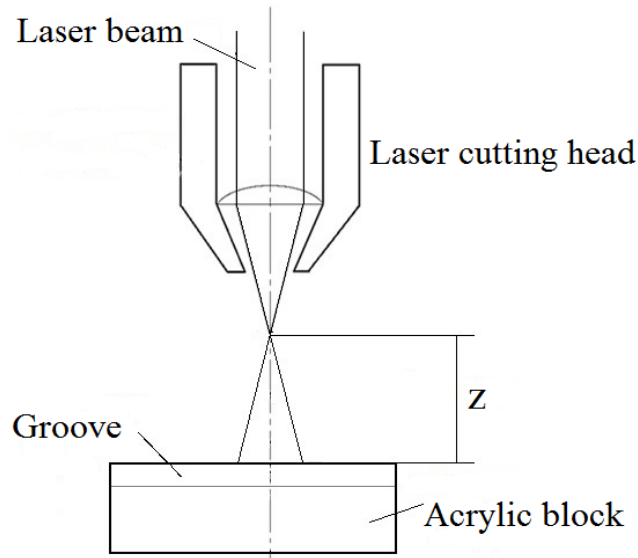


Figure 3.11- Quantifying surplus energy (Grooves).

Table 3.11- Experimental parameters.

Laser machine	Laser power	Cutting speed					Assist gas and pressure (N ₂)	Vertical distance (z)
	W	mm/s					bar	mm
IPG(2kW)	200	16.6	-	-	-	-	5	30
	400	16.6	33.3	50.0	66.6	83.3	5	30
Bystronic (4kW)	200	16.6	-	-	-	-	5	30
	400	16.6*	33.3	50.0	66.6	83.3	5	30
	500**	166.7	-	-	-	-	1	3
	800**	166.7	-	-	-	-	1	3
	1200**	166.7	-	-	-	-	1	3

* Failure in black-PMMA sample.

**Used to study the threshold experiments.

3.6 Maximum cutting speed

The purpose of this experiment is to identify the maximum cutting speed by increasing the cutting speed until a specific point at which a cut that completely separates the work piece into two parts is no longer produced. Achieving the maximum performance is an optimum combination of cutting speed and the laser power. The results of this experiment will be used to study the leaf shapes later.

3.6.1 Experimental procedure

The first step was to identify the relevant maximum cutting speed with a given laser power to cut different thicknesses. In the case of the IPG YLR-2000(2kW) laser machine, two different thicknesses 3 and 6mm of stainless steel 304L were cut using a 200 μ m fibre diameter. Nitrogen pressure was used according to work piece thickness and the laser power, the stand-off distance was 1mm using a 1mm nozzle. A focal length lens of 120mm was applied and the focus point position was on the surface of work piece. The results of maximum cuttings speed tests are shown in Table 3.12.

For the Bystronic Bysprint Fibre (4kW) laser machine, three different thicknesses 3, 4, and 6mm, of stainless steel 304L were used. The Nitrogen gas was used with pressures of 9, 10, 13bar and stand-off distances of 1, 0.7, and 0.6mm respectively according to work piece thickness. The results of maximum cutting speed tests are shown in Table 3.13.

Table 3.12- The initials maximum cutting speed for IPG YLR-2000(2kW).

Seq. W	Thickness of sheet	Laser power	Gas pressure (N ₂)	Cutting speed	Result	
	mm	W	Bar	mm/s	Case	Two part
1	3	1780	10	50	No cut	No
2				48.6	Cut	No
3				45.11	Cut	yes
4				43.6	Cut	yes
5		1200	8	29.8	Cut	No
6				29.4	Cut	yes
7				26.8	Cut	yes
8		500	6	6.8	Cut	No
9				6.6	Cut	yes
10				6.1	Cut	yes
11	6	1850	13	17.5	Cut	No
12				15	Cut	No
13				12.78	Cut	yes
14				11	Cut	yes
15		1200	10	7.5	No cut	No
16				6.8	Cut	No
17				6	Cut	yes
18				5.6	Cut	yes

Table 3.13- The initials maximum cutting speed for Bystronic Bysprint Fibre 3015 (4kW).

Seq.	Thickness of sheet	Laser power	Gas pressure (N ₂)	Cutting speed	Result	
	mm	W	Bar	mm/s	Case	Two part
1	3	4000	9	176.6	No cut	No
2				173.3	Cut	No
3				166.7	Cut	yes
4				150	Cut	yes
5	4		10	116.7	No Cut	No
6				113.3	Cut	No
7				103.3	Cut	yes
8				100	Cut	yes
9				98.3	Cut	yes
10	6		13	66.7	No Cut	No
11				60	Cut	yes
12				56.6	Cut	yes
13				50	Cut	yes

In these experiments, the maximum cutting speeds were specified for different work piece thicknesses using the flowchart in Figure 3.12. First, the fibre and sheet thickness are selected and then initial cutting carried out. The gas pressure is manipulated to generate minimum dross.

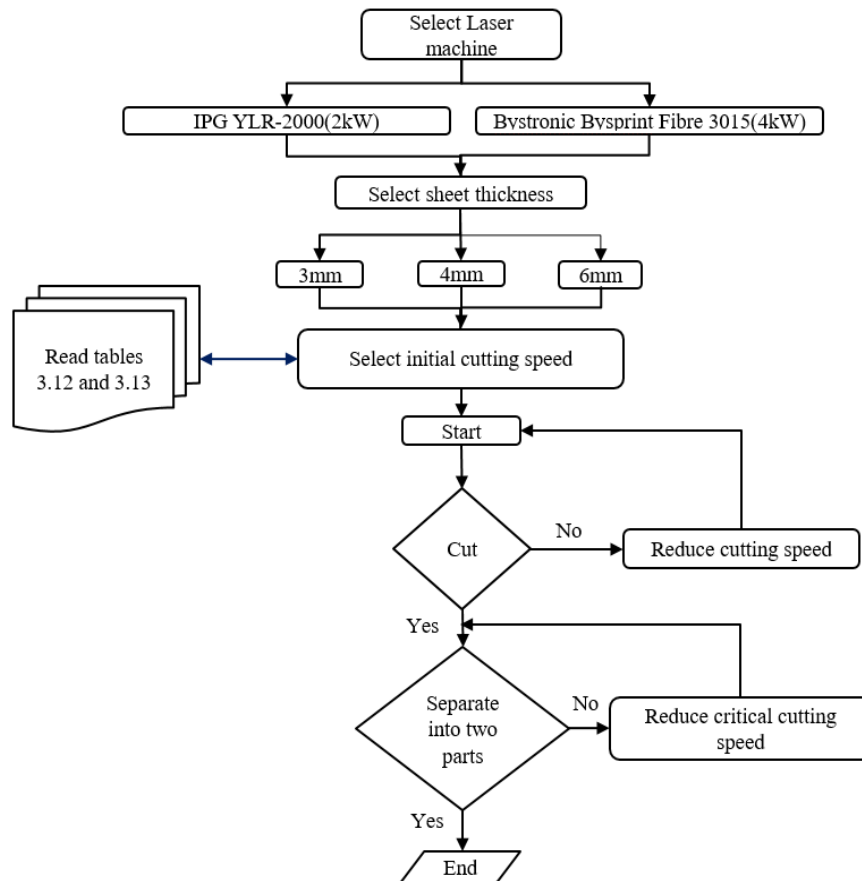


Figure 3.12- Maximum cutting speed flowchart.

3.6.2 Using black PMMA to investigate the surplus energy distribution

Laser light which is reflected off of the cut front or passes directly through the cut can be used to evaporate black PMMA and make an imprint, giving us quantitative and qualitative information about the light which is not consumed by the cutting process. The black PMMA block is kept stationary with respect to the laser cutting head during the cutting process and only the sheet metal was moved as shown in Figure 3.13.

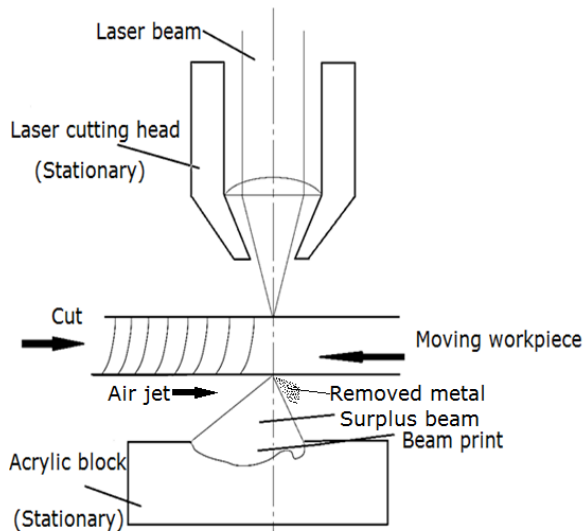


Figure 3.13- A schematic of the experimental setup.

The air jet aperture above the surface of the black PMMA sample was 5mm with 2bar gauge gas pressure to remove the plume of carbon dust generated. Metal and oxide drops were blown away sideways from the bottom of the cut zone and did not touch the acrylic block.

3.6.2.1 Effect of air jet at the lower part of cut edge

To ensure that carbon dust loaded vapour is removed from the interaction region an air jet was used. The 5mm diameter aperture was placed near to the surface of the black PMMA with a distance of 17.5mm between the bottom of the cut front edge and the surface of collector as show in Figure 3.14. Compressed air with a gauge pressure of 0.2MPa was supplied throughout the cutting process perpendicular to the cutting direction.

The air flow exiting from the aperture point removes the debris and oxide drops from the interaction zone so that they do not reach the acrylic block.

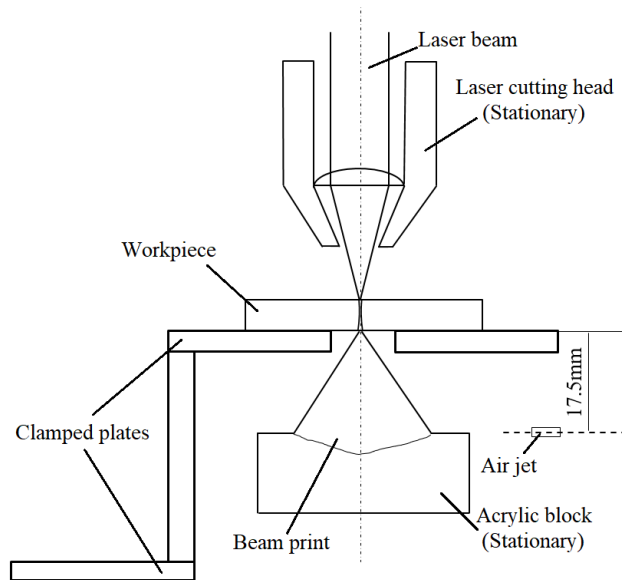


Figure 3.14-A schematic of the air jet position.

The air jet was positioned far enough from the bottom of the cutting region so that the cutting process itself is not affected by the air jet. There is however a slight effect on the leaf prints generated in the black PMMA. As seen in Figure 3.15 the presence of the air jet has introduced an axial asymmetry. The extent of this effect is equivalent to 2% of the evaporated volume.

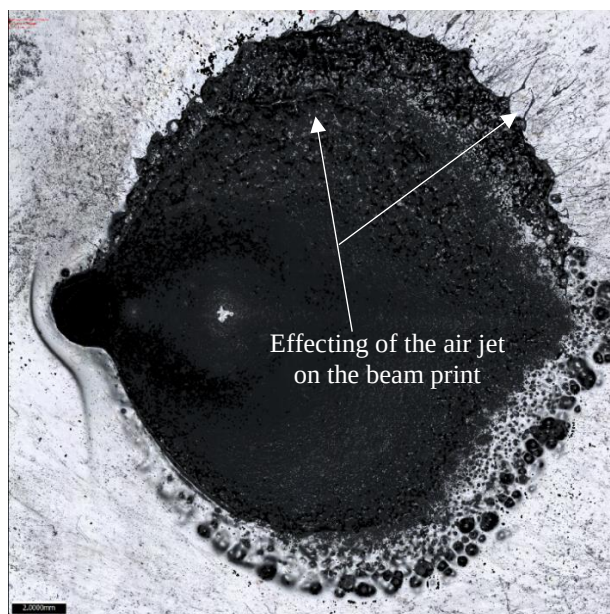


Figure 3.15- Influence of the air jet on the beam print.

3.6.2.2 Experimental procedure

The basic experiment is shown in Figure 3.17. The beam was delivered through a 200 μ m diameter fibre to a cutting head with a 125mm focal length collimating lens and a 120mm focal length focussing lens. The beam left the cutting head via a 1mm nozzle diameter through which nitrogen assist gas was delivered coaxially with the laser beam. For the majority of this work the focal plane was positioned 1mm above the metal sheet. Laser powers were used with cutting parameters shown in Tables 3.14 and 3.15. The majority of the work was carried out with a 2bar gauge pressure air jet flow for some time before and after the laser had turned off. It should be noted that the laser was only on for the times stated, however the assist gas continued to flow for some time before and after the laser had been turned off.

The main concept of this experiment involved cutting a variety of sheet metal thickness at a constant laser power with different cutting speeds. Any surplus beam released from the bottom of the cut zone was collected on the black PMMA. The black PMMA and the laser cutting head remained stationary during cutting as shown in Figure 3.16, allowing the distribution of the surplus energy to be determined. The steel to be cut is clamped in position on a slotted plate. This is positioned so that the cut line is above the 5mm wide slot. This ensures that the laser cuts through into free space, allowing free flow of assist gas and any dross as well as any direct or reflected laser beam through the cut kerf. The slotted plate is fixed on one side with screws in the CNC table. Two 10mm thick plates of 100x100mm² are fixed underneath slot plate as acceleration and deceleration plates. They play two roles; firstly, to given an accurate results of beam print without effect of acceleration and deceleration of table speed, by blocking the black PMMA until steady state cutting is established. Secondly, they

allow the exposure of the black PMMA to be determined accurately since by knowing distance between two plates, velocity and power, the total energy supplied can be calculated.

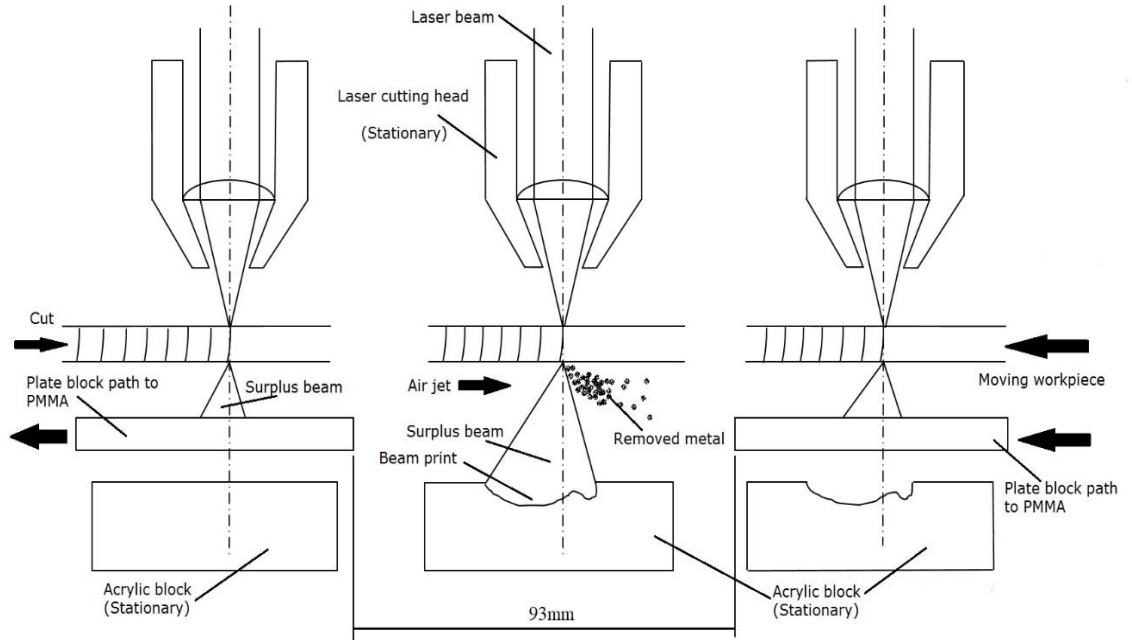


Figure 3.16- A schematic of the experimental set up.

The acrylic sample was fixed in place to avoid any bending or movement. The black PMMA block had adjustable movement in the z axis to allow an investigation of divergence and threshold effect. Acrylic material can be used to measure laser power by knowing the specific evaporation energy of it: 3.4kJ/cm^3 . Using the volume of an evaporated imprint (Equations 3.3 and 3.4) and the laser exposure time (Equation 3.6), it is possible to calculate the incident laser energy by applying Equation 3.7.

$$t = \frac{l_c}{c_s} \quad 3.6$$

Where t is the laser exposure time (s); l_c is the length of cutting line in this case 93 (mm) and c_s is the cutting speed (mm/s).

$$p_{surplus} = \frac{V_{mode\ print} * 3.4}{t} \quad 3.7$$

Where $p_{surplus}$ is the power surplus (W); $V_{mode\ print}$ is the evaporated volume (cm^3); 3.4 is the specific energy evaporation (kJ/cm^3) and t is the time (s). The Figure 3.17 shows the new design fixture used to investigate the surplus energy distribution.

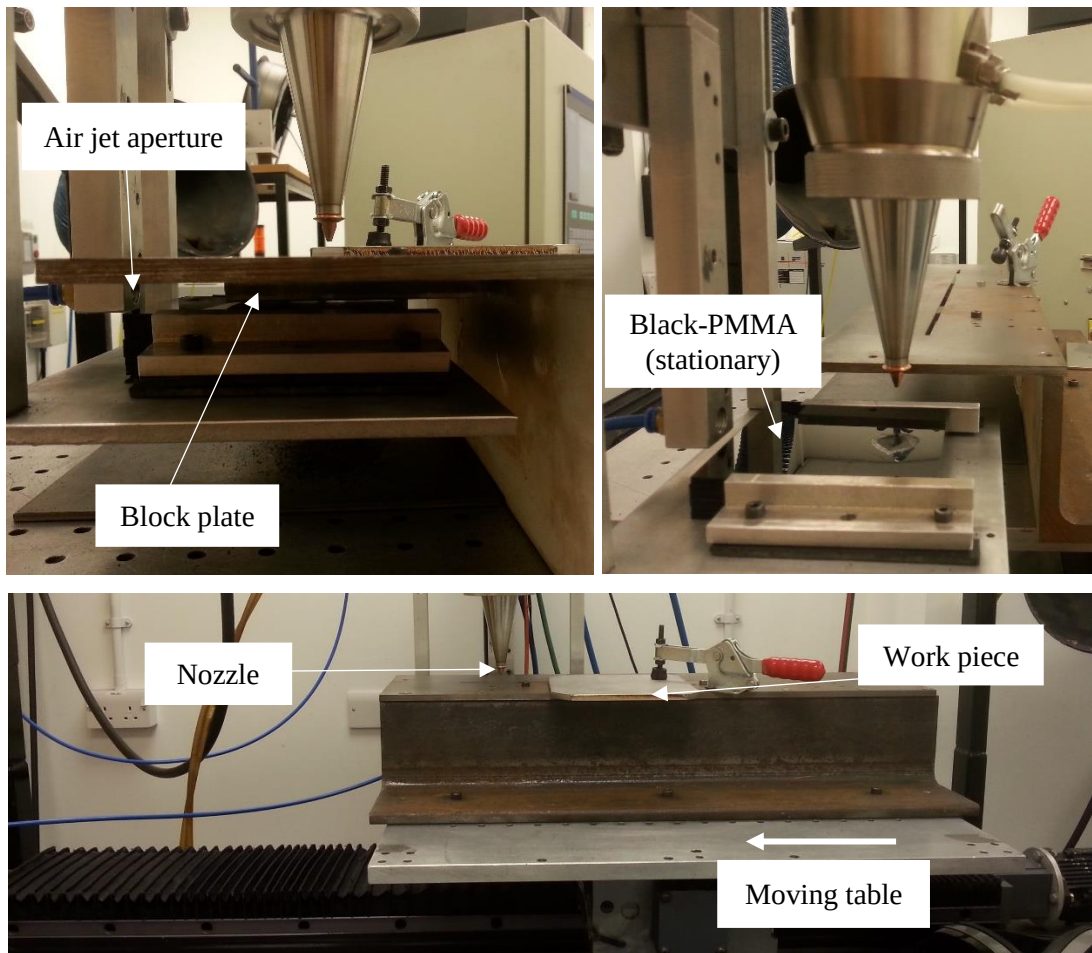


Figure 3.17- The new fixture design to investigate surplus energy on the IPG (2kW) laser system.

In Table 3.14 and 3.15 summarise the experiments carried out.

Table 3.14- Experimental parameters for cutting stainless steel 3mm.

Sample No.	Cutting speed		Laser power	Vertical distance(z')	Gas pressure (N ₂)	Cutting time
	Percentage of max. cutting speed	mm/s	W	mm	bar	s
1	90%	40.60	1780	17.5	10	2.29
2	92%	41.50				2.24
3	94%	42.40				2.19
4	96%	43.30				2.15
5	98%	44.21				2.10
6	100%	45.11				2.06
7	102%	46.01				2.02
8	104%	46.91				1.98
9	106%	47.81				1.94
10	108%	48.71				1.91
11	114%	51.41				1.81
12	118%	53.23				1.75
13	126%	56.84				1.64
14*	130%	58.65				-

*No cut

Table 3.15- Experimental parameters for cutting stainless steel 6mm.

Sample No.	Cutting speed		Laser power	Vertical distance(z')	Gas pressure (N ₂)	Cutting time
	Percentage of max. cutting speed	mm/s	W	mm	bar	s
1	90%	11.50	1850	17.5	13	8.08
2	92%	11.76				7.91
3	94%	12.01				7.74
4	96%	12.27				7.58
5	98%	12.52				7.42
6	100%	12.78				7.28
7	102%	13.03				7.13
8	104%	13.29				7.00
9	114%	14.57				6.38
10	118%	15.08				6.17
11	126%	16.10				5.77
12	132%	16.87				5.51
13*	138%	17.64				-

*No cut

Also, the surplus energy exiting the cut diverges with distance z' from the bottom of the cut as can see in Figure 3.18. This means the incident power density varies as a function of distance. Energy prints were obtained at different distances in order to investigate this effect. This allows the region in which valid quantitative surplus energy prints can be obtained to be determined.

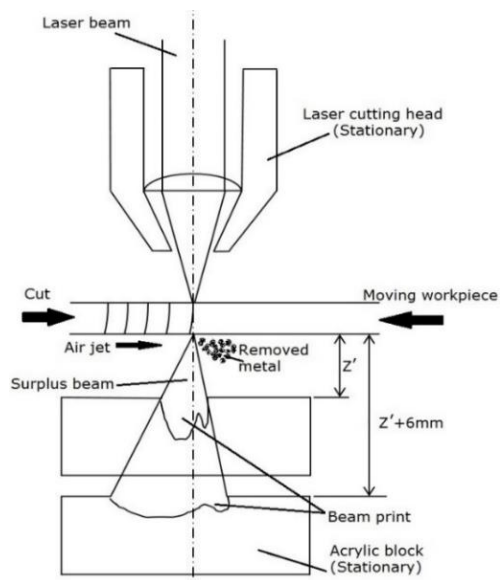


Figure 3.18- A Schematic of the experiment to investigate surplus energy as a function of distance.

Using 95% of maximum cutting speed give more accurate measurements, Table 3.16 shows the experiment parameters.

Table 3.16- Experimental parameters.

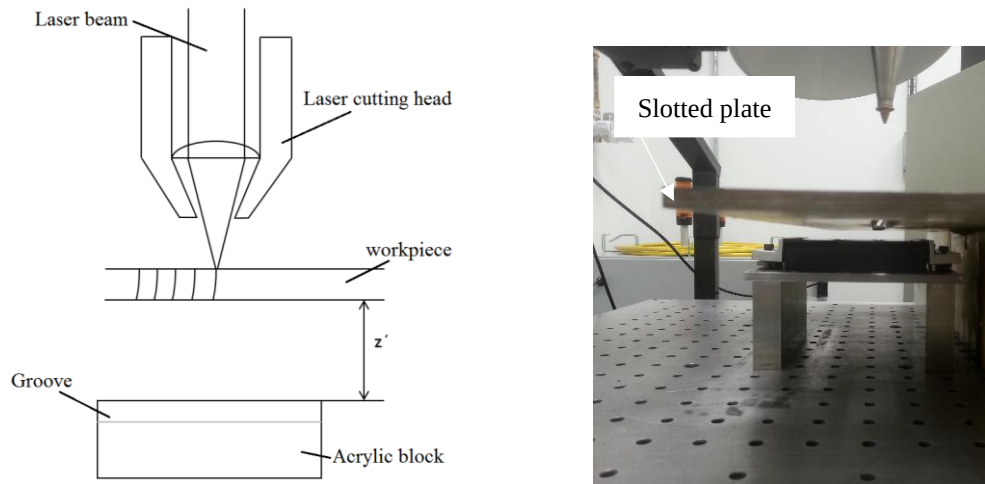
Thickness of work piece	Laser power	Cutting speed		Gas pressure (N ₂)	Vertical distance(z')	Cutting time
mm	W	Percentage of max. cutting speed	mm/s	bar	mm	s
3	1780	95%	42.8	10	17.5	2.17
					23.5	
					29.5	
					35.5	
6	1850	95%	12.1	13	17.5	7.68
					23.5	
					29.5	
					35.5	

3.6.3 Quantifying surplus energy distribution (Grooves)

The aim of this experiment is to compare the quantitative and qualitative information about the light which is not consumed in the cutting front for different laser machines. There are many variants of these machines depending on design. A PMMA target which is stationary with respect to the laser as used in earlier experiments is not possible for all machines. In the following experiments the PMMA was stationary but the laser moved (Figure 3.19). When cutting stainless steel at speeds below the maximum cutting speed, grooves were evaporated in target below the cutting zone. (Appendix 2 shows the additional laser power/cutting speed and sheet thicknesses used).

3.6.3.1 Experiment Procedure

The cutting parameters and setup used varied with the cutting machine specification. An air jet with 2bar pressure was employed above the black PMMA surface to remove the plume of carbon dust generated. Nitrogen assist gas is used in the cutting experiments at pre-set industrial pressures. Tables 3.17 and 3.18 show a summary of the experiments. In the IPG YLR-2000(2kW) case the laser beam was delivered through a 200 μ m diameter fibre to a cutting head with a 125mm focal length collimating lens and a 120mm focal length focussing lens. The beam left the cutting head via a 1mm nozzle diameter.



a-A schematic of the groove experiment setup.

b-A fixture for IPG (2kW) laser machine.

Figure 3.19- The groove experimental setup.

Table 3.17- The experimental parameters for the IPG YLR-2000 (2kW) laser system.

Thickness of sheet	Laser power		Cutting speed			Gas pressure (N ₂)	Vertical distance (z')
mm	W		Percentage of max. cutting speed	mm/s		Bar	mm
3	1800	1200	100%	43.7*	29.4**	12	8.5
			90%	-			
			80%	-			
			70%	-			
6			100%	12.5*	6**	15	
			90%				
			80%				
			70%				

*Used at laser power 1800W.

**Used at laser power 1200W.

Table 3.18- The experimental parameters for the Bystronic Bysprint Fibre 3015 (4kW) laser system.

Thickness of sheet	Laser power	Cutting speed		Gas pressure (N ₂)	Vertical distance (z')
mm	W	Percentage of max. cutting speed	mm/s	Bar	mm
3	4000	100%	166.7	9	3
4		100%	103.3	10	
6		100%	56.7	13	

3.6.3.2 Calculating the surplus energy (Groove experiments)

To calculate the surplus energy which evaporated the PMMA grooves it was necessary to calculate the groove evaporation rate. The calculation of the grooves are divided into two procedures: In the Bystronic (4kW) fibre machine case the calculation was done as in section 3.5.1.1. For the IPG (2kW) fibre machine experiments the weight loss of the target PMMA was assessed as follows.

3.6.3.2.1 Weight percentage method

The method used here was to establish the mass per unit area of the PMMA sheet before the groove was created, then cut a representative small rectangular area from the grooved target and measure its dimensions. The representative area was then weighed and this weight was compared to the calculated weight of a similar sized rectangle in ungrooved sheet. From this comparison the ‘missing mass’ could be calculated, and the energy needed to remove this mass could be assessed (Appendix 3).

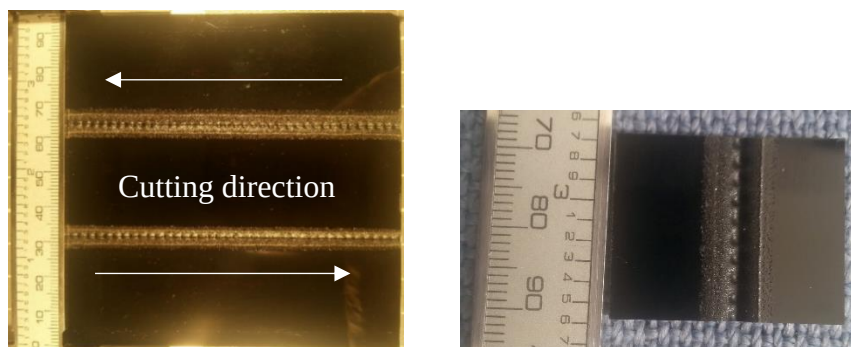


Figure 3.20- Photographs of groove created on CFBA sample in 3mm stainless steel (laser power 1800W, N₂ 12bar, and 8.5mm vertical distance from bottom of cut to the surface of sample). Left) Original sample. Right) Interest sample.

We begin with an original target of dimension $(W * L)_{target}$ then, after grooving we cut a smaller sample of dimension $w * l$ (length is in direction of groove). We can calculate the theoretical original mass of this sample before grooving (Equation 3.8).

$$\mathbf{mass}_{pre-grooved\ sample} = \frac{(w * l)_{sample}}{(W * L)_{target}} * \mathbf{mass}_{target} \quad 3.8$$

Where $(w * l)$ are width and length of the sample (mm), $(W * L)$ are width and length of the whole target (mm).

We can then subtract the experimentally measured mass ($m_{grooved\ sample}$) of the grooved sample from this pre-grooved mass to give the mass evaporated.

$$\mathbf{mass}_{evaporated} = \mathbf{mass}_{pre-grooved\ sample} - \mathbf{m}_{grooved\ sample} \quad 3.9$$

We can then calculate the mass evaporated per second can calculate the energy from the laser:

$$\mathbf{Mass}_{evaporated\ per\ second} = \frac{l}{C_s} * \mathbf{Mass}_{evaporated} \quad 3.10$$

Where l is the length of the sample (mm) and C_s is the cutting speed (mm/s), to compute the evaporated volume by apply the density of PMMA Equation 3.11:

$$\mathbf{V}_{evaporated\ per\ second} = \frac{\mathbf{m}_{evaporated\ per\ second}}{\rho} \quad 3.11$$

Where ρ is the density of black-PMMA $1.188(g/mm^3)$. The evaporated laser power can be found by applying the Equation 3.12:

$$\mathbf{P}_{evaporated\ power} = \mathbf{V}_{evapoated\ per\ second} * (3.4) \quad 3.12$$

3.7 Metallographic Sample preparation

The first step in preparing a specimen for metallographic examination is to determine the region of interest. The kerf width of the sample is measured then pictures are taken before and after sectioning by the optical microscope. Abrasive cutting was used to cut the sample using appropriate abrasive blades (ACU-thin 11-4207-010 Buehler). A lubrication and feed rate are considered important factors effects during cutting to minimize damage. (Figure 3.21).

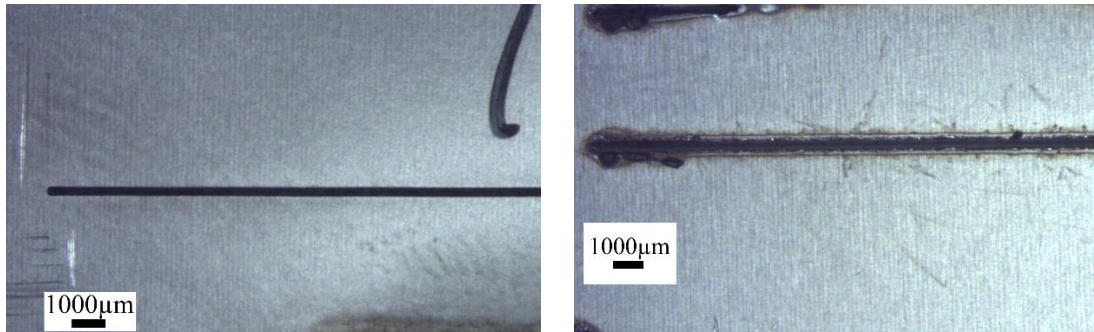


Figure 3.21- The upper and the lower surface of stainless steel 304L 3mm, laser power 4000W, N₂ 9 bar and cutting speed 166.6mm/s. Left) Upper cutting kerf. Right) Lower cutting kerf.

The cold resin method was employed to prepare of both types of a sample (both the black PMMA and Stainless Steel 304L). Mixing a liquid resin and hardener then poured over sample. In order to observe the heat affected zone (HAZ) each stainless steel sample was sectioned, ground and etched in Glyceregia (ASTEM 407). The methodology of preparing of etchant is as follows:

1. 15cc HCl (37%)
2. 10cc C₃H₈O₃(Glycerol)
3. 5cc HNO₃(69%)

The etchant solution is used fresh after preparation and swabbing on a surface of work piece.

3.8 Observation and measurement

The kerf width is measured accurately at a part of the cut path where the cutting speed is steady. To increase the precision of measurements, the kerf width was measured at five points after and before abrasive cutting. Figure 3.22a, shows a typical sample.

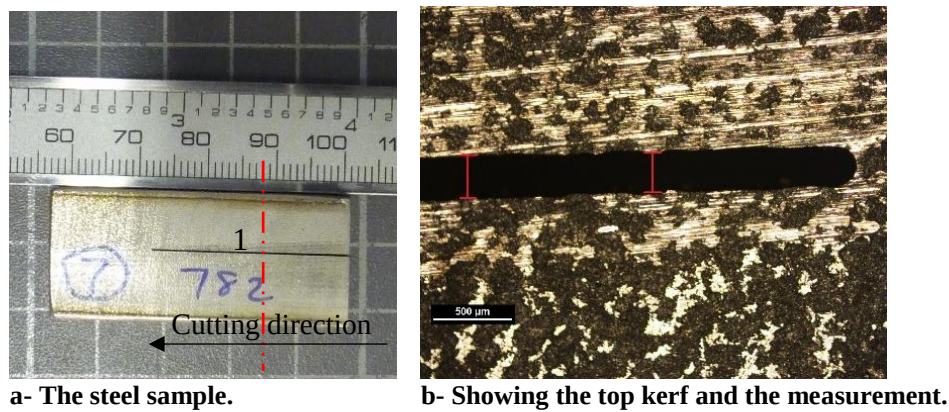


Figure 3.22- Showing the work piece of stainless steel 6mm cut at 13.09mm/s and laser power 1850W.

All samples of black PMMA and stainless steel work pieces were observed and measured under a digital microscope (Nikon model ECLIPSE LV100ND) and 10X lens was used for measurements, some images taken with 20X (Figure 3.23).

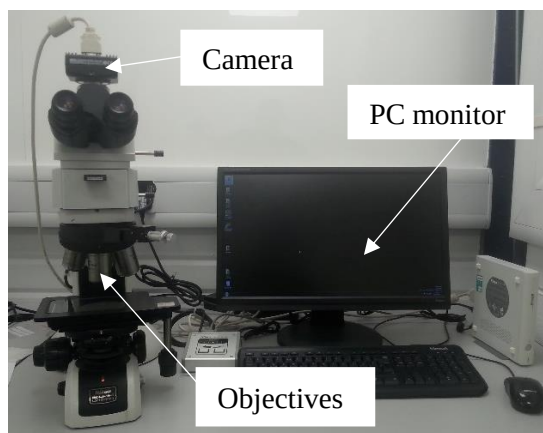


Figure 3.23- Nikon Digital microscope used to measure the kerf details.

3.9 Optical 3D surface metrology

The Focus-variation microscopy (FVM) instrument is able to measure form and surface micro-topography of a component as a 3D coordinate measurement. The principle operation of FVM instrument, is based on focussing a beam of light on a relatively small area at the sample surface. The light is reflected from the surface and the returned to the optical system of the microscope and the (amplitude) data interrogated (Figure 3.24). Image characterisation is geometric (length, width and depth) and photometric (colours, brightness and contract) [101]. Measurements and analysis of active surfaces are completed within seconds [102].

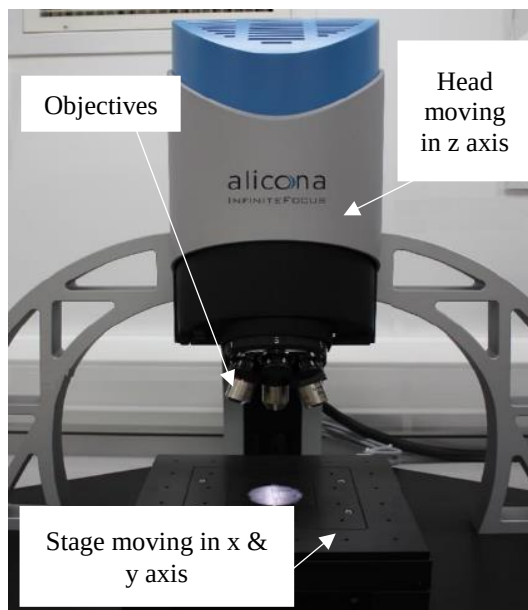


Figure 3.24- The Alicona infinite focus device used to measure beam print.

Various features and functions of the Alicona equipment were employed to scan the evaporated imprint on a black PMMA sample. The measurements obtained were fed into a Mat Lab programme to calculate the evaporated volume as described in section 3.4.5 (Figure 3.25). Also, to build up a 3D image of the leaf shape and their profiles as shown in Figure 3.26b.

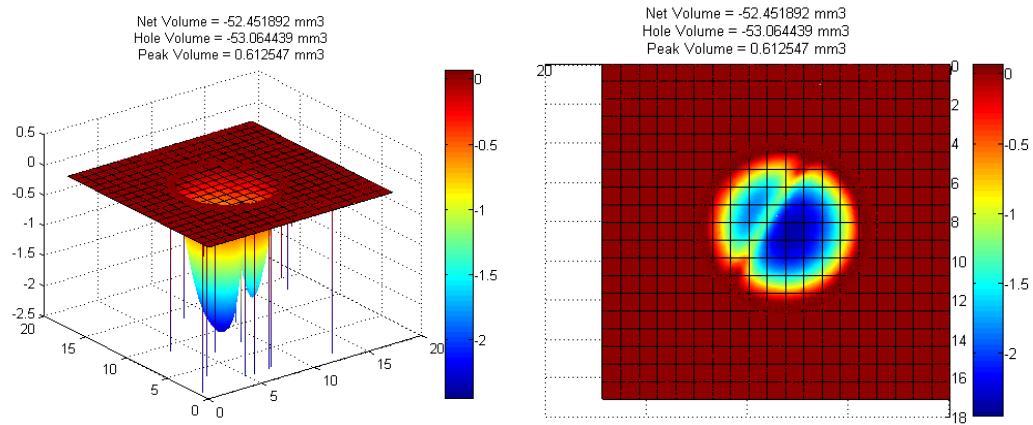
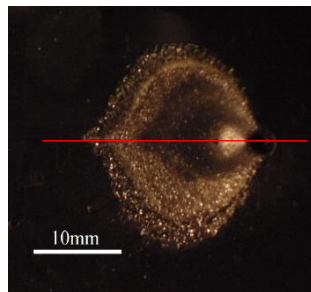
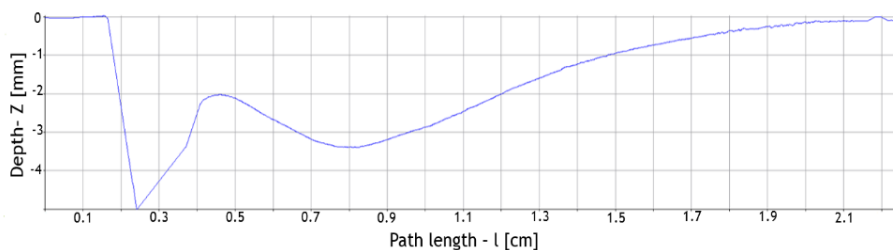


Figure 3.25- The evaporate volume of a qualitative print at 400W, 500ms and 45mm.

In Figure 3.26, obviously the light rays hitting the beam print are gathered and reflected into an optical system [103]. This technology also can be used to determine the topography of the material surface and profilometers have also been used to calculate the surface roughness and form [104]. In Figure 3.27, the surface roughness profiles of three materials are given.



a- 'leaf' print.



b- The cross-section of beam print

Figure 3.26- Characteristics of collecting the surplus power cut 3mm stainless steel at laser power 1780W, 42.86mm/s, N₂ 10bar, distance from the bottom of cut to the surface of black PMMA 17.5mm. a) The 'leaf' print. b) Cross-section of 'leaf' print taken by Alicona instrument.

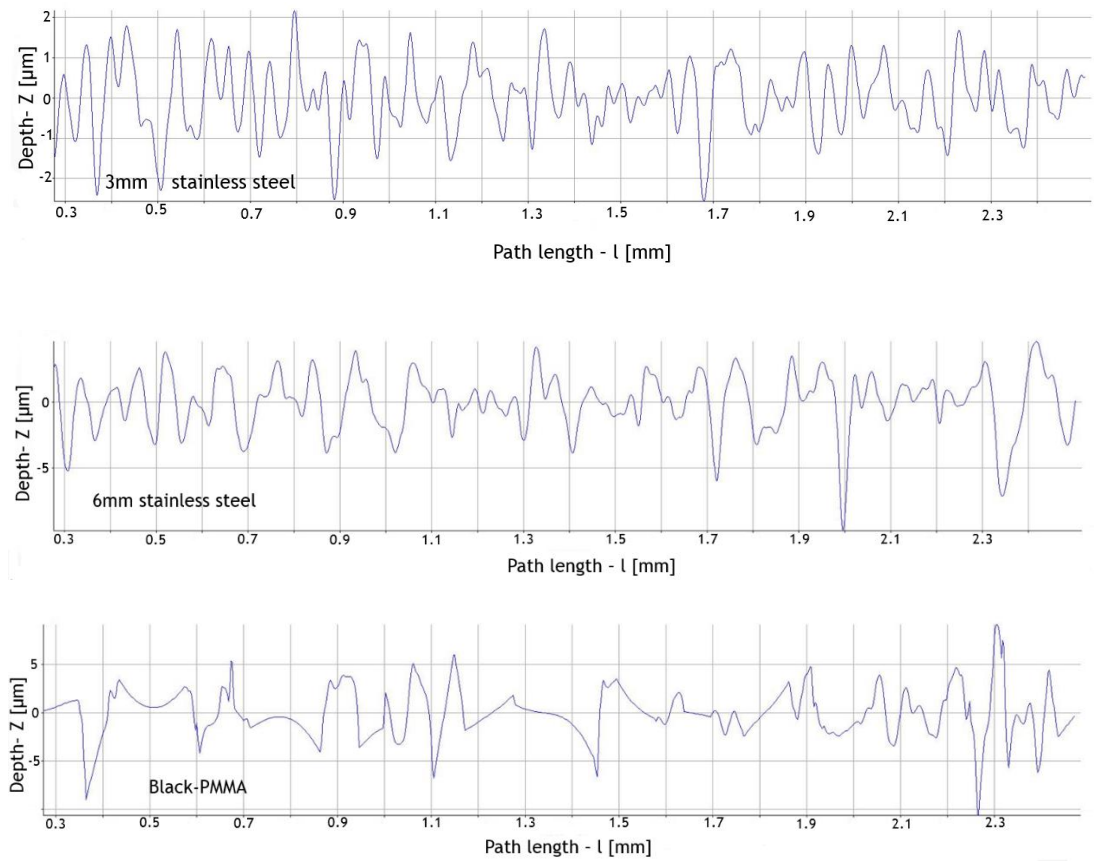


Figure 3.27- Indicating results of surface profile measured of different materials and thickness.
Top) 3mm stainless steel. Middle) 6mm stainless steel. Bottom) CFBA.

4 Fibre laser-CBFA interactions and the specific ablation energy

4.1 Outline

In this chapter experimental results on the thermal degradation of Poly-methyl methacrylate and its interaction with a fibre laser are presented. The purpose of this chapter is to find the specific ablation energy of carbon filled black acrylic as a function of laser power, irradiation time, laser beam diameter and rate of gas flow in the evaporation zone.

4.2 Thermal degradation of acrylic

In order to understand the thermal decomposition of poly methyl methacrylate and the influence of the carbon black additive on thermal degradation, thermogravimetric analysis/ Differential scanning calorimetry (TGA/DSC) and thermomechanical analysis tests were performed. The following figures present the results of transparent and black PMMA under the same conditions with an inert gas flush in the interaction zone.

4.2.1 Thermogravimetric Analysis (TGA)

The TGA test revealed the degradation behaviour of PMMA at a heating rate 5°C/min ranging from 20-500°C under inert gas (Argon) as shown in Figure 4.1. The thermal decomposition of PMMA can be expressed in terms of the glass transition temperature

(T_g), the decomposition start temperature (T_{DS}) and the decomposition finish temperature (T_{DF}) are summarised in Table 4.1.

Table 4.1- The thermal stability values of poly methyl methacrylate.

Poly methyl methacrylate	T_g	T_{DS}	T_{DF}
Transparent (Clear)	116°C	239°C	404°C
Black	113°C	165°C	395°C

As soon as the temperature of the Poly (methyl methacrylate) reached 114°C, the polymer started turning from the solid glassy state to a glassy rubbery state. If more energy is added, the polymer exceeds the glass transition temperature (T_g), and may not return to its original condition [105]. PMMA undergoes very little melting near to the melting temperature. However, the differential scanning calorimetry test revealed that melting does not involve a significant amount of latent heat (see section 4.2.2). At around 160°C the PMMA suffers little melting but swelling (bulging) on the surface of the sample can be identified in the region adjacent to the light interaction [106]. A difference in decomposition start and finish temperatures was seen between the clear and black PMMA. For black PMMA, the decomposition started slowly at 170°C and then accelerated from about 320°C until full decomposition at 395°C with a drop of weight of about 0.008%/°C. But in clear PMMA, the decomposition temperature started at 239°C with minimal mass loss to 320°C then rapid mass loss and was fully decomposed at 404°C with loss of weight of about 0.003%/°C.

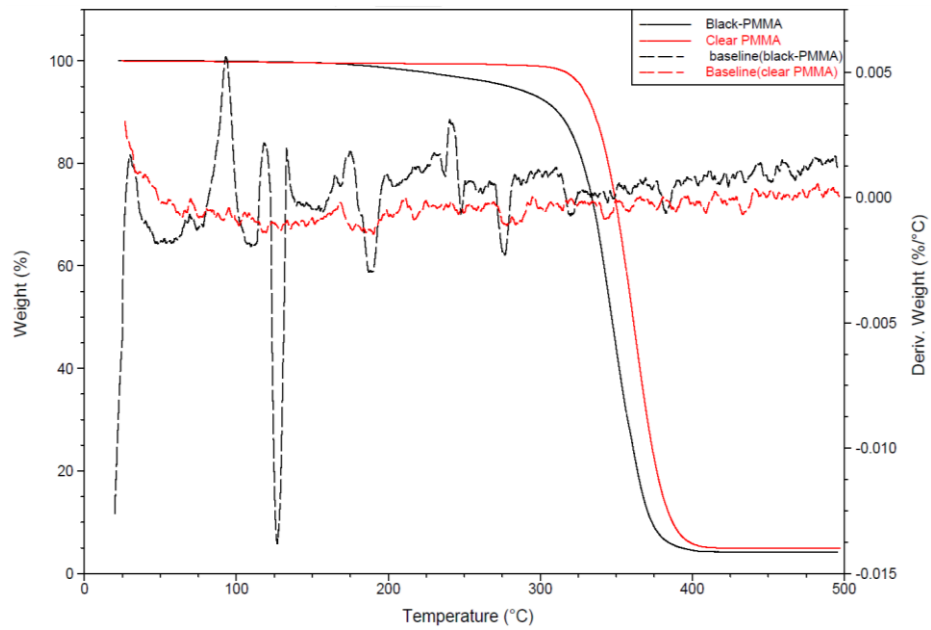


Figure 4.1-TGA results for black and transparent Poly methyl methacrylate.

It is obvious from Figure 4-1 that the addition of carbon has only a small effect on the degradation of PMMA. the PMMA $(C_5O_2H_8)_n$ decomposed into monomer MMA (methyl methacrylate) units and carbon dioxide (CO_2), with an approximate 90%/10% split [92].

4.2.2 Differential scanning calorimetry (DSC)

The DSC test detected the heat capacity of the PMMA at a heating rate $2^\circ C/min$ over a range from $20-490^\circ C$ under inert gas condition (Nitrogen) as shown in Figure 4.2. Table 4.2 shows the differential scanning calorimetric (DSC) results from both types of poly methyl methacrylate.

Table 4.2- The DSC measurements.

Poly methyl methacrylate	Peak temperature		Latent heat capacity	
	1 st	2 nd	Melting	Evaporation
Clear PMMA	285°C	358°C	7.2J/g	712J/g
Black PMMA	243°C	350°C	60J/g	576J/g

It is observed that the DSC curve for PMMA shows two endothermic peaks. The first endothermic peak detected at 243°C is attributed to the melting temperature of black PMMA with a melting latent heat capacity of nearly 60J/g. The first peak for clear PMMA was observed at 285°C with a melting latent heat capacity of about 7.2J/g. The strong endothermic peak at 350°C is attributed to complete decomposition of black PMMA constituents with vaporisation latent heat capacity about 576J/g. Finally for clear PMMA a strong peak at 358°C with a vaporisation latent heat capacity near to 712J/g was detected. At the end of thermal degradation above 425°C the volatile fragments essentially consist of the monomer [107].

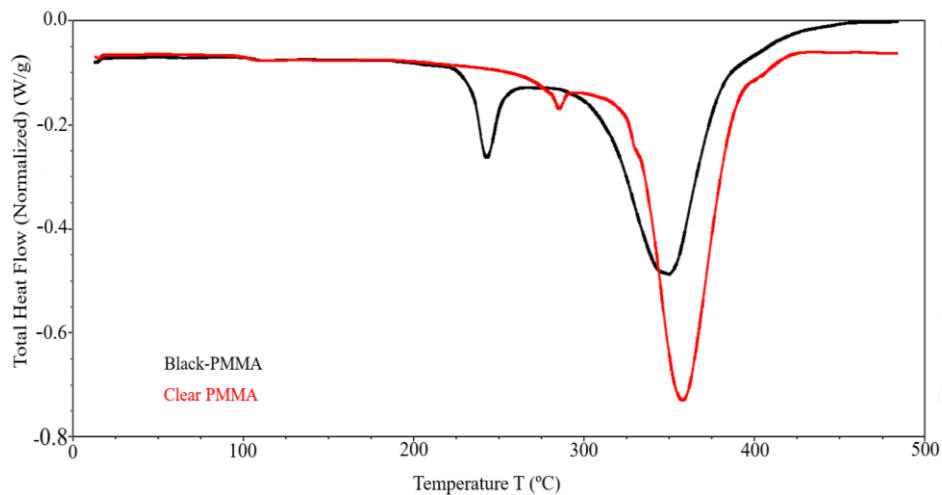


Figure 4.2- DSC results for black and transparent poly methyl methacrylate.

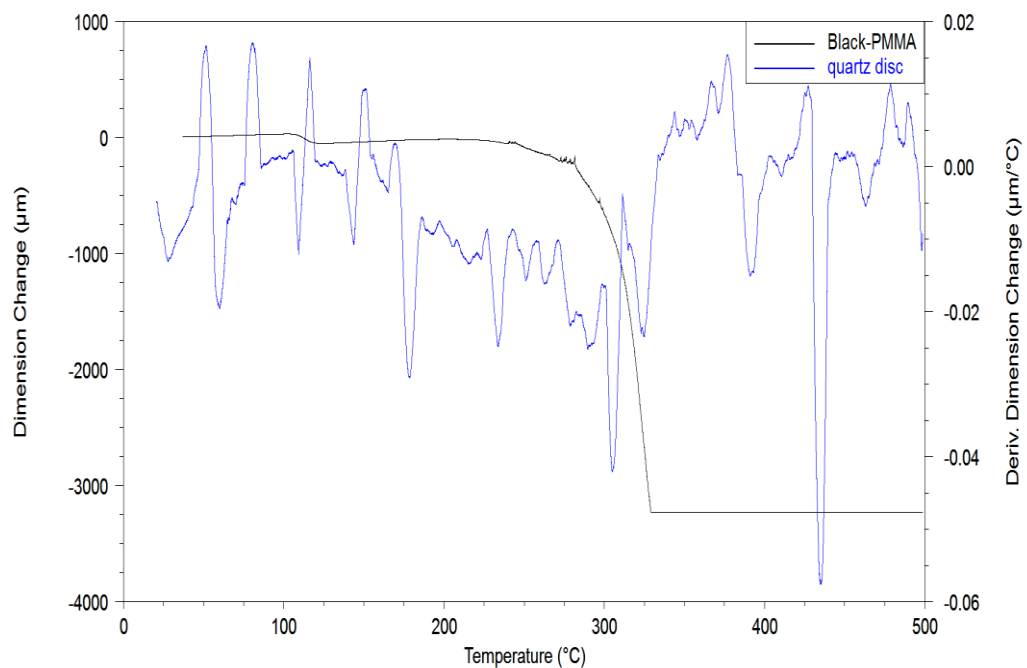
4.2.3 Thermomechanical Analysis (TMA)

The TMA test revealed the thermal expansion of the PMMA with a heating rate of 5°C/min from 20-500°C under inert gas condition (Argon) as shown in Figure 4.3 and Table 4.3.

Table 4.3- The TMA results

Poly methyl methacrylate	Tg	Probe Penetrated	
		Start	End
Black PMMA	113°C	239°C	329°C

It is clear that in the TMA curve of black PMMA, there is minimal dimensional change in the vertical direction until the glass transition temperature is reached. At 113°C the material is slightly penetrated by the lightly loaded probe, more heat added to the sample produced a slight change in dimensions. As the melting point is reached at 239°C the probe penetrates of the black PMMA at a rate related to the viscosity. Finally at 329°C full probe penetration occurs with stability in load with accurate deriv. dimension change of about 0.045µm/°C

**Figure 4.3- TMA result of black PMMA.**

4.3 The evaporation of black acrylic by fibre laser

The purpose of this section to determine the specific ablation energy of the carbon filled black acrylic (CFBA) as a function of the laser power, time irradiation, gas pressure, beam diameter and air jet. Full details of these experiments are explained in section 3.4; however, a summery is presented in Table 4.4.

Table 4.4- Summary of the laser drilling parameters.

Characteristics	Values
Laser power range	400 to 1000W
Gas pressure range	0 to 14bar
Fibre diameter	600 μ m
Time irradiation range	100 to 1000ms

4.3.1 Establishing the specific ablation energy

As mentioned before in chapter 3, the laser beam was delivered by a 600 μ m fibre diameter to a cutting head having a 125mm focal length collimating lens and a 120mm focal length focussing lens. The 2bar gauge pressure of nitrogen assist gas was delivered coaxially with the laser beam via a 1mm diameter nozzle. The focal plane was positioned 6mm above the acrylic sample.

In order to establish the specific ablation energy of carbon filled black acrylic the laser beam was vertically incident on a stationary black PMMA target. To allow accurate measurement of the evaporated holes, five holes were created for each power/exposure time combination, and the mean and standard deviations of the results were obtained.

Figure 4.4 shows the relationship between the power/exposure time and volume evaporated.

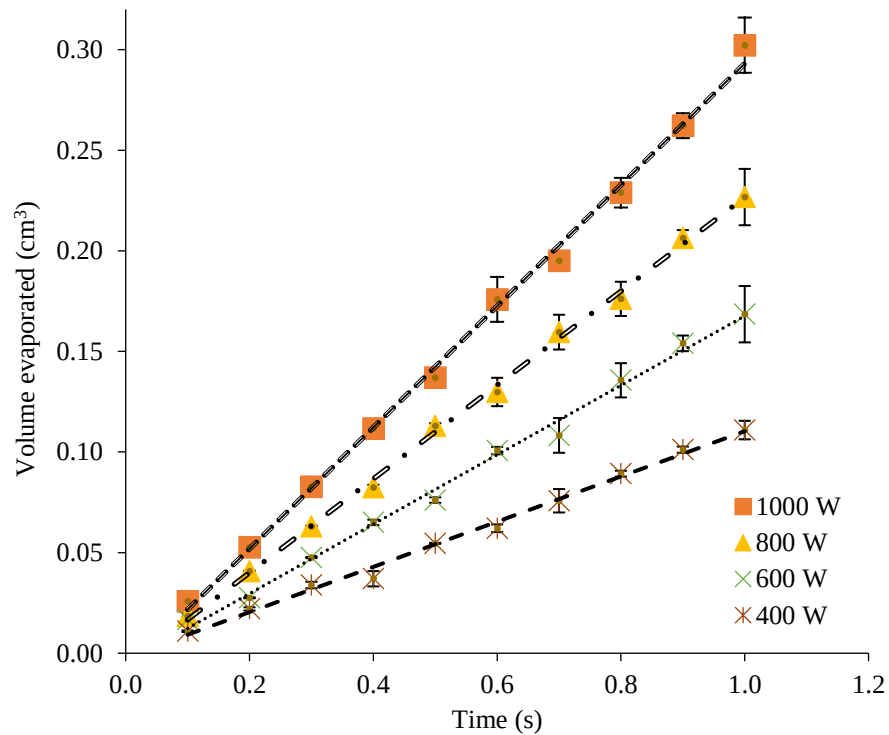


Figure 4.4- Evaporated hole volumes for different laser powers and exposure times, error bars indicate standard deviation.

As shown in Figure 4.4, clearly there is a linear relationship between hole volume and irradiation time for all power levels used. As the hole develops the ablation front moves into the acrylic producing a slightly diverging blind hole (Figure 4.5).

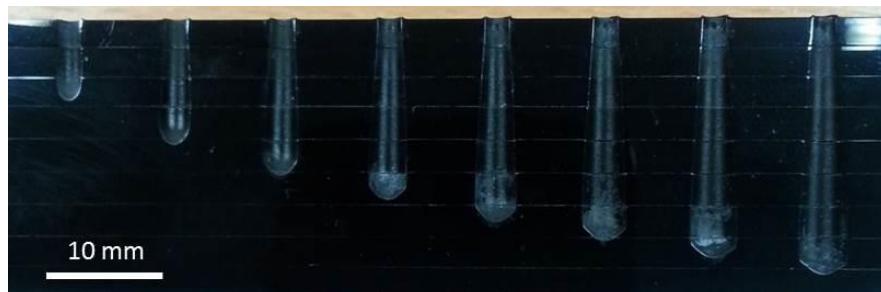


Figure 4.5- Holes evaporated at 800W laser power at time exposure 0.1 to 0.8s.

This suggests that the volume of material removed is proportional to the energy input. The specific ablation energy can be identified by combining the results in Figure 4.4, by multiplying the laser power by the time for each result - as shown in Figure 4.6.

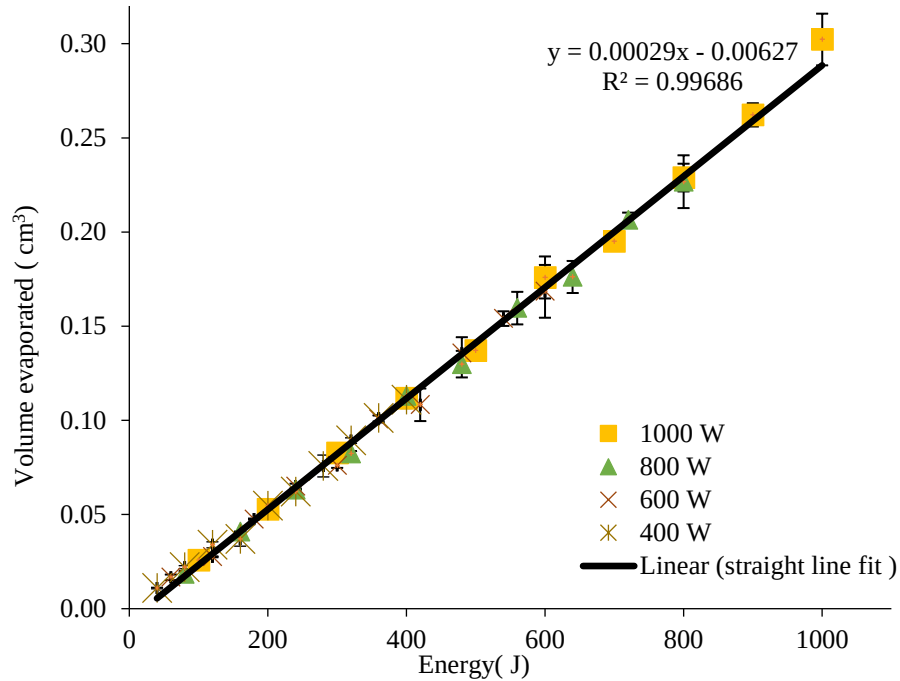


Figure 4.6- Volume of material evaporated as a function of energy.

Figure 4.6 reveals that the results clearly converge to give a very good straight line fit with a R^2 value of 0.9969. The specific evaporation energy of carbon filled acrylic in this case is found to be 3.44 kJ/cm^3 which is slightly higher than the 3.0 kJ/cm^3 value found by Miyamoto et al. for transparent acrylic and CO_2 laser light [108]. The 15% increase in specific evaporation energy can be attributed to the fact that evaporation of carbon filled acrylic by a fibre laser is a two stage process rather than the more efficient single stage process of transparent acrylic evaporation by CO_2 laser.

It can also be observed in Figure 4.6 that the straight line fit passes close to the origin, intersecting with the x axis at a small positive value. This is consistent with a

threshold which needs to be exceeded before degradation of CFBA, and subsequent material loss occurs. This threshold effect can have a considerable effect on the amount of acrylic evaporated if the laser beam and the acrylic target are moving with respect to one other. This is investigated in the next chapter.

4.3.2 SEM image of a cross section

The scanning electron micrograph in Figure 4.7 shows a typical cross section of the black PMMA material close to the surface after evaporation has taken place. It is apparent that the penetration depth of the 1 μ m light in this material has been limited to approximately 100 μ m. In this 100 μ m thick sub-surface layer there are pores which range in diameter from a few microns up to approximately 50 μ m. The appearance of this layer is consistent with an evaporation process involving absorption of the laser light by the carbon particles trapped in solid suspension within the otherwise transparent acrylic. The sub-surface layer represents a possible source of error in quantitative analysis, since material has absorbed energy from the laser beam but has not been removed [93]. This means that the relationship between energy input and volume of material removed is not entirely linear. However, the results show that this is a minor effect when the volume evaporated is considerably more than the residual melted layer.

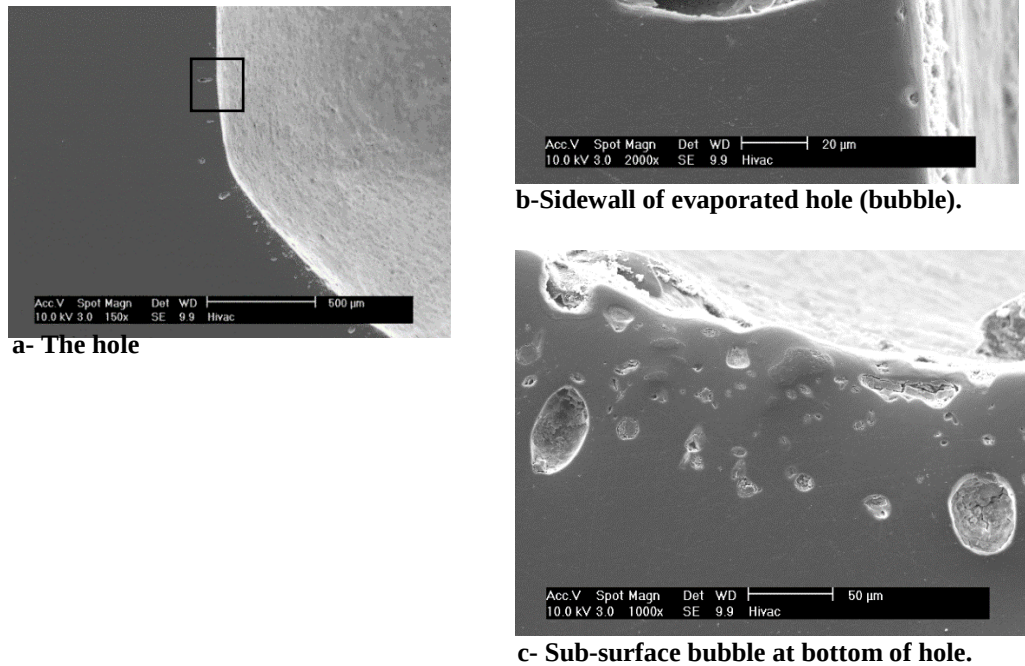


Figure 4.7- SEM image of a cross section of the evaporated surface showing evidence of sub-surface boiling at 800W and 0.5s exposed time.

Figure 4.8 shows the presence of carbon dust inside a pore, left behind after the acrylic has evaporated. During beam printing this dust is given off as a black plume of smoke which can absorb and diffract the laser beam. This can reduce the amount of energy which reaches the acrylic target. This is discussed in the next section.

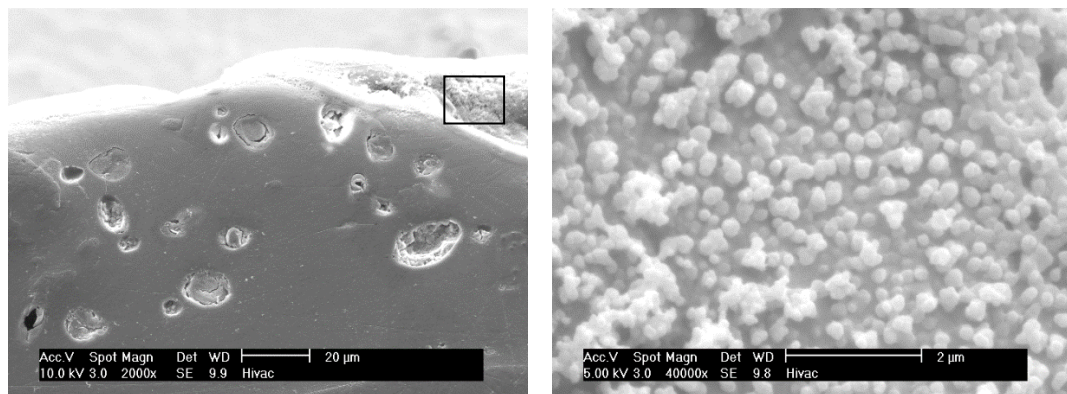


Figure 4.8- Carbon particles at bottom of evaporated hole (800W and 0.5s). Left) The bottom of the evaporated hole. Right) Carbon particles in pore.

4.3.3 The effect of flow gas on the evaporation volume

The results presented so far in this chapter were obtained using a 2bar nitrogen assist gas. This section investigates the effect of assist gas pressure on specific ablation energy results. For an intense laser beam (near the focus) the evaporation volume is directly proportional to the incident energy as shown in Figure 4.6. However, the evaporation produces a plume of vapour which contains the monomer methyl methacrylate and carbon dust. This plume is extremely absorptive of the laser beam and, if it is not dispersed by a nitrogen or air jet, it will shield the underlying acrylic sample and dissipate the beam, resulting in fluctuating and artificially high figures for the specific energy of evaporation.

Figure 4.9 shows that the average vaporisation energy rose to approximately 5.7kJ/cm^3 and was non-linear in the absence of a flushing gas. In the experimental set up used here, a 1 bar assist gas supply is sufficient to flush the vapour plume from the interaction area. The reason why the specific evaporation energy discovered here is considerably lower than that suggested by other workers is due to the fact that those earlier workers did not employ an effective flushing gas.

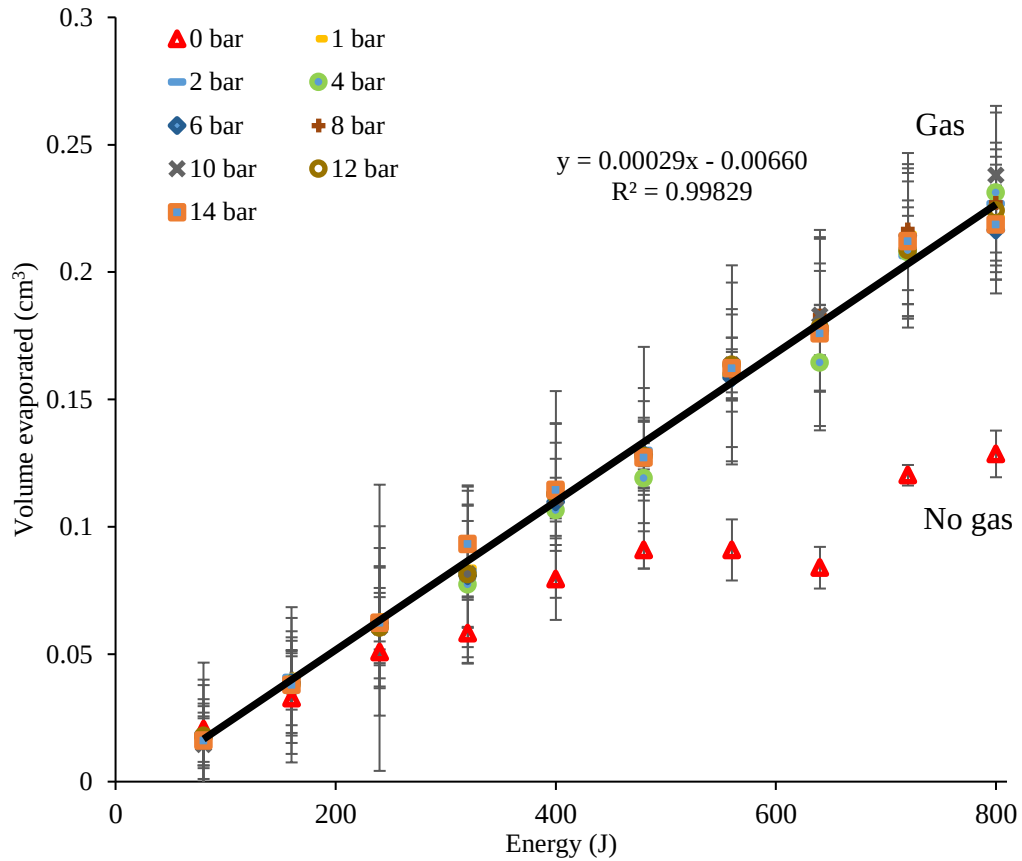


Figure 4.9- Evaporated volume of the black PMMA as a function of 1 μ m wavelength laser energy for different gas pressure conditions.

4.3.4 The effect of stand-off on the evaporation volume

The effects of the stand-off distances on volume evaporated was investigated. The work done with 800W and nitrogen gauge pressure was 2bar for all vertical distances. Figure 4.10 shows that, in the range shown here, the stand-off distance has only a small influence on the volume evaporated. This distance determines the spot size and therefore the power density of the incident beam. Also, the stand-off has effects on the flow pattern of the assist gas [17].

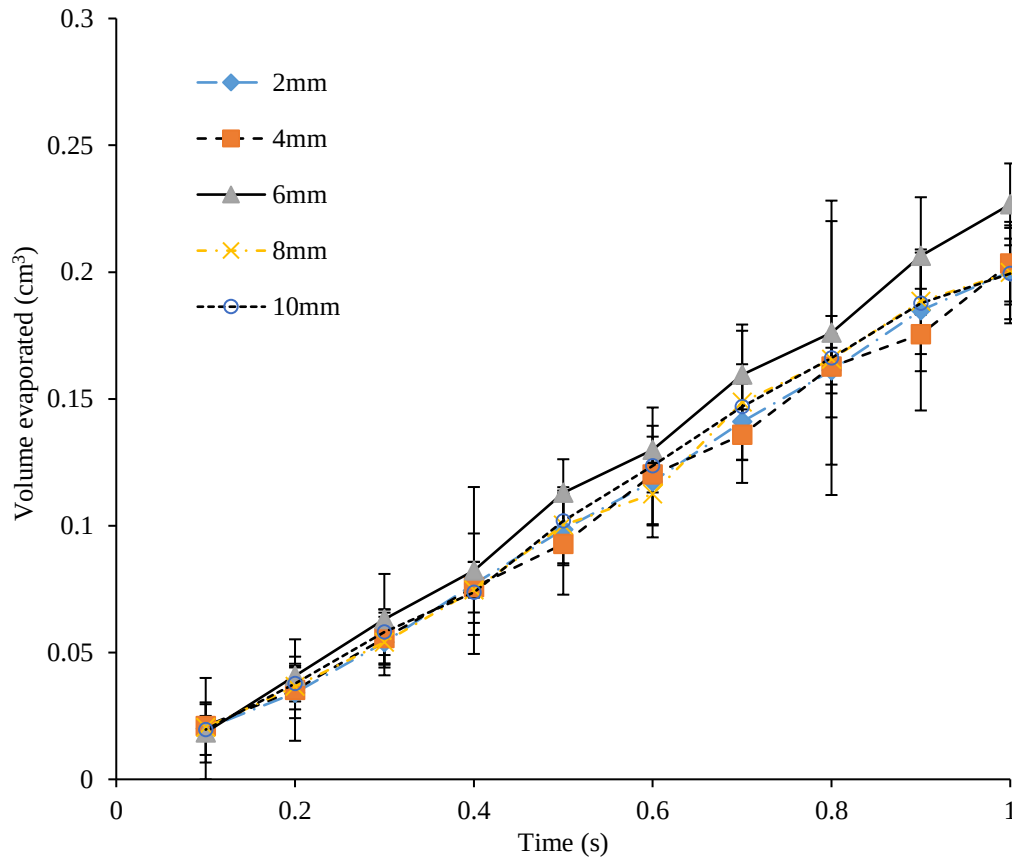


Figure 4.10- The effect of vertical stand-off distance on evaporated volume of CFBA (800W laser power and N₂ 2bar).

4.3.5 Qualitative print

As a trial experiment a piece of wire was put in path of the beam in order to produce a qualitative beam print with a known ‘fault’. The results revealed that qualitative information can be contained in the beam print left in the CFBA [109]. The work done used 400W laser power, 0.5s exposure time and 2bar gauge pressure of nitrogen.

The 3D measurement data of the beam print was analysed with Mat lab. Figure 4.11 shows clearly the model of the substrate with its evaporated indentation and the blocking of the beam by the wire. The amount of swelling of the periphery of the evaporated area was related to the vertical distance from the focal plane. The swelling at short distances is lower than at long distances.

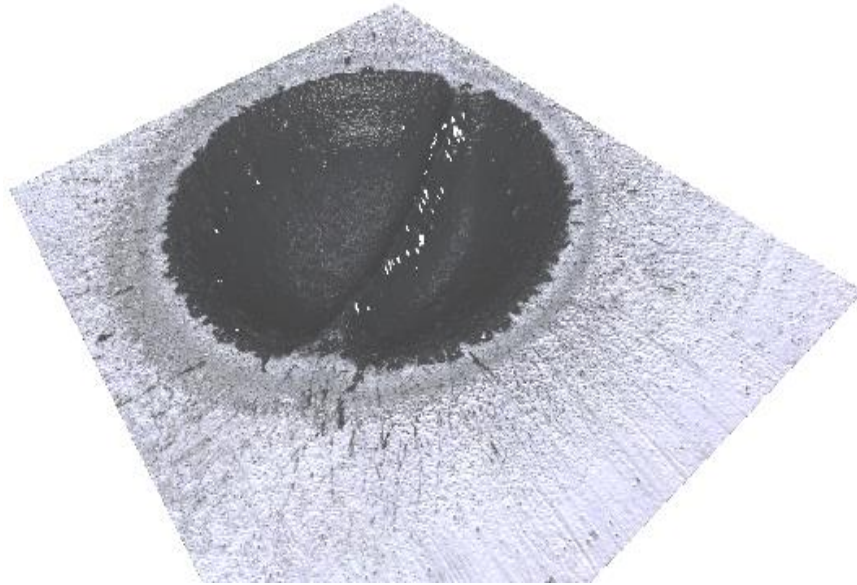


Figure 4.11- The 3D image of the beam print at 400W, 0.5s, N₂ 2bar at 50mm vertical distance.

The depth of the centre of the dome is deeper at short compared to long distances and the diameter was smaller at short distances as shown in Figures 4.12, 4.13 and 4.14.

Table 4.5-Experimental parameters

Characteristics	Value
Laser power	400W
Time irradiation	0.5s
Gas pressure(N ₂)	2bar
Vertical distance	45mm
Fibre diameter	600 μ m

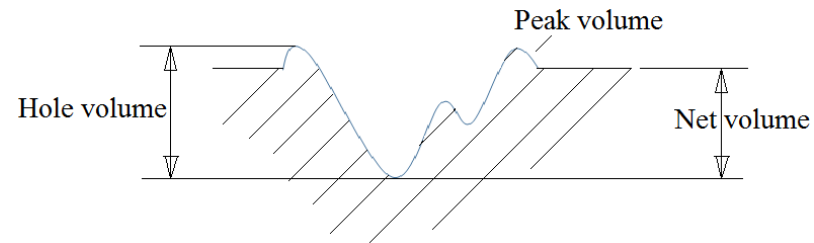
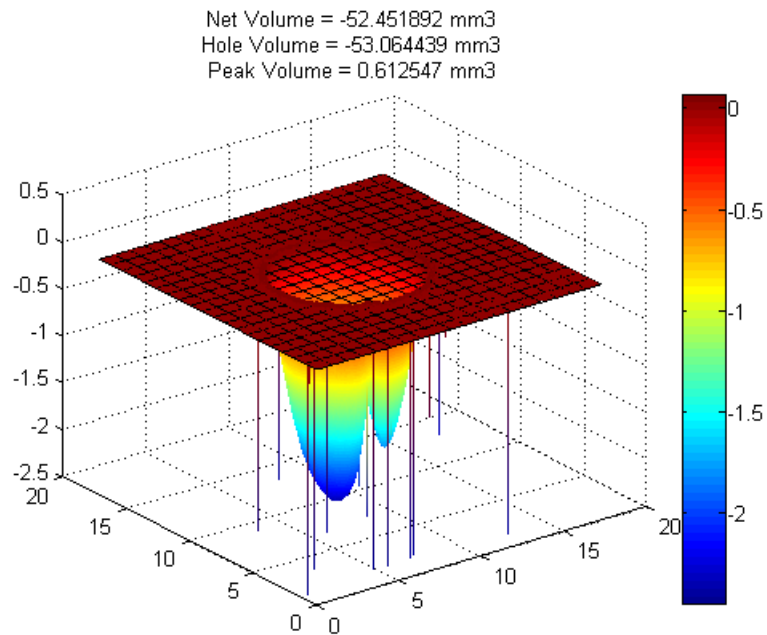
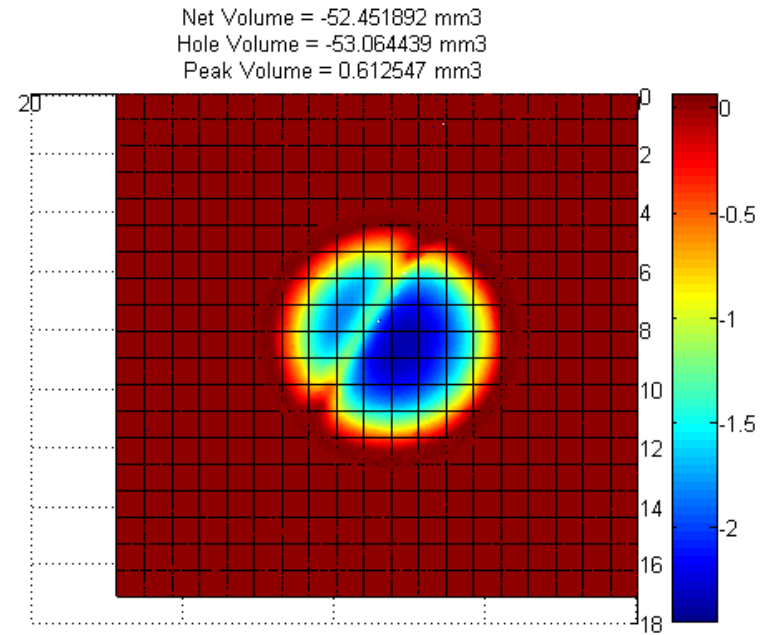
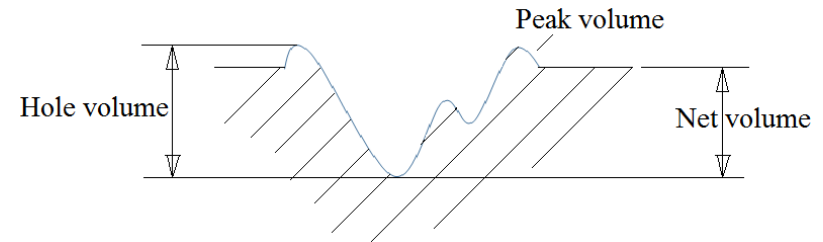


Figure 4.12- Mat lab analysis of the Qualitative value of the beam print taken at 45mm.

Table 4.6-Experimental parameters.

Characteristics	Value
Laser power	400W
Time irradiation	0.5s
Gas pressure(N ₂)	2bar
Vertical distance	50mm
Fibre diameter	600 μ m

Net Volume = -51.547222 mm³
Hole Volume = -52.253130 mm³
Peak Volume = 0.705908 mm³



Net Volume = -51.547222 mm³
Hole Volume = -52.253130 mm³
Peak Volume = 0.705908 mm³

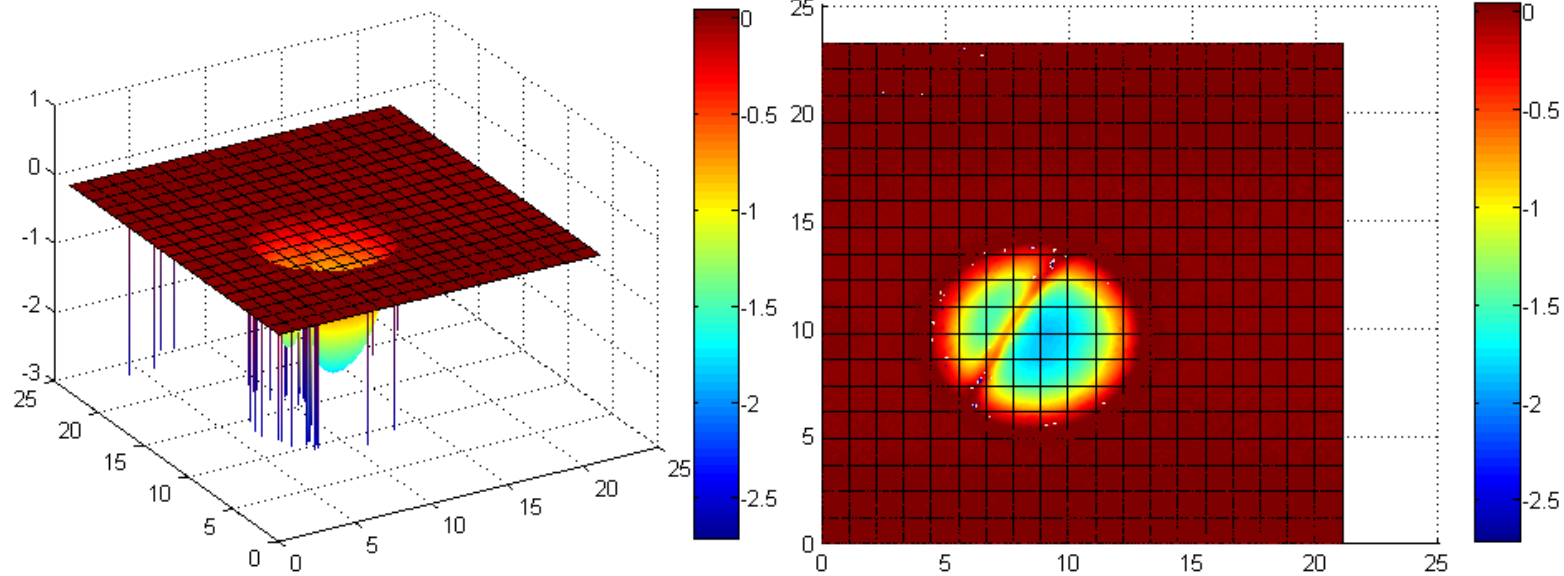


Figure 4.13- Mat lad analysis of the qualitative value of the beam print taken at 50mm.

Table 4.7-Experimental parameters.

Characteristics	Value
Laser power	400W
Time irradiation	0.5s
Gas pressure(N ₂)	2bar
Vertical distance	55mm
Fibre diameter	600μm

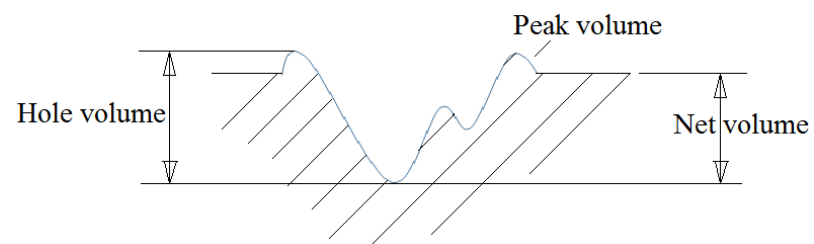
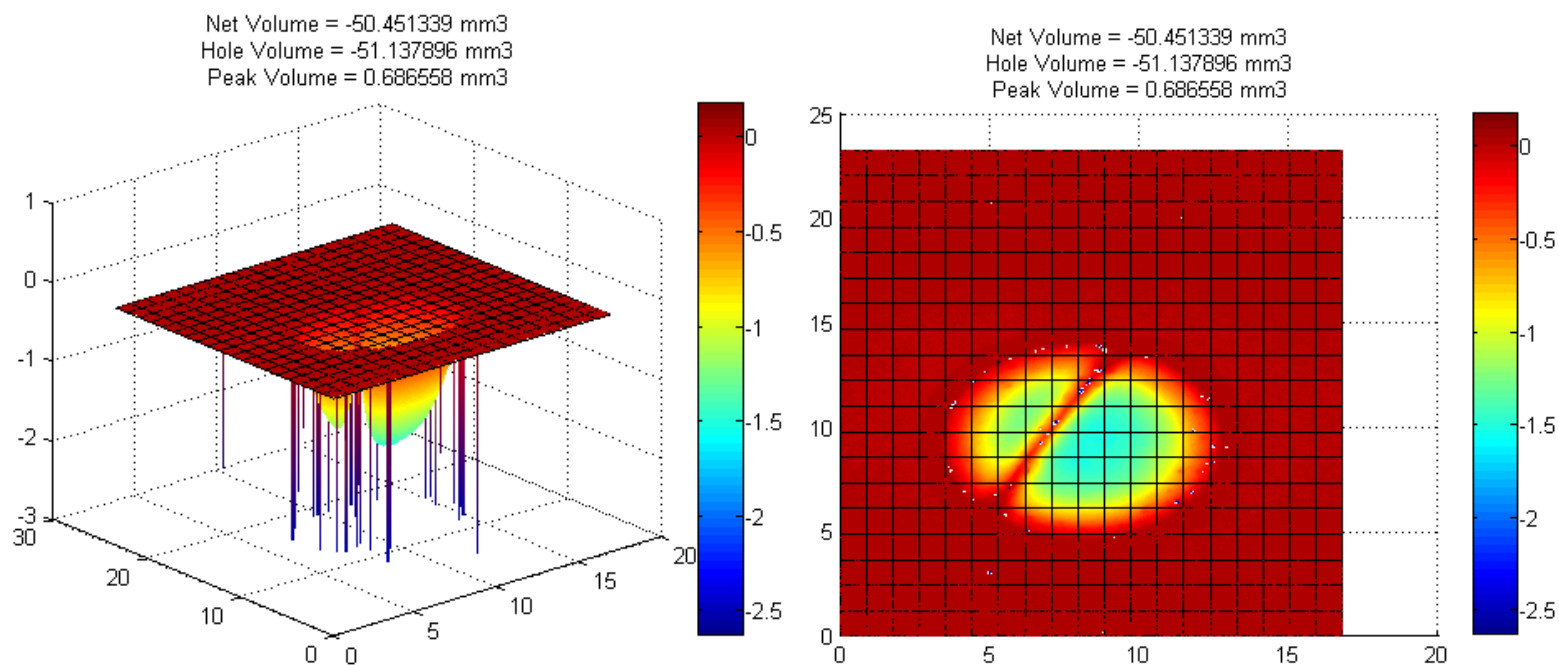


Figure 4.14-Mat lab analysis for the qualitative value of the beam print taken at 55mm.

Comparison of the evaporated volumes was carried out as described earlier. The evaporated volumes of black PMMA were related to the interaction time and laser power at different vertical distances from the nozzle. Table 4.8, shows that there was very little difference in the volume of material evaporated as a function of fibre diameter or distance from the focal plane in this case.

Table 4.8-Summary of all experiments that have same laser power and irradiated time (400W and 0.5s).

Name of experimental	Laser power	Time	Fibre delivery diameter	Vertical distance	Volume evaporated
	W	s	μm	mm	cm³
Specific ablation energy*	400	500	600	6	0.054
Qualitative print**				45	0.053
				50	0.052
				55	0.051
Beam propagation***			200	21	0.054
				30****	0.053
				40	0.055
				59	0.051

* Calculate the evaporation volume to determine the specific ablation energy of CFBA.

**Used MATLAB to calculate the evaporated volume.

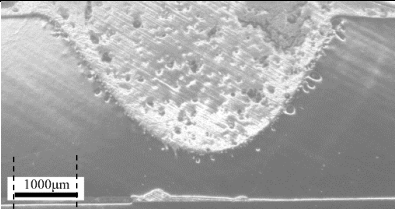
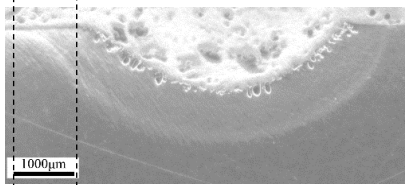
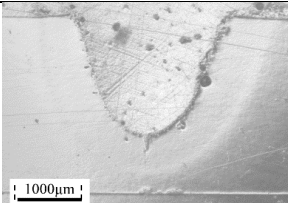
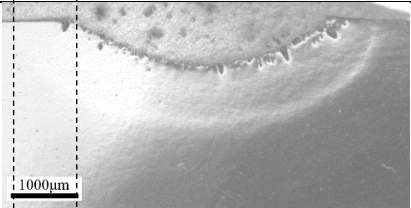
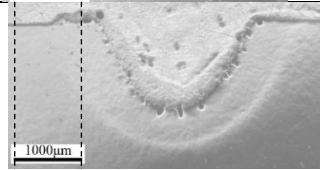
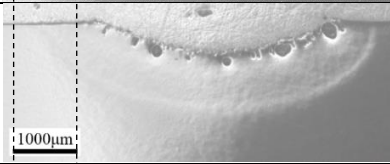
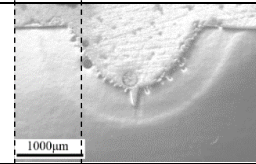
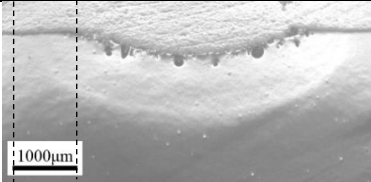
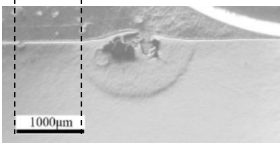
***Used weighting method to find the evaporated volume.

****Calculated by PTC Creo3.

4.4 Comparison of the surplus energy of IPG YLR-2000 (2kW) and Bystronic Bysprint Fibre 3015 (4kW) laser machines

The type of investigation above can be applied in order to investigate the surplus beam coming out from the bottom of the cut zone. The CFBA sheet is employed to collect the primary losses which exceed the evaporation threshold (transmitted and reflected energy). Because the laser is moving with respect to the CFBA target a groove is evaporated in the target. The experiments were carried out under identical conditions of cutting (laser power, cutting speed, assist gas and pressure, and stand-off distance) for both laser machines (IPG (2kW) and Bystronic (4kW)).

Table 4.9-Summary of groove experiments.

Cutting speed mm/s	IPG (2kW)	Bystronic (4kW)
16.66		
33.33		
50		
66.7		
83.33		

In Table 4.9, by comparing the shape of cross section for the resultant grooves tracks it was possible to determine variations and similarities in samples for the IPG (2kW) and Bystronic (4kW) machines. It was demonstrated that the amount of CFBA removal rate decreases as the scan speed (cutting speed) is increased (causing lower interaction time between the laser beam and CFBA).

From the results shown in Figure 4.15 it is evident that at lower scanning speeds the cross section areas of Heat affected zone (R) and the removed (A) are high and with increasing speed both areas decrease sharply initially (16 and 33.3mm/s) and then reduce gradually with increasing speed. This is due to the fact that at lower scanning speed the threshold effect is minimised because most of the beam – material interaction is above the threshold for evaporation. At higher scanning speeds, the threshold effect becomes more important.

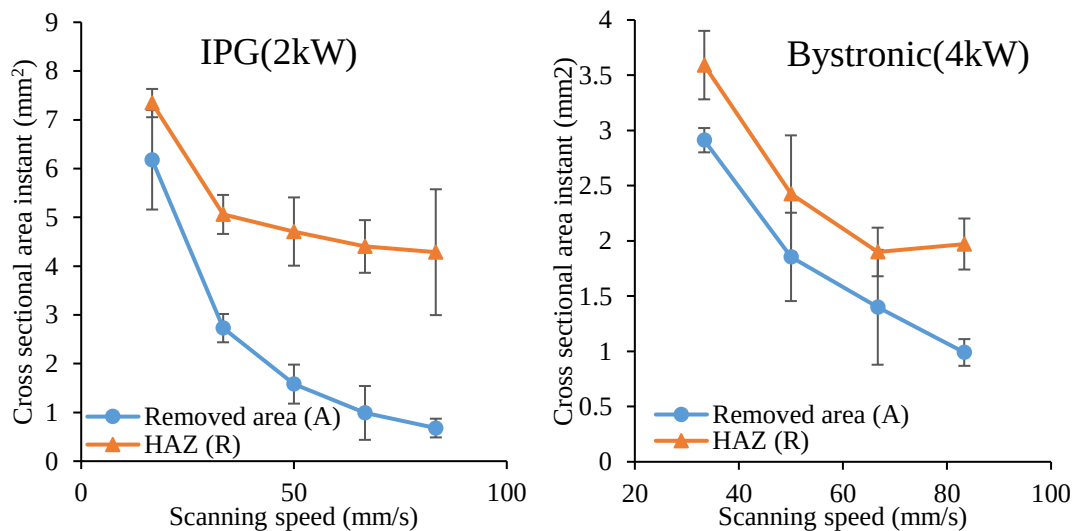


Figure 4.15- Comparison of cross section area between IPG (2kW) and Bystronic (4kW).

The absorption of energy by the CFBA creates an evaporated groove and an associated HAZ. Interesting results may be created by combining the energy of evaporation and the energy which created the HAZ in each case by applying Equation 3.5. These results are presented in Figure 4.16.

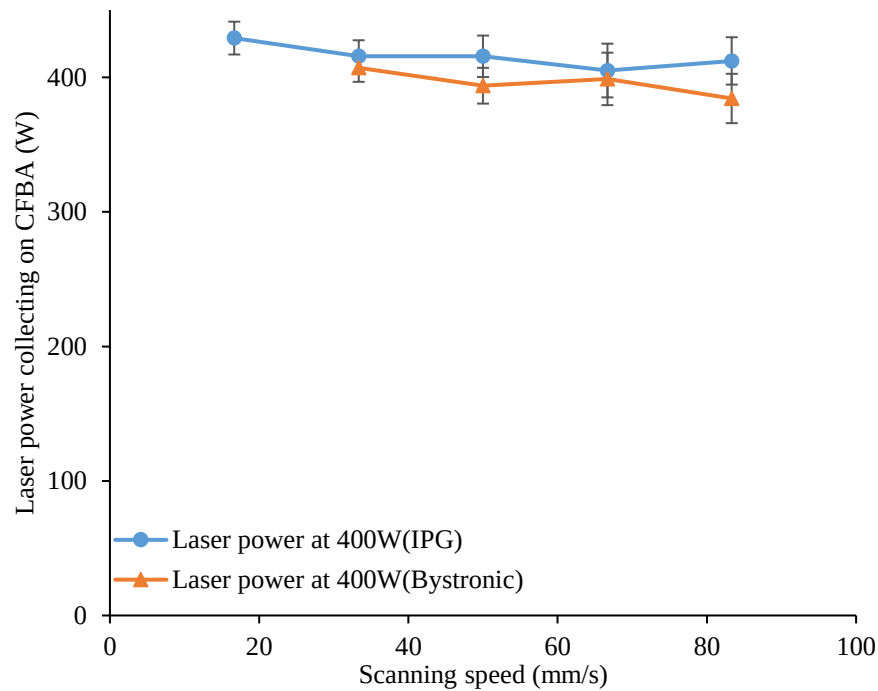


Figure 4.16- The results of comparison between IPG and Bystronic.

It can be seen that the total is approximately the same for both lasers and at all these speeds. The total is equal to the 400W output power of the lasers. This is because the IPG laser, which created less evaporation, produced a bigger HAZ (see Figure 4.15).

The reduced evaporation/bigger HAZ for the IPG laser was due to the fact that the beam was more divergent and therefore produced a broader, shallower groove. But for this broader, less intense, beam less of the interaction was above the threshold for evaporation, so a bigger HAZ was created, as shown in Table 4.9.

4.5 Laser-CBFA interactions discussion

In this chapter, the specific ablation energy of the black PMMA which can be used for quantitative and qualitative measuring tool for one micron laser beams has been determined. The thermal degradation has also been studied, both at TGA/DSC and laser-material interaction. The interaction of the laser beam through PMMA was used to determine the specific ablation energy for conditions which better represent these experimentally.

The results suggests, linear relationship between hole volume and irradiation time for all power levels used, this suggests that the volume of material removed is proportional to the energy input, consolidated to reflect the volume of material evaporated as a function of energy.

It was found that ablated PMMA needs to achieve a certain temperature. This temperature is reached as a result of absorption of laser beam. Subsequently leads to generate a plume of smoke which can absorb and diffract the laser beam. Also, the penetration depth of the beam irradiate in the black-PMMA has been limited. This limitation leading to generate the sub-surface bubble and swelling at edge.

4.6 Summary

The main aim of this chapter is to establish the specific ablation energy of carbon filled black acrylic (CFBA). Using a variety of laser irradiation times and different parameters (laser power, stand-off and with or without gas) to determine the ablation energy. The most significant points are shown as follows:

- The thermal decomposition of PMMA has been assessed using TGA and DSC. TGA analysis proved that carbon filler reduced its thermal decomposition and the glass temperature was not influenced by it. But the latent heat capacity of melting and evaporation are affected by the carbon filler as shown in DSC analysis.
- The results showed a linear relationship of a typical hole volume and irradiation time for all power levels used. This suggests that the volume of material removed is proportional to the energy input. Therefore, the results can be consolidated to reflect the volume of material evaporated as a function energy to establish a specific ablation energy of 3.44kJ/cm^3 (for an intense beam where threshold effects are unimportant.).
- Optical micrographs of a typical cross section of the CFBA close to the surface after evaporation show that the penetration depth of the fibre laser in this material is limited to approximately $100\mu\text{m}$.
- The laser-CFBA interaction produced a plume of vapour which contains the monomer methyl methacrylate and carbon dust which can absorb the laser beam resulting in fluctuating and incorrect values for the specific energy of evaporation. However, this effect can be avoided by ensuring sufficient gas flow (at least 1 bar in this case) near the surface of the CFBA.
- CFBA can be used as a quantitative energy measurement tool for fibre lasers only under restricted conditions. Quantitative measurements can only be relied

upon when intense beams are involved to produce deep narrow beam prints. Gas flushing is also necessary to remove the monomer/carbon dust cloud.

- CFBA can be used as qualitative measuring tool for 1 μ m laser beams.

4.7 Overall

A specific ablation energy of carbon filled black acrylic (CFBA) 3.4J.mm⁻³ has been determined. This is an increment on melt volume dependent results, as long as the limitations are understood. The CFBA can be used for quantitative work under the following condition: a 1 bar assist gas supply is sufficient to flush the evaporated material from the interaction area, the target material must to be stationary with respect to cutting head and it has sufficient distance close to the beam intensity.

5 The ‘Leaf’ prints

In this chapter experimental and modelling results relating to the reflection and transmission of the laser beam in the cut zone are analysed and discussed. Aims: to understand more about the efficiency of laser cutting and the laser-material interactions which take place in the cutting zone using the CFBA as a quantitative and qualitative analytical tool as discussed in chapter 4.

5.1 Experimental results of the surplus energy distribution

The basic experimental arrangement is shown in Figures 3.13 and 3.17, the main concept involved cutting stainless steel sheet of a variety of thickness and laser power at suitable cutting speeds. During cutting some surplus laser beam was emitted from the bottom of the cut zone. This energy is called the ‘primary losses’ [69] as it is energy which has been lost from the laser-material interaction and it is ‘primary’ because it still has the same wavelength as the laser light (conductive losses would be called ‘secondary losses’). These primary losses hit a black PMMA block below the cutting zone, leaving a beam print in that block. The CFBA sample and the laser cutting head remain stationary during the cutting process and only the work piece material was moved. A horizontal air jet above the evaporated zone was used to disperse the evaporating smoke plume.

Full details of the experiments were described in chapter 3; however, a summary of the parameters is presented in Table 5.1.

Table 5.1- Summary of parameters used.

Characteristic	Values		
Laser power range(cutting speed)	Low power*	500W	6.6mm/s
	Medium power	1200W	29.4mm/s
		1200W	6 mm/s
	High power	1780W	45.1mm/s
		1850W	12.8mm/s
Assist gas (pressure)	N ₂ (10bar to 13bar)		
Percentage of max. cutting speed	90% to 130%		
Sheet thickness	3mm to 6mm		
Vertical distance***	17.5mm		
	17.5mm to 35.5mm**		

*Used to cut 3mm only.

** Used to study the threshold energy as a function of distance (section 6.3).

***The distance from bottom of the cutting zone to the black PMMA.

5.2 Qualitative analysis of primary losses from the cut zone

The primary losses of the laser beam undergo absorption/reflection/scattering from the particles in its path which have just left the bottom of the cut zone as shown in Figure 5.1. Also, the fibre laser beam diverges rapidly because it undergoes multiple reflections inside the cutting zone and this increases the divergence angle from the cutting zone exit [110].

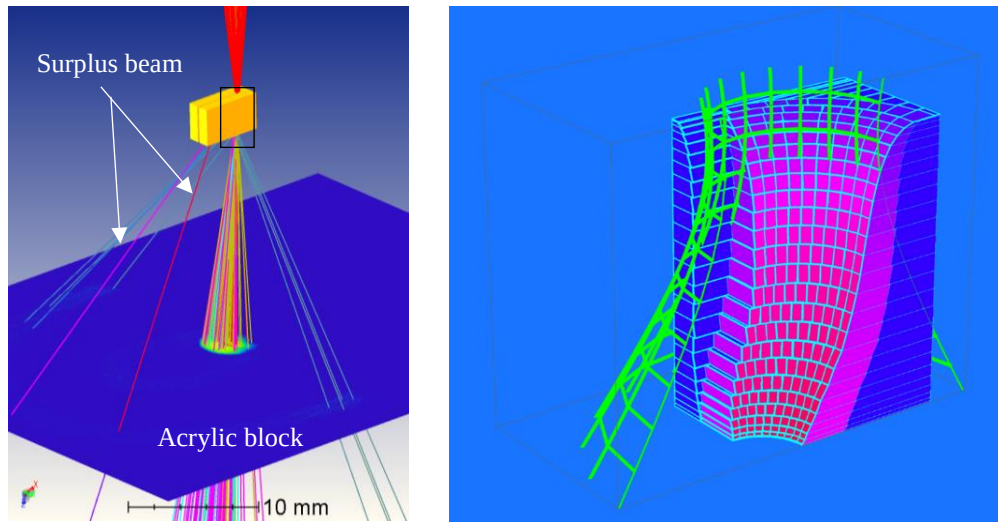


Figure 5.1- CALCut software used to simulate the cutting process of 3mm stainless steel and collected the surplus laser beam by PMMA sheet. Left) Black PMMA collection sheet. Right) Calculation of the cutting front.

Using an experimental set-up similar to that shown in Figure 5.1Left, the CFBA was positioned 17.5mm below the bottom of the work piece. In order to ensure that only the surplus energy from steady state cutting at the selected speed was collected, additional pieces of steel, 10mm in thickness, were fixed below the cutting zone for the first part of the cut and the final part of the cut. These steel sheets blocked the path to the black PMMA sample during time that the table was accelerating and decelerating and helped in the calculation of the exposure time in each case because the distance between the shields was 93mm for all the following prints presented in this chapter.

The high absorptivity of carbon filled acrylic, combined with its high evaporation efficiency and low thermal conductivity, means that a laser-evaporated beam print will be a good first order approximation of the energy distribution of the beam exiting the bottom of the cut zone at any point (as long as the depth to width ratio of the beam print remains below 3:1). However, a number of factors must be considered when observing these beam prints;

1. There is an energy density threshold for any particular laser-material interaction.
2. The laser beam diverges rapidly as it exits the bottom of the cut zone. This is a more important consideration for fibre lasers then it is for their CO₂ counterparts because the fibre laser beams undergo multiple reflections inside the cutting zone and this increases the divergence angle from the cutting zone exit.

The early experimental results revealed beam prints which were completely different from those obtained from CO₂ laser cutting. In CO₂ laser cutting the beam print clearly shown robust evidence that any laser energy which was not consumed during the cutting process was emitted as interference fringes [69]. In fibre laser cutting however, a typical beam print of the beam leaving the bottom of the cutting zone was leaf shaped. Typical examples are presented in Figure 5.2.

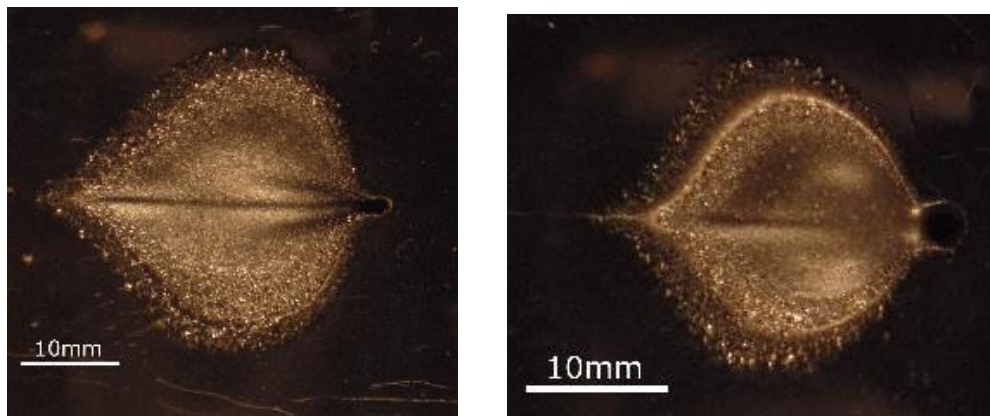


Figure 5.2- Typical ‘leaf’ print evaporation patterns taken from below the cutting zone. Left) Print taken 30mm below the cutting zone when cutting 6mm stainless steel at 12mm/s. Right) Print taken 30mm below the cutting zone when cutting 3mm stainless steel at 43mm/s.(laser power 1850W, N₂ 13bar for 6mm and laser power 1780W, N₂ 10bar for 3mm).

Distinctive ‘Leaf print’ evaporation patterns similar to those shown in Figure 5.2 were found under almost all experimental conditions investigated during this work. Figure 5.2Left and Right show results from 6 and 3mm thick samples cut at 12.14mm/s and 42.8mm/s respectively but the leaf prints are surprisingly similar. Focus-variation

microscopy was used to build a 3D profile image of a typical leaf print as show in Figure 5.3.

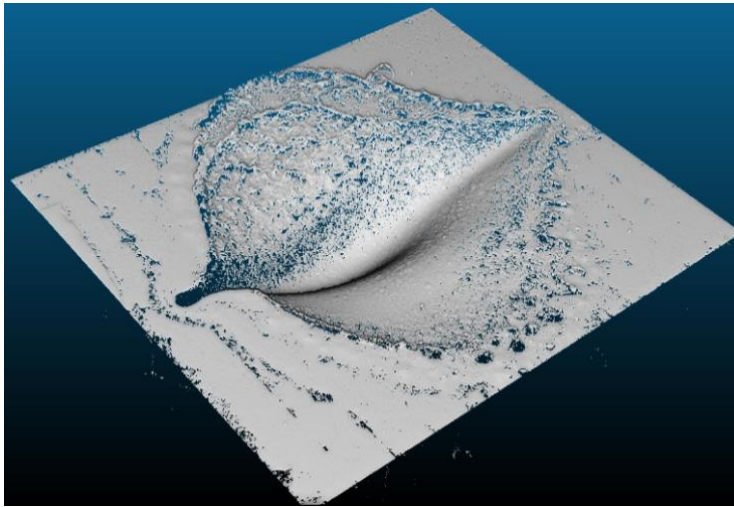


Figure 5.3-3D profile of the leaf print taken 23.3mm below the bottom of the cutting zone when cut 6mm stainless steel at 12.14mm/s(laser power 1850W and N₂ 13bar).

In each case there is clear evidence of a deep evaporated hole at the ‘stem’ end of the leaf, which was largely created by the vertically impinging transmitted beam. The shallower ‘leaf’ is an evaporation pattern created by the reflected portion of the beam. This consists of two wings joined by a central, deep line.

To better understand the interaction involved these features of the leaf print have been replicated by using CALCut software to calculate the geometry of the cutting front and Zemax software to compute the resulting power density distribution below the cutting kerf [58, 111]. These results were achieved with the help of D. Petring and S. Stoyanov, Figure 5.4, taken from their work, shows evidence of the high energy density spot at the stem end together with indications of a central line surrounded by widespread symmetrical energy density which fades with distance from the central line. At this stage the CALCut software does not take into account the interaction of the beam with the

particles leaving the bottom of the cutting zone and this may account for the discrepancy between Figure 5.2 and Figure 5.4.

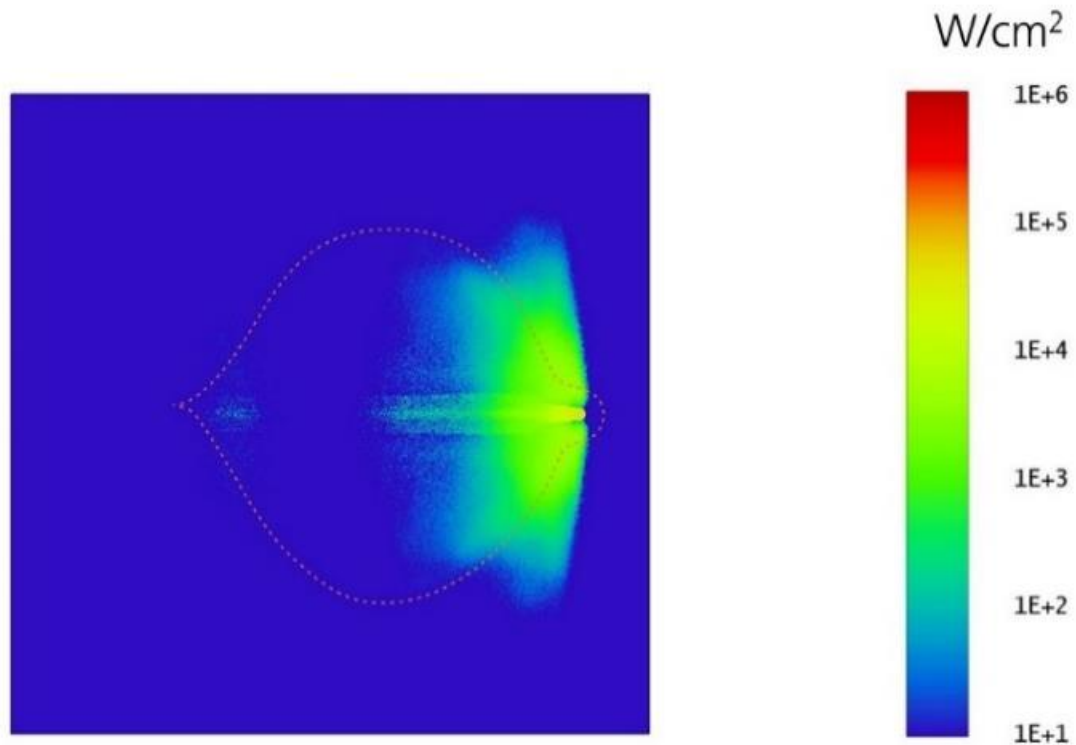


Figure 5.4- A theoretical calculation by using CALCut and Zemax software of the primary losses emitted from the cut zone showing some of the same features as the experimental leaf traces shown in Figure 5.2. The experimental result for the 3mm stainless steel is shown as a dashed line, the simulated power density distribution is presented as a logarithmic colour scale.

Figure 5.5 is a schematic of the creation of a leaf print below the cut zone. It seems clear that the 'stem' of the leaf is a deeper hole created by the transmitted beam whereas the body of the leaf is an evaporated pattern related to the part of the beam which has been reflected from the cutting zone and/or scattered by the stream of droplets leaving the bottom of the cutting zone. This figure has been drawn to scale and demonstrates the wide angle of divergence of the beam as it leaves the cutting zone.

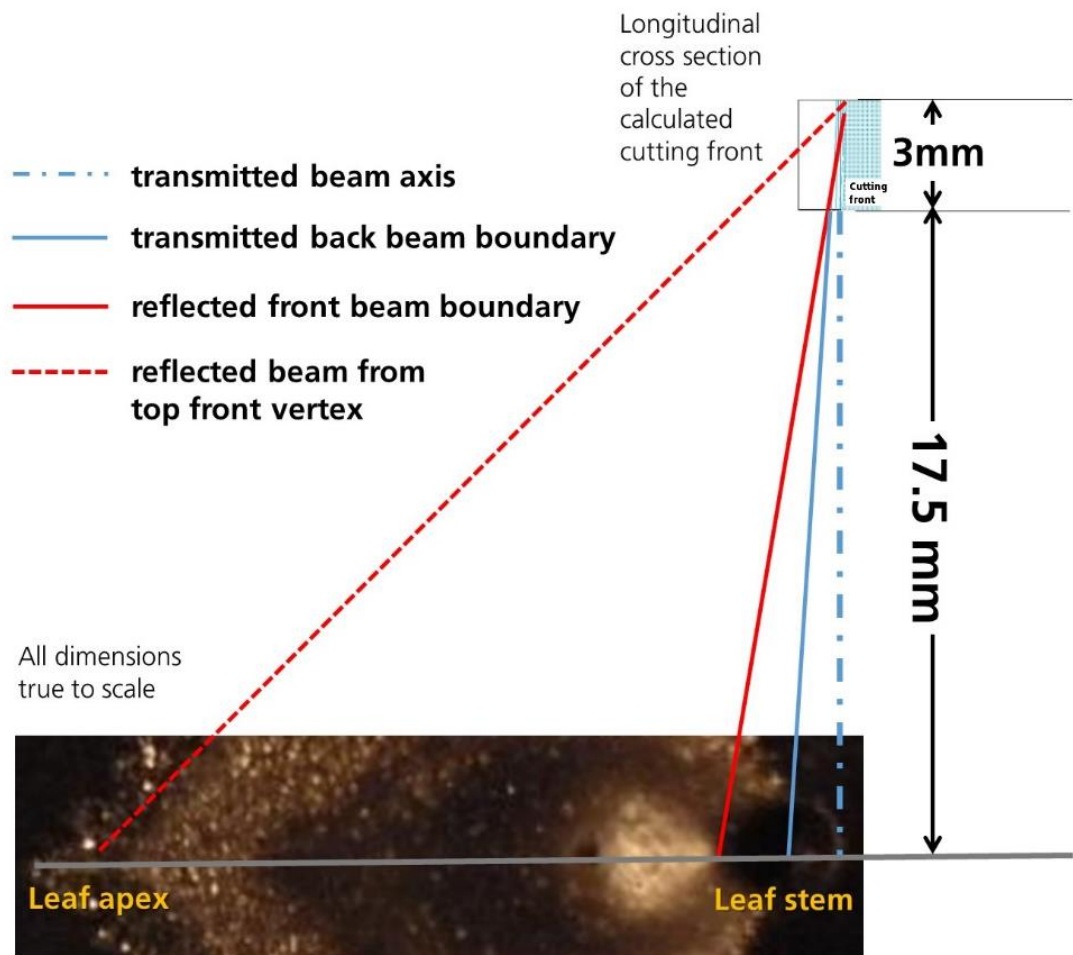


Figure 5.5- A schematic of the leaf print pattern is a combination of transmitted and reflected laser beam when cut 3mm stainless steel.

5.2.1 The effect of the cutting speed on the 'leaf' shape

In Figure 5.6 it is shown that at highest cutting speed the 'leaf' shape largely disappears leaving a small print which is elongated in the direction of travel. Obviously the beam absorption on the cut front is larger at higher speed due to reabsorption of multi-reflected light from the top of the cut front [13, 69]. At even higher speeds than the maximum cutting speed no light can escape from the bottom of the cutting zone because the cutting zone does not penetrate all way through the material.

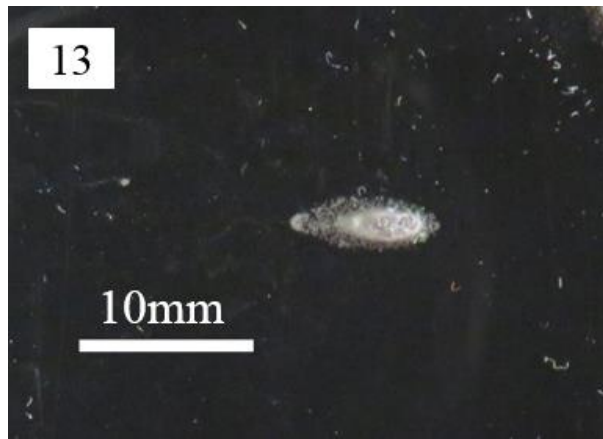


Figure 5.6-‘leaf’ print pattern taken at high cutting speed when cut 3mm stainless steel at laser power 1780W, 57mm/s, N₂10bar and 17.5mm vertical distance between the bottom of cut zone to CFBA.

The summary for the results of the energy collected in the beam prints is shown in Figure 5.7 and 5.8 which shows that the proportion of reflected and transmitted energy decreases with increasing cutting speed under otherwise similar cutting conditions.

5.2.1.1 The effect of cutting speed on ‘leaf’ shape when cut 3mm stainless steel

Figure 5.7 shows the energy collected in the beam print as a function of cutting speed. The experimental results take the cutting speed up to a maximum of 126% of ‘max’ speed which is the speed at which cutting was not possible. At this speed the laser beam did not penetrate the material and so no energy could leave the ‘cutting’ zone. The subject of maximum speed in laser cutting is complicated. The ‘% of max speed’ referred to in Figure 5.7 and in other places in this chapter refer to the maximum commercial cutting speed-which is usually approximately 85% of the speed at which the laser can actually cut. This safety margin of 15% is to ensure that cutting is of commercially acceptable quality and that the cutting process is robust. This is the reason why some of the results in Figure 5.7 are above 100%.

Figure 5.7 follows the overall trend of reducing primary losses with increasing cutting speed. This is because more laser energy is used up in the cutting at higher speeds. As speed increases the shape of the cutting front changes from an almost vertical straight line to a line which is inclined in the direction of cutting [13]. This inclined line catches more of the laser beam so primary losses are reduced.

At speeds above the commercial maximum the bottom of the cutting zone becomes very inclined and this leads to much more surface roughness on the cut edge.

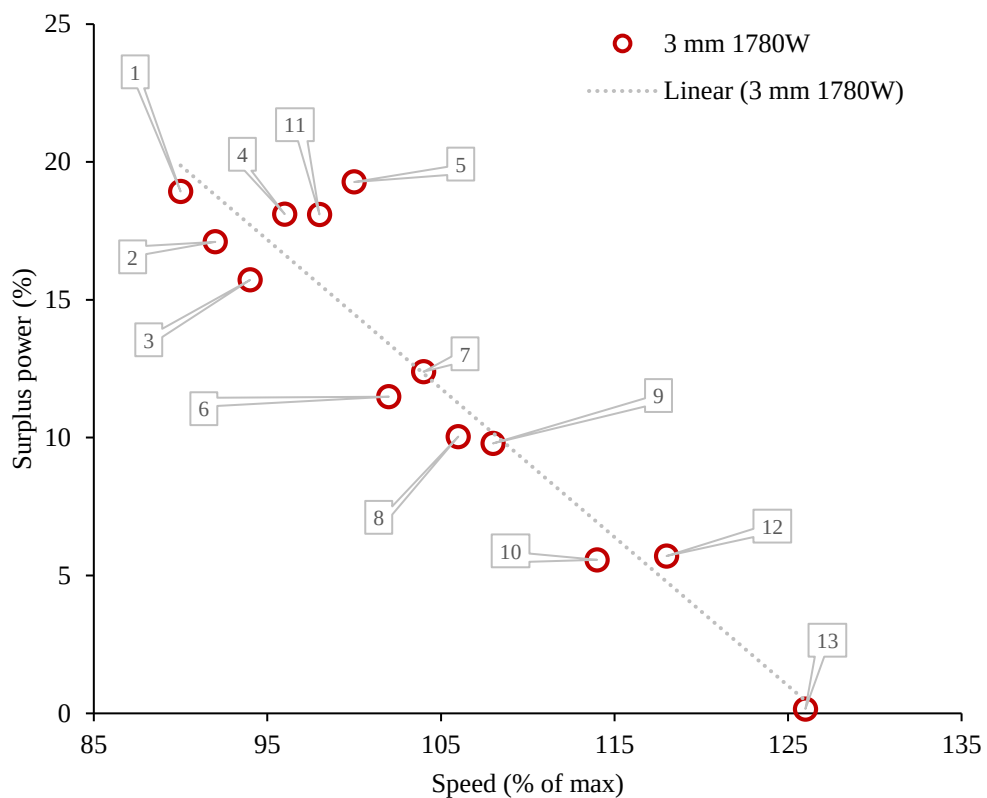
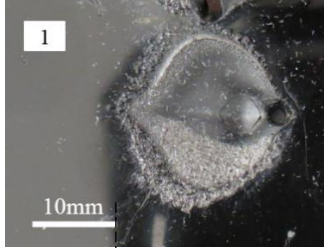
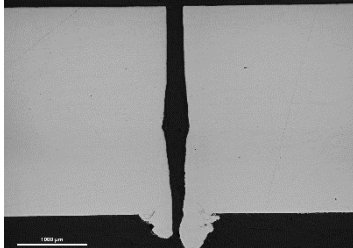
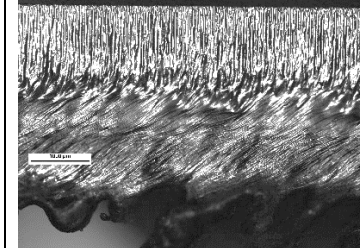
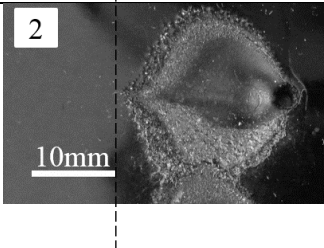
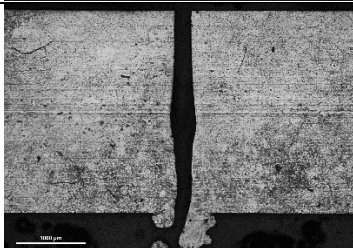
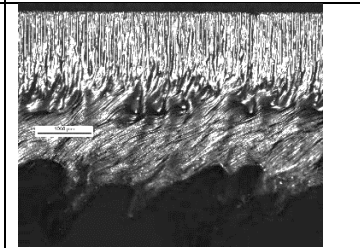
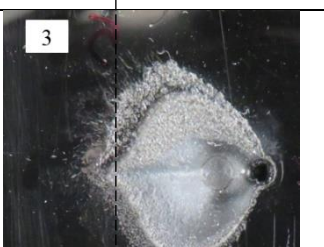
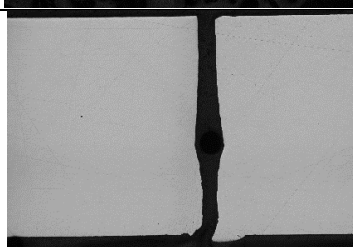
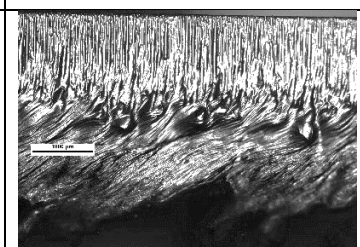
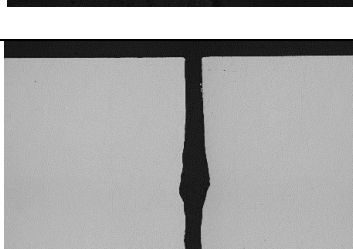
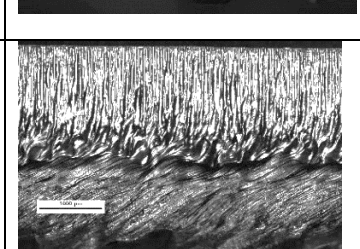
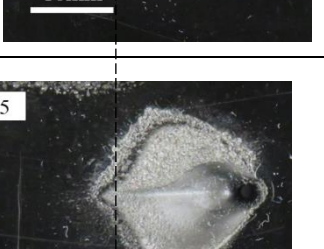
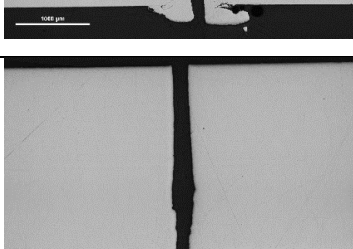
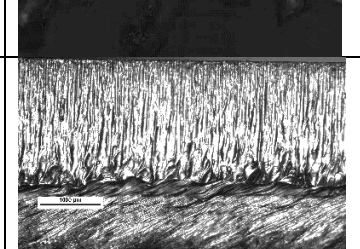


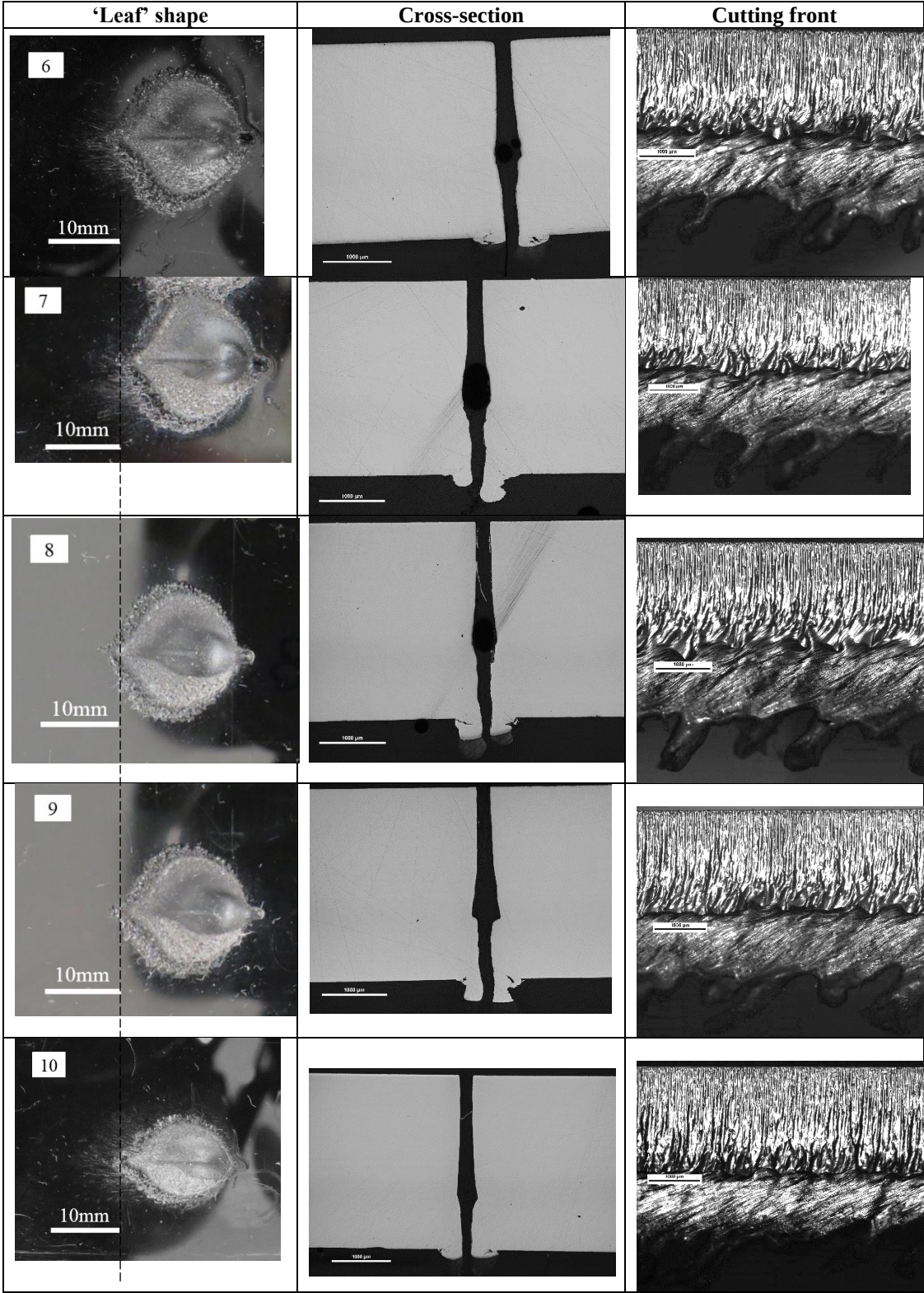
Figure 5.7- The surplus energy percentage collected on black-PMMA when cut 3mm stainless steel with laser power 1780W, N₂ 10bar and max. cutting speed 43mm/s. (Numbers represent ‘leaf’ print shape at different cutting speeds see Table 5.2).

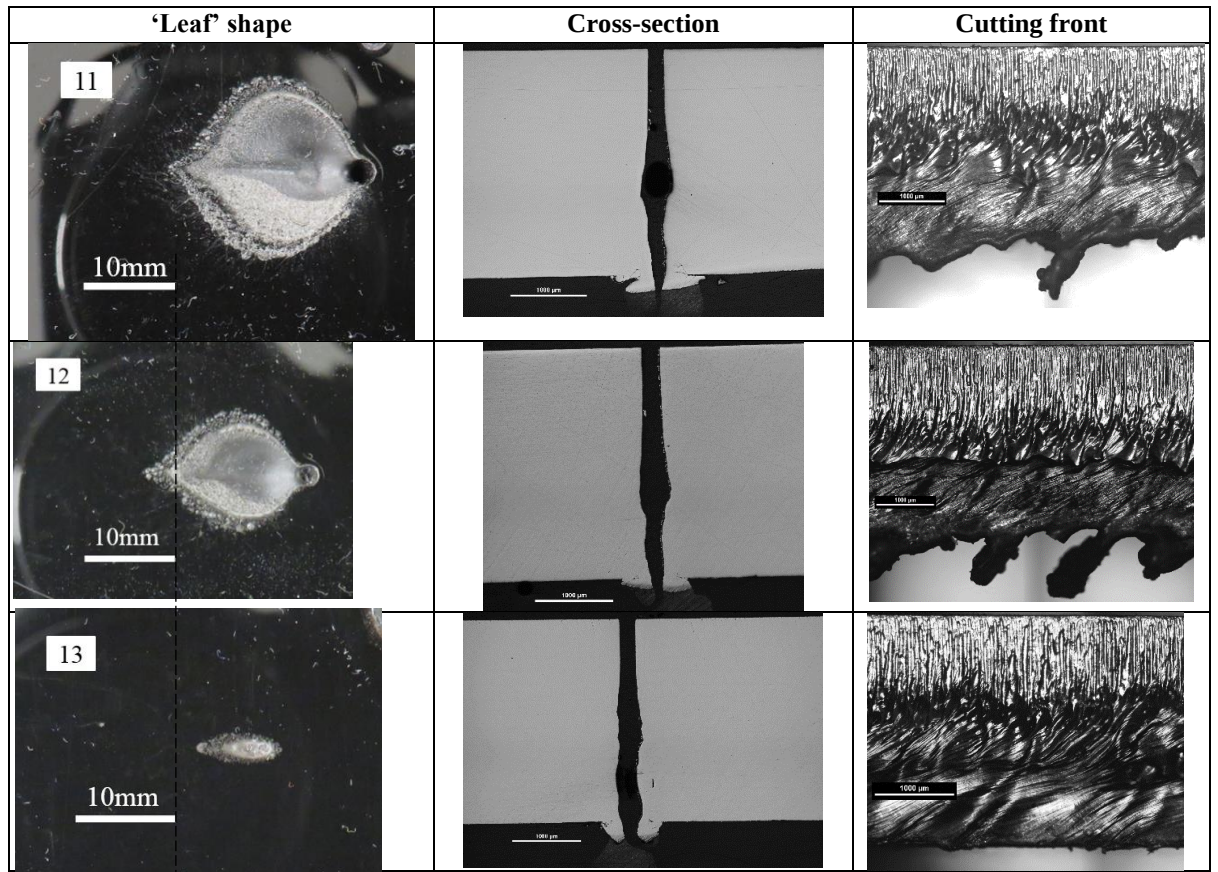
It is clear from Figure 5.7 that there is an approximately linear relationship between cutting speed and surplus power collected. In this case the surplus power collected at 100% cutting speed was approximately 12%.

Table 5.2 presents the results from the leaf print experiments when cutting 3mm stainless steel. In each case Table 5.2 shows the leaf shaped beam print, the cross section of the cut and the cut edge. The parameters used in the production of samples 1-13 can found in Table 3.14.

Table 5.2- Photographs of the ‘leaf’ print shape, the cross section of the cut and the cut edge for 3mm stainless steel at different cutting speeds under the same cutting parameters.

‘Leaf’ shape	Cross-section	Cutting front
		
		
		
		
		





5.2.1.2 The effect of cutting speed on ‘leaf’ shape when cut 6mm

Figure 5.8 shows that, as in the case for 3mm material, there is an approximately linear relationship between the surplus energy collected and the cutting speed. In the case of the 3mm material the surplus power at 100% cutting speed was approximately 12%. In the case of the 6mm material this value has increased to approximately 25%. This is probably due to fact that the beam cut the 6mm material more slowly. This increased the interaction time between the laser and the acrylic target. This would probably lead to more efficient evaporation because the laser power would have more time to exceed the threshold for evaporation.

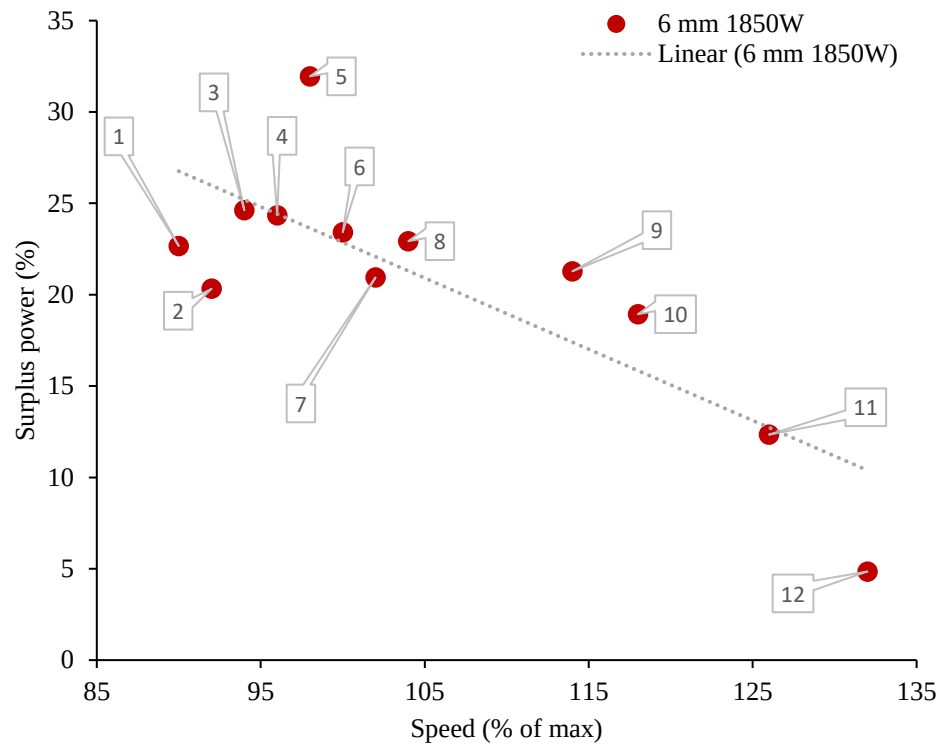
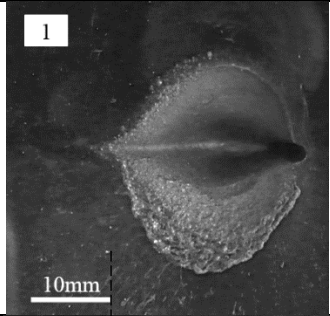
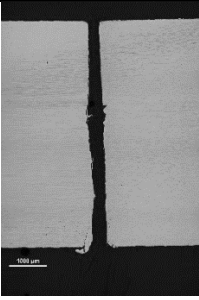
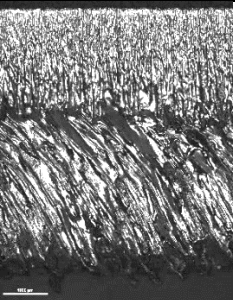
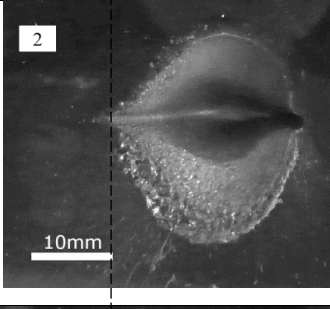
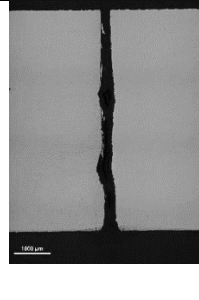
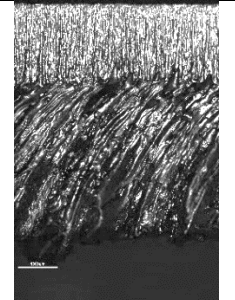
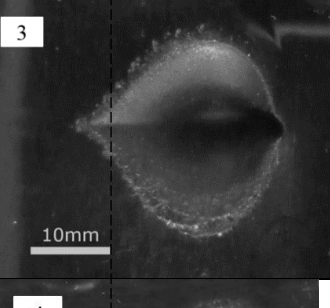
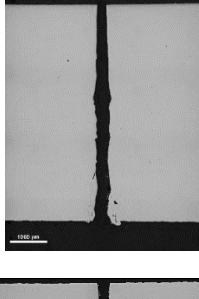
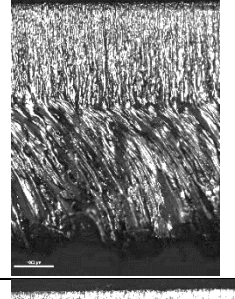
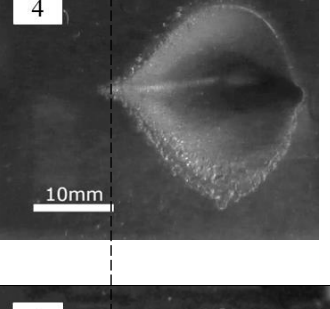
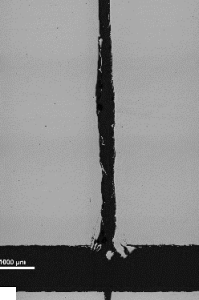
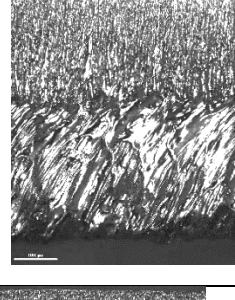
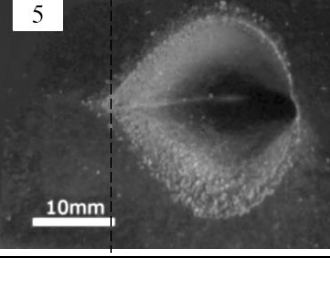
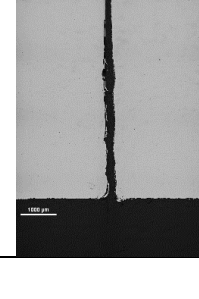
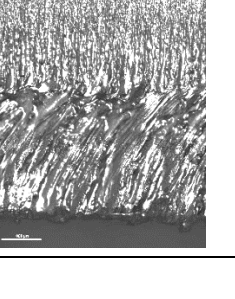
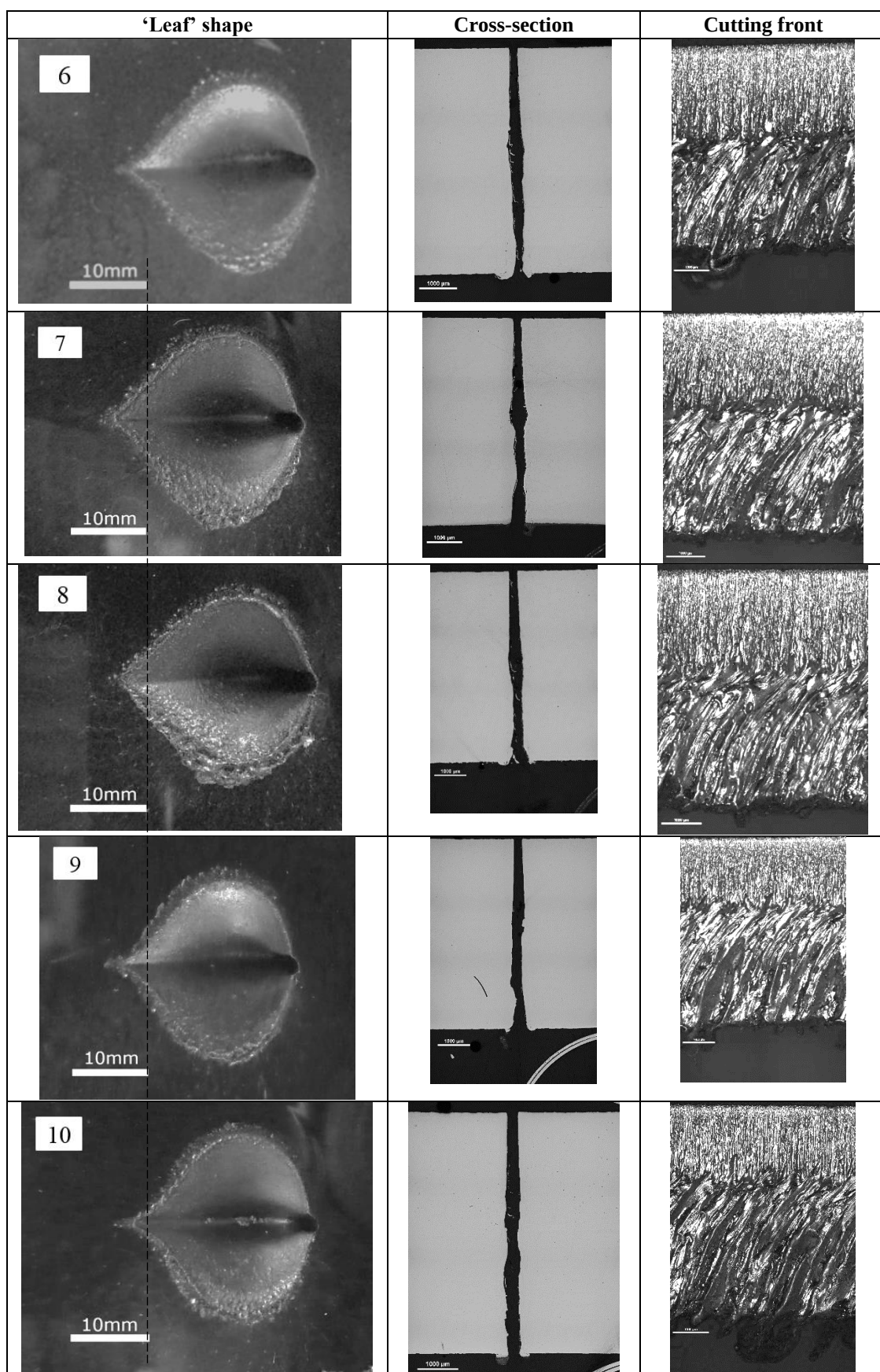


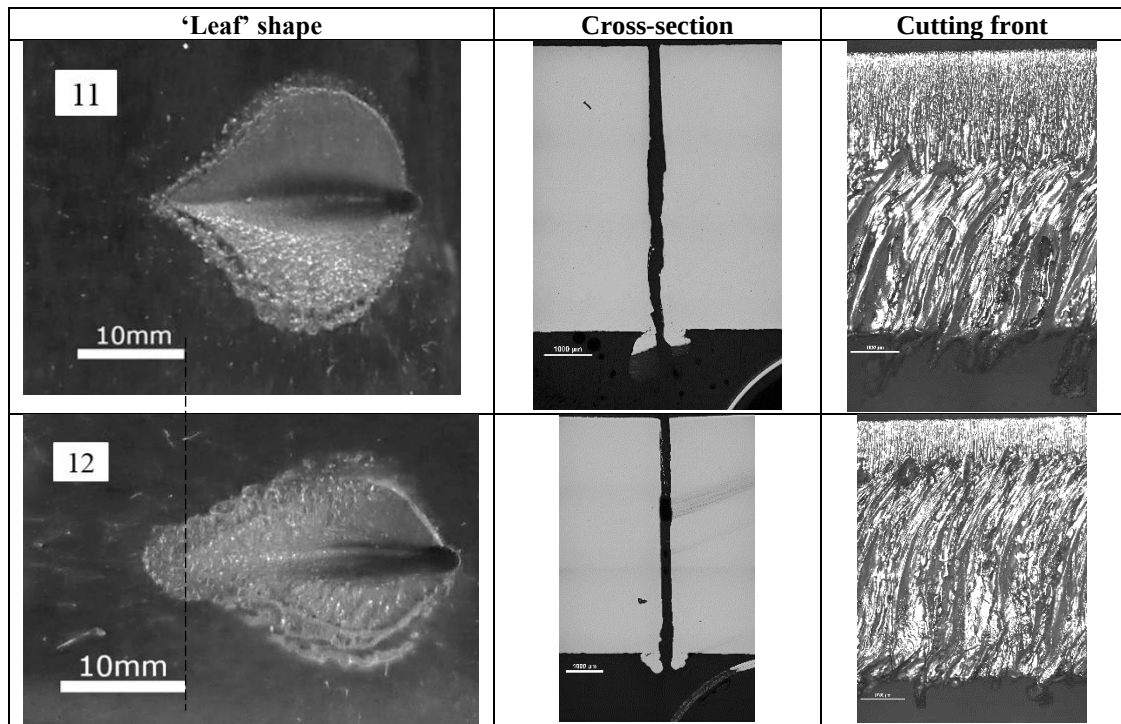
Figure 5.8- The surplus energy percentage collected on black PMMA when cut 6mm stainless steel with laser power 1850W, N₂ 13bar and max. cutting speed 12.1mm/s. (Numbers represent 'leaf' print shape at different cutting speeds see Table 5.3).

Table 5.3 shows that, overall, the 'leaf' shape collected below the 6mm cutting is similar in shape to those collected under the 3mm material. However, the 6mm leaf prints are approximately 50% longer and 50% broader than the 3mm leaf prints. This enlargement of the leaf prints is because of a broadening of the incident beam. The collected beam gets broader when cutting thicker material because thicker material means that the laser beam experiences more multiple reflections and each time the beam is reflected it is deflected further from the vertical. So deeper cut fronts (thicker materials) mean more reflections which means that the beam leaving the bottom of the cut front will be more diverging. A more diverging beam gives broader leaf prints.

Table 5.3- Photographs of the ‘leaf’ print shape, cross-section of the cut and cut edge for 6mm stainless steel at different cutting speeds under the same cutting parameters.

‘Leaf’ shape	Cross-section	Cutting front
		
		
		
		
		





5.2.2 The influence of the laser power on ‘leaf’ shape

To complete the investigation about the ‘leaf’ shape, cuts were carried out in 3mm and 6mm thick stainless steel at different powers and the surplus energy was collected as leaf prints as before.

5.2.2.1 The effect of the laser power on ‘leaf’ shape when cutting 3mm

Figure 5.9 shows the expected linear relationship between % surplus power collected and cutting speed when cutting 3mm stainless steel with 1200W (upper line) and 500W (lower line). In the case of 1200W the % surplus when cutting at 100% speed is approximately 15%, for 500W the % surplus when cutting at 100% speed is 7%. The low result for the 500W beam could be because a lot of the surplus energy which impinges on the target is below the threshold for evaporation. This energy is reflected

or conducted away and therefore does not contribute to the evaporation so an artificially low surplus % is recorded.

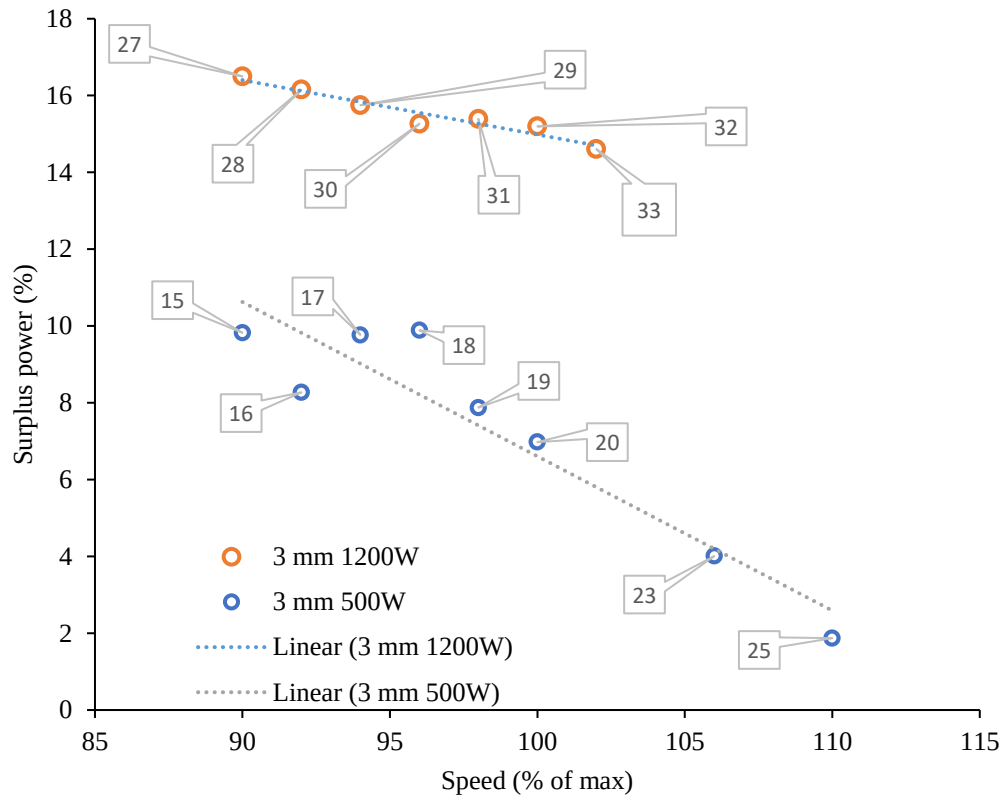
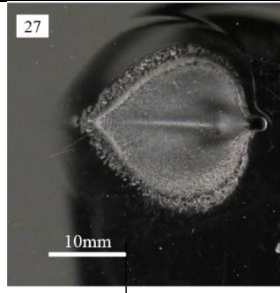
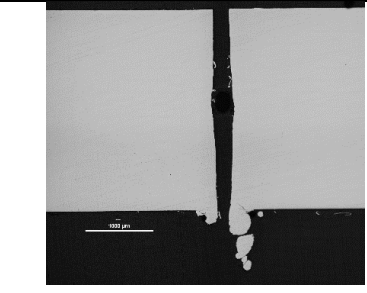
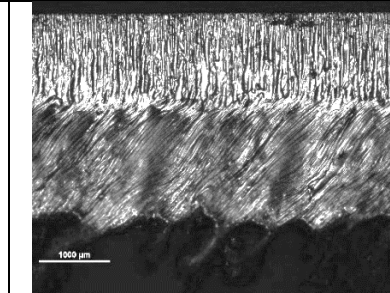
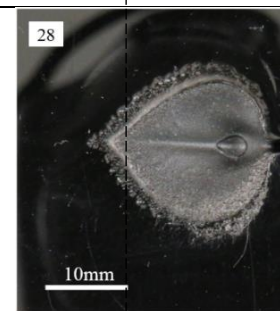
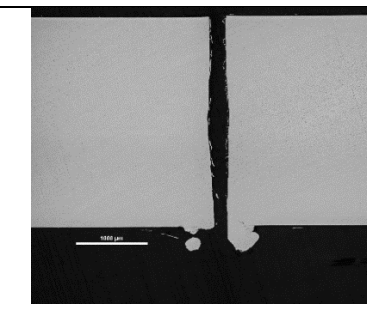
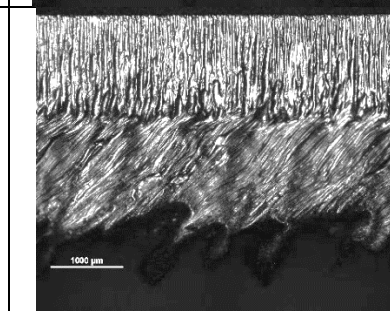
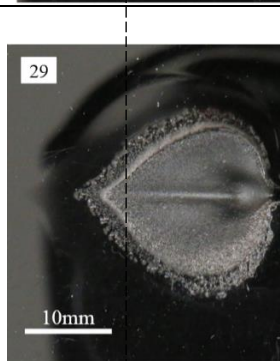
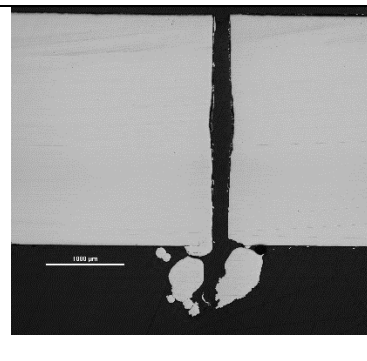
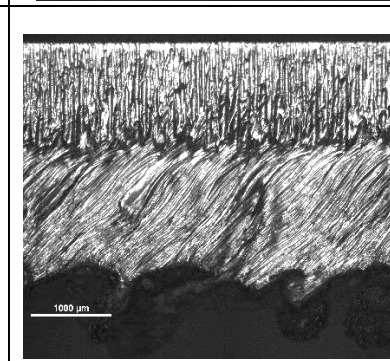
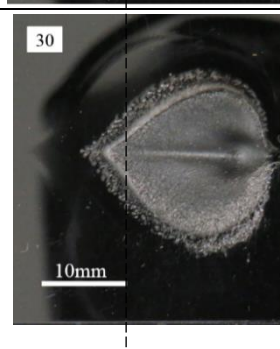
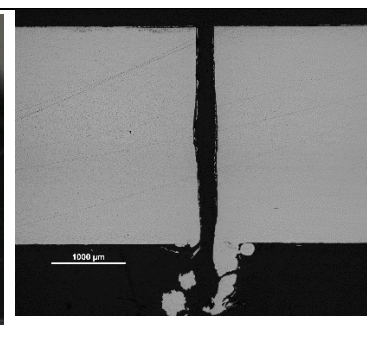
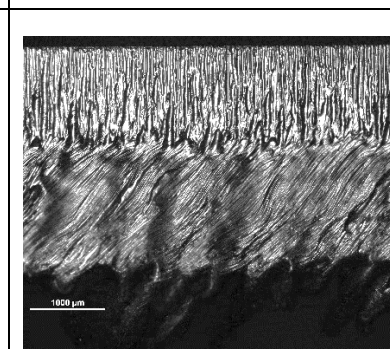
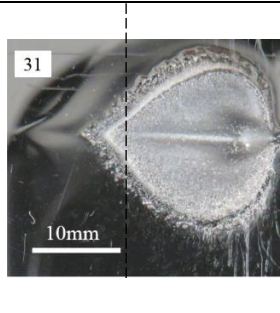
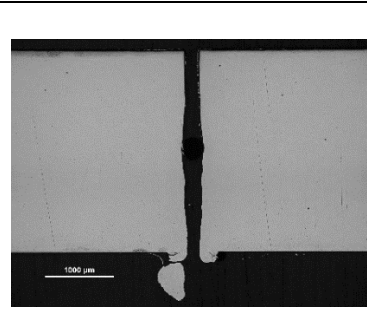
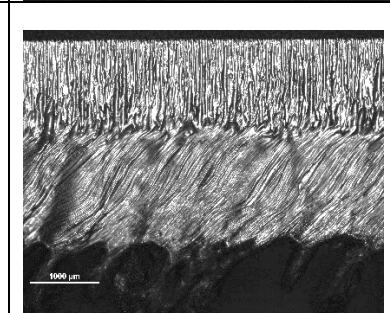


Figure 5.9- The surplus energy percentage collected on black PMMA when cut 3mm stainless steel. Upper line) with laser power 1200W, N₂ 8bar at max. cutting speed 29.4mm/s. Lower data) with 500W, N₂ 6bar at max. cutting speed 6.6mm/s. (Numbers represent 'leaf' print shape at different cutting speeds see Table 5.4 and Table 5.5).

Table 5.4 shows the leaf print photos taken for 3mm stainless steel cutting at 1200W and Table 5.5 shows the results for 500W. The 1200W and 500W results shown in Tables 5.4 and 5.5 show similar leaf geometries to the 3mm results for higher power (1780W) given in Table 5.2. This shows that the cut fronts reflect in a similar way for lower powers cutting at lower speeds. This means that the cut fronts must be of a similar shape. This is confirmed by the similarity in cut front curves in the cut edge photos shown in the two tables.

Table 5.4- Photographs of the ‘leaf’ print shape, cross-section of the cut and cut edge for 3mm stainless steel at different cutting speeds under the same cutting parameters (Laser power 1200W).

‘Leaf’ shape	Cross-section	Cutting front
		
		
		
		
		

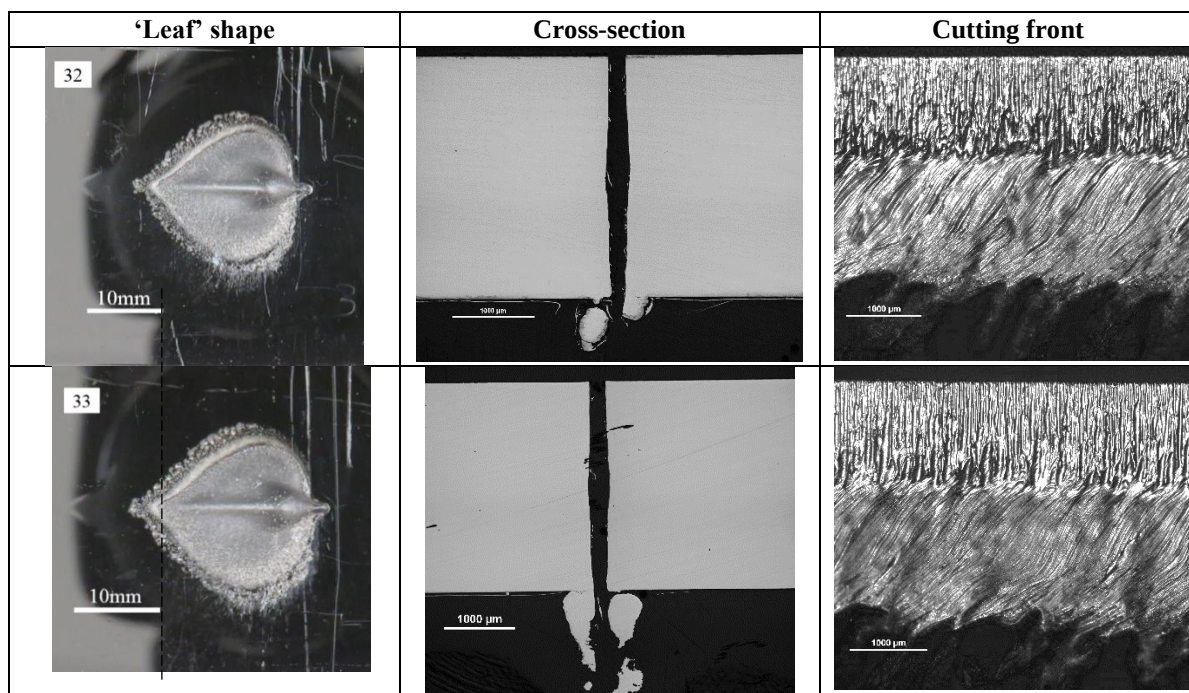
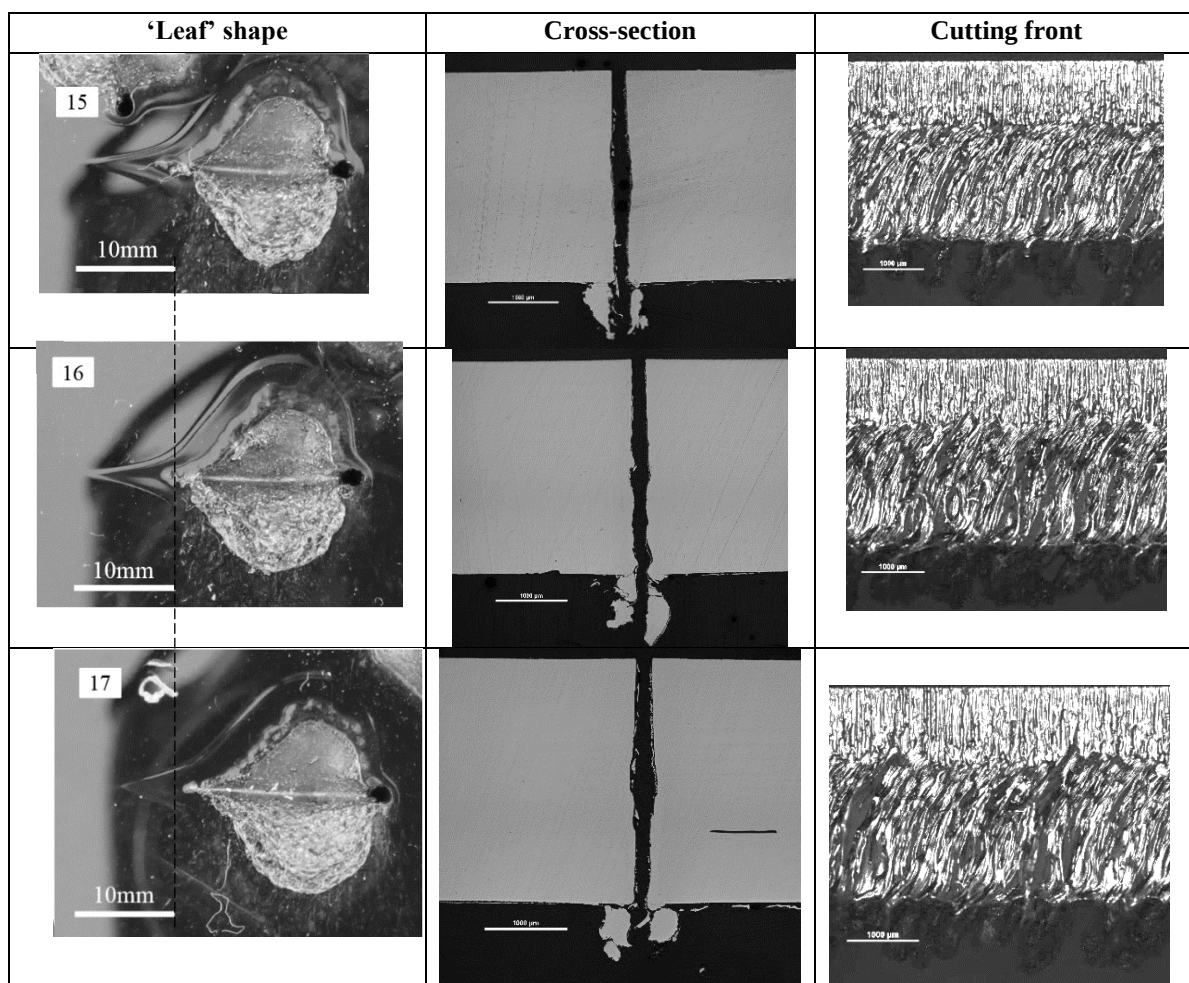
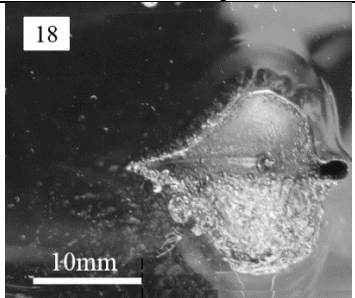
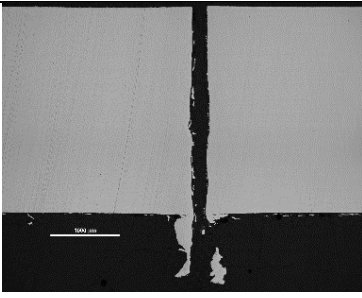
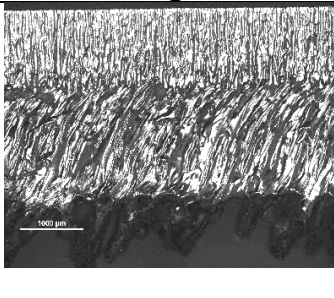
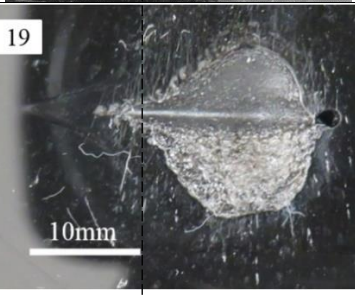
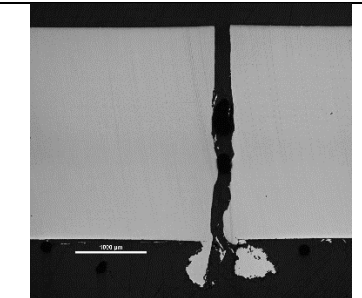
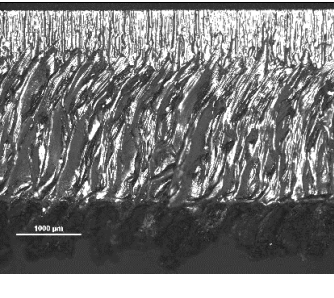
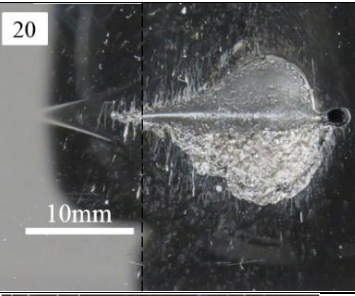
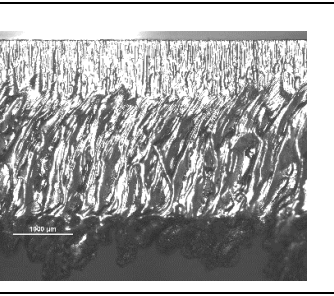
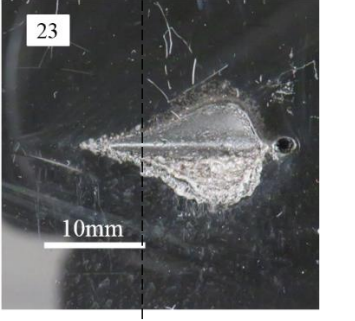
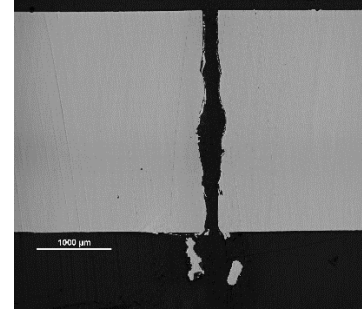
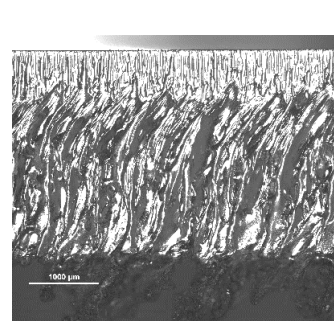
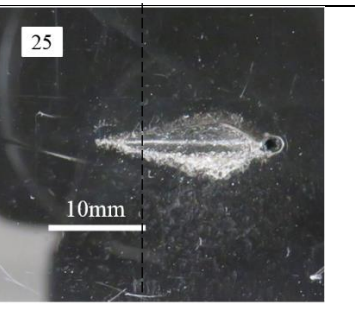
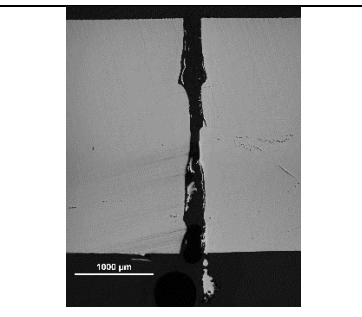
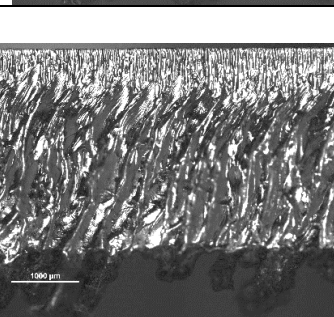


Table 5.5- Photographs of the ‘leaf’ print shape, cross-section of the cut and cut edge for 3mm stainless steel at different cutting speeds under the same cutting parameters (Laser power 500W).



‘Leaf’ shape	Cross-section	Cutting front
 <p>18</p> <p>10mm</p>	 <p>1000 μm</p>	 <p>1000 μm</p>
 <p>19</p> <p>10mm</p>	 <p>1000 μm</p>	 <p>1000 μm</p>
 <p>20</p> <p>10mm</p>	 <p>1000 μm</p>	 <p>1000 μm</p>
 <p>23</p> <p>10mm</p>	 <p>1000 μm</p>	 <p>1000 μm</p>
 <p>25</p> <p>10mm</p>	 <p>1000 μm</p>	 <p>1000 μm</p>

5.2.2.2 The effect of the laser power on ‘leaf’ shape when cutting 6mm

The lowest power of 500W could not cut 6mm stainless steel successfully so only 1200W was investigated. In Figure 5.10, it is evident that there is, once more, a linear relationship between cutting speed and surplus power %. In this case the % surplus power collected at 100% cutting speed was approximately 5%. This is far less than the surplus power found at higher laser powers and higher cutting speeds. This is probably a result of most of the surplus power being below the threshold for evaporation, because the surplus beam is greatly diverged by increased multiple reflections in the 6mm thick cutting kerf [69].

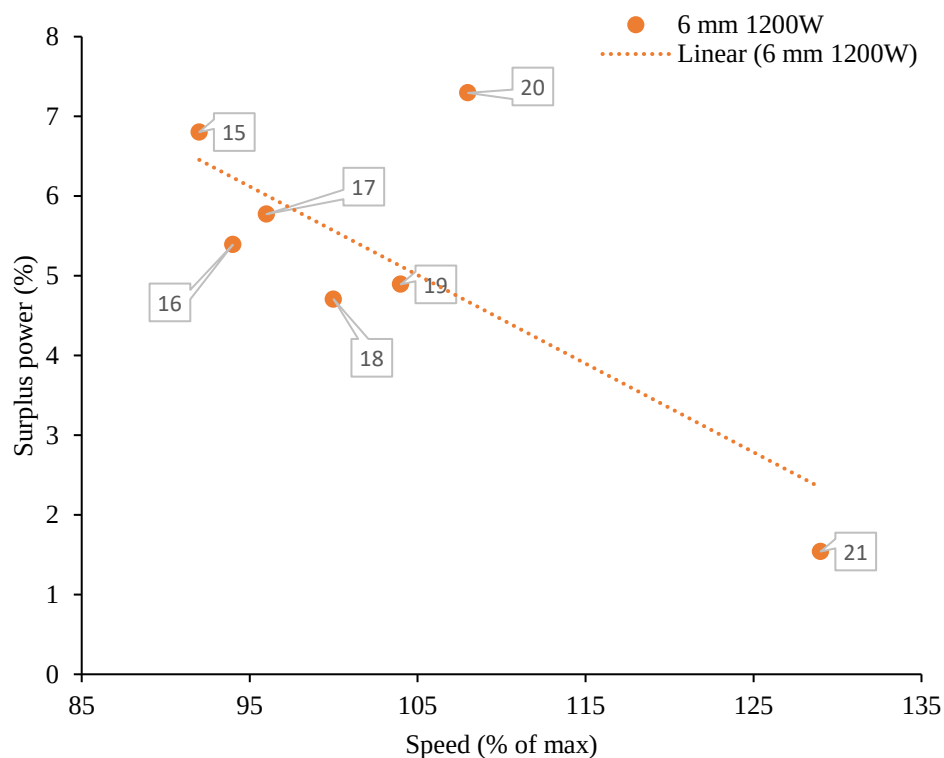
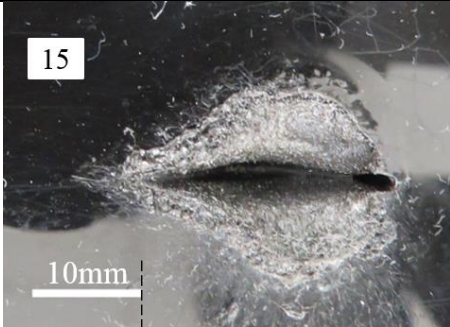
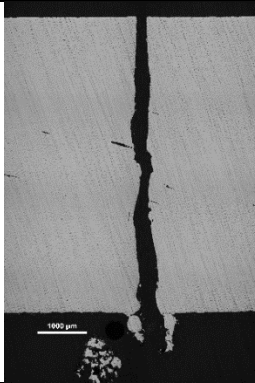
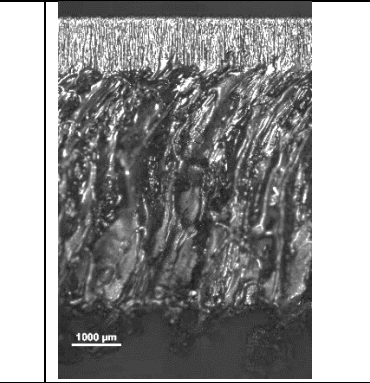
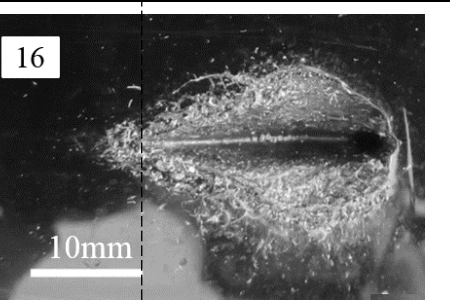
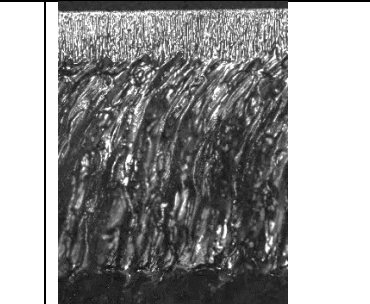
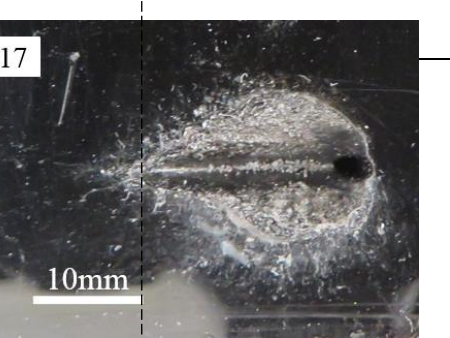
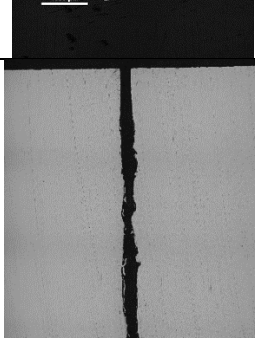
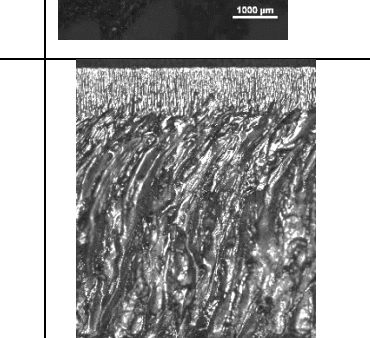
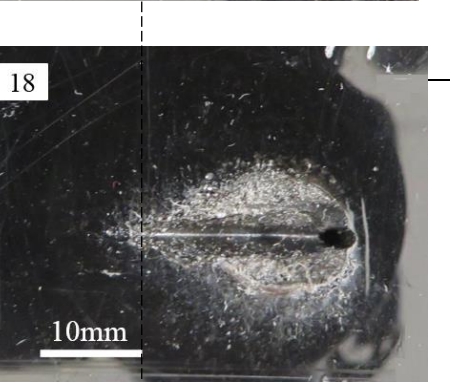
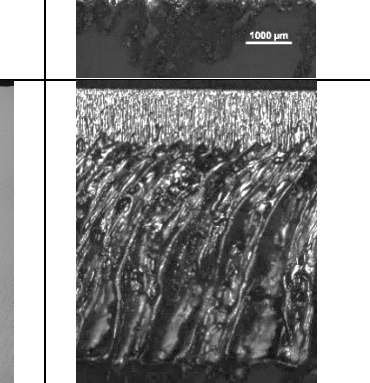
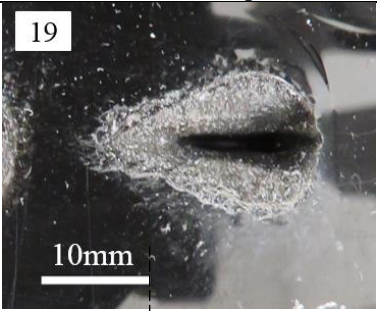
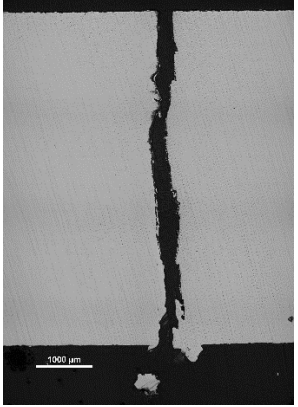
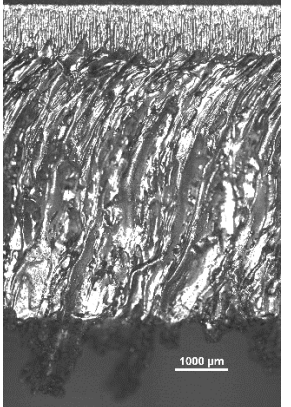
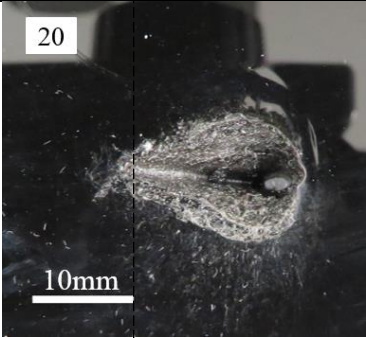
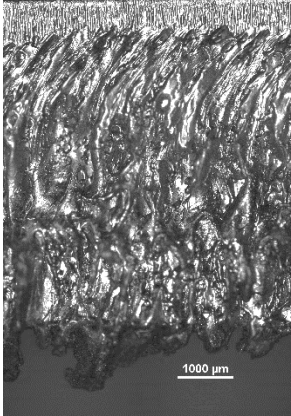
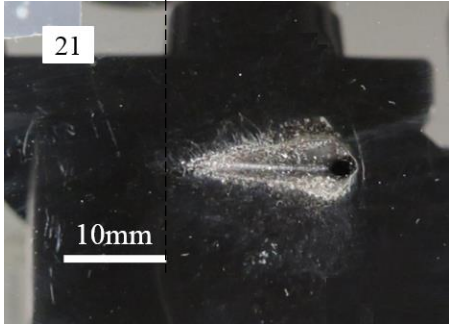
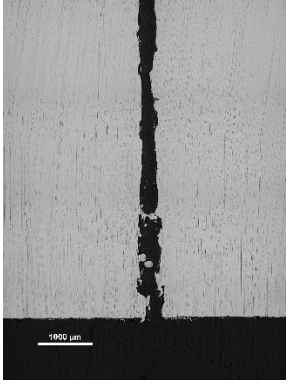
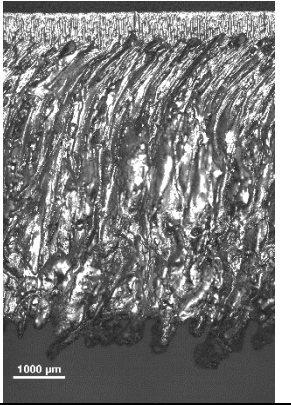


Figure 5.10-The surplus energy percentage collected on black PMMA when cut 6mm stainless steel with laser power 1200W, N₂ 6bar and max. cutting speed 6mm/s (Numbers represent ‘leaf’ print shapes at different cutting speeds see Table 5.6)

Table 5.6 makes it clear that even when the surplus energy beam is of low power the leaf print effect is robust. Throughout all these types of experiments carried out during this research the distinctive leaf shape was clearly identifiable.

Table 5.6- Photographs of the ‘leaf’ print shape, cross-section of the cut and cut edge for 6mm stainless steel at different cutting speeds under the same cutting parameters (Laser power 1200W).

‘Leaf’ shape	Cross-section	Cutting front
		
		
		
		

‘Leaf’ shape	Cross-section	Cutting front
<div data-bbox="341 219 719 528"><div data-bbox="363 232 411 271">19</div><div data-bbox="389 456 475 495">10mm</div></div>	 <div data-bbox="826 573 879 589">1000 μm</div>	 <div data-bbox="1294 573 1347 589">1000 μm</div>
<div data-bbox="357 633 724 969"><div data-bbox="389 656 437 694">20</div><div data-bbox="399 898 485 936">10mm</div></div>	 <div data-bbox="826 1021 879 1037">1000 μm</div>	 <div data-bbox="1294 999 1347 1014">1000 μm</div>
<div data-bbox="325 1137 775 1462"><div data-bbox="373 1167 421 1205">21</div><div data-bbox="399 1357 485 1395">10mm</div></div>	 <div data-bbox="826 1447 879 1462">1000 μm</div>	 <div data-bbox="1129 1485 1182 1500">1000 μm</div>

5.3 The effect of cutting speed on the cut front

In all work pieces cut, it was observed that the top part of the cut edge is generally a great deal smoother than the lower part of it.

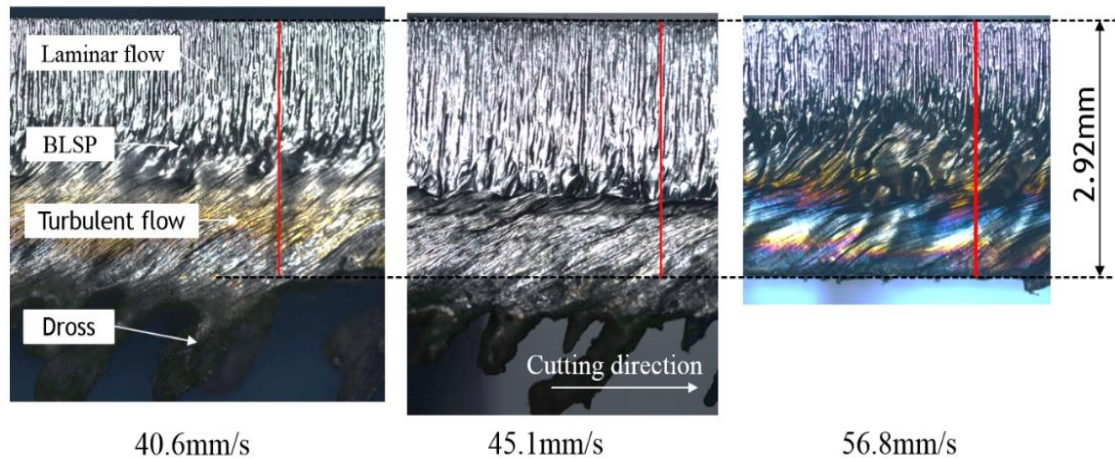


Figure 5.11- The cut front of 3mm stainless steel at different cutting speeds (laser power 1780W, N₂ 10bar and different cutting speed).

In Figure 5.11 three different cut edges are shown. The point along the cut edge where the flow separation occurs is referred to as the boundary layer separation point (BLSP). This BLSP is clearly seen in each case. Above this point a laminar flow regimes dominates and below it there is a back-flow of the melt material adjacent to the kerf wall and flow transitions into a turbulent flow in which the melt particles move in random paths. This transition to turbulent flow can cause disturbances in the laser cutting process. Such fluctuations in cutting may give increased cut edge roughness [112].

5.4 Theoretical modelling

To better understanding the interaction between the incident light and the cutting surface, and the behaviour of the primary energy losses (surplus energy) that is not directly involved in cutting process and the factors affecting it, a ray-tracing model has been used. This work was carried out in collaboration with Alotaibi et al. [57]. The work simulated predictions for the factors that affect the profile of the surplus beam and compared these with experimental results for 1.07 μm fibre laser cutting of 6mm thick stainless steel as described in the previous section.

5.4.1 Simulation methodology

A ray-tracing simulation was developed using MAT Lab software. In order to use a 2D model the 3D cut kerf geometry has been simplified: cut front and kerf walls have been considered as straight inclined lines as shown in Figure 5.12.

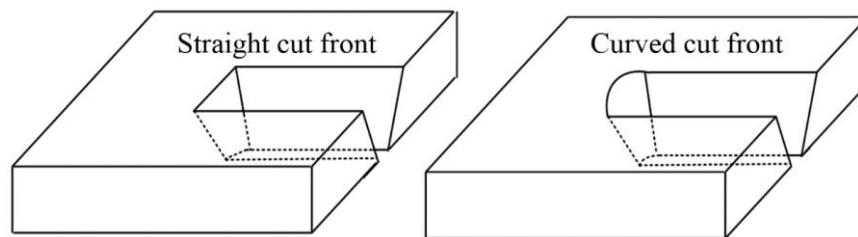


Figure 5.12- Schematic for straight cut front and real curved cut front.

The simulation was built by firing a number of photons of unit energy from a point 1.3mm above the surface over a range of directions so that the beam had diverged to a 200 μm spot at the surface like the laser beam used in this work. The direction of each

photon was determined by using random numbers, generated using the randn MATLAB function, that are normally distributed across the 0.153rad range. This is equivalent to assuming the beam had a Gaussian beam profile, but in reality the beam has an M^2 value of 25.7 and is therefore not a perfect Gaussian. Fresnel reflection and absorption equations were used to determine the extent of absorption at each reflection as a function of the angle incidence. The refractive index adopted and put into the Fresnel equation was that of molten iron obtained from [12, 113]. Each photon was ray traced until it either reached the collection sheet or its energy dropped below 1% of its initial energy or it was reflected back towards the source.

Black PMMA was located at a distance 17.5mm from the bottom of cut, as shown in Figure 5.13. The location and energy of each photon reaching the collection sheet was recorded and presented as an intensity profile.

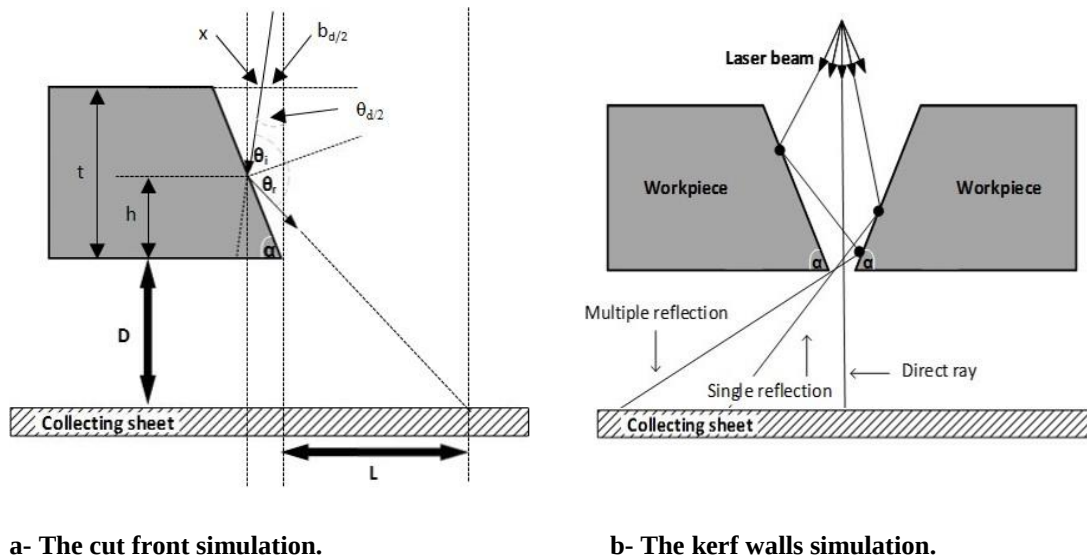


Figure 5.13- Schematic of two 2D ray-tracing simulation.

The equations used in this work are described in appendix 1. Two types of simulation have been run; for the cut front and kerf walls. The cut front simulation involves a single

piece of material as shown in Figure 5.13a, to simulate energy redistribution along the direction of the cut. The kerf walls simulation included the two kerf walls Figure 5.13b, and simulated the energy redistribution perpendicular to the cut direction. Intensity profiles have been determined for different cut front and kerf wall inclinations.

All the intensity profiles presented show the sum of the intensity of all photons reaching the collecting plane through the 6mm work piece thickness and 0.31mm bottom kerf width, unless otherwise specified. The width of each bin in the histograms is 0.1mm and zero on the x (distance) axis denotes the centre of the beam.

A pseudo 2D intensity profile was obtained by combining results from cut front and kerf wall simulations. This was obtained by treating the intensity profile generated by the cut front as a row matrix and multiplying this by a column matrix representing the modelled kerf wall intensity distribution.

5.4.2 Cut front simulation

The effect of the cut front inclinations is investigated by employing various cut fronts to simulate the experimental results. When the laser strikes the cut front the light will often be split into two parts. The first part passes directly through the cut zone and reaches the collecting plane with no losses, as shown in Figure 5.14d. The second part reflects off the cut front, the partial absorption during this interaction decreases the intensity of this reflected beam.

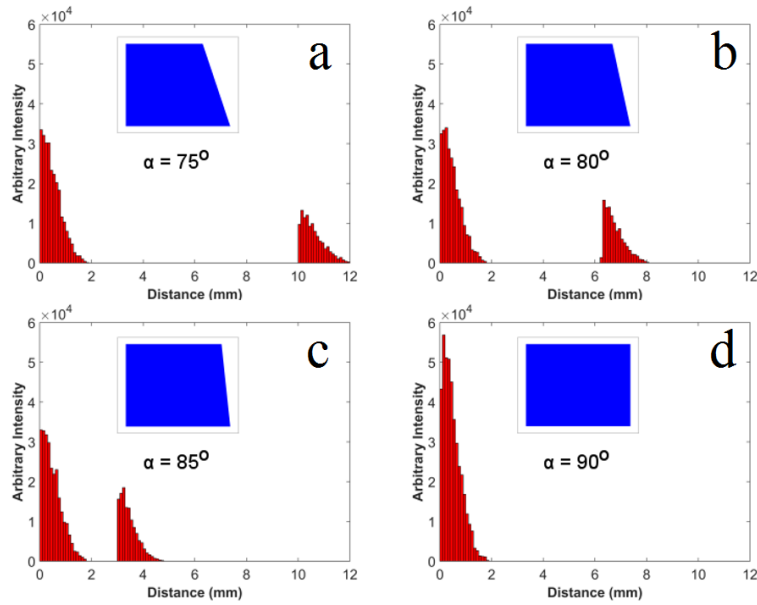


Figure 5.14- Simulations of different cut front inclinations.

5.4.3 Kerf walls simulation

The effect of the kerf walls is studied by using different kerf wall inclinations. For these simulations, the laser beam was centred on the midpoint of the bottom kerf as show in Figure 5.15.

In figure 5.15 the higher central peak corresponds to the portion of the light beam that passed directly through the kerf without interacting with the material. The other portions of the beam are of decreased intensity because they have undergone reflection and hence had their intensity reduced by partial absorption during reflection and so never reach the collection plate at high intensity. The intensity profiles for kerf wall inclinations of 30° and 45° are essentially identical, they have the same spread and the slight differences in the shape of the sole, central, peak are attributed to the process of using randn to determine the direction of each specific photon.

For kerf wall inclinations greater than 45° distinct side lobes with lower intensities than the main peak are detected. As the inclination angle (α) increases, the separation between the side lobes and the main peak decreases.

Narrowing the cutting kerf by half for 80° and 85° , as illustrated in Figure 5.15, widens the energy distribution. As discussed by Petring [58], the angle of incidence is progressively decreased by multiple reflections within the cutting channel. As well as increasing the extent of absorption at each reflection, this results in an increased angular spread of photons exiting the bottom of the cut, producing a large spread in the detected energy distribution at the collection plate.

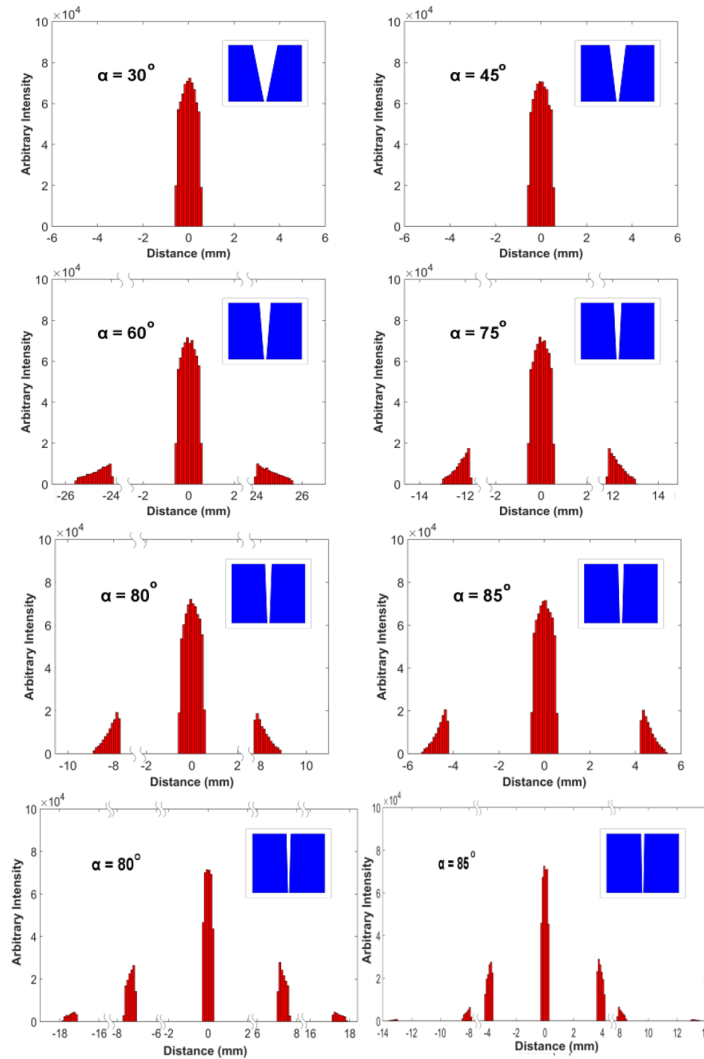


Figure 5.15- Intensity profiles for different kerf walls inclinations.

5.4.4 Kerf wall roughness effect

To investigate the effect of the kerf wall roughness, a single bump was attached to one side of the wall. The effect of the position of this bump on the collected intensity distribution is shown in Figure 5.16. The presence of the bump increases the spread of the intensity distribution, and decreases the size of the central peak.

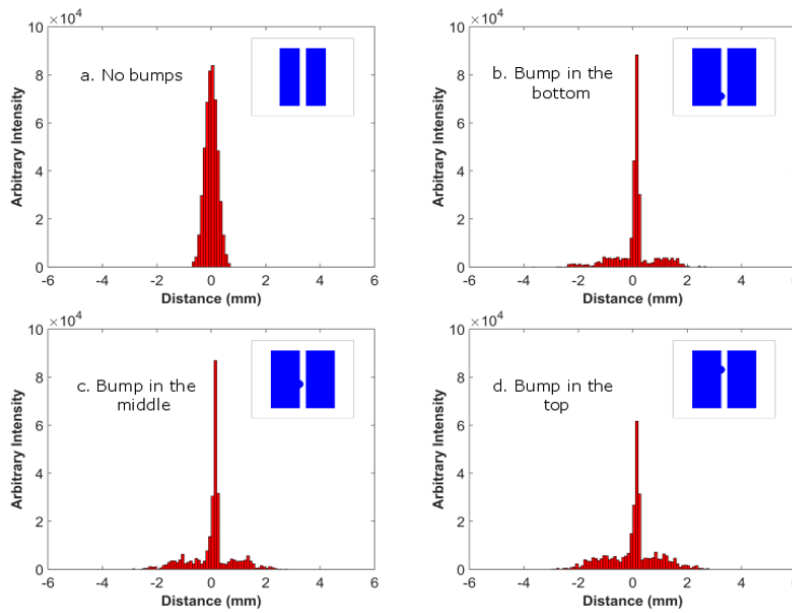


Figure 5.16- Intensity profiles for the kerf wells with different bumps.

It is seen that nearer the bump is to the top of the kerf the greater the effect it has. This can be understood by considering the ray diagram in Figure 5.17, after the bump is hit the angle of incidence is first dramatically changed and then more progressively decreased by multiple reflections within the cutting channel as discussed by Petring [58]. The higher up the cut this happens the more extensive the change in angle of incidence will be, and hence when the photons exit the cut they will be dispersed through a larger range of angles.

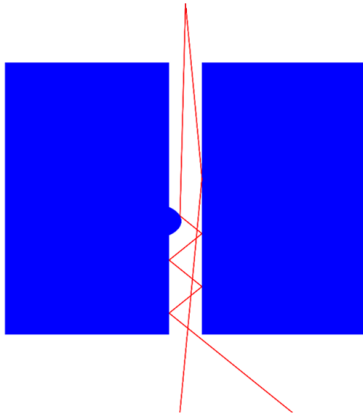
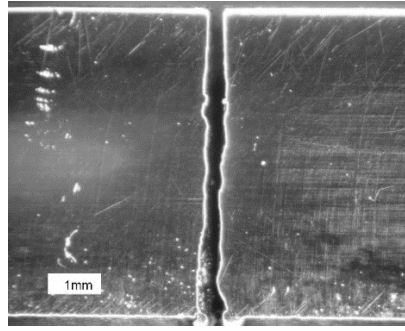


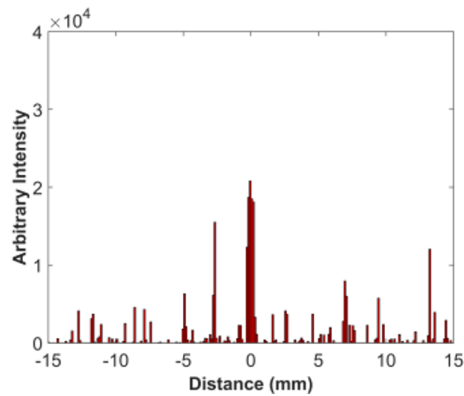
Figure 5.17- Simulation of bump at one side well.

In Figure 5.18a, real kerf geometries were extracted from metallographic cross-sections and imported into the model. It must be noted that these cross-sections show the final surface of the kerf walls and that this is not necessarily the same as a snap shot view of the roughness that existed during the cutting process. Nevertheless, it is clear that the assumption of flat kerf walls, and cut front, is not correct.

The modelled intensity profile from a real kerf geometry is shown in Figure 5.18b. The presence of roughness has resulted in a spread in the intensity distribution. As for the intensity distributions shown in Figure 5.16, this spread is attributed to multiple reflections within the kerf. The irregularity of the real surface has produced an irregular intensity distribution. The central, straight-through, peak is still clear however the distinct side lobes have now disappeared, being replaced with a less distinct, irregular intensity profile.



a- Cross section for 6mm stainless steel (Laser power 1850W, cutting speed 12mm/s and N₂ 13bar).



b-Modelled collected intensity distribution.

Figure 5.18- Cross-section of real cut and simulation of intensity distribution.

It clear that in Figure 5.18a shows some adherent dross at the bottom of the kerf, the effect of dross has also been modelled. Circular features representing dross were added to the bottom of the cut edge, with the centre point of the circular dross centred on the bottom corners of the kerf walls (Figure 5.19).

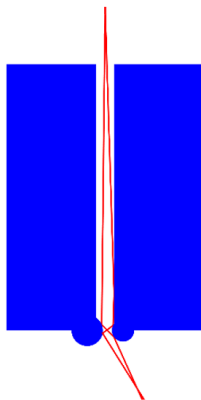


Figure 5.19- Ray tracing diagram showing effect of dross on path of photon through cut kerf.

In Figure 5.20 shows that the presence of dross modifies the modelled collected intensity profile. The lateral spread of the profile increases and the width of the straight-through peak decreases as part of it becomes blocked by the dross. Asymmetrical dross results in asymmetry in the collected intensity profile.

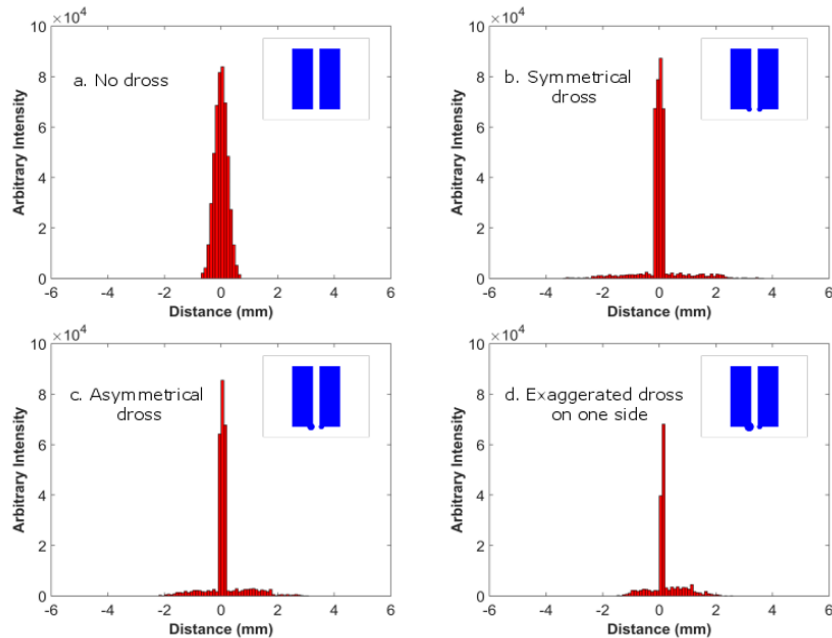
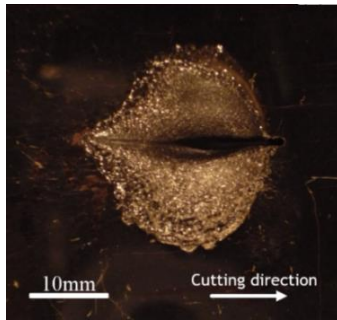


Figure 5.20- Simulation of intensity profile as a function of dross.

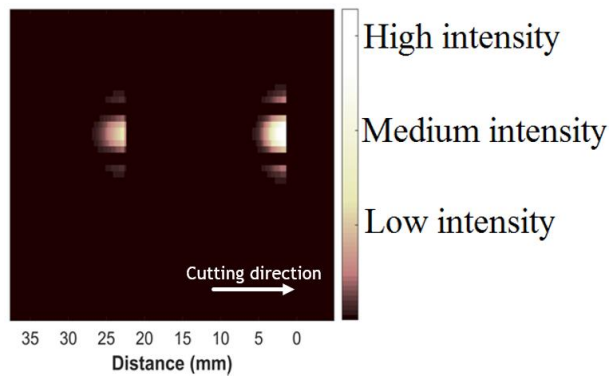
5.4.5 Comparison between modelled and experimental results

Figure 5.21 shows experimentally obtained and modelled 2D surplus energy distributions. The relationship between the lateral extent of the intensity profile generated by the cut front and cut front inclination angle was shown earlier. The 2D surplus energy distribution shown below was generated using a cut front inclination of 66° . The good match in lateral extent of the two distributions could be taken to indicate that this is the actual cut front inclination. However, this inclination is not as large as would be expected from the published literature on fibre laser cutting [13].

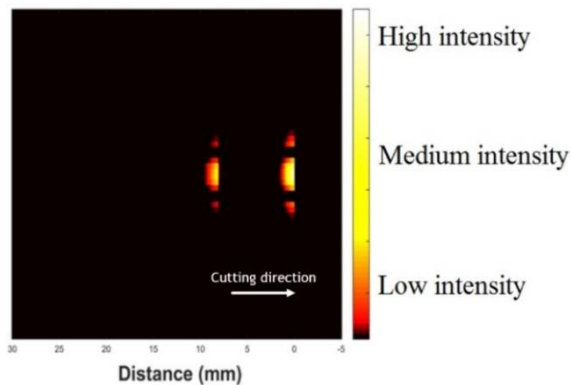
It must be noted that the modelled 2D energy distribution did not include any effects of dross or roughness of the cut front, effects which results presented above show would increase the spread of the energy distribution, hence it is not appropriate to attempt to match the extent of spread of the energy distribution here and a different approach is required.



a-Experimental result from cut 6mm stainless steel (Laser power 1850W, cutting speed 12mm/s, N₂ 13bar, and 17.5mm the collection distance from the end of nozzle to CFBA)



b-Modelled of the cut front inclination 66°.



c-Modelled of the cut front inclination 77.5°

Figure 5.21- The results of experimental and modelled 2D surplus energy distributions.

Examination of the experimental profile clearly shows a main, central, region starting with the straight through beam, then broadening to a maximum after approximately 10mm. This will be the location of the beam reflected from the cut front. The modelled 2D surplus energy distribution has been regenerated to take this into account. It was found that a cut front inclination of 77.5° placed the main reflected beam in the same region as the broadest point of the central part of the experimental surplus energy distribution. This is in line with previously published reports of cut front geometry [13]. The remaining area of the experimental 2D surplus energy distribution, i.e. the area that extends approximately 10mm from the main central region, is attributed to the effect of roughness producing a large spread in the directions of photons exiting the cut. This is consistent with the geometry of this region: symmetrical about the cut line, due to the two sides of the kerf but extending only backwards, away from the cut front along the cut line since in this direction there is only the cut front with no rear wall to generate multiple reflections.

5.5 Relationship between two models and limitation

Use of the simple 2D model allows effects of the cut wall geometry and the cut front geometry to be considered in isolation. This is a limitation as full 3D consideration of light propagation in the cut leaf cannot be carried out. However the simple modelling allows some aspects of cutting to be investigated.

The main findings are which parts of the leaf print are affected by which parts of the cut front geometry. The leaf print dimensions can be tied in with the modelled results, however the overall leaf shape cannot. This indicates that the leaf shape is controlled by aspects of cutting not included in the model, such as cut front curvature. This can be

used to indicate what features of any further model development should be prioritised in order to better understand the leaf prints.

5.6 Beam print discussion

The beam prints collected for a wide range of powers, cutting speeds and different thicknesses demonstrate that fibre laser cutting produces distinctive leaf shape beam prints.

These leaf prints can be used quantitatively. It is seen that the amount of surplus, wasted, power decreases as cutting speed increases. However, the threshold effect must not be forgotten. Lower power laser beams will produce lower intensity irradiation of the CFBA, with a greater proportion of that irradiation being below the evaporation threshold.

Leaf print shape and dimensions can be used to provide qualitative insight into the fibre laser cutting process. Similarity in leaf print width has been shown to correspond to similarity in kerf wall profile. The length of the leaf print has been shown to be determined by the cutting front inclination.

What has not been explored in this work is the curvature of the edges of the leaf print. It is expected that this is related to the curvature of the cut front. Such curvature was not incorporated into the simple 2D ray tracing modelling work reported here. More detailed modelling is required to explore this effect.

5.7 Summary

In this chapter the results of experiments which gave qualitative information about the primary energy losses (also referred to here as ‘surplus power’) from the cutting process were presented. Theoretical models have also been investigated in order to understand the laser density distribution below the cutting kerf. The first model was able to calculate the geometry of the cutting front and surplus density distribution below the cutting kerf by using two software packages; CALCut and Zemax. The second model was able to study the additional factors that affect the profile of the surplus beam.

5.7.1 Results from experiments

The ‘leaf’ print evaporation patterns were found to be of similar geometry for the 3 and 6mm thick stainless steel cutting trials. In each case there is clear evidence of a deeper evaporated hole at the ‘stem’ end of the leaf, which was largely created by the vertically impinging transmitted beam. The shallower ‘leaf’ is an evaporation pattern created by the reflected portion of the beam. This consists of two wings joined by a central, deeper line.

The leaf prints taken below the cutting process for the thicker material were larger in size (50% longer and 50% broader) this is due to the fact that a thicker material has a deeper cutting zone which will result in more multiple reflections. If more multiple reflections take place the beam emitted from the bottom of the cutting zone will be more divergent and will give bigger leaf prints.

5.7.2 The effect of various cutting speed on the results ‘leaf’ evaporation shapes

- The investigation of the ‘Leaf’ shapes revealed that at highest cutting speed the ‘leaf’ shape largely disappears leaving a small print which is elongated in the direction of travel.
- The results of the amount of material removed from the CFBA for various speeds for both thicknesses indicate that as cutting speed increases the surplus laser light decreases in linear manner.

5.7.3 The effect of laser power on the results ‘leaf’ evaporation shapes

Three laser powers were used to investigate ‘leaf’ shapes at various cutting speeds and the surplus power was measured.

- The results of ‘leaf’ shape demonstrate the absorption of incident energy by the target material increases with increases in laser power.
- At low laser powers the amount of surplus energy evaporating the PMMA target reduces rapidly. This is probably because a greater proportion of the surplus beam is below the energy threshold for evaporation.

5.7.4 Theoretical Models results

Theoretical models of the laser-materials interactions and the additional factors that influence the profile of the surplus energy were investigated.

5.7.4.1 CALCut and Zemax Software

- The ‘leaf’ shapes were formed by a high energy density spot at the stem end together with indications of a central line surrounded by widespread symmetrical energy density which fades with distance from the central line.
- There is clear evidences that the stem of the ‘leaf’ is a deeper hole created by the transmitted beam whereas the body of the ‘leaf’ is an evaporated pattern related to the part of the beam which has been reflected from the cutting zone and/or scattered by the stream of droplets leaving the bottom of the cutting zone.

5.7.4.2 2D ray-tracing model

The models studied the intensity distribution of the surplus beam exiting the kerf as a function of the cut kerf inclination angle. The results can be summarised as follows:

5.7.4.2.1 The effect of cut front

- The model shows that the laser beam splits into two parts when it hits an inclined cut front.

5.7.4.2.2 The effect of kerf walls

- The kerf wall inclination greater than 45° gives distinct side lobes with lower intensities than the main peak.

- As the inclination angle (α) increases the separation between the side lobes and the main peak decreases.

5.7.4.2.3 The effect of kerf walls roughness

- The bigger effect of the position of the bump on the collected intensity distribution is nearest to the top of the kerf.
- Increasing the number of bumps increases the spread of the intensity distribution and decreases the size of the central peak.
- The effect of dross increases the lateral spread of the profile and the width of the straight through peak decreases as part of it becomes blocked.

5.7.5 Overall

The results presented in this chapter establish that the beam prints collected using CFBA placed stationary with respect to the laser head during fibre laser cutting have a distinct “leaf” shape. The leaf stem is clearly associated with the directly transmitted beam whereas the body of the leaf is generated by reflected and/or scattered laser irradiation.

The leaf prints can be used in both quantitative and qualitative analysis of fibre laser cutting.

Full understanding of the leaf prints, and all they can reveal about the cutting process, has not yet been achieved. Further modelling work, which includes cut front curvature, is required so that this can be done.

6 Threshold effects in the interaction between carbon filled acrylic and fibre lasers

The purpose of this chapter is to understand the effect of an energy/power threshold on the ablation of carbon filled black acrylic (CFBA) and how this depends on the characteristics of the laser beam and the properties of the material that is being ablated. To become ablated the acrylic needs to achieve a certain temperature. This temperature is reached as a result of absorption of energy, which is a function of power and exposure time. However, at low energy densities the acrylic can conduct and reflect enough laser light that the ablation temperature threshold will not be reached.

If the laser does evaporate a beam print in the material it will also form a heat-affected zone (HAZ) surrounding the evaporated print as shown in Figure 6.1. This HAZ is created by sub-ablation threshold absorption of heat from the laser beam. The surface changes made in the HAZ show that there two thresholds for this laser-material interaction;

- a- The threshold for ablation
- b- The threshold for HAZ creation

The results previously presented in section 4.2.2 on the thermal behaviour of black PMMA attributed a melting temperature of 243°C to CFBA according to the Differential Scanning Calorimetry (DSC). This will be the temperature reached at the interface between the HAZ and the ablation zone. This means that the energy threshold for ablation must equal the energy needed to raise the surface temperature to 243°C.

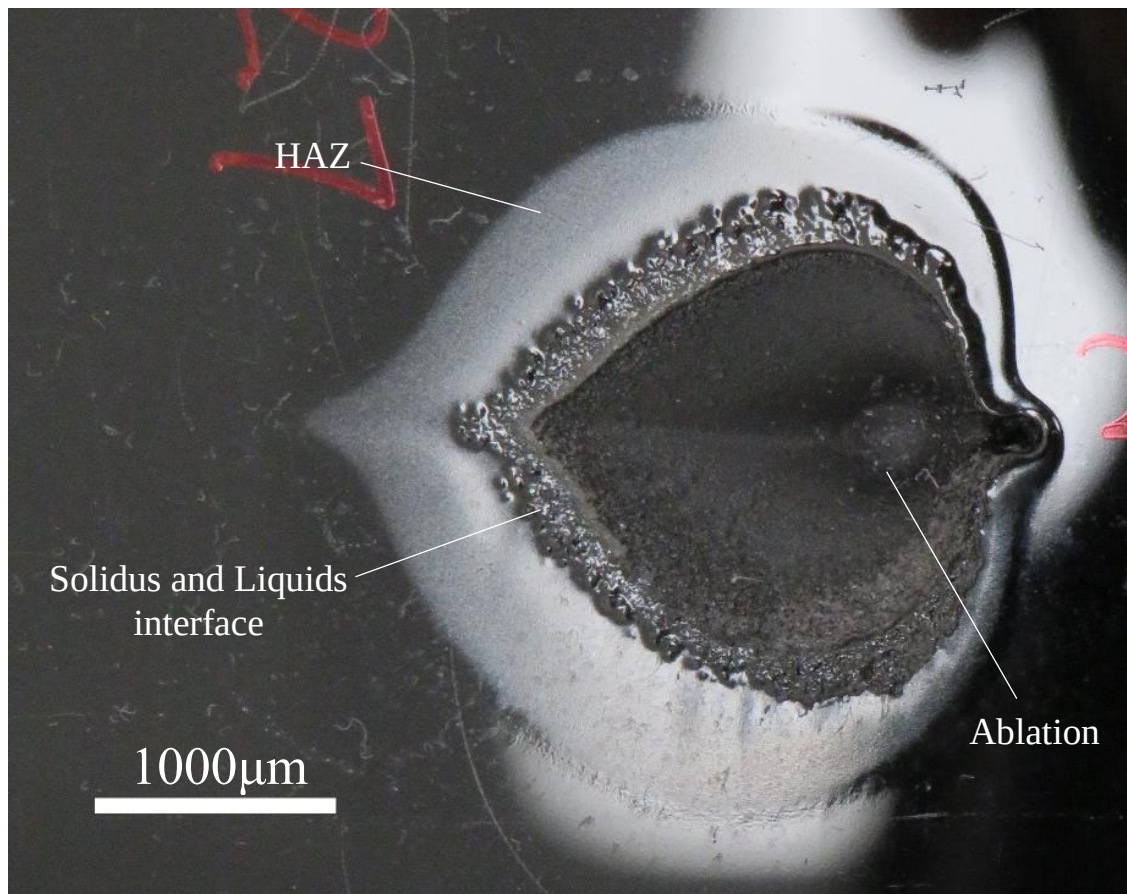


Figure 6.1- The HAZ, solidus and liquids and the ablation zones of a ‘leaf’ shape print taken below the cutting zone when cutting 3mm stainless steel at laser power 1200W, N₂ 8bar, 27.5mm/s and vertical distance between bottom of cut to CFBA is 17.5mm.

It has been observed that the width of ‘leaf’ prints initially gets bigger, then smaller with increasing distance of the CFBA target from the beam focus. This is attributed to a threshold-limited effect, illustrated in Figure 6.2.

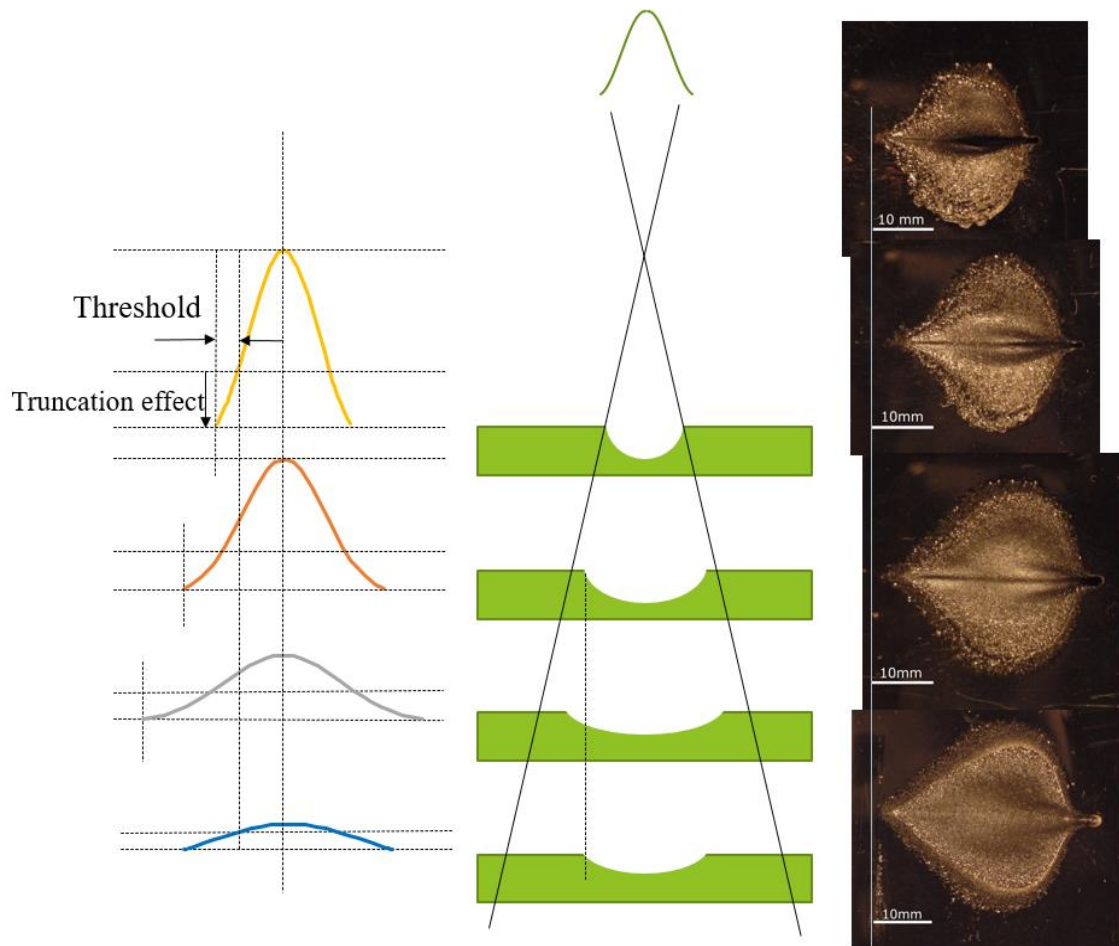


Figure 6.2- The effect of threshold on ‘leaf’ shape print as a function of distance when cutting 6mm stainless steel at laser power 1850W, N₂ 13bar, 12.15mm/s and different vertical distances between bottom of cut and the CFBA target of; 17.5, 23.5, 29.5 and 35.5mm.

As can be seen in the figure above, the threshold effect truncates the effect of the laser beam when the beam is greatly defocussed. This truncation effect means that, for a greatly defocussed beam, a large part of the laser beam incident on the CFBA does not contribute to the ablation of the material. In these circumstances leaf prints and beam prints in black PMMA cannot be used for quantitative work.

The next section of this chapter compares experimental measurement of standard circular beam prints with measurements of the laser beam profile in order to determine

the extent of the threshold effect. The chapter then goes on to discuss leaf prints and finally, grooves produced by defocussed moving beams.

6.1 Beam profile results

More details of the experimental set-up were described in chapter 3; however, a brief summary of the parameters used is presented in Table 6.1. Circular beam prints were made in CFBA targets held 15mm below the focus of the beam at different power and exposure times.

Table 6.1- The experimental parameters.

Descriptions	Values
Laser power	500, 1200 and 1800W
Vertical distance from focused beam to CFBA	15mm
Irradiation time	1,2,3,4 and 5ms
Assist gas type and pressure	N ₂ 5bar
Fibre delivery diameter	200µm
Focal length of collimator	125mm

Actual beam energy profiles were measured using a PRIMES beam analyser at a series of planes with different distances from the focal point (Figure 6.3).

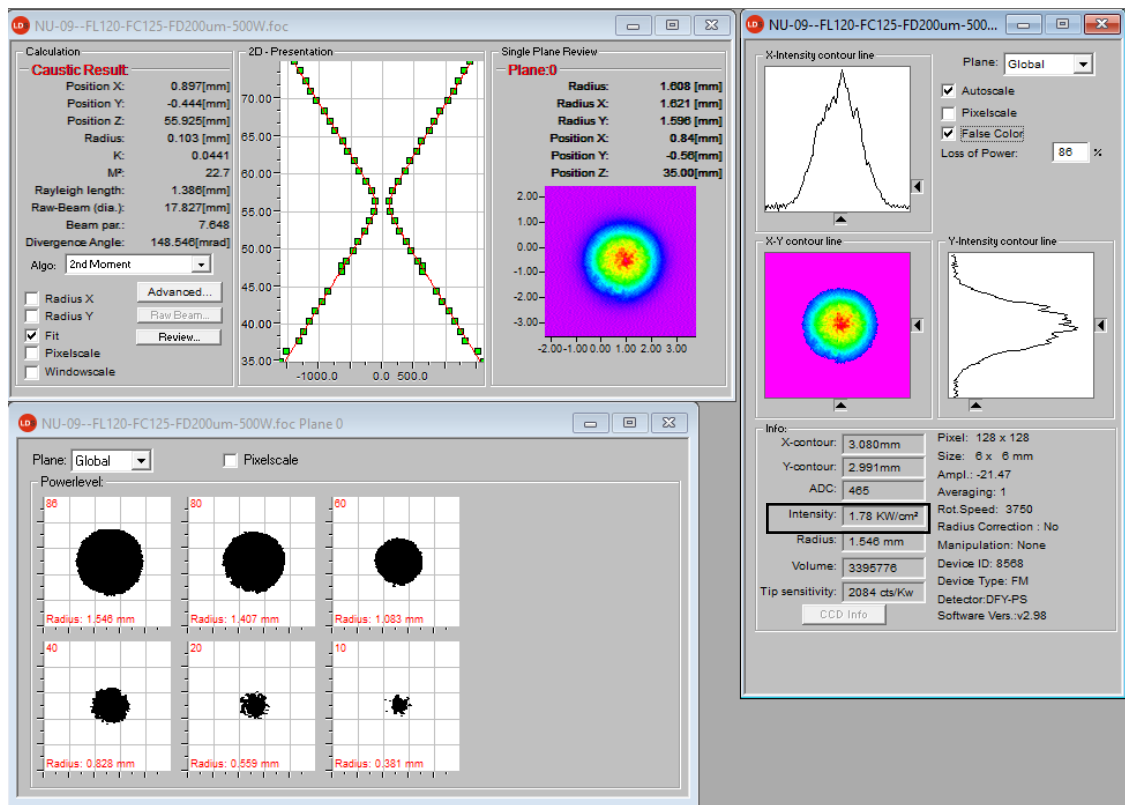


Figure 6.3- Focussed beam profile of 200µm with FL 120mm for laser power 500W.

As shown in the PRIMES laser diagnostic software screen shot, one output is an approximately circular print within which the energy density is above a chosen value (kW/cm^2). That chosen value is at the perimeter of the shape and, in this experiment, the energy density then rises towards the centre of the beam.

The circles created by the software were then compared to circular beam prints taken at different powers, interaction times and distances from the focus of the beam. Typical results determined in this way are presented in Table 6.2.

Table 6.2- The experimental results.

Laser power	Irradiation time	Distance from focus	Radius measured	Intensity that match radius	Energy density at edge
W	ms	mm	mm	kW/cm ²	J/cm ²
500	1	15	0.343	11.79	11.79
	2		0.793	8.36	16.72
	3		0.877	6.68	20.04
	4		0.957	5.72	22.88
	5		1.003	5.19	25.95
1200	1		0.88	16.13	16.13
	2		1.06	10.45	20.9
	3		1.103	9.33	27.99
	4		1.155	6.45	25.8
	5		1.171	7.56	37.8
1800	1		1.025	16.23	16.23
	2		1.102	13.04	26.08
	3		1.191	10.41	31.23
	4		1.244	10.28	41.12
	5		1.25	8.36	41.8

From Table 6.2, it is clear that there is no single, well-defined, threshold energy density (J/cm²) value. For 500W beam the value varies from 11.79 at an interaction time of 1ms to 25.95 at an interaction time of 5ms. At higher powers the range is even bigger. For example, for 1800W it is 16.23 at 1ms but 41.8 at 5ms.

Similarly, if time is fixed but power increases then a larger diameter beam print is produced, as illustrated in Figure 6.4.

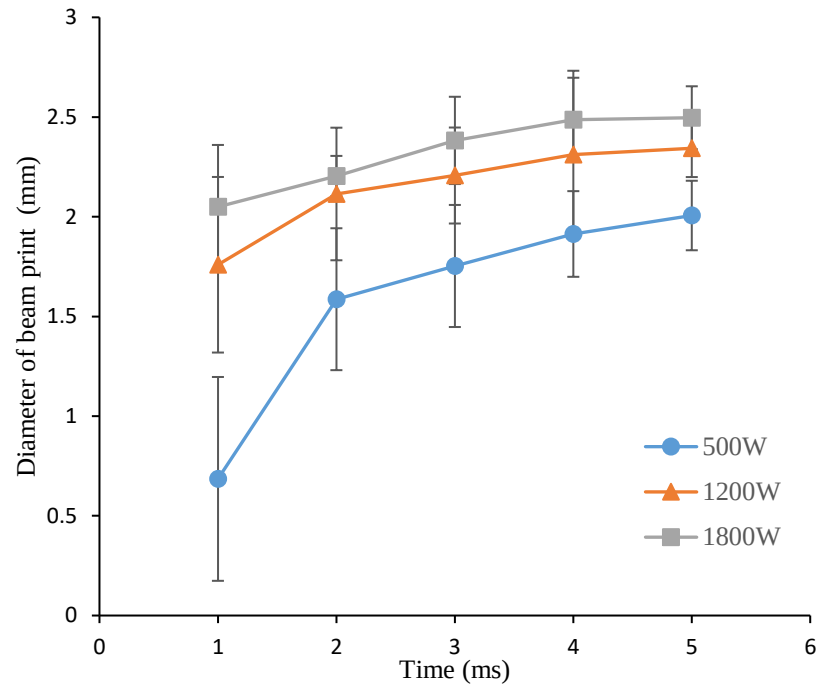
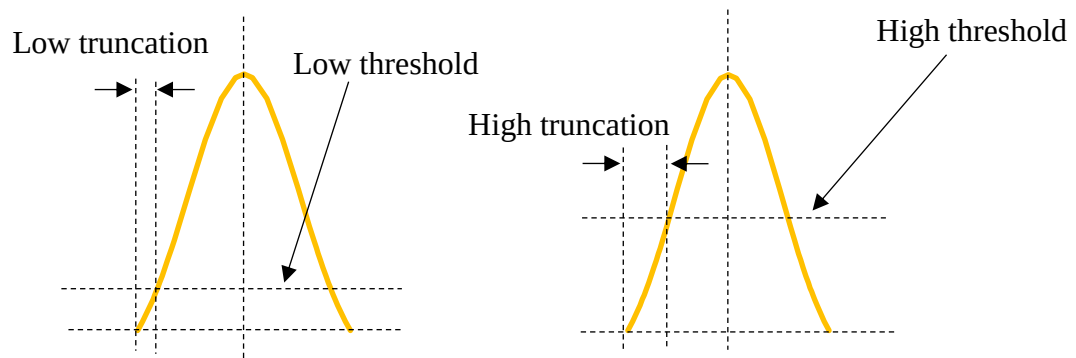


Figure 6.4- Increases in laser power tend to increase the diameter of beam print.

There will always be some kind of threshold effect, the key thing to be aware of is when this is significant enough to prevent the quantitative use of black PMMA. The threshold effectively truncates the intensity distribution of the beam as shown in Figure 6.5. When the threshold level is low compared to the beam intensity then there is minimal truncation of the beam (the truncation line is close to the x axis). When the threshold level is higher compared to the beam intensity then there is significant truncation of the beam (the truncation line is somewhere between the x axis and the maximum intensity).



a-A small threshold effect

b- A large threshold effect.

Figure 6.5-The level of truncation of the ablated area depends on how high the threshold for ablation is.

When significant truncation occurs this indicates that there is a significant threshold effect. This means that a significant proportion of the incident energy does not contribute to removing black PMMA, hence a smaller than expected beam print or leaf print is generated. The incident energy that does not remove black PMMA is reflected or conducted away through the sample and can generate a surrounding heat affected zone.

The heat affected zone is the region of material in which the temperature is not high enough to remove black PMMA, but it is high enough to generate some observable effect on the material. For black PMMA this corresponds to the region in which surface distortion was observed (see section 4.3.2 for details of absorption depth). Typical heat affected zones are visible in Figure 6.6.

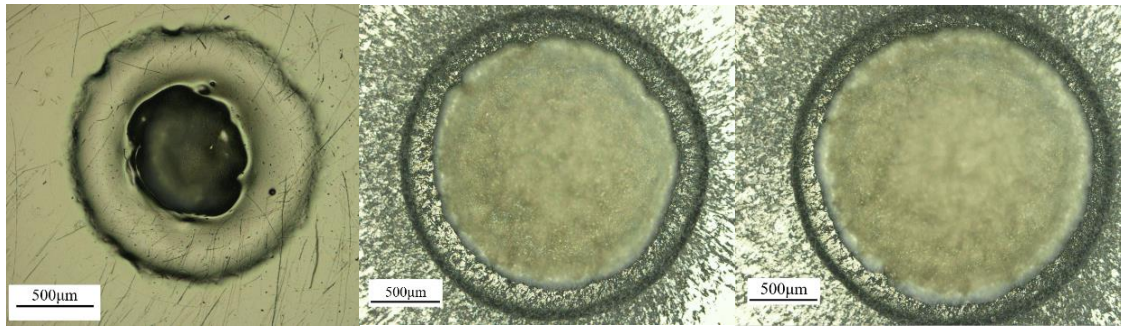
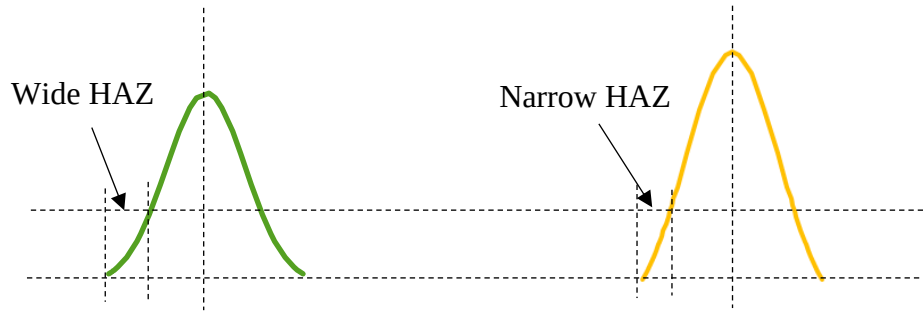


Figure 6.6-The Heat affected zone for a target CFBA at vertical distance 15mm from focused beam with different laser power and same irradiation time 1ms. Left) 500W. Middle) 1200W. Right) 1800W.

It has been seen that the width of the heat affected zone decreases as power increases, with all other parameters remaining constant. This can be explained by considering the thermal gradients generated in the material.

When using a higher power, there is a more rapid spatial variation of intensity, i.e. the gradient of the beam profile through the threshold point is higher. This decreases the dimensions of the area of black PMMA which is heated, but which does not reach the threshold temperature. This is illustrated schematically in Figure 6.7a, which assumes that the width of the beam changes only a little with increasing power- a point which is confirmed in the beam analyser information presented in Figure 6.8. If the width of the beam remains almost constant when the power is increased then the slope of the energy curve becomes more acute with increasing power- as shown in Figure 6.7.



a-At lower power with higher HAZ region b-At higher power with lower HAZ region

Figure 6.7-Lower power beams can give a broader HAZ.

When power increases there is a smaller distance between the threshold point and the edge of beam as illustrated in Figure 6.7b.

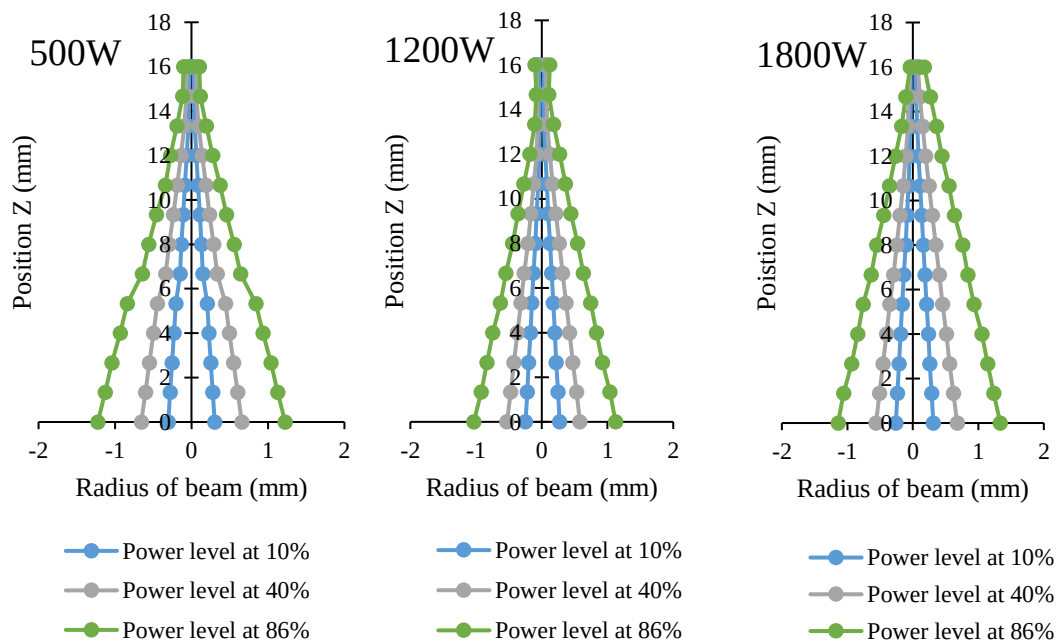


Figure 6.8- Measured laser beam results from PRIMES beam analyser software.

6.2 Threshold effect as a function of distance

The initial increase in beam print width with distance from focus is due to the beam expanding and the region heated above threshold expanding in size, as seen in the first three levels in Figure 6.2. However, as the beam expands, the intensity progressively decreases. There comes a point where this decrease in intensity means that the area of the beam which exceeds the threshold starts to decrease with distance, as seen for the final level of Figure 6.2.

In Figures 6.9 and 6.10 the increase and subsequent decrease of the beam print diameter as a function of distance from the focal plane has been mapped and superimposed on the beam analyser results. In each case the ablation energy density has been taken as being the density at the edge of the beam print created 15mm below the focal plane (see Table 6.3). The radius at which this energy level is reached has then been calculated for all the other distances from the focal plane and the rise and fall of the beam print diameter is clear. For the higher power beams the effect is much smaller than for the 500W beam as would be expected. Figures 6.9 and 6.10 also confirms the fact that the results are different for all the interaction times – so this type of beam print is not reliable quantitatively.

When using transparent PMMA to obtain beam prints from CO₂ lasers there are rules of thumb which are different depending on why you taking a beam print [4].

- 1- For a beam print which identifies where the beam is (e.g. is it hitting the centre of the mirror?) then the beam print should be taken as quickly as possible to create a shallow impression on the acrylic.

- 2- For a beam print which identifies the mode (energy density distribution). The beam print should be approximately as deep as it is wide (if the mode print is too shallow it will not give a clear energy distribution, but if it is too deep then the hot gasses have time to erode the shape of the indentation and the mode print will be smoothed out and inaccurate).
- 3- For quantitative beam prints, they should be as narrow as possible to minimise threshold effects- and should have an aspect ratio of five (depth) to one (width) or more.

If we remember rule 3 it is not surprising that these shallow beam prints are not useful quantitatively.

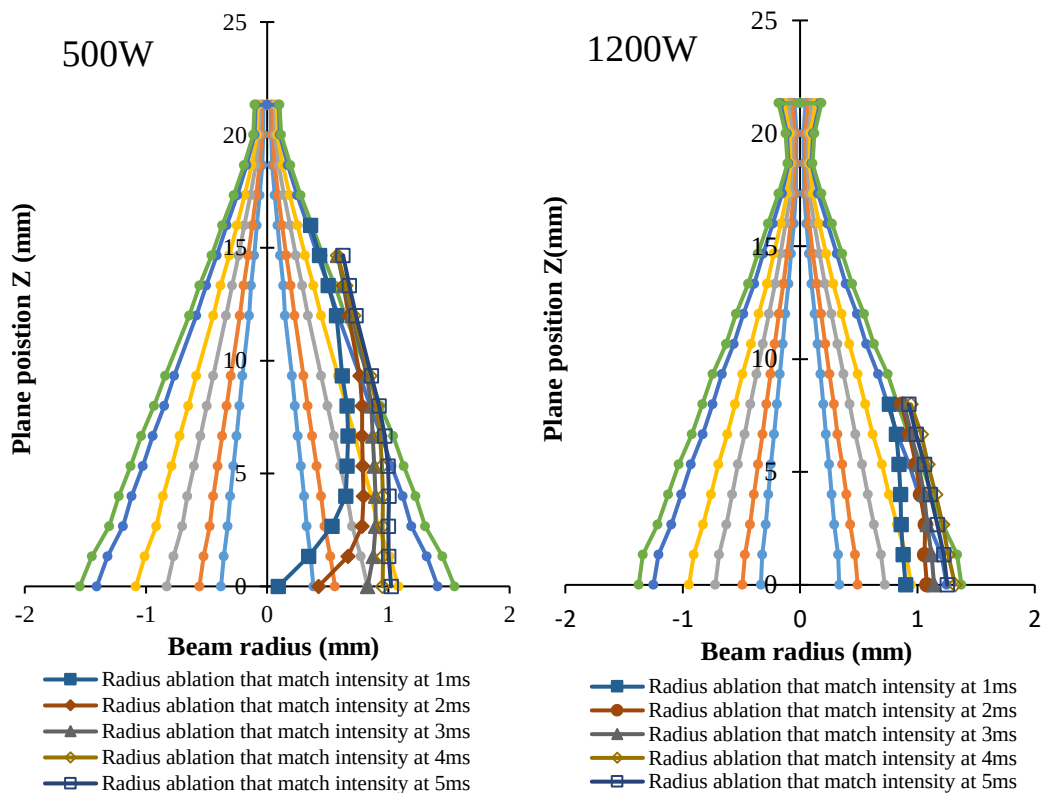


Figure 6.9- The intensity distribution that matches the radius of experimental results at laser power 500W and 1200W, taken print at 15mm from focused beam and irradiated time 1, 2, 3, 4 and 5ms.

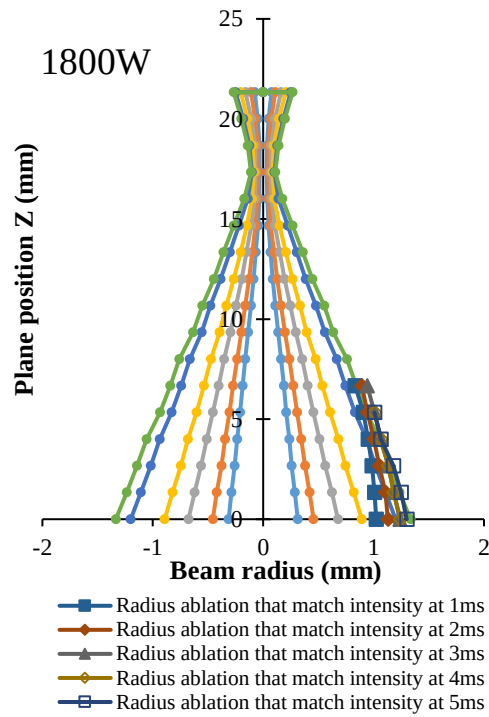


Figure 6.10- The intensity distribution that matches the radius of experimental result at laser power 1800W, taken print at 15mm from focused beam and irradiated time 1, 2, 3, 4 and 5ms.

Table 6.3- The dimensions of beam print taken 15mm below the focal plane for different power and irradiation times.

Laser power	Irradiation time	Distance from focus	Hole dimensions		Width of HAZ "both side"
			diameter	depth	
W	ms	mm	mm		mm
500	1	15	0.685	0.09	0.888
	2		1.586	0.077	0.419
	3		1.753	0.168	0.462
	4		1.913	0.242	0.317
	5		2.006	0.316	0.330
1200	1		1.759	0.108	0.388
	2		2.114	0.224	0.299
	3		2.206	0.350	0.324
	4		2.310	0.464	0.212
	5		2.343	0.542	0.226
1800	1		2.049	0.138	0.259
	2		2.204	0.327	0.329
	3		2.382	0.495	0.302
	4		2.487	0.643	0.285
	5		2.496	0.767	0.299

Threshold effects are of wider relevance to laser material processing applications such as laser surface melting, laser hardening etc. In these processes area coverage can be increased by defocussing a beam, however this is no longer beneficial once the area above the relevant threshold decreases rather than increases.

It is therefore useful to know when this effect is occurring. For black PMMA the presence of a visible heat affected zone is an indication that not all incident energy is being used to remove material. The presence of a heat affected zone can therefore be regarded as indicating that the sub-threshold heating effect is becoming important.

6.3 Investigate of ‘leaf’ shape prints as a function of distance

To investigate the changes in shape and size of the ‘leaf’ beam prints taken below cutting zones as a function of distance from the cutting zone, photographs of the leaf prints were taken by using a single set of cutting conditions at different distances from the bottom of the cutting zone to the surface of the black PMMA.

More details of the experimental set-up were described in chapter 3; however, a brief summary of the parameters is presented in Table 6.4.

Table 6.4- The experimental parameters.

Laser power	Thickness of work piece	Cutting speed	Gas pressure (N₂)	Vertical distance(z') from bottom of cut to CFBA			
W	mm	mm/s	bar	mm			
1780	3	43	10	17.5	23.5	29.5	35.5
1850	6	12	13				

Photographs of the leaf prints for the 6mm cutting are presented in Figure 6.2. The 3mm cutting results are presented in Figure 6.11. One main point of interest is that, although the detailed shape of the leaf changes slightly, the overall size of the print (indicated by large red circles) does not substantially change even though the distance from the cutting zone has approximately doubled, from 17.5mm to 35.5mm. It is clear from Figure 6.11, and from the fact that the ‘stem’ hole diameter increases linearly with distance, that the reflected portion of the beam must also be growing in diameter. The lack of increase in the diameter of the body of the leaf print must therefore be associated with a sub-threshold effect. The reflected beam gets broader with distance but the outer wings of the beam do not exceed the damage threshold and are therefore not recorded in the print. This demonstrates that such ‘leaf’ prints can only be quantitatively useful.

From a qualitative point of view it is interesting that the leaf prints taken at a larger distance from the cutting zone show a more pronounced central line, which is probably the contribution of reflections from the central portion of the cutting front. In the prints taken closer to the cutting zone this deeper central line is integrated out in the generally more energetic evaporation event taking place as a result of there being a higher power density.

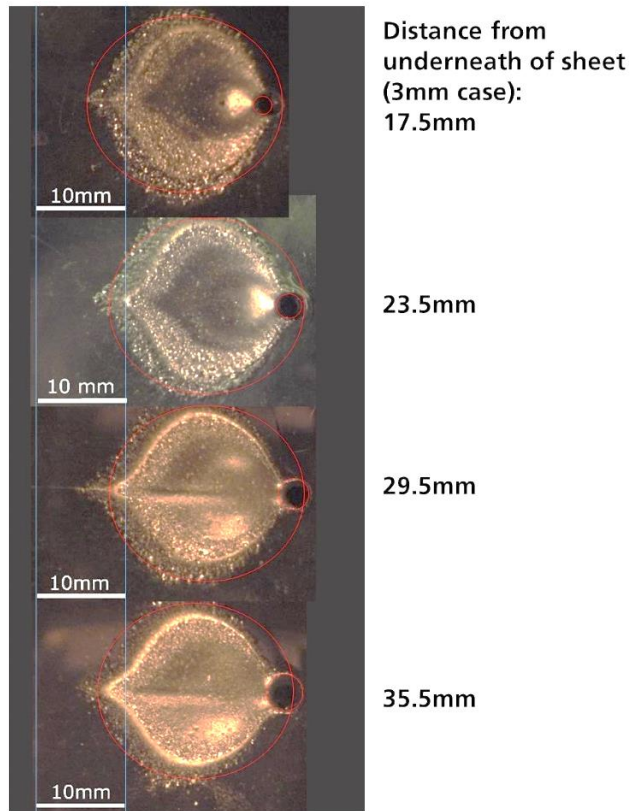


Figure 6.11- Photographs of the leaf print taken under same cutting parameters at different distances from the bottom of the cutting zone.

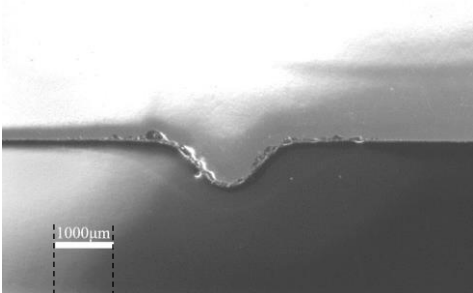
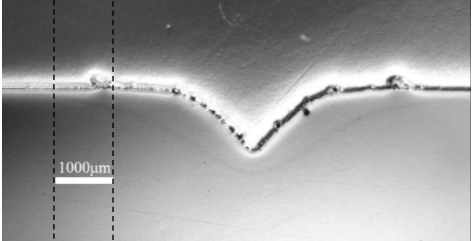
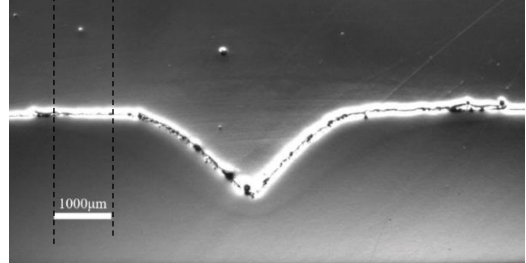
6.4 Primary losses from the cutting zone

Experiments were carried out based on the type of experimental set-up described in Figure 3.20a to determine the surplus energy leaving the bottom of the cut zone during fibre laser cutting of stainless steel and to identify sub-threshold effects.

More details about these experiments are given in chapter 3. In this case the cut material and the target CFBA sheet were both stationary and the laser head was moved at typical cutting speeds for the material involved (see Table 3.18).

For each cut this resulted in an evaporated groove in the CFBA sheet as shown in Table 6.5. A cross section of the groove was measured later to estimate the volume of material evaporated per second during the cutting process. The cross-sectional area of the groove multiplied by the cutting speed multiplied by the specific energy of evaporation then gives a result related to the magnitude of the primary losses (in the vertical direction) at energy levels which exceed the evaporation threshold.

Table 6.5- The cross section of evaporated grooves at different cutting speed and thicknesses.

Thickness of work piece mm	Cutting speed mm/s	Cross sectional of groove	
3	166.7		
4	103.3		
6	56.7		

As discussed earlier, the evaporation of any solid material by a laser beam involves overcoming a threshold energy density. As mentioned in section 4.3.2, this threshold can be reduced to a trivial component of the overall interaction when dealing with a high power beam close to its focus of a stationary target.

However, a broad, defocussed beam moving rapidly over the surface of a target might leave little or no groove of evaporation because the interaction does not exceed the threshold energy density. A likely result is that a combination of movement and defocusing will result in an evaporation pattern which involves only a fraction of the primary losses.

In order to minimise threshold effects during the cutting/evaporated groove experiments, the target sheets of CFBA were placed as close as possible to the bottom of the cut zone without interfering with the ejection of melt and cutting assist gas from the bottom of the cut. Initial trials indicated that a distance of 3mm was suitable and this was used when cutting 3, 4 and 6mm thick material. This proximity of the acrylic target to the bottom of the cut zone had the advantage that a separate plume-flushing air jet was unnecessary, because the cutting gas jet itself flushed the plume from the area.

Table 6.6- The results of cutting experiments.

Thickness of work piece	Cutting speed	Cross sectional area of evaporated groove (A)	HAZ (R)	Displaced area (M)	Primary loss
mm	mm/s	mm ²	mm ²	mm ²	W
3	166.7	0.728	3.108	0.044	450
4	103.3	1.239	3.211	0.140	460
6	56.7	2.339	4.071	4.071	467

The results of the ‘cutting/groove’ experiments presented in Table 6.6, suggest that the above threshold average primary losses from the cut zone account for only approximately 11% of the output power of the laser (Bystronic 4kW) in each case. The CALCut model suggests that at most 40-45% of the beam power is absorbed on the cutting front and contributes to the cutting process. However, this does not necessarily mean that a primary loss level of at least 55-60% could be detected below the sheet. In fact, the effects listed at the beginning of Chapter 5 have to be taken into account.

There are a number of reasons why the experimental values for primary losses and theoretical values calculated from absorption estimates are so different. One consideration is the direction of travel of the reflected beam. In the case of a CO₂ laser cutting front the reflective surface is relatively smooth and almost vertical. This means that the reflected portion of the beam travels almost vertically downwards (as shown in Figure 2.34b) to impinge on the acrylic target. However, a fibre laser cutting front is covered in bumps, as demonstrated in the CALCut simulation [114]. The geometry of these bumps directs a proportion of the reflected beam back down the kerf where it is subject to more absorption/reflection interactions [57]. This means that not all of the reflected beam interacts with the acrylic target.

Another consideration is the interaction of the beam with the stream of droplets leaving the cutting zone. The absorption events will remove energy from the beam and the scattering effect will reduce the energy density of some areas of the beam to below the threshold for evaporation of the acrylic.

The divergence of the one micron wavelength beam leaving the bottom of the cut zone is very high compared to that of a CO₂ laser beam as a result of multiple reflections

[115]. In other words, the multiple reflections tend to deflect the beam towards the horizontal and this results in a large divergence of the primary losses beam as it emerges from the bottom of the cutting zone. This effect is increased when thicker materials are cut.

One other important point was raised at the beginning of this chapter – there is no clear value for the threshold energy for ablation.

To identify the effect of beam movement and related threshold effects on the results shown in Table 6.6, groove trials involving only the target CFBA with no cutting process above were carried out. The beam was defocussed until grooves of similar width and cross sectional area were generated at the same cutting speed as one of the runs in Table 6.6 (166.7mm/s). It was discovered that an 800W beam gave a similar groove shape and volume (an evaporated cross-sectional area 0.76mm^2 as compared to 0.72mm^2 in Table 6.6) as shown in Table 6.7.

Table 6.7- The results of the grooving with no metal.

Laser power	Cutting speed	Assist gas and pressure (N_2)	Cross sectional area of evaporated groove (A)	HAZ (R)	Displaced area (M)	Primary loss
W	mm/s	bar	mm^2	mm^2	mm^2	W
500	166.7	1	0.446	0.686	0.0168	261
800			0.755	0.879	0.0354	439
1200			1.251	0.824	0.0272	719

This indicates that the groove created at 166.7mm/s in Table 6.6 was created by approximately 800W of energy rather than 450W. This increases the estimated primary losses vertically below the cut zone to 50% of the laser power. This is in better agreement with the CALCut prediction. However, it is clear that black acrylic cannot be used quantitatively in this kind of experiment.

6.5 Beam propagation

Laser beam propagation was investigated with two experimental techniques. First method was taking the beam print at different vertical distances when the target sample is stationary. In the second technique the sample was moved at different cutting speeds.

More details of the beam propagation experiments were given in chapter 3; however, in Table 6.8 some of the laser drilling and cutting parameters are presented.

Table 6.8-Summary of some laser drilling and cutting parameters employed at CFBA.

Characteristics	Laser power	Time	Vertical distances	Assist gas and pressure	Cutting speed
	W	s	mm	bar	mm/s
Stationary**	400*	0.5**	21-154**	5*	-
Movement*		-	30*		83.33*
		-			66.66*
		-			50*
		-			33.33*
		-			16.66**

*used in both laser machine at IPG YLR-2000 and Bystronic Bysprint Fibre 3015.

**Used only in IPG YLR-2000.

6.5.1 Beam print as a function of distance

To diagnosis the local energy density cross section of the laser beam black PMMA was used as a target material. The beam leaves an imprint on the material related to energy distribution [4]. Analysis was then carried out to determine the cross section of laser beam density and build a volume evaporated of it by using PTC Creo 3 software. The results revealed the laser beam had a nearly Gaussian profile as can be seen in Figure 6.12.

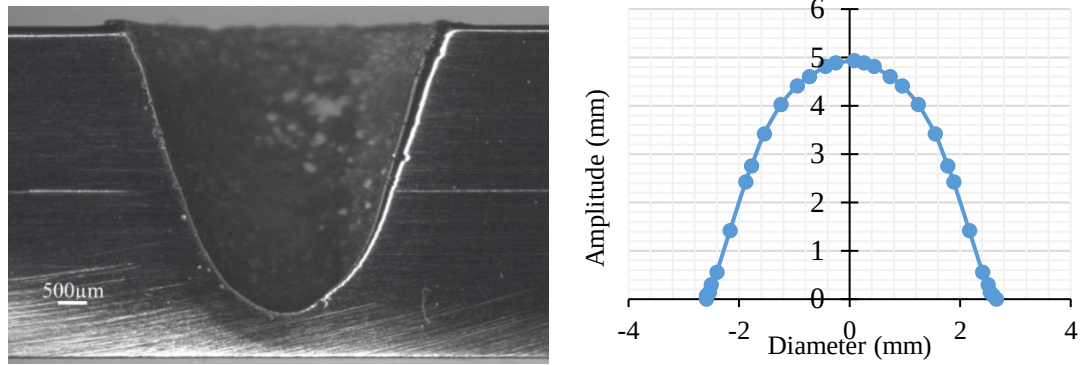


Figure 6.12-The beam print at 400W and 0.5s at 30mm vertical distance from the end of nozzle to CFBA. Left) Cross-section of beam print. Right) The Gaussian beam print.

To generate a 2D beam print image you need to know the volume, amplitude and diameter of the beam print which is assumed to be symmetrical. The PMMA sample was therefore ground along its central axis and photographed. To recreate the 2D laser imprint in the black PMMA, a PTC Creo 3 model was created.

6.5.1.1 Gaussian beam as a function of distance

Beam prints were made into the PMMA surface at different distances from the focal plane then compared with their theoretical values. In Figure 6.13, it can be seen that, as distance increases, the beam print initially gets larger (divergence dominated), but will then get smaller (threshold dominated). The beam was found to be very circular at short distances but more irregular shapes at large distances. Also, the maximum depth was determined and found to be inversely proportional with vertical distance as mentioned earlier in this chapter.

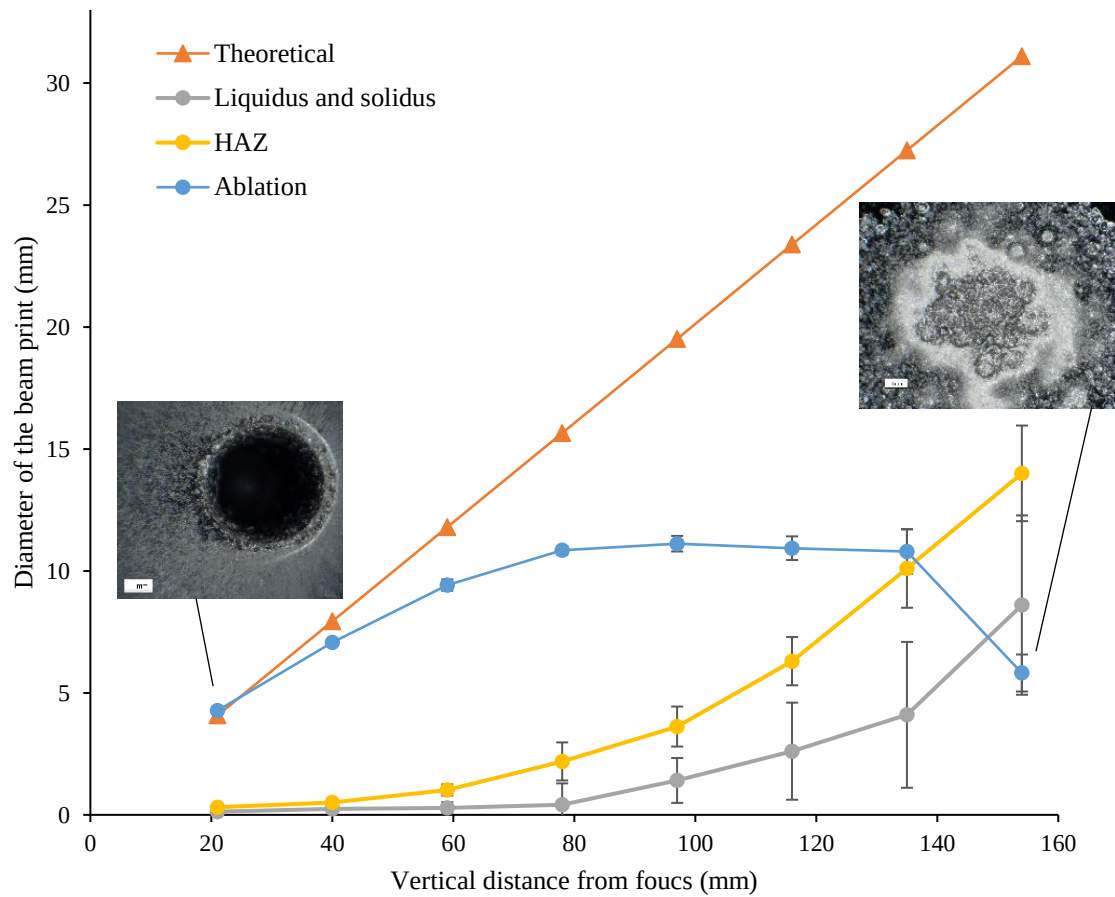


Figure 6.13-The diameter of beam print as a function of distance.

Figure 6.14 shows that the amount of material evaporated by the laser beam initially increases then decreases as a function of distance from the focal plane. The slight increase is probably due to an increase in ablation efficiency at an optimum energy density. The decrease which follows this is due to the defocussing of the beam. As the beam is defocussed the beam has less energy density and a lot of the energy in the beam is below the threshold for evaporation.

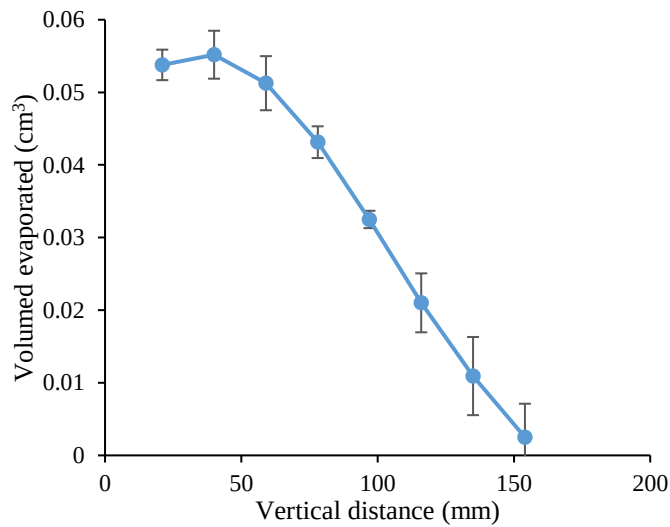


Figure 6.14-The volume evaporate of material as a function of distance.

6.5.2 Groove produced in moving CFBA

Tests were performed to determine the evaporation of PMMA at a variety of speeds (see section 4.4). This produced grooves in the PMMA. The results showed that the threshold value was inversely proportional to cutting speed, as can be seen in Figures 6.15 and 6.16. The profile of the grooves is not determined just by the irradiance distribution of the laser beam, but also by thermal properties of black PMMA material.

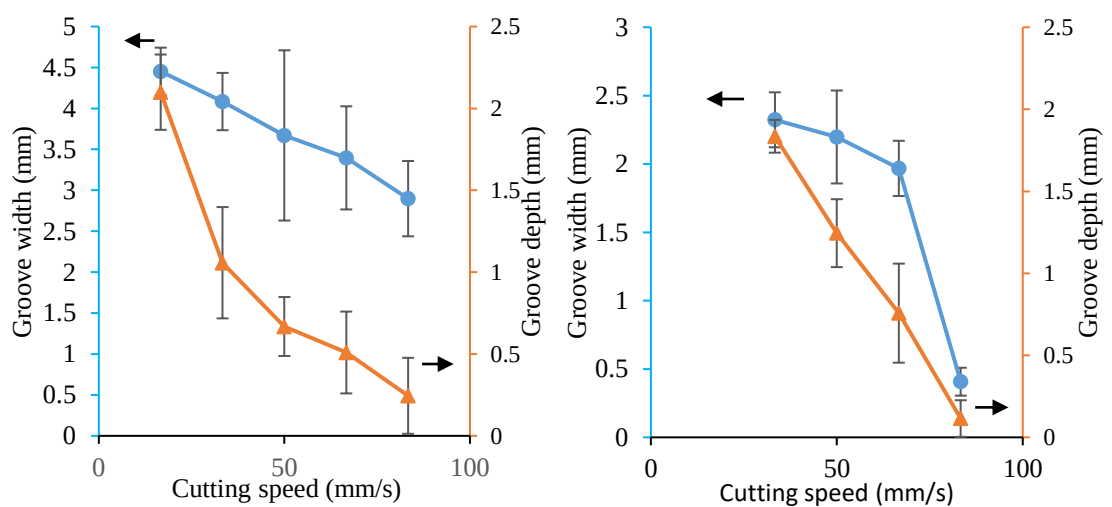


Figure 6.15-The groove details as a function of cutting speed at 400W and 30mm vertical distance between the end of nozzle to CFBA for both laser machines. Left) IPG. Right) Bystronic.

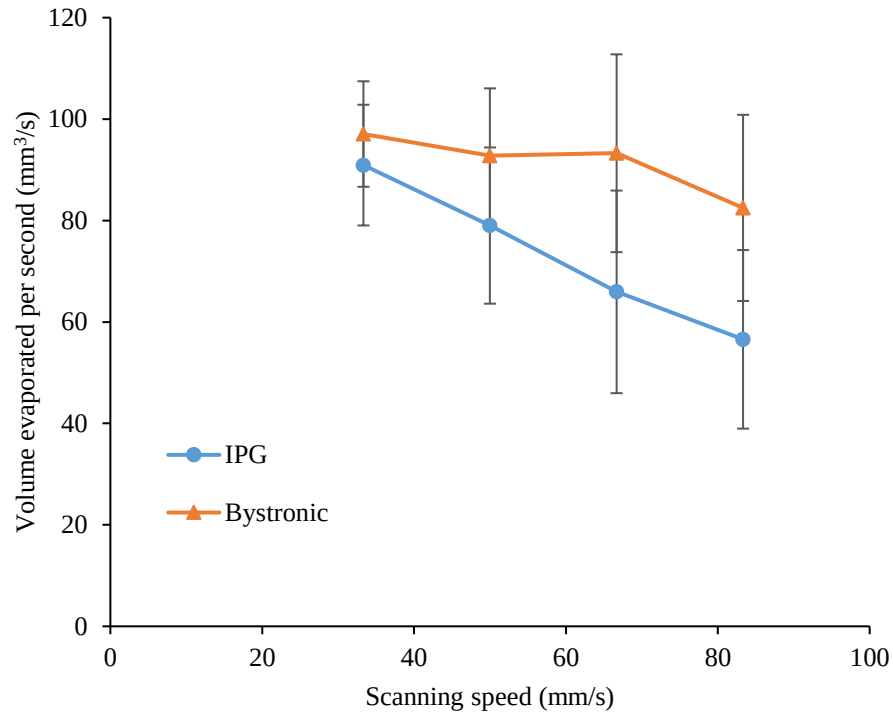


Figure 6.16-Comparsion between volumes evaporated for both laser machines

These results show that increasing process speed makes the evaporation process less efficient in the same way as defocussing the beam makes the evaporation less efficient. As process speeds increase the interaction time between the laser and the material decreases. This makes the interaction time too short for evaporation to take place at the edges of the beam. As speeds increase the beam radius at which evaporation takes place gets smaller and smaller so the groove gets narrower and shallower.

This shows that black PMMA cannot give quantitative results if the laser beam and the target material are moving with respect to each other.

6.6 Threshold effect discussion

Variation between the theoretical beam size and beam print size with distance from focus has been shown to indicate that a threshold effect is occurring.

Exploration of the threshold effect has clarified the conditions under which quantitative work can be done. This is effected by both power density and irradiation time, but is not a simple combination of these factors. CFBA can be used in quantitative work when deep beam prints are generated rapidly.

The threshold effect is relevant to both grooves, generated when the laser head moves with respect to the CFBA, and leaf prints, formed when the laser head is stationary with respect to the CFBA.

6.7 Summary

The main summary that can be drawn from the above Chapter is that several process factors can influence on the threshold value. Two main points are:

- CFBA is evaporated by fibre lasers but there is a threshold energy density of evaporation which is not a simple combination of power multiplied by time.
- This threshold is the reason why the diameter of beam prints and leaf prints initially increases then decreases with distance from the focal plane.

This chapter demonstrates that the threshold for evaporation of carbon filled acrylic by a fibre laser prevents the use of this material for quantitative measurements in most cases. CFBA can only be used quantitatively when the beam is very concentrated and stationary and very deep beam prints can be produced quickly (as in chapter 5).

However, CFBA can be useful for qualitative research into the energy distribution of the beam below the cutting zone.

6.7.1 Overall

CFBA can be used for quantitative work in fibre laser cutting as long as the threshold effect is minimised.

7 Summary and conclusions

The aim of this work was to investigate the use of carbon filled black acrylic (CFBA) as a qualitative and quantitative tool for use with fibre lasers. The work can be divided into three main sections, presented in chapters 4, 5 and 6. The overall conclusions from these chapters are presented below.

7.1 Fibre laser-CBFA interactions and the specific ablation energy

The specific evaporative energy of CFBA when illuminated with a high intensity stationary fibre laser is $3.4\text{kJ}/\text{cm}^3$. Quantitative evaporation experiments will only yield a value of $3.4\text{kJ}/\text{cm}^3$ under the following conditions;

- 1- The beam and the acrylic target must be stationary with respect to one and other.
- 2- The beam must have sufficient intensity (high power and close to focus).
- 3- There must be an air jet acting on the target zone sufficient to purge the area of the carbon-laden smoke.
- 4- The volume evaporated must be deep and narrow (i.e. it must have a high aspect ratio).

7.2 The ‘leaf’ beam print

The laser power which is reflected off, and which passes through, the cutting zone during fibre laser cutting of stainless steel has a leaf-type power density distribution indicative of a complex reflection history within the cutting zone.

- 1- The cut front inclination affects the main reflected beam.
- 2- The kerf wall inclination can generate multiple reflections which broaden the spatial spread of the surplus energy.
- 3- Any dross and surface roughness in the cut zone broadens the spatial spread of surplus energy, with the effect of roughness being more significant the nearer the top of the cut it occurs.
- 4- It is extremely difficult to extract quantitative information from beam prints created in this way because the beam is defocussed and a lot of the energy in the beam is below the threshold for evaporation.

7.3 The threshold effect

- 1- CFBA can be evaporated by fibre lasers but there is a threshold energy density of evaporation which is not a simple combination of power multiplied by time.
- 2- This threshold is the reason why the diameter of beam prints and leaf prints initially increases then decreases with distance from the focal plane.
- 3- This chapter demonstrates that the threshold for evaporation of carbon filled acrylic by a fibre laser prevents the use of this material for quantitative measurements in most cases. CFBA can only be used quantitatively when the beam is very concentrated and stationary and very deep beam prints can be produced quickly (as in chapter 5).
- 4- However, CFBA can be useful for qualitative research into the energy distribution of the beam below the cutting zone.

7.4 Overall

This work has demonstrated that CFBA can be used as a cheap and useful process analysis tool in fibre laser cutting, much as transparent PMMA is already widely used in CO₂ laser work. A specific ablation energy of 3.44kJ.cm⁻³ has been determined for the CFBA used in this work. This allows measurements of process efficiency and surplus energy to be made. The conditions under which quantitative work can be carried out are clarified: the threshold effect must be minimised and there must be sufficient flushing

of evaporated material. Details are given of experimental set ups that allow these conditions to be met.

Whilst there are limitations on when quantitative work can be carried out with CFBA this thesis has detailed how this can be done. This represents an advance on the previous, velocity dependent, guidance on how CFBA could be used in fibre laser cutting.

A novel experimental set up has been developed that allows the CFBA to remain stationary with respect to the cutting head. This permits beam prints to be generated. The distinctive leaf shape beam prints thus generated are reported here for the first time. The leaf prints can be used for both quantitative and qualitative work. The basic features, the stem and body of the leaf, can be understood as being due to the transmitted and scattered beams respectively. The length and width of the leaf print have been correlated to cut front inclination and kerf wall profile respectively. However, there is much more information that could be extracted from the leaf prints. The shape of the curved edge will be related to the cut front curvature. More work, particularly including 3D modelling work, will be required to fully understand the leaf prints.

The influence of the threshold effect on leaf print dimensions as the distance between CFBA and focus changes is explained. The threshold effect explored here is not only relevant to CFBA and fibre laser cutting but has relevance to a wide range of laser material processing applications, particularly those such as cladding and surface treatment where an expanded beam may be used. Since any irradiation that is below the threshold represents wasted energy, it is important that the threshold effect is properly understood. Further work can be done on threshold effects in these other laser materials processing applications.

8 Future work

The future work was identified during the research reported in chapter 5 including the necessity of examining the phenomenon of reflection of the fibre beam in the cut zone for a wider variety of materials. All experimental done with one type of laser system with simulation to better understand of this phenomenon. Further work is needed to investigate the factors that influence on the surplus energy that exiting from the cutting zone, specifically:

1. The effect of the size of the laser spot by changing the diameter of deliver fibre/ using different cutting head.
2. Study a variety of focal positions with respect to the sheet thickness and material.
3. Further information is required to fully understand the existing beam prints, e.g. using recordings by high speed infrared cameras.

We now know the specific energy of vaporisation for CFBA and that threshold effects related to power density and scanning speed need to be studied, or calculated with reference to the specific energy of evaporation identified in this work. The simulation of the temperature distribution in the CFBA can be carried out to increase understanding of energy losses due to the threshold effect.

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10 Appendix 1

$$x = \frac{\frac{t-b_d}{2} \tan \alpha}{\tan \alpha + \frac{1}{\tan \theta_d \frac{1}{2}}} \quad 10.1$$

Where t is the thickness of sheet, b_d is the half angle of the laser beam, θ_d is half angle divergence of the laser beam, and α is the angle of cut inclination.

$$h = \left(x + \frac{b_d}{2}\right) \tan \alpha \quad 10.2$$

And
$$t - h = \frac{x}{\tan \theta_d \frac{1}{2}} \quad 10.3$$

Than
$$\tan \alpha = \frac{h}{x + \frac{b_d}{2}} \quad 10.4$$

And
$$\tan \theta_d \frac{1}{2} = \frac{x}{t - h} \quad 10.5$$

Calculating L which gives the spread of the intensity distribution as a function of the collection plate position.

$$L = (D + h) \tan(\pi + \theta_d \frac{1}{2} - 2\alpha) - \left(x + \frac{b_d}{2}\right) \quad 10.6$$

Where L is the maximum distance from the origin at which photons are detected (mm) and D is the vertical distance between bottom of the cut to the surface of collection sheet (mm).

10 Appendix 2

```
function Results = process3Dfile(filePath, specimenType)
%-----
% Results = process3Dfile(filePath, specimenType)
%
% This function calculates several results from the 3D profilometry
% files. It calls GUIs when necessary and hence can not run unattended.
% Results calculated and saved to file:
% (1) Volume results: netVol, volHole, volPeak, maxDepth, maxHeight
% (2) Average round profile and average form profile.
%
% All inputs are optional. If no filepath is specified a file dialog box
% will be opened. If a File is specified and not the specimenType then the
% function expects the filename to be of the form XX_R_3D.txt or
% XX_F_3D.txt. If the filename is not of this form the user will be
% prompted to manually specify the type.
%
% Inputs: specimenType - string: F/R - Flat or Round surface
%         filePath      - Location to the surface profilometry file
%
% Output: Results       - Contains the wear volume results
%
% Results = process3Dfile(filePath, specimenType)
%-----

%*****
% Author: Stephen Pearson
% Date: 31/01/2012
%
% Revision History:
% 30/01/2012, Stephen Pearson - As released
% 10/02/2012, Austin Warmuth - Changed .m file to a function that was able
% to calculate wear scar data from not only a round, but also a flat.
% 21/03/2012, Stephen Pearson - Modified the output field names to be
% suitable for using as Struct names. Also changed the file write behaviour
% to overwrite instead of append. Made the function so that the arguments
% are optional and it will attempt to auto-detect if the surface is flat or
% round before processing it. Increased the number of decimal places in the
% results file
% 22/03/12, Stephen Pearson - Removed the whitespace from the 'Base Units'
% field in the output file so it is a valid struct field name.
% 27/03/12, Stephen Pearson - Modified volume results to be a .txt file
% instead of a .csv to be consistent with other files.
% 03/04/2012, Stephen Pearson - Modified to save the transposed (col vect)
% 2D round profile.
% 02/04/2013, Austin Warmuth - Modified to produce flat profile.
%*****
```

```

import profilometry.*

% Check the arguments the function has been called with. Build the Base
% name for saving the 2D profiles. if the filename is of the form
% XX_R_3D.txt baseName will be XX_R
switch nargin
    case 0
        % No file path or specimenType specified. Let the surface_load func
        % open a file dialog box and attempt to auto-detect if the surface
        % file is a flat or round. If the type can not be determined from
        % the file name the user will be prompted.
        [Surface filePath] = surface_load();
        [~, name, ~] = fileparts(filePath);
        % The filename should be of the form XX_F_3D or XX_R_3D
        specimenType = name(end-3);
        baseName = name(1:end-3);
        if (strcmpi(specimenType, 'R') || strcmpi(specimenType, 'F')) == 0
            % Couldn't identify the specimen type from the filename so
            % prompt the user
            specimenType = input('Enter Specimen Type[F,R]: ','s');
            baseName = name;
            if (strcmpi(specimenType, 'R') || strcmpi(specimenType, 'F')) ==
0
                error('Invalid specimen type entered: %s. F/R are valid
options',...
                    name)
            end
        end
    case 1
        % Only the filepath specified. The function will first try to
        % identify the specimenType from the filename. If it can't the user
        % will be prompted.
        if exist(filePath, 'file') == 0
            error('Invalid file specified: %s', filePath)
        end
        [~, name, ~] = fileparts(filePath);
        % The filename should be of the form XX_F_3D or XX_R_3D
        specimenType = name(end-3);
        baseName = name(1:end-3);
        if (strcmpi(specimenType, 'R') || strcmpi(specimenType, 'F')) == 0
            % Couldn't identify the specimen type from the filename so
            % prompt the user
            specimenType = input('Enter Specimen Type[F,R]: ','s');
            baseName = name;
            if (strcmpi(specimenType, 'R') || strcmpi(specimenType, 'F')) ==
0
                error('Invalid specimen type entered: %s. F/R are valid
options',...
                    name)
            end
        end
end
end

```

```
[Surface, ~] = surface_load(filePath);
case 2
    % filePath and specimenType specified. Load the file and use the
    % specified specimenType.
    if exist(filePath, 'file') == 0
        error('Invalid file specified: %s', filePath)
    end

    [~, name, ~] = fileparts(filePath);
    baseName = name;

    if (strcmpi(specimenType, 'R') || strcmpi(specimenType, 'F')) == 0
        error('Only F/R are valid arguments for specimenType, not:
%s', ...
            specimenType)
    end
    [Surface, ~] = surface_load(filePath);

otherwise
    error('Incorrect number of arguments')
end

% Removes the form on round surfaces creating a flat surface for wear
% volume calculations.
if strcmpi(specimenType, 'R')
    [FlatSurface, FormSurface] = surface_removeform(Surface);
else
    FlatSurface = Surface;
end

% Call a GUI to allow the user to determine the limits of the wear scar.
scarBounds = surface_guifindscar(FlatSurface);

% Level the surface by using a best fit plane outside of the wear scar.
[LevelSurface, levelZ] = surface_level(FlatSurface, scarBounds);
% If it is a round specimen level the form surface as well - it is used
% later
if strcmpi(specimenType, 'R')
    FormSurface.z = FormSurface.z - levelZ;
end

% Calculate the wear volume. This function expects the surface to have
% already been leveled so it integrates above and below the Z=0 plane.
Results = surface_clacwearvol(LevelSurface, scarBounds(1), scarBounds(2));

% Because there isn't material on the ends of the wear scar on the flats
% the scan is done on a portion of the sample. Taking an average wear
% volume per unit length and knowing the specimen is 10mm in width the wear
```

```

% volume is corrected.

width = 10;
if strcmpi(specimenType, 'F')
    scanLength      = max(Surface.y);
    Results.netVol   = (width*Results.netVol) /scanLength;
    Results.volHole  = (width*Results.volHole)/scanLength;
    Results.volPeak  = (width*Results.volPeak)/scanLength;
end

% Save data to file in the same directory as the original file. If the file
% already existis this will replace it.
[sPath sName sExt] = fileparts(filePath);
resultsPath = strcat(sPath, '\Volume Results', 32, sName, '.txt');

dateTime    = datestr(now);
sourceName  = strcat(sName, sExt);
resNames    = fieldnames(Results);

fid = fopen(resultsPath, 'w+'); % 'w+' option for overwrite or create

fprintf(fid, 'Date, %s\r\n', dateTime);
fprintf(fid, 'SourceFile, %s\r\n', sourceName);
fprintf(fid, 'BaseUnits, mm\r\n\r\n');

for i=1:length(resNames)
    fprintf(fid, '%s, %.8f\r\n',...
            char(resNames(i)), Results.(char(resNames(i))) );
end

fprintf(fid, '\r\n');
fclose(fid);
% Find the 2D round profile and save to file XX_R_2D.txt in the same
% directory as the input file.
if strcmpi(specimenType, 'R')
    [ProfileR, FormProfile] = surface_2dprofilround(LevelSurface,
FormSurface, scarBounds);
    % Save the profile to file [X; Yprofile; Yform]
    M = [ProfileR.x, ProfileR.y, FormProfile.y];
    path2dR = fullfile(sPath, [baseName, '_2D.txt']);
    csvwrite(path2dR, M);
    pathSBR = fullfile(sPath, [baseName, '_SB.txt']);
    csvwrite(pathSBR, scarBounds);
end

if strcmpi(specimenType, 'F')
    ProfileF = surface_2dprofileflat(LevelSurface, scarBounds);
    % Save the profile to file [X; Yprofile; Yform]
    M = [ProfileF.x, ProfileF.y];
    path2dF = fullfile(sPath, [baseName, '_2D.M.txt']);
    csvwrite(path2dF, M);
    pathSBF = fullfile(sPath, [baseName, '_SB.txt']);
    csvwrite(pathSBF, scarBounds);
end

```

```
end

% *****Make some plots to display the data*****

% Plot the flattened, level surface and overlay a plane at Z=0.
[~, fileName, ~] = fileparts(filePath);
figTitle = strcat('Level Surface', 32, fileName);
hLS = figure(...
    'Name', figTitle,...
    'NumberTitle', 'off' );
s = surf(LevelSurface.x, LevelSurface.y, LevelSurface.z);
shading interp
colorbar
title(sprintf(['Net Volume = %f mm3\n',...
    'Hole Volume = %f mm3\n',...
    'Peak Volume = %f mm3'],...
    Results.netVol, Results.volHole, Results.volPeak));

hold on
X = linspace(min(LevelSurface.x), max(LevelSurface.x), 20);
Y = linspace(min(LevelSurface.y), max(LevelSurface.y), 20)';
Z = zeros(length(Y), length(X));
p = surf(X, Y, Z);
set(p, 'facealpha', 0);

end % process3Dfile
```

10 Appendix 3

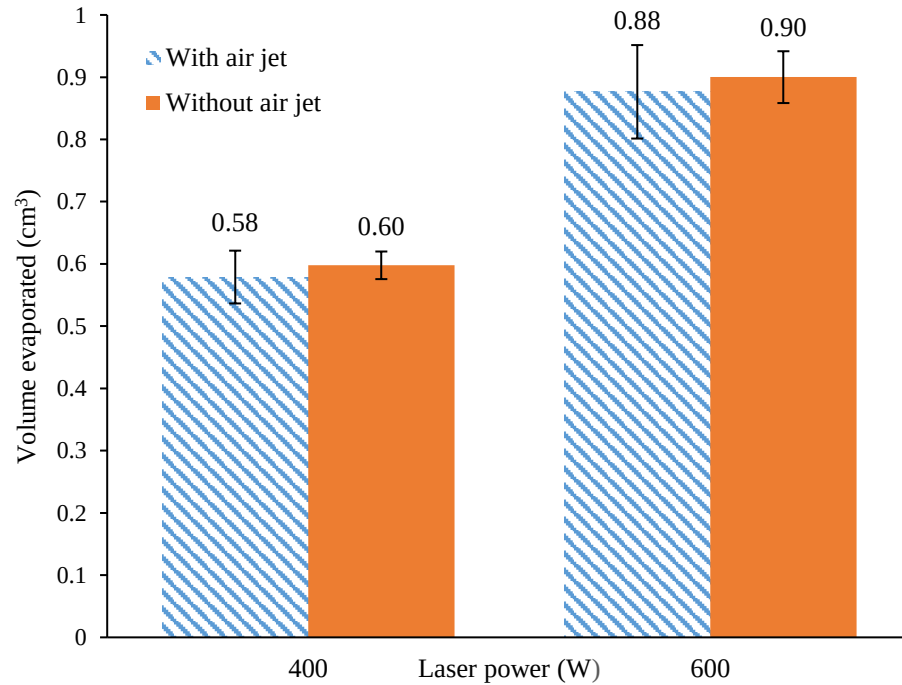


Figure 10.1- Changing in volume evaporated in both cases with and without air jet (400-600W laser power, stand-off distance 6mm and N₂ 2bar)

Table 10.1-Experimental parameters for cutting stainless steel 3mm.

Sample No.	Cutting speed		Laser power	Vertical distance(z´)	Gas pressure (N ₂)	Cutting time
	Percentage of max. cutting speed	mm/s	W	mm	bar	s
1	90%	5.9	500	17.5	6	15.7
2	92%	6.1				15.35
3	94%	6.2				15.03
4	96%	6.3				14.72
5	98%	6.5				14.41
6	100%	6.6				14.13
7	106%	7				13.33
8	110%	7.2				12.84
9	126%	8.2				-

Table 10.2- Experimental parameters for cutting stainless steel 3mm.

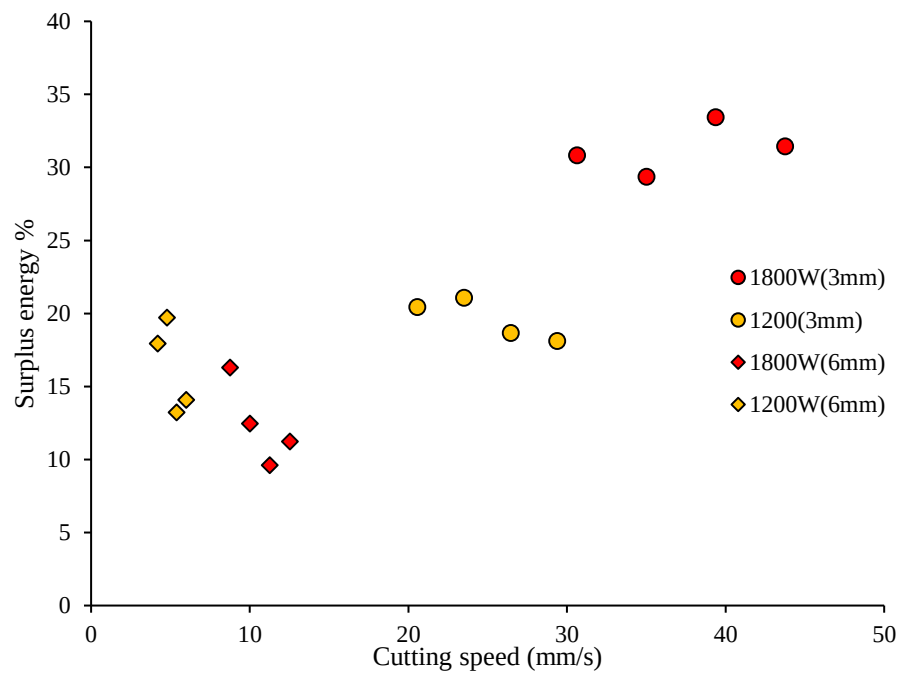
Sample No.	Cutting speed		Laser power	Vertical distance(z')	Gas pressure (N ₂)	Cutting time
	Percentage of max. cutting speed	mm/s	W	mm	bar	s
1	90%	26.6	1200	17.5	8	3.52
2	92%	27				3.44
3	94%	27.6				3.37
4	96%	28				3.3
5	98%	28.8				3.23
6	100%	29.4				3.16
7	102%	29.9				3.10
8	104%	30.5				3.04
9	106%	31.1				-

Table 10.3- Experimental parameters for cutting stainless steel 6mm.

Sample No.	Cutting speed		Laser power	Vertical distance(z')	Gas pressure (N ₂)	Cutting time
	Percentage of max. cutting speed	mm/s	W	mm	bar	s
1	92%	5.5	1200	17.5	10	16.85
2	94%	5.6				16.49
3	96%	5.7				16.15
4	100%	6				15.5
5	104%	6.3				14.79
6	108%	6.5				14.35
7	129%	7.7				12.3
8	132%	7.9				-

Table 10.4- Experimental parameters for cutting stainless steel 3 and 6mm (grooving).

Sample No.	Cutting speed		Laser power	Vertical distance(z´)	Gas pressure (N ₂)	Surplus energy
	Percentage of max. cutting speed	mm/s	W	mm	bar	%
1	100%	43.7	1800	8.5	12	31.4
2	90%	39.3				33.4
3	80%	35				29.4
4	70%	31				31
5	100%	29.4	1200			18.1
6	90%	26.5				18.6
7	80%	23.5				21.07
8	70%	20.6				20.4
9	100%	12.5	1800		15	11.23
10	90%	11.2				9.6
11	80%	10.02				12.44
12	70%	8.77				16.29
13	100%	6	1200			14.07
14	90%	5.4				13.2
15	80%	4.8				19.7
16	70%	4.2				17.9

**Figure 10.2- Results of surplus energy of grooves experiments.**

