Lappeenranta University of Technology

Department of Mechanical Engineering

FIBER LASER CUTTING OF MILD STEEL

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Abstract

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Fiber laser for materials processing have undergone a rapid development in the past several years. As fiber laser provides a combination of high beam quality and a wavelength that is easily absorbed by metal surfaces, the named future laser is expected to challenge the CO_2 and Nd:YAG lasers in the area of metal cutting.

This thesis studied the performance of fiber laser cutting mild steel. In the literature review part, it introduced the laser cutting principle and the principle of fiber laser including the newest development of fiber laser cutting technology. Because the fiber laser cutting mild steel is a very young technology, a preliminary test was made in order to investigate effect of the cutting parameters on cut quality. Then the formal fiber laser cutting experiment was made by using 3 mm thickness S355 steel with oxygen as assistant gas. The experiment was focused on the cut quality with maximum cutting speed and minimum oxygen gas pressure. And the cut quality is mainly decided

by the kerf width, perpendicularity tolerance, surface roughness and striation patterns.

After analysis the cutting result, several conclusions were made. Although the best result got in the experiment is not perfect as predicted, the whole result of the test can be accepted. Compared with CO_2 laser, a higher cutting speed was achieved by fiber laser with very low oxygen gas pressure. A further improvement about the cutting quality might be possible by proper selection of process parameters. And in order to investigate the cutting performance more clearly, a future study about cutting different thickness mild steel and different shape was recommended.

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List of symbols and abbreviations

CO_2	Carbon dioxide
Nd: YAG	Neodymium –Yttrium Aluminium Garnet
CW	continuous wave laser power
R_a	an integral of the absolute value of the roughness profile
CNC	computer numerical control
TEM_{00}	Gaussian mode
z_0	the beam waist position
w_0	the waist diameter
Θ_0	the half of full divergence angle
BPP	Beam Parameter Product
M^2	times diffraction limit factor
K	beam quality factor
d_{foc}	the focus radius
d	the diameter of the focal spot
f	the focal length of the lens
λ	the wavelength of the laser light
D	the diameter of the unfocused laser beam
BLS	boundary layer separation points
Rz	Mean height of the profile
HAZ	Heat affect zone
DPSSL	diode pumped solid state laser
SM	single mode
NA	Numerical Aperture
u	perpendicularity tolerance
a	cut thickness

Literature Review

1. Introduction

The emergence of CO_2 and Nd:YAG lasers for material processing in the early 1970's has made a major impact on industrial cutting applications. Laser cutting have many principles as the same as the conventional fusion cutting methods. But the laser cutting excels in applications requiring high productivity, a high edge quality and a minimum waste, due to the fast and precise cutting process. Mild steel is a daily used material and dominantly used in the laser cutting industry. In the last few years, the rapid development of high power fiber lasers provides more efficient, robust new technologies for materials process. These modern solid-state lasers operate at near IR spectral region and offer multitude of advantages over conventional lasers and shows great promise to open up new applications. /1, 2, 3/

This thesis consists of two parts – the literature review and experimental part. In the first part, the laser cutting process, parameter and property are present including the characteristic of fiber laser inside. And then detailed information about fiber laser is discussed in the following chapter of high power fiber laser system and laser cutting mild steel with high power fiber laser.

In the experimental part, the performance of fiber laser cutting 3 mm mild steel was investigated. Because fiber laser cutting mild steel is a very young technology, preliminary test experiment was carried out to investigate how the setting parameters affect the cutting result by using the material Fe 52D. After that, the formal experiment was done by using material S355. Measurements about the cut quality were focused on kerf width, perpendicularity tolerance, surface roughness and striation pattern. After the analysis of the cutting result, a conclusion about the whole experiment is made in the end of this study.

2. Laser cutting principle

Laser cutting is a thermal cutting process as shown in Figure 2.1. the principle components includes the lasers power source with some shutter control, beam guidance train, focusing optics and a means of moving the beam or workpiece relative to each other. When the beam is required, the shutter mirror is rapidly removed by a solenoid or pneumatic piston. And the beam generated with the laser power source passes to the beam guidance which directs the beam to the focusing optic. The focusing optic can be either transmissive or reflective. The reflective optics consists of parabolic off-axis mirrors. The focused beam then passes through and melts the material throughout the material thickness and a pressurized gas jet. The gas jet is needed both to aid the cutting operation and to protect the optic from spatter. /1, 4/

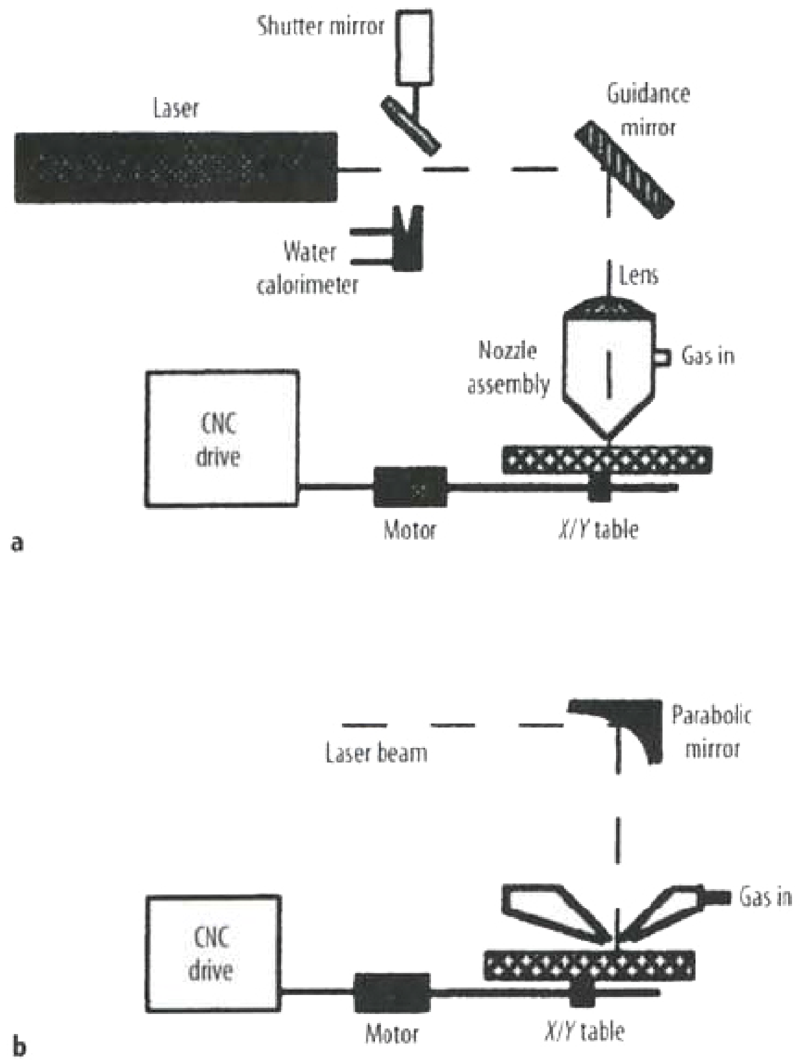


Figure 2.1 General arrangement for laser cutting: a. transmissive optics; b. Reflective optics./4/

2.1 Laser fusion cutting

In this process, the laser beam heats up the material to melt, using an inert gas such as nitrogen, to blow away the melted material. The inert gas also can help protect the heated material from the surrounding air as well as protecting the laser optics. The process is shown in Figure 2.2. /4, 5/

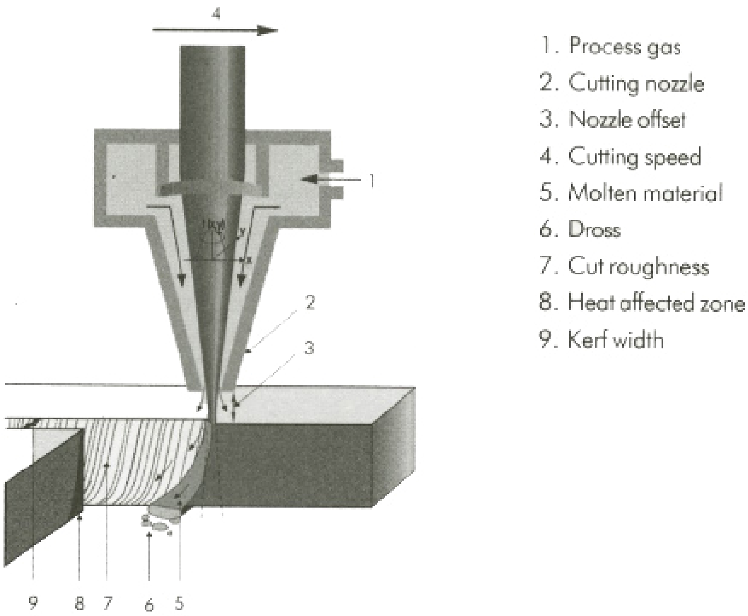


Figure 2.2 Operating principle of laser fusion cutting /6/

The energy requirements are lower than in the vaporization cutting. Laser fusion cutting is mainly used for metal material this is also include highly alloyed steels like stainless steel, aluminum and titanium alloys. The advantage of this process is that the cut edge is free of oxides with high quality. The main problem need to be avoided is the adherent melt at the bottom edges of the kerf, especially for cutting thick material. This problem can be solved by using high pressure gas jet (above 10 bars). /1, 4, 5/

2.2 Laser oxygen cutting

In this process, the laser beam heats the material in an oxidizing atmosphere into the melting point of the material. Therefore an additional source of energy is obtained from the exothermic oxidation reaction of the oxygen with the material. And the molten material is rapidly removed away by the assist gas as shown in Figure 2.3. /5/

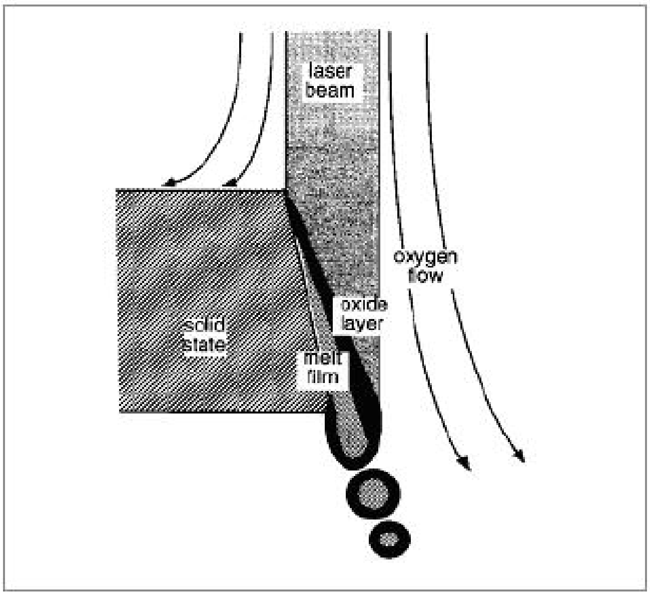


Figure 2.3 Basic Principle of laser oxygen cutting /7/

The laser oxygen cutting is mainly used for steel and low-alloyed steel. Compared to the vaporized cutting method, about one twentieth of the energy is required with a very high processing speed. However, the cut edge is oxidized. /4, 7/

2.3 Laser vaporization cutting

In the process of vaporization cutting, the material is heated beyond its melting temperature and eventually evaporated. Therefore, a keyhole is generated in the evaporated position. The keyhole causes a sudden increase in the absorptivity, because of the multiple reflections. And then it results the keyhole deepens rapidly, so vapor is generated and escapes. The process gas can help the material removal. Figure 2.4 is a schematic of laser vaporization cutting. /5, 7/

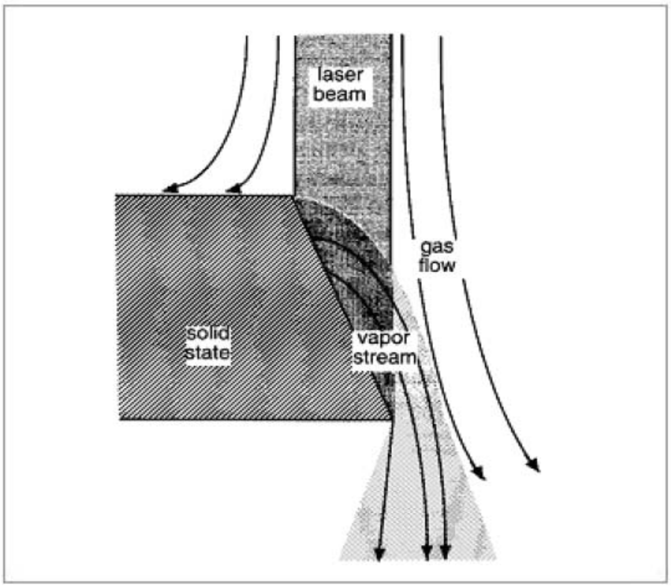


Figure 2.4 Basic principle of laser vaporization cutting /7/

The energy requirements of this process depend upon the thermal properties of the base material, but are usually quite high.This method is usually used to cut material which do no melt such as wood, carbon and some plastic. /4, 7/

3. Laser cutting parameters

The process of laser cutting involved many parameters, which can be generally divided into two main categories—beam parameters and process parameters. /4/

3.1 Beam parameters

These are parameters that characterize the properties of the laser beam which include the wavelength, power, intensity and spot size, continue wave and pulsed power, beam polarization, beam mode and quality.

3.1.1 Wavelength

The wavelength depends on the transitions in the process of stimulated emission. /1/

with respect to the physical mechanisms involves in energy coupling and the process efficiency, stability and quality, the wavelength plays a most decisive role. /5/ It has important effect on material's surface absorptivity. For a specific material type, there is a certain wavelength which can have the maximum absorption of laser energy with a lowest reflection. For example, CO_2 laser is the typical choice for non-metallic material, due to its high absorption of these materials. Due to the shorter wavelength of fiber lasers (in the range of 1 μm almost the same as Nd-YAG laser) compared to CO_2 lasers (10.6μm), it leads to the higher absorption in metallic materials as shown in Figure 3.1. /8, 9/

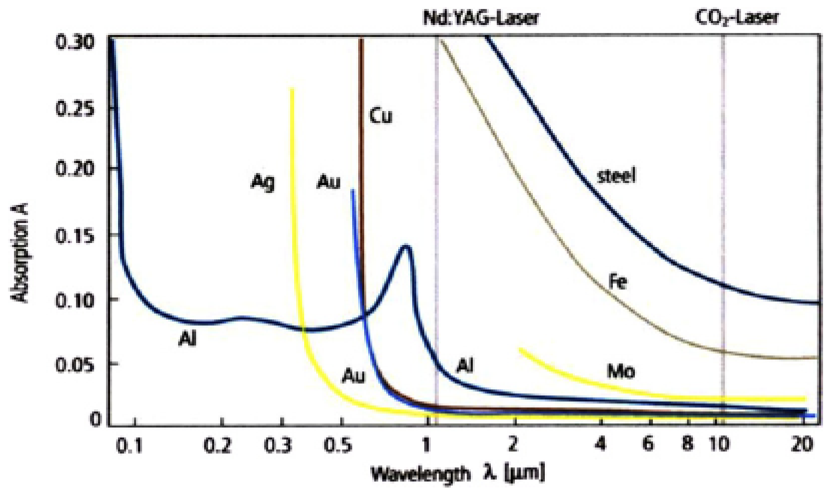


Figure 3.1 Absorption of a number of metals as a function of laser radiation wavelength in room temperature /9/

3.1.2 Power, intensity and spot size

The size of a laser system is usually specified in the term of power. The power of laser system is the total energy emitted in the form of laser light per second. Without sufficient power, cutting cannot be started. /1, 8/

The intensity of the laser beam is the power divided by the area over which the power is concentrated. The high intensity of laser beam has advantages in laser cutting. First, it causes rapid heating of the material, which means that little time is available for heat to dissipate into the surrounding material. And with the result, it has a high cutting speed with good quality. Additionally, the reflectivity of most metals is much lower at high intensities, compared to the low beam intensity. Moreover, the intensity determines the thickness of material which can be cut. /1/

Spot size is the irradiated area of laser beam. In the application of laser cutting, it always required to focus the beam into minimum spot size. This is necessary to maximize the energy density and to produce precision cuts with small kerf width. Due to the better beam quality of fiber laser with very low divergence, the user can get spot diameters substantially smaller than conventional lasers producing longer working distances. A 1-kW laser can be focused to 50 μm spot size with a 100 mm focal length lens. An 8 kW can be focused to a spot size of 0.6 mm with a 250 mm focal length lens. /1, 48/

3.1.3 Continuous wave (CW) and pulsed laser power

Both the continuous wave and pulsed laser power can achieve the high intensity needed for laser cutting. The cutting speed is determined by the average power level. Thus the highest speed can be obtained with high average power levels. Therefore, a high power CW laser is suitable for smooth, high cutting rate applications, particularly with thicker sections. /1, 8/

However, when the average power is high, the removal of molten or vaporized material is not efficient enough to prevent some of the heat in the molten/vaporized material from being transferred to the kerf front causing heating of the workpiece and deterioration of the cut quality. Especially for cutting narrow geometries in complex sections, it can be difficult to achieve good cut quality with the high power CW laser due to the overheating effect. Because the high peak power in the short pulses ensures efficient heating while the low average power results in a slow process with an effective removal of hot material from the kerf, pulsed laser beams can produce better cuts for that case. And a lower energy pulsed beam is preferred for cutting of fine components due to the precision compared to the CW beam. /1, 8/

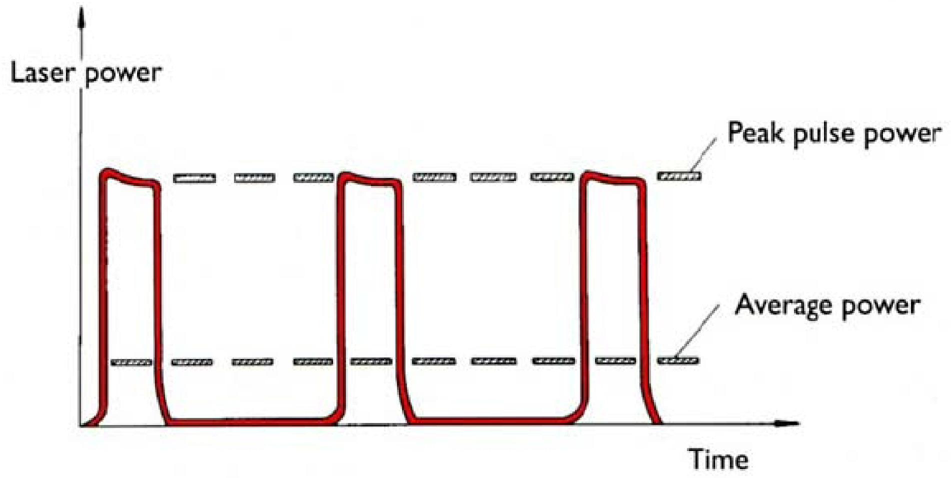
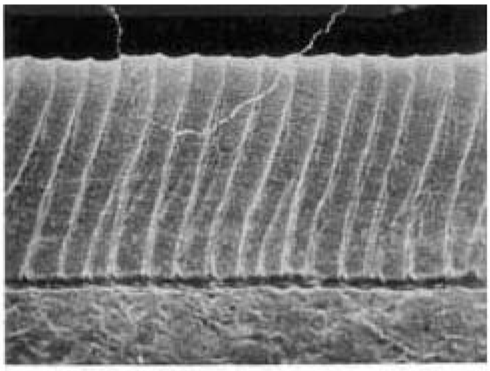


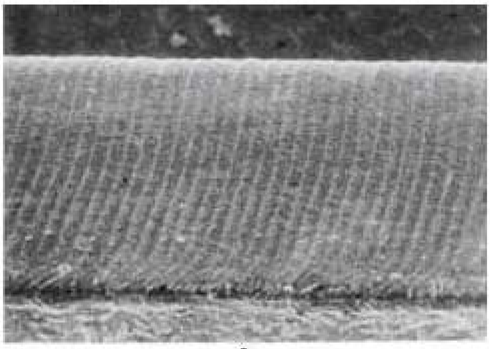
Figure 3.2 Definitions-pulsed operation. /8/

Normally, the cutting speed of pulsed laser is much lower than the CW laser beam. In order to obtain a significant increase cut quality by pulsed laser, the average power has to be normally below 200 watt, often resulting in cutting speeds that are only 10% of those obtainable in the CW mode. The peak power has to be with in the range of 1 to 10 kilowatt for cutting metallic materials, and each pulse has to be long enough to realize the cutting, which means typical pulse lengths of the order of 1-3 milliseconds./8/

In the book of CO_2 laser cutting, there is a comparison of CW laser and pulsed laser beam cutting mild steel, with all other cutting conditions kept constant for the two samples. The striation of the cutting has been shown in the Figure 3.3. The roughness of the pulsed sample (Ra) was only 25% of the continuous wave sample. It has been reported many CNC laser cutting machines switch from continuous wave to pulsed mode when going round small radii or corners, due to the better quality achieved by the pulsed laser beam. /2/



a



b

Figure3.3 A comparison of **a** continuous wave laser cutting and **b** pulsed laser cutting. /2/

3.1.4 Polarization

Every photon or "light particle" is made up of an electrical and magnetic vector at right angles to each other as shown in Figure 3.4a. The laser beam polarization is caused by the electromagnetic oscillations and it affects the absorption of light in the kerf. The polarization can be linear, circular, elliptic or random. The linear polarization means all the photons have their electrical and magnetic vectors aligned parallel to each other, as illustrated in Figure 3.4b. /2, 8/

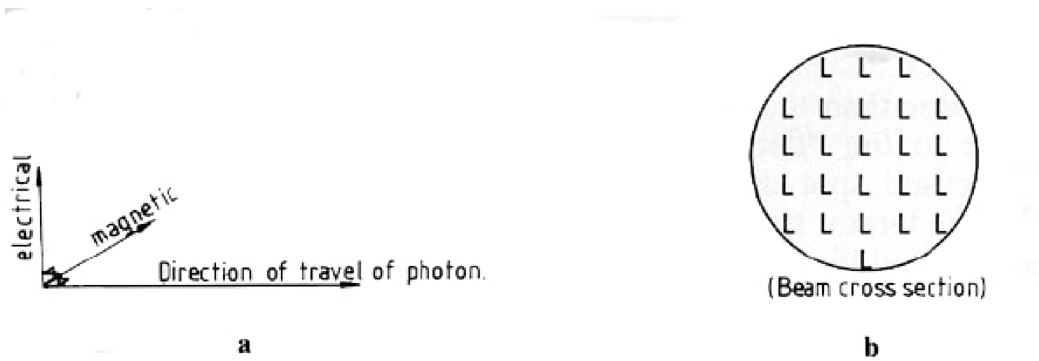


Figure 3.4 **a**. A schematic of the electrical and magnetic vectors which are associated with a photon. **b**. The alignment of the vectors in a linear polarized laser beam. /2/

During the cutting process, Linear and elliptic polarized light is absorbed differently in different directions, which means the beam is better absorbed in certain cutting directions than others, as show in Figure 3.5. /8/

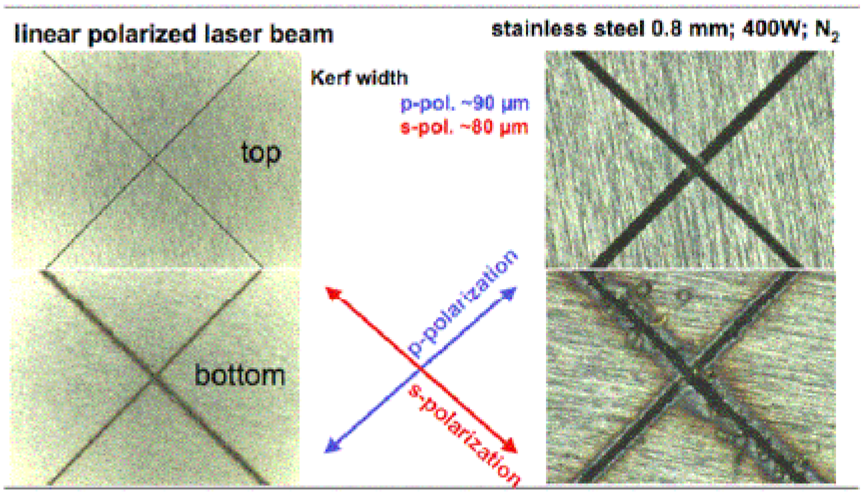


Figure 3.5 Cutting with linear polarized fiber lasers. /11/

Therefore the polarization has to be circular or random when cutting is to be performed in more than one direction. The electrical and magnetic vectors in the circular polarization are at 90° to the direction of propagation follow a circular pattern, as shown in Figure 3.6. Therefore this circular polarized beam has uniform properties and gives equally cutting properties in all the directions. When the polarization is simply uncontrolled, the polarization is random. If the polarization is not totally uncontrolled, it maybe causes varying cutting results in different directions. /8/

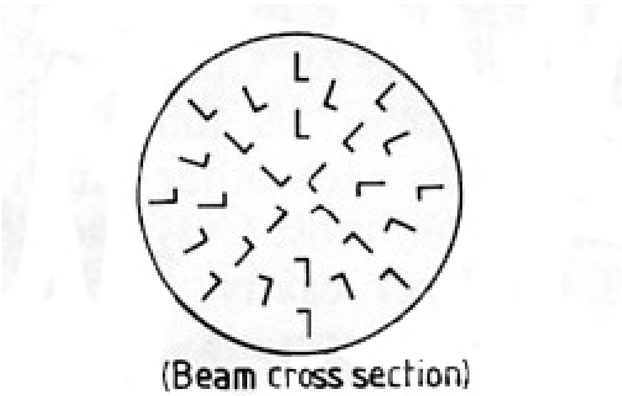


Figure 3.6 The alignment of a circular polarized beam.

Due to the nature of the fiber laser, fiber laser is typically randomly polarized. To polarize a fiber laser may take a specialty fiber and/or architecture which may affect the efficiency of the laser. /11, 12/

3.1.5 Laser mode

The mode of a laser beam describes the energy distribution through its cross section. It can be measured by exposing a sheet of acrylic to the unfocused beam for a few seconds or by using beam analyzing equipment. The mode mainly has two affections on the laser cutting process. The first one is the size of the focused spot and thus the intensity of the focused beam. The other one is that if there is a zone of elevated energy density in the beam outside the major spot, it can cause heating of the material outside the kerf, resulting in poor cut quality. Thus the quality and speed of laser cutting is highly dependent upon the mode of laser beam. /2/

Therefore, a good mode of laser beam always is essential for laser cutting. The ideal mode would be Gaussian mode, as illustrated in the Figure 3.7. This mode has a cross section with a single dense round spot of energy which increases towards the beam centre at the same rate as a Gaussian curve. The Gaussian mode is also called as TEM_{00}, due to the transverse electromagnetic mode of the zero order. A Gaussian mode provides a very small focused spot size with a very high density of laser beam. /2/

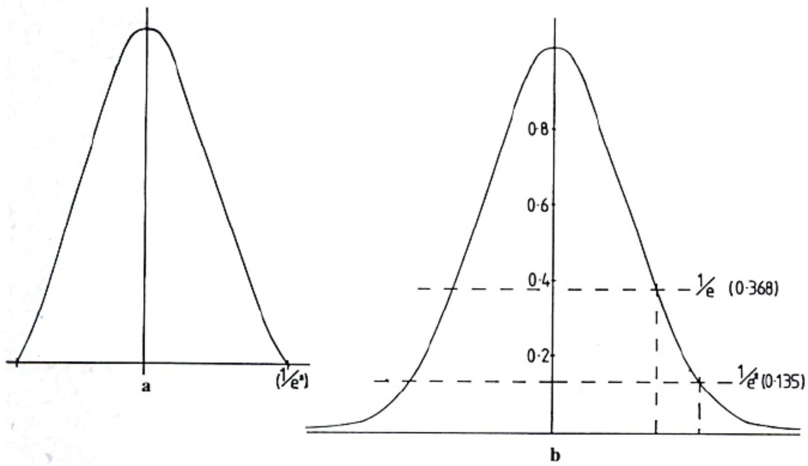


Figure 3.7 **a**. Energy distribution of a Gaussian beam **b**. the mathematically calculated Gaussian curve.

However, in practice, high-power laser often deliver higher order modes which give a larger focused spot size. In the fiber laser system, as the beam is near Gaussian mode, the intensity can be very high in a small spot. /2, 8, 11/

3.1.6 Beam quality

The laser beam quality is characterized by the mode of a laser beam./1/ Any rotational symmetrical laser beam may be characterized by the following three parameters (as shown in Figure 3.8): /6, 8/

(1) z_0 is the beam waist position

(2) w_0 is the waist diameter

(3) Θ_0 denotes the half of full divergence angle

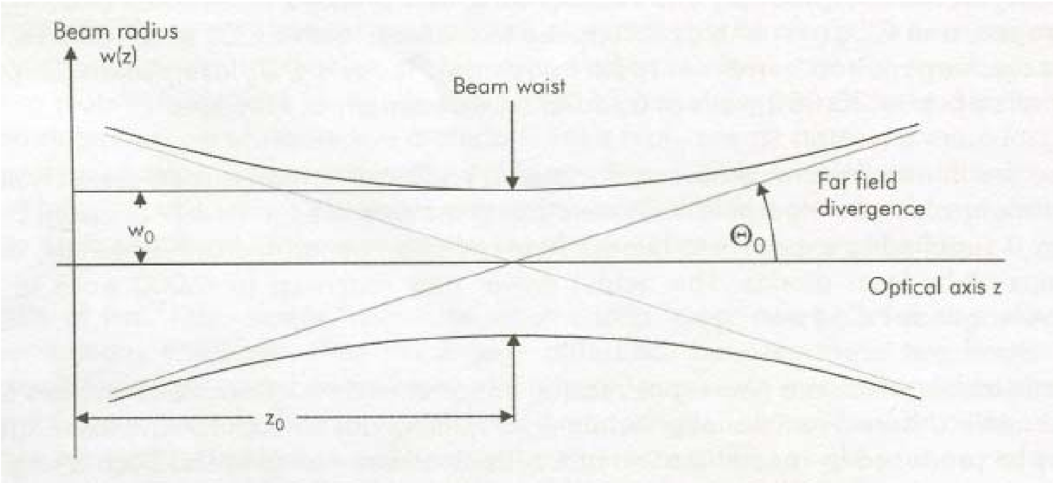


Figure 3.8 Definition of parameters for beam propagation and beam characterization formulas /6/

The Beam Parameter Product (BPP) is widely used to characterize the quality of the beam. The BPP is described by the beam quality factor K (in the USA and Great Britain, K is used as beam quality factor. M^2 is related to K by the relation $M^2=1/K$). The beam quality factor describes how close a laser beam is to a Gaussian mode. For a Gaussian mode $M^2=1$ whereas higher order modes gives M^2 high than one. Therefore, a low BPP characterizes a high beam quality. In the following, it is the equation referred to the BPP where a detailed discussion can be found. /6, 8, 13/

$$BPP = \Theta_0 w_0 = \lambda M^2 / \pi \quad \ldots\ldots\ldots\ldots \qquad (1)$$

In this equation, λ the wavelength and M^2 the time's diffraction limit factor which tells how much larger is the BPP of the laser under consideration compare to the physically lowest value of λ / π for a beam in the TEM_{00} mode. Only during the last few years, it becomes also accepted by the user of laser technology as a property of the equipment that is purchased like wise with power, efficiency of wavelength. /6, 13/

In the conclusion, using BPP or M^2 to comparing laser source is depended on different aims: if the considered objects are lasers with different wavelengths, the BPP should be used, whereas M^2 is the appropriate parameter when considering with equal wavelength. With fiber lasers and diode lasers usually the BPP is used to define the beam quality. /13/

3.2 Process parameters

These are parameters that characterize the properties of the laser beam which include focusing of laser beams, focal position and dual focus lens, process gas and pressure, nozzle diameter, stand-off distance and alignment, and cutting speed.

3.2.1 Focusing of laser beams

The focal length of lens is about the distance from the position of focal lens to the focal spot. In the fiber laser system, the laser beam is delivered by the fiber optics and use a collimator to form the divergent laser beam. After that, it comes to the focusing lens or mirror and it focuses the parallel laser beam onto the workpiece, as shown in the Figure 3.9. The cutting process requires the spot size is small enough to produce the high intensity power. The focal length of the lens has a large impact on size of the focal spot and the beam intensity in the spot. Since the far-field angle of divergence Θ_0 and the beam characteristic number K are known, the focus radius can be calculated according Equation 2, /1,8/

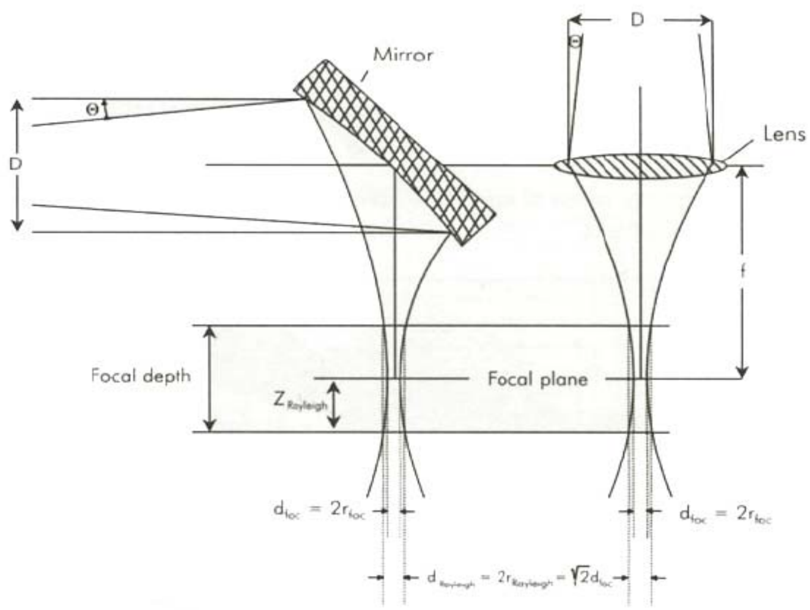


Figure 3.9 Focusing of laser beams

$$d_{foc} = \frac{4\lambda}{\pi} \cdot \frac{f}{D \cdot K} \quad .... \quad (2)$$

Within the equation and Figure 3.9, d is the diameter of the focal spot; f is the focal length of the lens; λ is the wavelength of the laser light; D is the diameter of the unfocused laser beam at the lens; K is the beam quality factor which equals to $1/M^2$.

Since the BPP is an invariant quantity during focusing, by combining with equation 1, the Equation 2 can be written as:

$$d_{foc} = (4\lambda / \pi) M^2 f / D = 4 f / D \cdot BPP \quad .... \quad (3)$$

The rayleigh length distance is the distance from the focus at which the cross sectional area of the laser beam has doubled. The depth of focus is twice as long as the Rayleigh distance. /6/

$$Z_{Rayleigh} = \frac{2 \cdot f^2 \cdot \lambda}{D^2 \cdot \pi \cdot K} \quad .... \quad (4)$$

The equations above indicate that a small spot diameter is favored by a short focal length, good mode, large raw beam diameter at the lens and short wavelength of the laser beam. This means that with a short focal length of lens, it produces a small spot size and a short depth of focus, resulting in high speed and good quality cutting of thin material. However, when cutting thicker materials, a short focal length will result in slanting cut edges, so the focal length has to be optimized in the term of thickness of the base material. With fiber laser, because of the low divergence, the depth of focus is very large. /6, 8, 11/

3.2.2 Focal position

In order to get optimum cutting result, the focal point position must be controlled. There are two reasons: the first reason is that the small spot size obtained by focusing the laser beam results in a short depth of focus, so the focal point has to be positioned rather precisely with respect to the surface of the workpiece; the other one is differences in material and thickness may require focus point position alterations./8/

When cutting with an inert gas, for example nitrogen assisted laser cutting of stainless steel, it is generally known that the focus position should be as close as possible to the bottom surface of the material. Because it needs to produce a wide kerf that allows a large part of the gas flow to penetrate the kerf, eject molten material and avoid the formation of burrs/dross on the lower part of the cut edge. At the same time, the level of beam intensity on the upper surface, still have to be capable of vaporizing material. /1, 14/

When cutting with oxygen, for example oxygen assisted laser cutting of mild steel, the maximum cutting speed is achieved when the focal position is at the upper surface for thin sheets or about one third of the plate thickness. That is because of the relatively low melting point of the oxides and lower viscosity of the molten material, compared to the conditions for nitrogen assisted stainless steel cutting. This process always requires a sharp and highly intensive focusing on the surface in order create sharp edges and to avoid uncontrolled self-burning in the cut edge. However, when the material thickness increases, problems arise due to a remarkably dross formation regarding the separation of the cut edges. One method of solving the problem as mentioned in Chapter 3.2.1 is to increase the focal length as well as increase the power. And the other is by using a newly developed dual focus lens first described by the Force Institute in Denmark. /1, 14/

3.2.3 Process gas and pressure

The process gas has five principle functions during laser cutting. An inert gas such as nitrogen expels molten material without allowing drops to solidify on the underside (dross) while an active gas such as oxygen participates in an exothermic reaction with the material. The gas also acts to suppress the formation of plasma when cutting thick sections with high beam intensities and focusing optics are protected from spatter by the gas flow. The cut edge is cooled by the gas flow thus restricting the width of the HAZ. Without an assist gas, it is impossible to use a laser for cutting at high speed with good quality if the thickness is more than a few tenths of a millimeter. The importance of assist gas increases as the material thickness increases./1/

The choice of cutting gas is one of the significant factors for the cutting result. In industry, the commonly used gases are the oxygen and nitrogen. Nitrogen is mainly used for stainless steel and aluminum, whereas the oxygen is used for mild steel. /1, 8/

Nitrogen is the predominant inert cutting gas, due to its relatively cheap price. The purity is relatively not important, provided it is above 99.8%. And Inert cutting gas pressure is generally higher than those used with oxygen. /1/

In the process of oxygen cutting, the presence of oxygen contributes an exothermic reaction, which effectively increasing the laser power. Around 50% of the total energy for cutting process is supplied by the oxidation reaction. Thus, it results into high cutting speeds and the ability of cut thick material. When cutting thick material, the gas pressure must decrease with the increasing of thickness, in order to avoid the burning effect, whereas the nozzle diameter is increased. Gas purity is important-mild steel of 1 mm thickness can be cut up to30% more quickly using 99.9 or 99.99% purity, in comparison with the standard oxygen purity of 99.7%. The shortcoming of oxygen cutting is the relatively poor cutting edge quality due to the oxidation, in comparison of inert gas cutting. Therefore, it requires carefully control of the parameters to minimize dross adherence and edge roughness. /1, 5, 8/

3.2.4 Nozzle diameter, stand-off distance

Nozzle is used to deliver the assist gas. Because the assist gas is the essential in laser cutting, nozzle geometry and alignment are important. The nozzle has three main functions in the laser cutting process: to ensure that the gas is coaxial with the beam; to reduce the pressure to minimize lens movements and misalignments; and to stabilize the pressure on the workpiece surface to minimize turbulence in the melt pool./1,8/

The nozzle design, particularly the design of the orifice, determines the shape of the cutting gas jet, and thus the quality of the cut. The diameter of the nozzle orifice ranges between 0.8 to 3 mm, and is selected according to the material and plate thickness. If the diameter of nozzle is too large, it will provide insufficient gas flow to expel molten material, and result in high gas consumptions; contrarily, if the diameter is too small, it will create difficulties in alignment and localizes the gas, resulting in a rough edge. Therefore, the diameter of nozzle should be carefully chosen. /1/

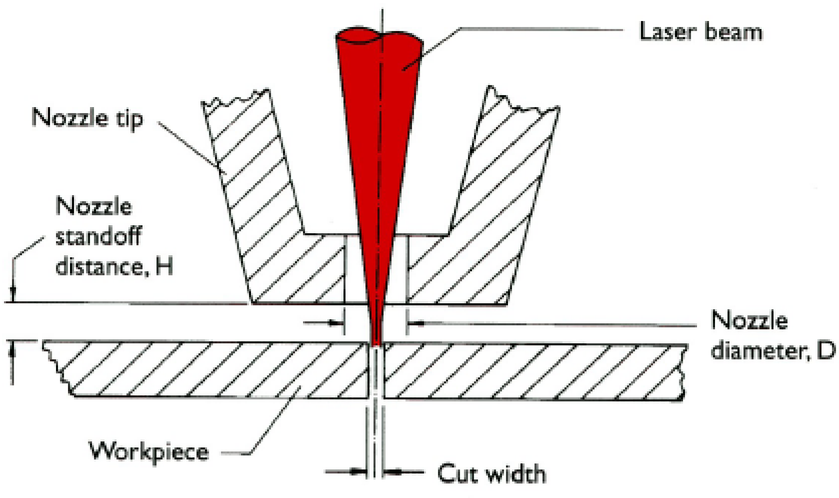


Figure 3.11 The definitions involved with nozzle. /8/

The stand-off distance, which is the distance between the nozzle and the workpiece, is also an important parameter. It influences the flow patterns in the gas, which have a direct bearing on cutting performance and cut quality. Nozzle stand-off distance larger than the diameter of the nozzle will result in turbulence and large pressure changes in the gap between nozzle and workpiece. The stand-off distance is usually selected in the same range as the diameter of cutting nozzle-between 0.5 and 1.5 mm-in order to minimize turbulence. A short stand-off distance provides stable cutting conditions, although the risk of damage to the lens from spatter is increased. The stand-off distance is optimized to maximum the cutting speed and quality. /1, 8/

3.2.5 Nozzle alignment

The alignment of the nozzle with the nozzle beam is also important for the cut quality. Nozzle misalignment is a common cause of poor cut quality, as the process is extremely susceptible to small imperfections in the alignment of the cutting gas jet with the laser beam. The gas flow from the nozzle generates a pressure gradient on the material surface which is, of course, coaxial with the nozzle itself. The focused laser beam establishes the position of the cutting zone and will lie directly under the central core of the gas jet in the coaxial nozzle system. Figure 3.12a shows equilibrium set up of coaxial nozzle system. However, if the gas jet is not coaxial with the laser as in Figure 3.12b, the movement of gas away from the centre produces an overall flow across the top of the cut zone, which will cause poor cut quality, especially in laser cutting mild steel with oxygen. /2/

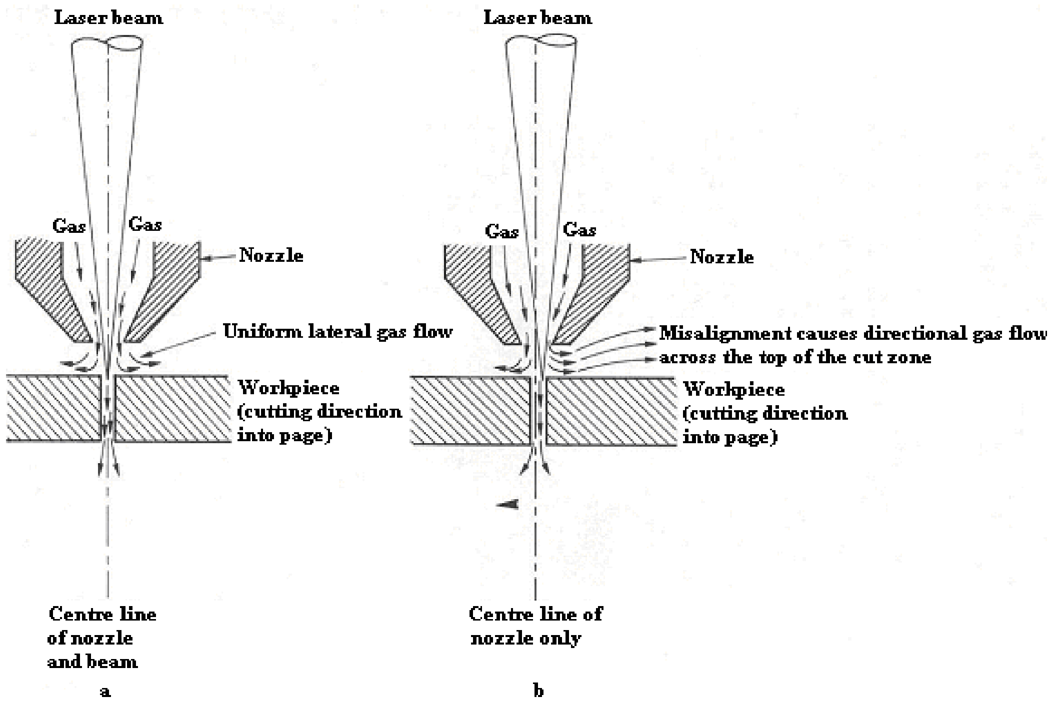


Figure 3.12 a. The equilibrium set up when the gas jet and laser beam are coaxial. B. Nozzle-beam misalignment. /2/

A major symptom of nozzle misalignment when cutting mild steels is a secondary shower of sparks which splash away from the cut zone across the top surface of the cutting material. Figure 3.13 illustrates clearly this effect. /2/

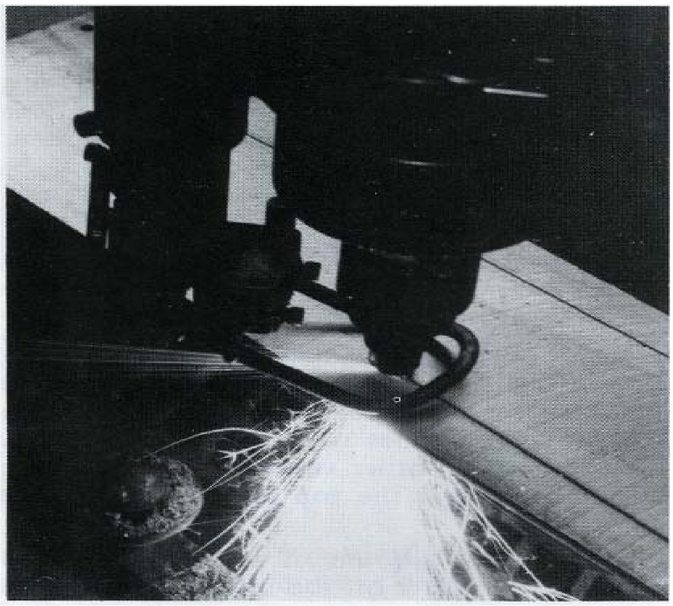


Figure 3.13 a secondary shower of sparks traveling across the sheet surface when cutting mild steel with oxygen. /2/

And Figure 3.14 shows the poor quality associated with it. Simply adjusting the position of the nozzle by moving it in the direction the sparks traveling can cure this effect. /2/

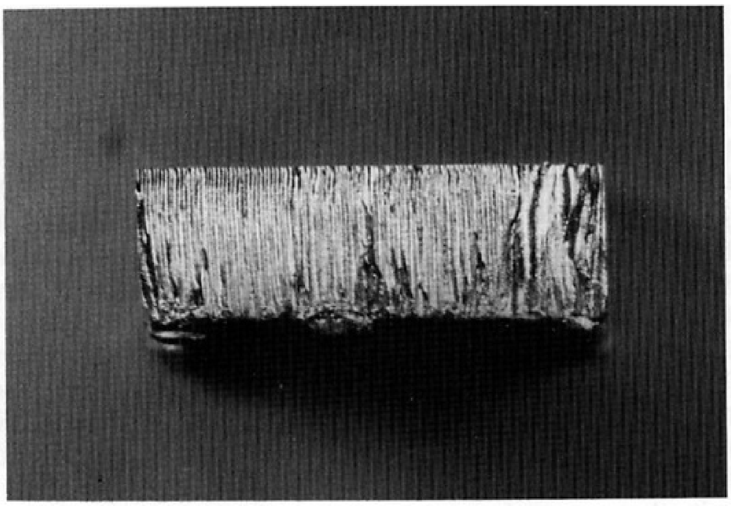


Figure 3.14 the poor quality cut obtained when the nozzle and beam are misaligned./2/

Another major symptom of nozzle misalignment is a reduction in the major shower of sparks leaving the bottom of the cut zone when cutting in certain directions. This problem is caused by the oxygen jet having its centre ahead of the focused beam and it will result dross adhesion. This problem can be cured by moving the nozzle in the opposite way of the cutting direction in which the shower of sparks is poorest. /2/

3.2.6 Cutting speed

The cutting speed must be balance with the gas flow rate and the power. As cutting speed increases, the cutting time decreases and less time for the heat to diffuse sideways and the narrower the HAZ. The kerf is also reduced due to the need to deposit a certain amount of energy to cause melting. However, striations on the cut edge become more prominent, dross is more likely to remain on the underside and penetration is lost. When the cutting speed is too low, excessive burning of the cut edge occurs, which degrades edge quality and increases the width of the HAZ. In general, the cutting speed for a material is inversely proportional to the thickness. /1, 4/

4. Characteristic properties of the laser cutting

The characteristic properties of laser cutting are used to describe the cut quality which includes the kerf width, perpendicularity tolerance, striation patter, surface roughness, burrs and dross attachment, and heat affected zone (HAZ).

4.1 Kerf width

The kerf is the slot that is formed during the laser cutting by removing the material. And kerf width is defined as the width of the cutting slot, which is typical a bit larger than the focused laser beam diameter. This represents the material removed either by evaporation or by melting and blowing. Because obviously it is a material waste process, it is desirable to keep the kerf width to a minimum. Therefore, it is important to choose the proper combination of the laser cutting parameters to produce a uniform and narrow kerf width. These parameters are the cutting speed, laser beam parameter, gas property and so on. /1, 5/

4.2 Perpendicularity tolerance

The perpendicularity or squareness and inclination tolerance (with the symbol of u), is the greatest perpendicular between the actual surface and the intended surface. The value of perpendicularity is equal to the sum of the angular deviation and the concavity or convexity of the surface. /2/ The perpendicularity includes not only the perpendicularity but also the flatness deviation for the bevel cut. /15/

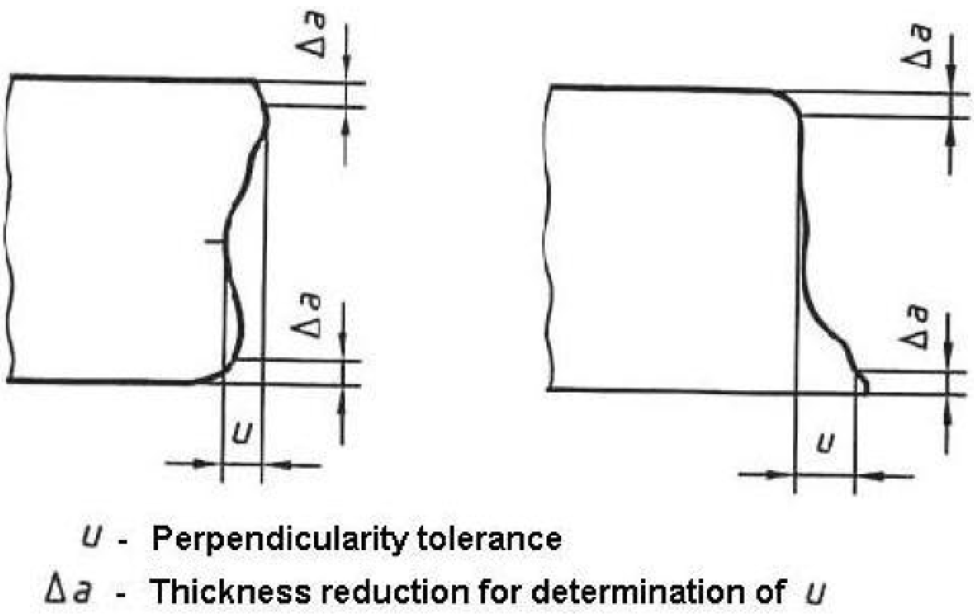


Figure 4.1 Perpendicularity tolerance of a straight laser cut /15/

4.3 Striation pattern

In the cut edge produced by laser cutting for example CO_2 cutting mild steel with oxygen, one always can observe the height and the spacing of the ridge-like striations. Striations always follow regular patterns. In thin section steel, these striations may be clear and regular from the top of cut edge to the bottom, as shown in Figure 4.2. /2, 5/

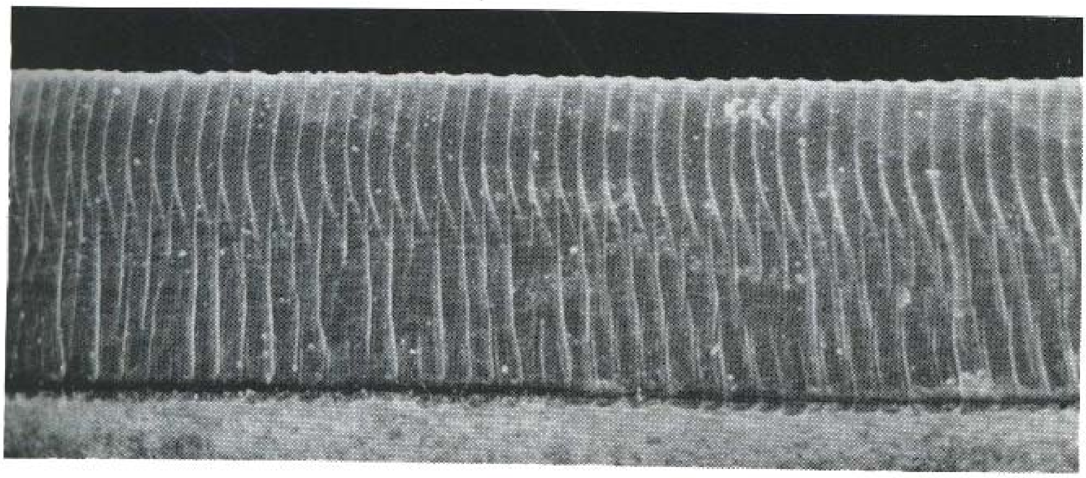


Figure 4.2 A typical mild steel cut edge (2.0 mm thick) showing the distinctive striation pattern. /2/

However, on the thick edge, these striations are more random ripples. These have been classified in a non-standard way in order to make the description of processing clear. The most noticeable visible effect on the cut edge is the location of the boundary layer separation points (BLS). It may be located at any point down the cut front depending on the input gas conditions. The striation pattern below the BLS location appears very chaotic and is indicative a poor melt eject conditions. /2, 16/

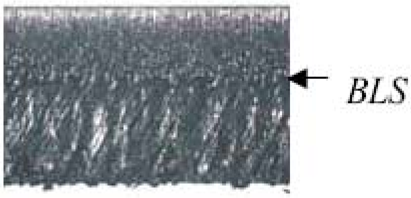


Figure 4.3 striation pattern and location of boundary layer separation point for 6 mm thick cut. /16/

The depth of the separation point is affected by cutting speed, gas pressure, focal position and nozzle diameter. In inert gas cutting, an increase in pressure consistently pushed the position of the separation point further down the cut front. /16/

The depth of the separation point is affected by cutting speed, gas pressure, focal position and nozzle diameter.

4.4 Surface roughness

The height of the striations is measured by a roughness indicator. Surface roughness is the irregularity or unevenness of the surface profile. It is measured as R_a and Rz5 (the index 5 in R_z5 was added to distinguish the arithmetic mean and the maximum height of profile of the five single profile elements). /1, 5, 15/

R_a, the arithmetic average height parameter, also called as the centre line average (CLA), is usually used roughness parameter for general quality control. It is defined as the average absolute deviation of the roughness irregularities from the mean line over one sampling length as show in Figure 4.4. This parameter is easy to define, easy to measure, and gives a good general description of height variations. The mathematical definition is, as follows: /17/

$$R_a = \frac{1}{l}\int_0^l |y(x)|\,dx \qquad \text{...........} \qquad 5)$$

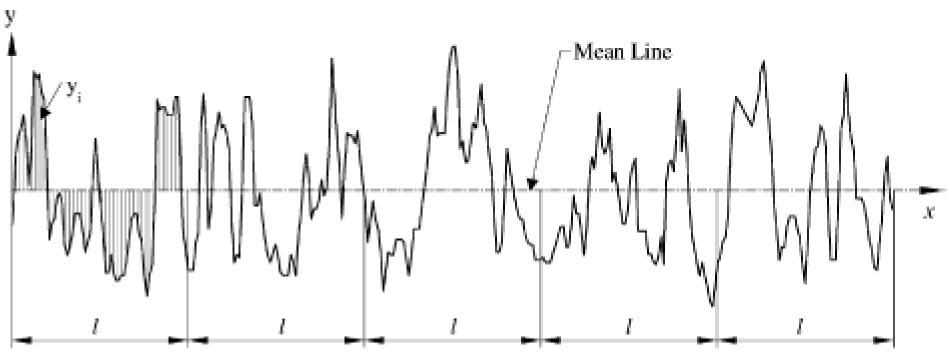
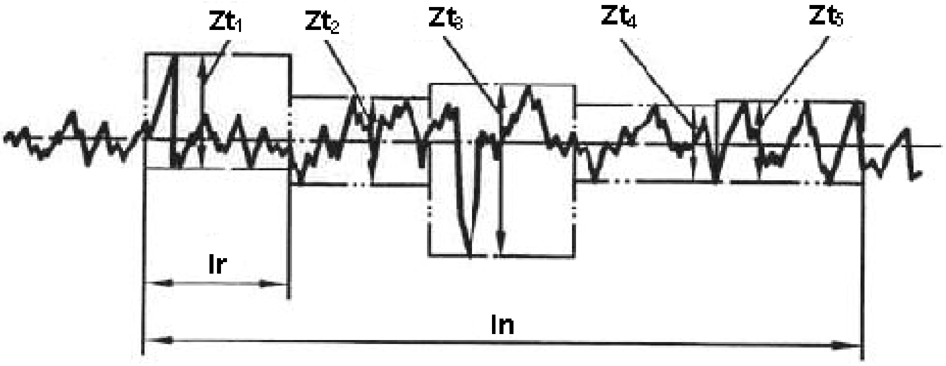


Figure 4.4 the average absolute deviation of the roughness. /17/

And R_z5 is the average value of roughness which is used in quality classification. In the measurement process of R_z5, a piece of 15 mm length from the species is chosen and divided into five partial measuring lengths. The distance between the highest peak and the lowest trough is determined for each partial measuring length. R_z5 is the average of these five distances, and is always measured in micrometers or micro inches. /1, 3/



Where

Zt_1 to Zt_5	represent single profile elements;
ln	is the evaluation length;
lr	is the single sampling length (1/5 of ln).

Figure 4.5 Mean height of the profile

4.5 Heat affected zone (HAZ)

Heat affect zone (HAZ), is the region adjacent to the kerf that has been thermally affected by the laser-cutting process. This region is affected by the cutting process in two ways. One is the surface discoloration produced due to the oxidation reaction. This surface oxidation is not permanent and can be removed by as simple a process as sanding the affected region. This region can also be easily measured by optical instruments. The second form of HAZ is the heat-treated zone adjacent to the cut-edge. This region is narrower than the surface oxidation region, and can only be measured through a micro-hardness test. Because of the difficulty associated with making hardness measurements, it is standard practice to report only the surface oxidation HAZ. /5/

The HAZ width increases as the energy input per unit length and the cut thickness increases. Although not normally included in quality assessment of a laser cut, HAZ width is important when cuts are to be made near heat sensitive component. It may place a maximum limit on the incident beam power or cut thickness, or a minimum limit on the cutting speed. /1/

4.6 Burrs and dross attachment

Dross is the molten metal that does not get away rapidly enough from the cut kerf and attaches it self to the underside cut-edge by re-solidification. And a burr includes not only the dross but also the slag which is formed by solidified oxides. The sharp of the burr is maybe the form of elongated droplets, or a rough, whisker-liker layer. Dross attachment could be due to several reasons such as low gas pressure, too great the stand-off distance, too high a velocity for cutting, or the viscosity of the molten metal being too high./1,5/

The mechanism of dross formation in laser cutting is not particularly clear. That is because the effect is uncertain how the jet of the assist gas affects on the flow of the molten metal generated at the cut front. There are lots of factors to affect the result, such as temperature of the molten metal to form a layer, viscosity coefficient, surface tension, gas flow rate and velocity, geometry of the cutting front and so on. Therefore, it is not simple to get a unique conclusion by using the mathematical theory. Takeji Arai and Noritaka Asano investigated the mechanism by using simulation analysis. The impacts of assist gas pressure, its velocity and viscosity coefficient of the molten metal have been studied based on the simulation. /18/

Dross attachment is undesirable as it causes the release of energy back to the metal leading to increased HAZ. Dross can be removed during process by the use of a gas jet from the underside of the workpiece, or removed mechanically after cutting. /1, 5/

5. High power fiber laser system

The high power fiber laser system has been developed recently which can be used in industrial application. In the following, firstly the development history of fiber laser is introduced. And then the component and character of high power fiber laser system is presented. In the end, the benefit and application area is stated.

5.1 The development history of fiber laser

During the last few years, the field of high power lasers has developed in a dramatic manner. In the early 1990s, the fiber laser is used to delivering some mW output power in the lab condition. Nowadays, it has already evolved to multi-kilowatt devices for use in material in industry.

There are two technical developments which give the prerequisites for the application of fiber in material processing: the optical communication industry ensures the preparation technology for highly transmissive single-mode fiber, and the optoelectronics industry made available the high-power laser diodes necessary for the pumping of the fiber. Therefore, it makes the possibility of increasing the power in fiber laser.

According to scientific and technical information published in the area of high power laser, the notion of high power means continue wave and average output powers of about 100 W and more. /19/

5.1.1 The development of diode pumped solid-state laser

Solid state lasers are lasers based on solid state gain media such as crystals or glasses doped with rare-earth or transition-metal ions, or semiconductor lasers. Ion-doped solid state lasers (also sometimes called doped insulator lasers) can be made in the form of bulk lasers, fiber lasers, or other types of waveguide lasers./20/

And the key point of the design of a solid state laser is how to get the pumping power into laser block and cool the block efficiently without distortion or break. /4/ Many solid state lasers are pumped with flash lamps or intense arc lamps. Such pump sources are relatively cheap and can provide very high powers. However, they lead to quite small power efficiency, moderate lifetime, and to strong thermal effects such as e.g. thermal lensing in the gain medium. /20/

Nowadays, with the availability of sufficiently high-power levels, the replacement of lamps by diodes to pump the laser crystals became of interest for systems to be used in materials processing. At the same time, a number of important achievements can be reached based on different pumping techniques and crystal geometries—rods, slabs, discs and fibers. Because of the high optical/electrical power conversion of the diodes and the more selective excitation of the laser-active medium, the overall efficiency of the laser system can be improved of 5% compared to lamp-pumped systems. Due to the quick heat release in the crystal, the temperature-dependent thermal lens effect is less pronounced yielding a higher beam quality. The diodes also have a longer lifetime which is beneficial of the running cost. Moreover, the higher pump intensities allow the use of active ions other than neodymium, e.g. ytterbium, resulting in basically higher efficiencies or wavelengths better suited for special applications. /13/

In the Figure 5.1, the geometries of the laser-active medium for DPSSL and the principle orientations between pump radiation and optical axis are summarized. /13/ The classical geometry of the solid-state laser is the rod. In the last decade, it developed two new geometries—the disk and the fiber laser geometry. The most prominent difference of disk and fiber laser compared to rod geometry is the relatively small volume of laser active medium. Figure 5.2 illustrates the geometric data for the different laser configurations. It can be see the active volume of disk and fiber geometry is three orders of magnitude smaller than in the rod. Another parameter difference is that the ration of surface to volume in much higher for the fiber. This result to a big advantage of fiber geometry—the heat, which is generated in the active medium, can be carried away to the environment or eliminated by a cooling system much faster in the fiber laser than in the disk or the rod and a thermal lens will not build up. /21/

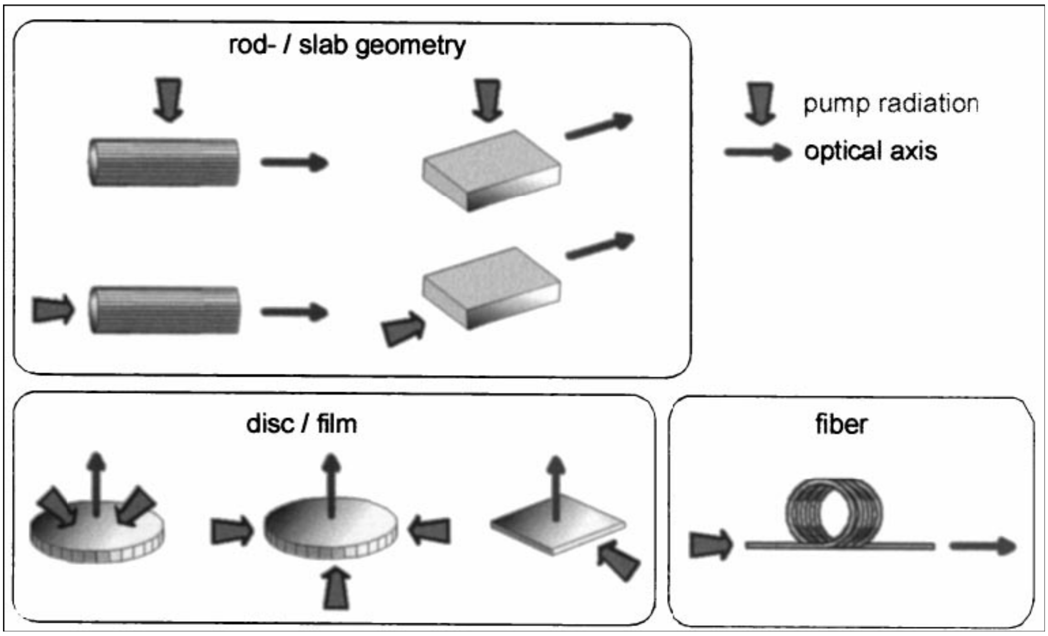


Figure 5.1 Schemes of diode pumped solid state lasers. /13/

In most of the solid-state laser, the active medium is homogenous material. In this point of view, the fiber laser is different from both rod and disk: it consists of at least two parts with different material properties—the laser active core for wave guiding and the surrounding passive cladding. Therefore, the propagation characteristics of the fiber laser radiation are completely determined by the refractive index structure of the core and not by an external resonator as in the rod and disk laser. The guiding mechanism prevents any influence from heating phenomena even more efficiently than the high surface-to-volume ration. /21/

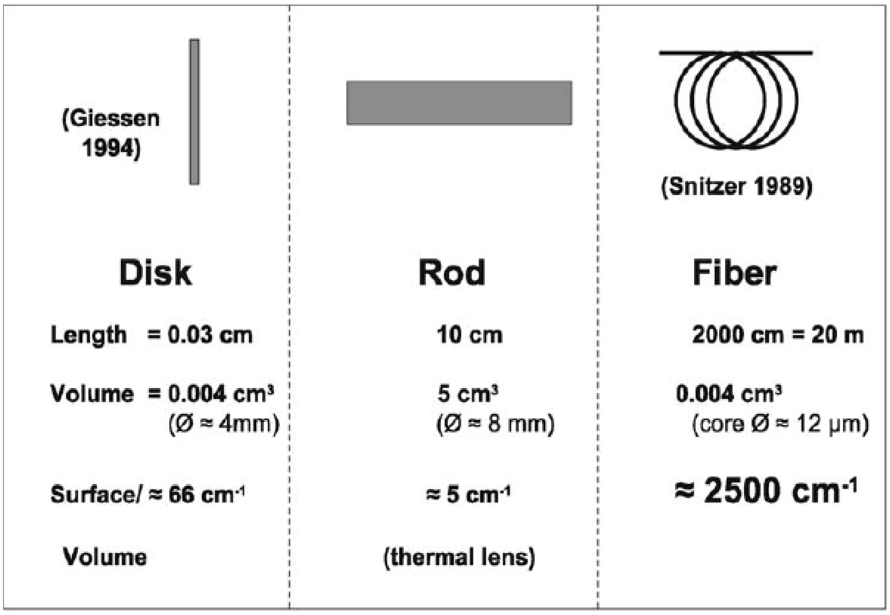


Figure 5.2 Typical dimensional parameters of the different laser geometries./21/

In most of the solid-state laser, the active medium is homogenous material. In this point of view, the fiber laser is different from both rod and disk: it consists of at least two parts with different material properties—the laser active core for wave guiding and the surrounding passive cladding. Therefore, the propagation characteristics of the fiber laser radiation are completely determined by the refractive index structure of the core and not by an external resonator as in the rod and disk laser. The guiding mechanism prevents any influence from heating phenomena even more efficiently than the high surface-to-volume ratio. /21/

5.1.2 The evolution of development of fiber laser

In the past several years, the fiber laser was mainly applied in the realm of the telecommunications industry. With the collapse of the telecommunications markets in the late 1990's, especially the winter of Internet in the year of 1999, fiber laser producers have to seek the other application of fiber laser, at last they shifted their focus on meeting the needs of industrial manufacturing. The shift to alternative markets requires higher power laser developments with an emphasis on operational and performance targets. /22, 23/

Since the demonstration of the potential of new technology in fiber laser, such as the power scaling of fiber laser and amplifiers with diffraction-limited beam quality using low-numerical aperture large-mode-area fibers, numerous high power single mode fiber lasers have been realized by several research groups. Pioneering contributions are done at the University of Southampton, Friedrich Schiller University of Jena, University of Michigan, IPG Photonics, SPI Laser. Their main achievements are summarized in Figure 5.3. This evolution has its origin in the inherent properties of fiber and also in the progress of fiber manufacturing technology and availability of reliable high power diode laser pump sources. /24/

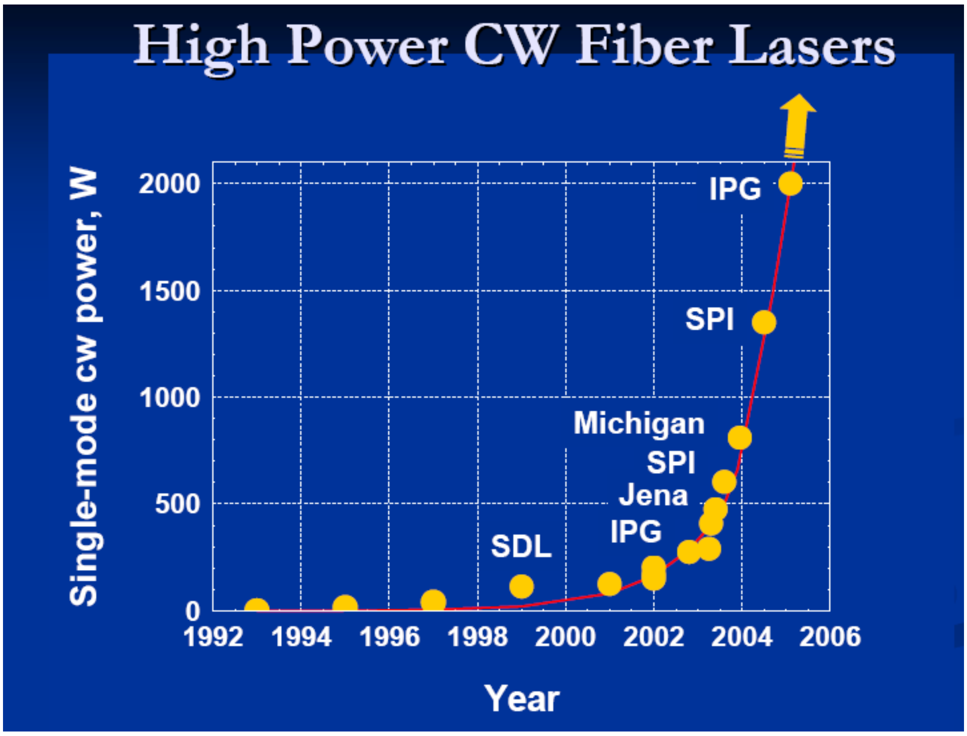


Figure 5.3 The single mode fiber laser power evolution. /25/

In the year of 2007, it has been reported the highest power of single-mode cw fiber laser is available at 3 kW and 50 kW in multimode fiber laser in IPG Laser. In the future, fiber laser technology will continue to improve the power levels soon to be available commercially to 100 kilowatts and beyond. Laser beam quality will improve by a factor of three over current levels and single-mode laser power will also be increasing for 3 kilowatt to higher level. kilowatt-class lasers will be available at 1.54 μm (Erbium wavelength), offering higher beam transmission through fibers at much longer distances. /25, 26, 27/

The market opportunity for materials processing fiber lasers is substantial. The estimated revenues for fiber lasers in 2005 were $123 million out of a total market size of $2.3 billion. Fiber laser growth has greatly outpaced the overall market growth and continues to gain momentum. The price one must pay for this technology will continue to decrease, further expanding the use of the technology in manufacturing plants worldwide. The acquisition costs of high-power fiber lasers are currently substantially below diode- and lamp-pumped Nd:YAG's and are said to be approaching the levels of CO_2. Considering the operational savings (see Figure 5.4 for a comparison of high-power laser costs), such as electrical power and their increased production capabilities, the value proposition for fiber lasers becomes even stronger. /27/

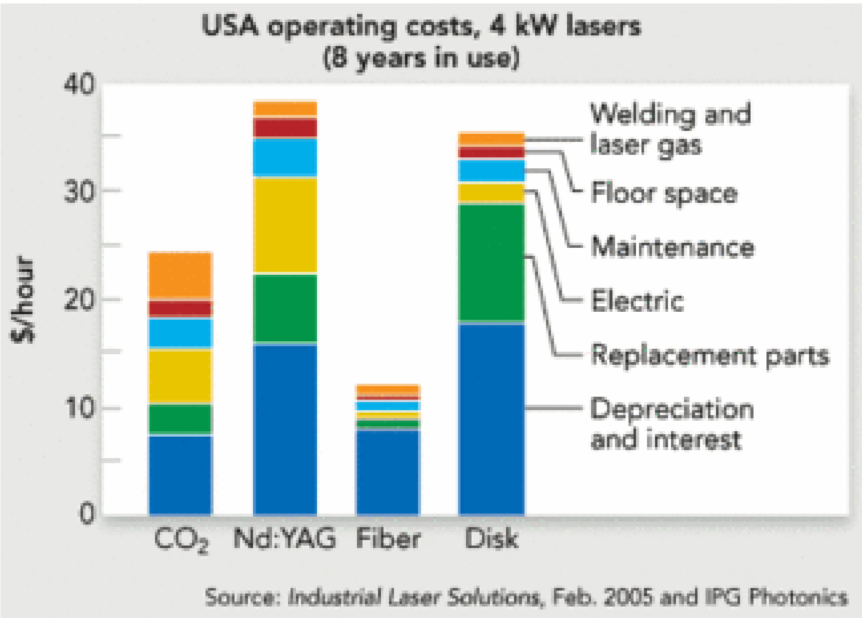


Figure 5.4 Comparison of operating costs for 4kW lasers /27/

5.2 Components of high power fiber laser system

In principle, the fiber laser is similar to any other diode pump solid state laser technology. The laser active media usually consists of a glass fiber pumped by diode. It is illustrated in the Figure 5.5. /28/

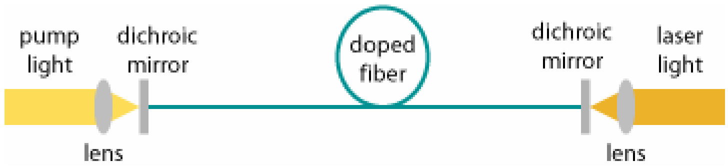


Figure 5.5 Setup of a simple fiber laser. Pump light is launched from the left side through a dichroic mirror into the core of the doped fiber. The generated laser light is extracted on the right side. /29/

5.2.1 Optical fiber

Optical fibers are a special kind of waveguides, which are usually made of silica glass. In the high power fiber laser system, the optical fiber is used as active medium to scale power and peak intensity. Therefore, maximizing fiber mode size and preserving single transverse mode beam are required about the optical fiber according to the purpose. /25, 29/

There are many different types of fiber used in high power fiber laser system with respect to different property:

- With respect to optical guidance:
  - Conventional index-guiding
  - Photonic Crystal effective index guiding
  - Photonic Crystal bandgap guiding
- With respect to modal properties:
  - Single transverse mode (SM) core fibers
  - Large mode area (LMA) fibers
  - Effectively single mode (ESM)
- With respect to polarization properties:
  - Polarization non-preserving fibers
  - Polarization preserving (high birefringence) fibers
  - Single polarization fibers

In most cases, the active medium is doped with rare-earth ions such as ytterbium, neodymium, praseodymium, erbium, or praseodymium, and their gain spectral ranges are illustrated in Figure 5.6. The majority of rare earth doped high power lasers consist of an Yb or Er dopants with output around 1070 nm and 1550 nm respectively. Higher efficiencies are achieved at 1070 nm compared with 1550 nm output. And one or several laser diodes are used for pumping. /25, 29, 30/

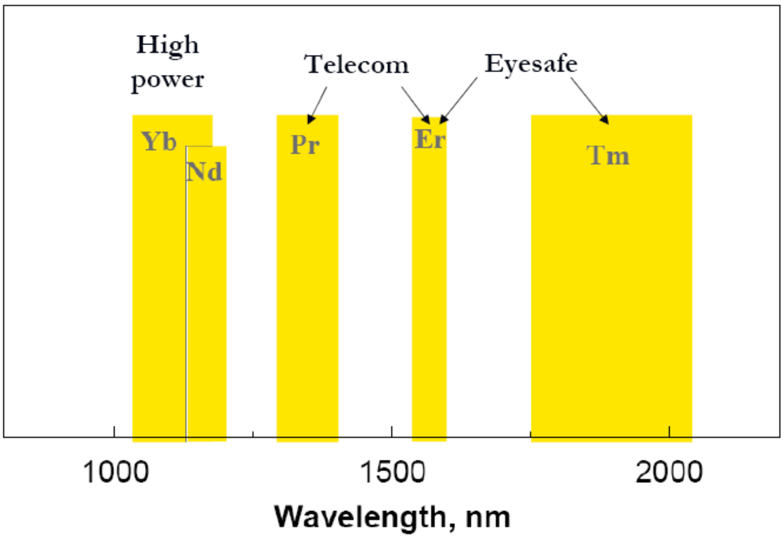


Figure 5.6 Gain spectral ranges of rare-earth doped fiber. /25/

5.2.3 Fiber laser pumping

With the core material doped rare-earth elements and a pump-radiation coaxially superimposed, the so called “core-pumped” fiber lasers were realized in the low-power regime (limit to 1W). This longitudinal pumping concept requires pump sources with M^2 values suitable to couple to the single mode fiber. Such single mode diodes were, and still are available only for low power. /13, 25/

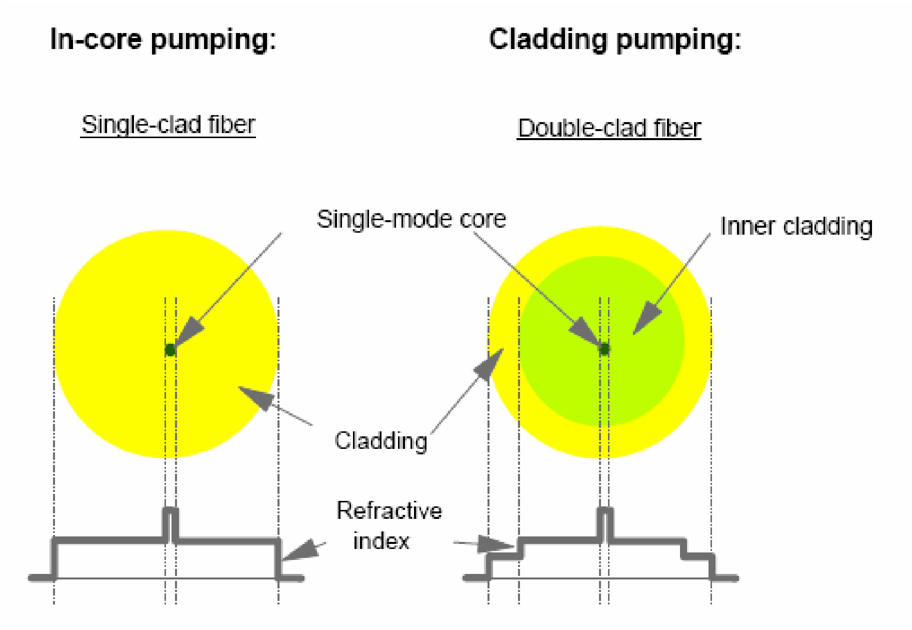


Figure 5.6 In-core pumping V.S. Cladding pumping /25/

High power fiber lasers are nearly always realized with double-clad fibers, which are end or side pumped with fiber-coupled high power diode bars or other kinds of laser diodes. The pump light is launched into an inner cladding (diameter of some 100 µm, NA≈0.4) rather than into the much smaller fiber core, in which the laser light is generated. The laser light can have very good beam quality – even diffraction-limited beam quality if the fiber has a single-mode core. /25, 31/

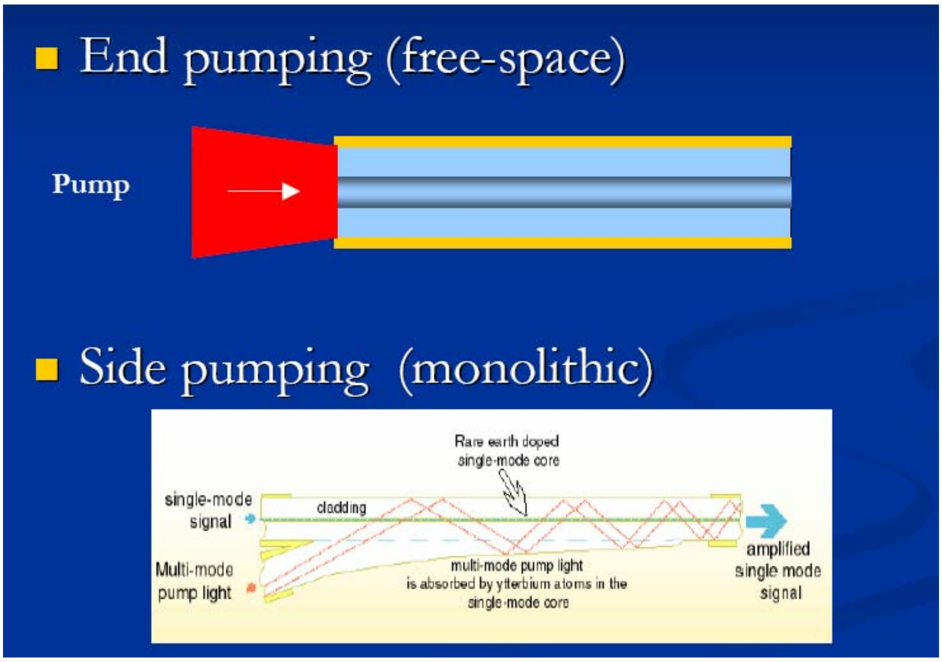


Figure 5.7 Double-clad fiber pumping /25/

However, in the double-clad fiber, intensity distribution can exist in the inner cladding which leads to a degradation of efficiency and reduce pump light absorption. An improvement can be made by breaking the cylindrical symmetry of the inner cladding. Geometries such as D-shaped or rectangular pump core, force the beam to follow more irregular or even chaotic paths and prevent the propagation of such undesired intensity distribution. It has proven both experimentally and numerically that the D-fiber has favorable properties compared to other structures, as shown in Figure 5.8. /21, 24, 25/

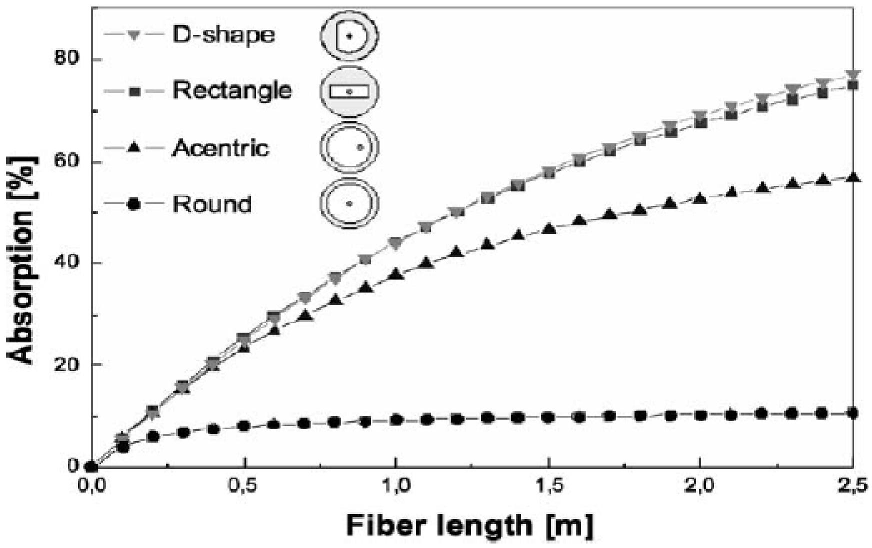


Figure 5.8 Model calculations for the absorption of different cladding-pumped structures in dependence on fiber length /21/

For the highest powers, one requires a rather large core area, because the optical intensities would otherwise become too high, and often also because a double-clad fiber with a large ratio of cladding to core area has weak pump absorption. For core areas up to the order of 1000 μm^2, it is feasible to have a single-mode core. Somewhat larger mode areas with still rather good output beam quality are possible with a slightly multimode core, where most of the light propagates in the fundamental mode. (One can to some extent suppress the excitation of higher-order fiber modes e.g. by coiling the fiber.) For even larger mode areas, the beam quality can no more be nearly diffraction-limited, but it can still be rather good compared e.g. with rod lasers operating at similar power levels. /31/

5.3 CW High power fiber laser system

A CW single mode core high power fiber laser is usually made of several meters of multi-clad single mode active fiber side pumped by single stripe multi diodes, as illustrated in Figure 5.9. The pump light is obtained from two sets of multimode high power laser diodes coupled from both sides through a pair of special multimode coupler. Then the light is launched into the first cladding of the multi-clad fiber. In laboratory setups, the cavity mirrors are ordinary dielectric mirror, as shown in the Figure 5.5. However, it is not suitable for practical mass fabrication and either not durable. For commercial products, it is used fiber Bragg gratings as end mirrors. The laser light exits the cavity through a single mode passive fiber that could be up to 50 meters long. /29, 33, 34/

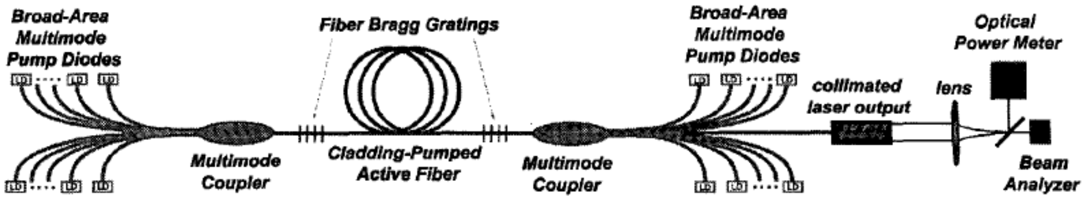


Figure 5.9 Monolithic fiber laser system/33/

In the single mode fiber laser, the output beam quality BPP is less than 0.38mm.mrad. The good mode quality allows the beam to be focused down to spot sizes as small as 10 µm. The ability to focus to small spot and a perfect beam produces high brightness and high power densities as high as 10^8w/cm^2, which is required for cutting thin metals applications. The total electrical to optical power efficiency (also called the wall plug efficiency) is greater than 20%. Single mode CW Ytterbium fiber laser systems of near infrared spectral range (1060-1080nm) are available from 1 to 3 kilowatts in IPG Photonics. These lasers are monolithic units that are completely sealed and do not need maintenance, mirror replacement or realignment. It has been reported the highest power of single-mode CW fiber laser is available at 3 kilowatt in IPG Laser. These single mode CW laser can also be operated in the pulsed mode by pulse width modulation. Based on the power evolution and the mode of operation, an array of applications can be accomplished with the single mode fiber lasers. /3, 4, 35, 27, 36/

In the multimode CW fiber laser, kilowatt and multi-kilowatt lasers are manufactured by combining single mode fiber modules and delivering the output through a single multimode fiber. Although the output is no longer single mode, the systems have excellent beam properties equal to or lower than conventional CO_2 or YAG lasers. In the area of multimode fiber laser system, IPG is the only one that has been able to scale the output power up to the tens of kilowatts. Its highest power installation to date is a 36 kW model that is being used by the nuclear industry. And nowadays the maximum power for commercial used high power fiber laser system is up to 50 kW. /9, 26, 35/

5.4 Characteristic properties of fiber laser system

5.4.1 Single mode fiber and multimode fiber

A fiber can support one or several propagation modes of the intensity distributions. An important distinction is that between single mode and multimode fibers. /42/

Single mode fibers usually have a relatively small core and can guide only a single spatial mode. Multimode fibers usually have a larger core and/or a larger index difference between core and cladding, so that they can support multiple modes with different intensity distributions, as shown in Figure 5.13. Launching light into a multimode core is much easier and more stable. /42/

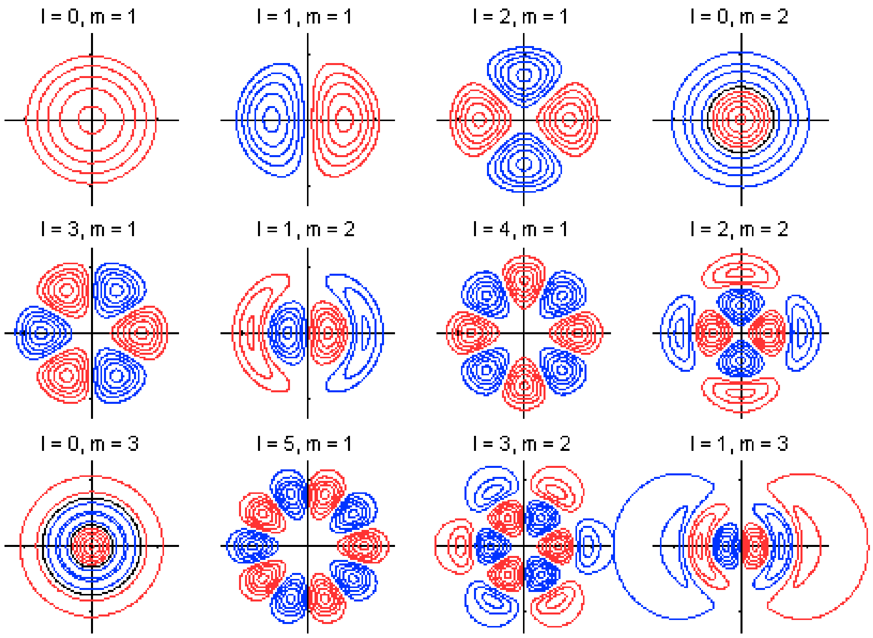


Figure 5.13 Modes of a fiber with a top-hat refractive index profile. The lowest-order mode (l = 1, m = 0, called LP01 mode) has an intensity profile which is similar to that of a Gaussian beam. Generally, light launched into a multimode fiber will excite a superposition of different modes, which can have a rather complicated shape. /13/

In fiber lasers and amplifiers, single-mode guidance allows achieving a high beam quality of the output. Multimode fibers are used for the transport of light from a laser source to the place where it is needed. For example, fiber-coupled high power diode bars use multimode fibers. Some high power fiber amplifiers are based on multimode fibers, because these can have larger mode areas. /42/

5.4.2 Power scaling

The power scaling of fiber lasers is a procedure for efficiently increasing the output power of the lasers. In the early days, the lack of suitable pump power limited power scaling of fiber lasers. As diode bar technology matured, fiber laser results increased, with the first report of operation in excess of 100 watts in 1999. Single mode fibers reached their upper limit in 2002 when the stimulated Raman threshold prevented output powers from reaching 150 watts. Today, the development of suitable methods of obtaining diffraction-limited beam quality from multimode fibers with large-mode-areas has once again made fiber laser power scaling mainly dependent on the available diode power. /43/

A straightforward way to achieve laser power in the kW-range is the incoherent coupling of several fiber lasers. Fiber coupling of several identical modules could be an appropriate technique, because it allows separate the pump diodes and their cooling arrangement from the laser head of a diode-pumped solid state laser. This could be done by either coupling the power of several modules into one single fiber or by transmitting the power of the modules via several smaller fibers individually to the work piece, the latter enabling an easy realization of the multi-focus technique. Although the output is no longer single mode, the system can produce good beam quality compared to the conventional laser. /13/

5.4.3 Numerical aperture

The numerical aperture of the step index-fiber where the corn has a constant refractive index is the sine of the maximum angle of an incident beam with respect to the fiber axis (see Figure 5.14). Thereby all modes of light entering the fiber at angles less than that which correspond to the NA, will be bound or confined to the core of the fiber. It is determined by the refractive index difference between core and cladding, more precisely, by the relation: /44/

$$NA = \sqrt{n_{core}^2 - n_{cladding}^2} \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

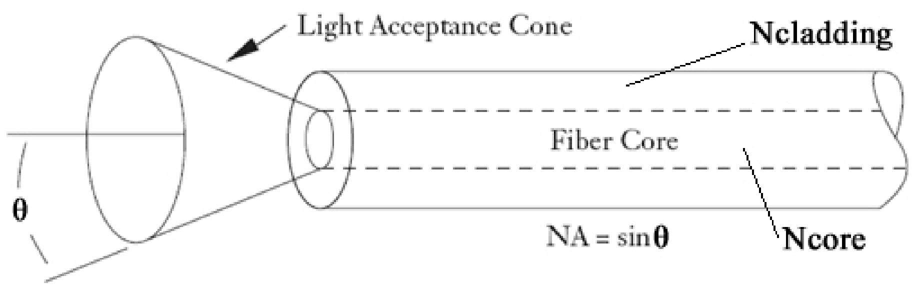


Figure 5.14 Illustration of numerical aperture

For a single-mode fiber, the NA is typically of the order of 0.1, but can vary roughly between about 0.05 and 0.4. Multimode fibers typically have a higher numerical aperture of e.g. 0.3. For photonic crystal fibers, very high values are possible. /44/

The larger the NA of a fiber is, the larger the light acceptance cone. And also the fiber can be more strongly bent before bend losses become significant. /44/

5.4.4 Bend loss

Bend loss in fiber laser system is the propagation losses caused by bending. When the fibers bent, they exhibit additional losses. Normally, these losses rise very quickly once a certain critical bend radius is reached. For a typical fiber, the effect of bend loss may become apparent when the radius of curvature decreases below 1-10 cm. However, for fiber with robust guiding characteristics, the critical radius can be very small (a few millimeters). Even without macroscopic bending of a fiber, bend losses can occur due to the micro-bends caused by imperfect fabrication conditions. Thus, it is very important for the high power laser system to ensure low-loss operation of the fibers even when it is bent. /45, 46/

In a single-mode fiber, bend losses can strongly increase for longer wavelengths beam, so that they often limit the usable wavelength range. For example, a fiber with a single-mode cut-off wavelength of 800 nm can normally not be used at 1500 nm. In multimode fibers, the critical radius is typically smaller for higher-order transverse modes. By properly adjusting the bend radius, one can introduce significant losses for higher-order modes without affecting the lowest-order mode. This is useful to know for the design of high power fiber system./45/

5.5 Fiber laser benefits

In the single mode fiber laser, the output beam quality BPP is less than 0.38mm.mrad.

In the multimode fiber laser, kilowatt and multi-kilowatt lasers are manufactured by combining single mode fiber modules and delivering the output through a single multimode fiber. Although the output is no longer single mode, the systems have excellent beam properties equal to or lower than conventional CO_2 or YAG lasers. A comparison of the beam quality associated between conventional lasers with fiber laser is shown in Figure 5.15. /9, 30/

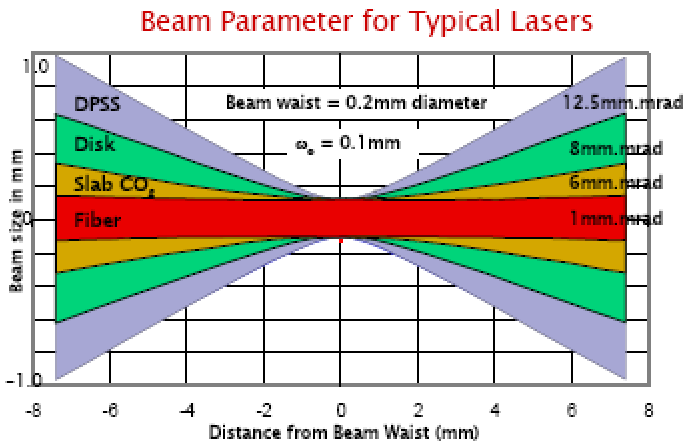


Figure 5.15 Performance characteristics for various laser types /30/

There is much to be done to apply fiber lasers to the wide range of processing applications, all current processes would benefit from the low BPP. In terms of general attributes, the fiber laser has the following benefits compared to the traditional laser systems: /9, 30/

- High beam quality which allows the user to produce spot diameters substantially smaller than conventional lasers.
- High power output and high electrical efficiency which greatly reduces the operating cost, showed in the Figure 5.4
- Flexible beam delivery and longer work distance. The delivery beam fiber for a 1 kilowatt system is 50 microns and for a 10 kilowatt system it is 100 microns. This allows for longer working distances and more consistent processing than conventional Nd:YAG lasers with fiber delivery.
- Essentially maintenance free during the entire lifetime because there is no need to replace diodes.
- No mechanical resonator, no user serviceable cavity optics, no cavity alignment, no pumps (no oil changes)
- Multiplexing potential

- Inbuilt redundancy
- Beam shaping potential
- Compact processing heads
- Small optics /9, 30, 35/

Expect cutting, welding, marking and other processes such as laser forming and rapid manufacturing to establish greater levels of performance with the new generation of high power fiber lasers. /30/

5.6 Applications

With the significant advantages compared to traditional laser systems, fiber lasers have the potential to completely dominate the material processing market in the future. Fiber lasers are demonstrating process and cost advantages across the entire spectrum of material processing applications including: metal cutting, welding, silicon cutting, ceramic scribing, spot welding, bending, powder deposition, surface modification and marking. Several examples are showed in the following about the application in industry: /34/

- Automotive: welding transmission components, welding a sheet metal, cutting hydroformed parts, marking, remote welding
- Computer: bending flexures, spot welding, annealing, silicon cutting.
- Aerospace: welding Aluminum and Titanium, surface build up on blades, cutting aerospace components
- Medical device: marking, cutting, spot welding
- Semiconductor industry: microfabrication. /25, 34/

In the conclusion, the fiber laser brings a cost effective alternative to current CO_2 and YAG laser for material processing. It will expand the application and acceptance of laser technology due to its wavelength range, reliability, compactness, efficiency and unique performance parameters. /34/

6. Laser cutting mild steel with high power fiber laser

Cutting with fiber laser is still a very young technology. The dynamics of how to get out the melt material out in fiber laser cutting is different from the traditional process of CO_2 laser cutting. That is because of the narrow beam, small spot size, high intensity and deep tremendous depth of focus as mentioned in Chapter 3. And these factors make the dynamics very complex in the process of fiber laser cutting. And there is still a lot of optimization can be done in cutting with fiber laser in the future years. /11, 48/

6.1 Cutting with high power fiber laser

In the past several years, laser cutting of thick material is normally dominated by CO_2 laser. However it has been proved that the major limitation of the performance of CO_2 laser cutting especially in thicker section cutting is normally not the laser power or the coupling of the laser beam into the material, but the melt ejection from the narrow cut kerf. Therefore the CO_2-laser is not suitable for cutting thicker section, as it creates strong shielding plasma in the keyhole, when high intensity CO_2-laser light is applied. /2, 48/

The new laser types such as the high power fiber lasers, however, have the potential of creating the high intensity beams and at the same time the wavelength makes it possible to transmit these beams down through a relatively deep keyhole cutting without deteriorating the intensity by interaction with vapor and/or plasma. /48/

Compared the cut front in the high power fiber laser melt cutting (Figure 6.1A) with in the melt cutting (Figure 6.1B), we can find the molten layer in front of the laser beam in the high intensity laser melt cutting is so thin due to the melt flow around the keyhole. As showed in figure 6.2, three different Zones(Ⅰ-Ⅲ) can occur in the cut kerf.

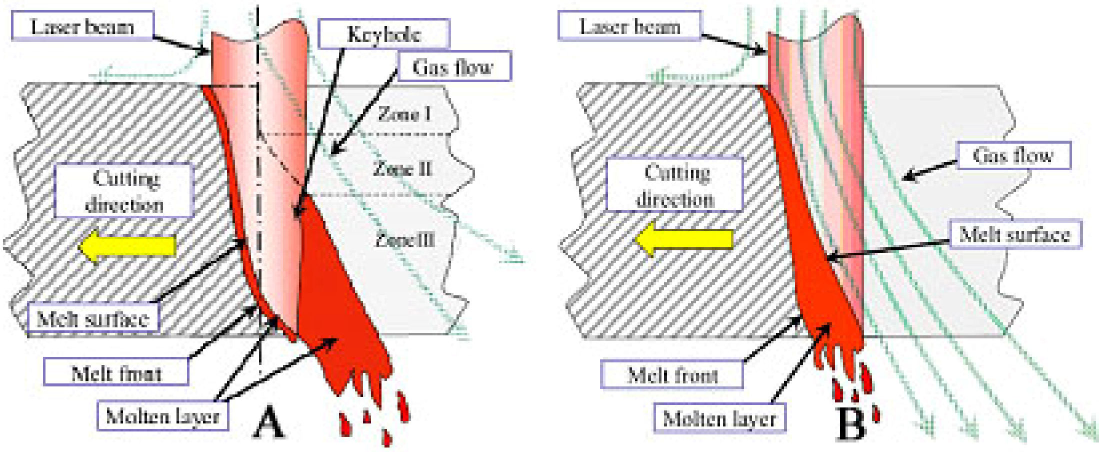


Figure 6.1 Cut front in A. laser melt cutting with high power fiber laser beam; B. Laser melt cutting with traditional laser source. /48/

In zone Ⅰ, the melt is blown out within the semi cylindrical cut front, basically in front of the laser beam. There are two sub zones within it. In the sub zone of Ia, there is a pure horizontal melt flow, and in Ib, there are an approximately horizontal flow around the centerline and a pure vertical flow in the sides of the cut kerf. In this zone, the striation pattern might be vertical lines, and it also might be varied betweens the striation lines down through the kerf. /48/

In zone Ⅱ, the melt flows around the laser beam coarse cut edge roughness might occur without striation pattern. In zone Ⅲ, a keyhole is formed around the laser beam and the vertical flow is behind it. Although uneven cut edges might be the result, the melt flow probably is more stable than in the zone Ⅱ, resulting in lower rough ness it this zone. /48/

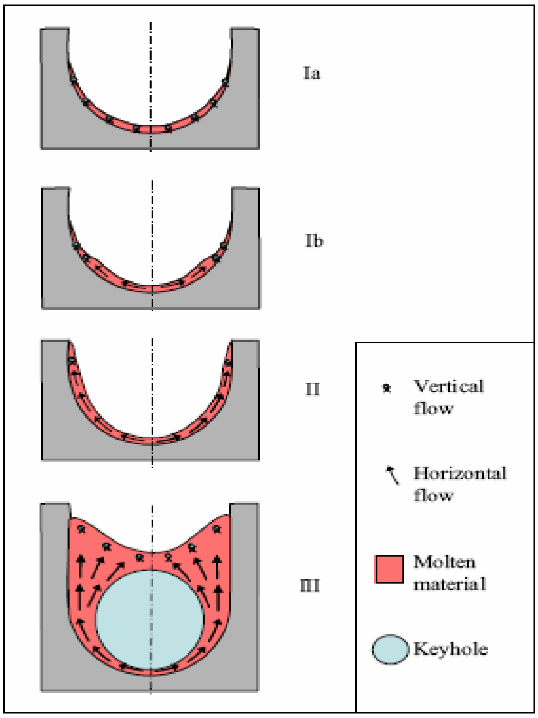


Figure 6.2 Horizontal cross sections of the front of a cut kerf from laser melt cutting with a high intensity fiber laser /48/

Due to the complex flow pattern in this kerf, the cut quality might be poorer than with traditional laser melt cutting. Furthermore, the flow pattern in zone Ⅱ and zone Ⅲ might widen the cut kerf, so that it will be much wider than the laser beam diameter. When take the cutting speed into consideration, the cutting mechanism of fiber laser will become more complex. /11, 48/

6.2 Fiber laser cutting mild steel

In the last years, it has been reported by IPG Photonics that a group of scientists were focusing on the fiber laser cutting mild steel. In Stuart Wood's presentation, it compared the cut quality of fiber laser cutting mild steel with CO_2 laser, as shown in Figure 6.3. When the speed is less than about 4 m/min, it is reported by the IPG's customer that the cut quality of fiber laser equal to or better than CO_2; when it comes to the speed between 4 m/min and 6 m/min, the cut quality of fiber laser almost equal to CO_2; the cut quality is not ideal for fiber laser when the speed exceeds 6 m/min. /11, 36/

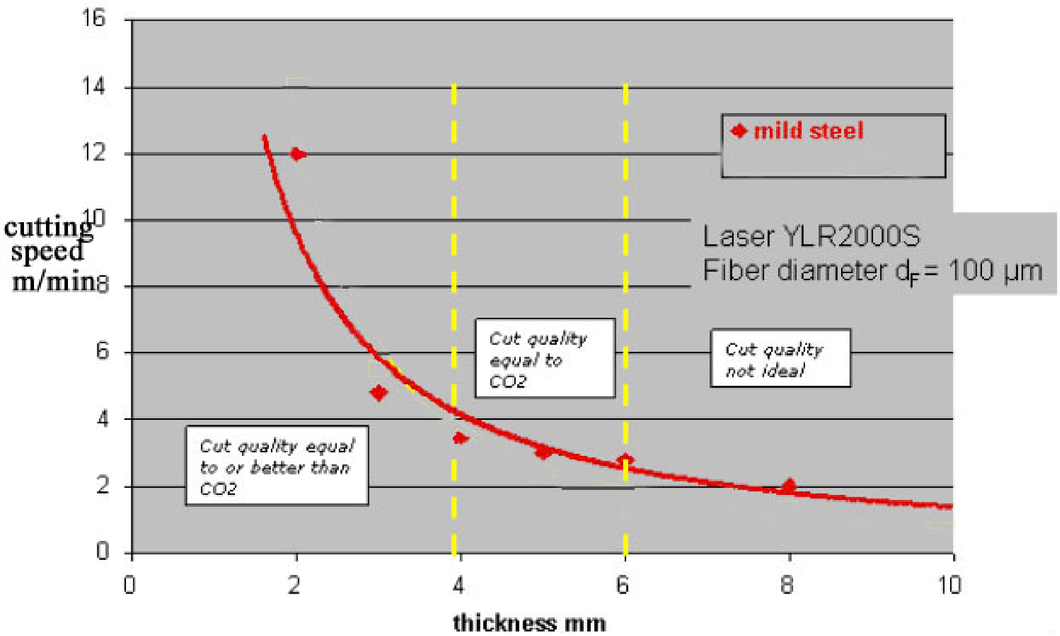
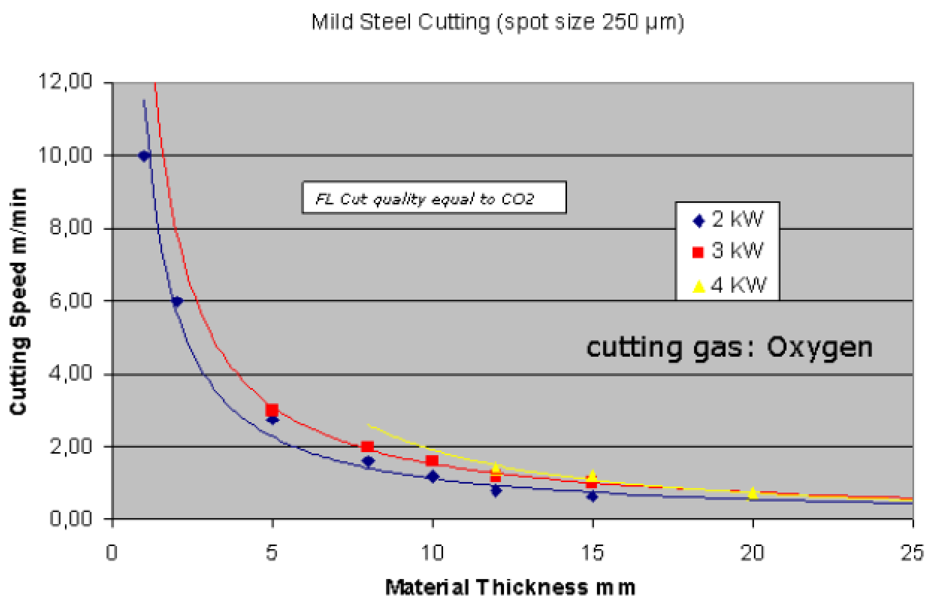


Figure 6.3 Cutting with 2 kW fiber lasers

And it also have been reported that the fiber laser cut quality of mild steel with thickness up to 20 mm is equal to CO_2, as shown in Figure 6.4. /11, 36/



/11/

Figure 6.4 Fiber laser cutting mild steel with oxygen

6.3 Laser cutting mild steel in industry

Mild steel is a dominated material in laser cutting industry. Mild steel is the most important material which undergoes a chemical reaction caused by laser during cutting. This chemical reaction increases the cutting speed as the Chapter 2 refers. However, it has the unfortunate side effect of increasing the sensitivity of the process to certain parameter, particularly the following four aspects:

1. Nozzle-beam misalignment
2. Poor axial symmetry of the laser mode
3. Contamination of the oxygen supply
4. Local overheating of the work piece.

The first three aspects have been referred in the Chapter 3. Due to aspect of local overheating, additional attention needs to be given in the cut initiation and termination in industry application, which has been discussed in the detail in the book of CO2 laser cutting (John Powell). And in our experiment, consider the overheating in the initiation and termination of cutting process, the beginning and end positions of the cutting slot are not took into the consideration for judging the experiment results.

Apart from these four parameters, the cutting process has a remarkably large "operating window" within which excellent cutting results can be achieved, unless maximum possible cutting speeds are required. In practice, most experienced laser user work at between 80% and 90% of the maximum cutting speed for a particular steel sheet thickness. /2/

The following will give us a rough guide to the flexibility of the main process parameters when cut at 85% of the maximum cutting speed: /2/

- Laser Power: it can be increased by up to 30% or decrease by 10% without seriously affecting the process.
- Focus Position: normally, the focus position should be on the material surface, however defocusing in either direction by 1% of the focal length will make only a

marginal difference to the cutting process.

- Sheet Condition: Local area of moderate surface corrosion or small (±10%) variations of thickness can be accommodated. Also mechanical damage has little or no effect.
- Oxygen supply: ±10% variation from the optimum set of the oxygen flow can be accommodated. However, the purity of oxygen is very critical to the process. For example, an addition of 1% contaminant can reduce cutting speed of 30%.

From the above statement, it is obvious that laser cutting mild steel is a reliable and rugged process if the four sensitive parameters (the condition and alignment of the nozzle, the symmetry of the mode, the oxygen purity and the avoidance of overheating) are given sufficient attention. /2/

Experimental Part

7. Purpose of this study

The new generation of high power fiber lasers presents several benefits for industrial application. The purpose of the experiment in this thesis is to investigate the cutting performance and how cutting parameters affect cut quality of fiber laser cutting mild steel. The high beam quality of fiber laser is expected to enhance cutting speeds. Due to the performance of fiber laser, the cut quality may be different from traditional laser cutting, for example wider cutting kerf.

In the following chapters, the process of experiment is presented in detail. After that the measurements result of the experiment is stated and analyzed. In the end of this part, a conclusion is made about this part.

8. Test material, equipment and procedure

In this chapter, the two kinds of material used in the experiment are introduced first. And then the statement about the whole work cell is given, including the cutting machine, power source, cutting head and control equipment. Finally, different equipment involve in measurements is briefly presented.

8.1 Test materials

There are two kinds of mild steel used in the cutting experiments, one is EN 10027:1993 S355 K2G3, the other is SFS 200:1986 Fe 52D, which are available in the form of sheets. The mechanical properties and chemical composition of these two materials are shown in the Table 8.1

Table 8.1 Mechanical properties and nominal chemical composition of the test materials

	Steel Grade		S355 K2G3	Fe 52D
Mechanical properties	Yield stress		355 Mpa	353 Mpa
	Impact strength	Test temperature	-20℃	-20℃
		Impact energy	27 J	2.8kpm
Chemical composition	C max %		0.20	0.20
	Si max %		0.55	0.55
	Mn max %		1.60	1.50
	P max %		0.025	0.045
	S max %		0.025	0.045

From the above table, although the yield stress and impact energy of these two materials are expressed in different units, actually they have almost the same value if converted into the same unit. Thus, it can be found the properties of these two materials are very close. And the test material thickness used for the cutting experiments is 3 mm.

8.2 Cutting equipments

The Cutting equipments consist of a 5-axis XY table, the power source of fiber laser, the cutting head and the gas feed system, as shown in Figure 8.1.

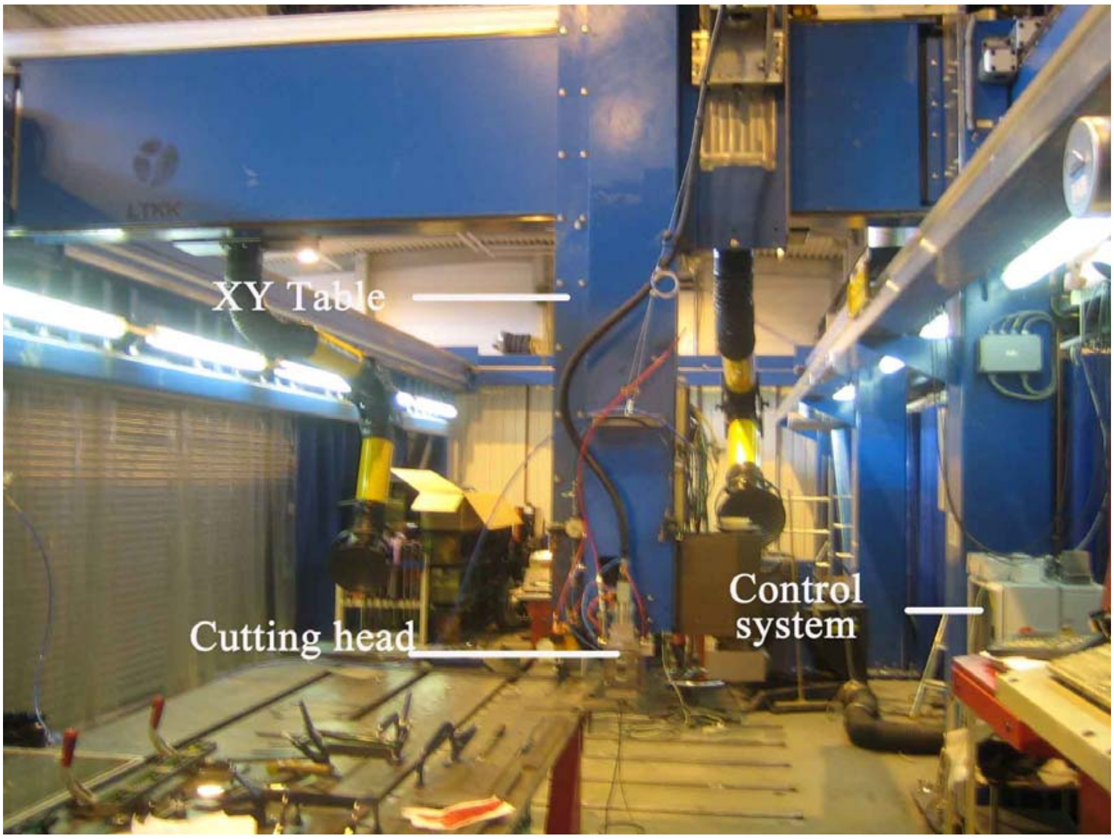


Figure 8.1 Work cell of fiber laser cutting mild steel.

The fiber laser equipment is YLR 5000S as shown in Figure 8.2A. The maximum output power can reach 5000 W. The specifications of the YLR 5000 are list in Table 8.2. The emission beam from the power source is transmitted to the cutting head by the connecting fiber.

Table 8.2 Optical characteristics of YLR 5000S

Nom.	Characteristics	Min.	Typ.	Max	Unit
1	Operation Mode	CW, QCW			
2	Polarization	Random			
3	Emission Wavelength	1070		1080	nm
4	Emission line width		3	6	nm
5	Beam Parameter Product(BPP)		4	4.5 *	mm*mrad
6	Output Fiber Core Diameter	100			μm
7	NA of the Fiber	0.2			
8	Fiber Length		30		m
9	Fiber Cable Bend Radius: Unstressed Stressed			 100 200	mm

* The BPP has been measured in the experiment which equals to 4.2 mm*mrad, therefore, this value is used as BPP in the following calculation.

The emission beam from the power source is transmitted to the cutting head by the connecting fiber. The cutting head is the commonly used Precitec HP 1.5” (High pressure) with a collimating length 100 mm, as shown in Figure 8.2b. And a focusing lens of focal lengths 5” (127 mm) and 7.5” (190.5mm) were used in the experiment. The calculation of the spot size for both 5” and 7.5” focal lengths is shown in the following:

From table 8.2:

NA 0.2= $\sin\theta$ (θ is half of the divergence angle)

Thus the unfocused beam diameter $D = 2 \cdot 100mm \cdot \tan\theta = 40.8mm$

By using the Equation 3, with f=127 mm and BPP=4.2 mm*mrad

$d_{foc} = (4\lambda / \pi)M^2 f / D = 4 f / D \cdot BPP = 52.3$ μm

For the focal length 190.5mm

$$d_{foc} = (4\lambda/\pi)M^2 f/D = 4f/D \cdot BPP = 78.4\ \mu\text{m}$$

A B

Figure 8.2 A. Fiber laser Source YLR 5000s

B. Cutting head HP 1.5”

The cutting head is drive by the control system. When the cutting process starts, the assist gas was transported by the gas supply system and ejected through the co-axis nozzle to the work piece. The purity of the oxygen gas in the experiment reached 99.999%.

8.3 Test procedure

The cutting process is simply shown in Figure 8.3. First, the test sample was fixed in the XY table. After setting the testing parameters, the cutting head moved to the start position. Then the cutting process began with the ejection of the assistant gas. The cutting head moved along the Y axis with the working distance error compensation controlled by the capacitive height sensor. The cutting slots are straight lines with 200 mm length. The cutting slots were kept at sufficient distance apart from each other and the compressed air is used for cooling the workpiece after each cut in order to avoid interference and heat affection. If the cooling work is ignored, the heat conducted in the material will change the absorption of the wavelength. And with the heat collecting more and more, even it can cause the temperature of the workpiece reach its ignition point.

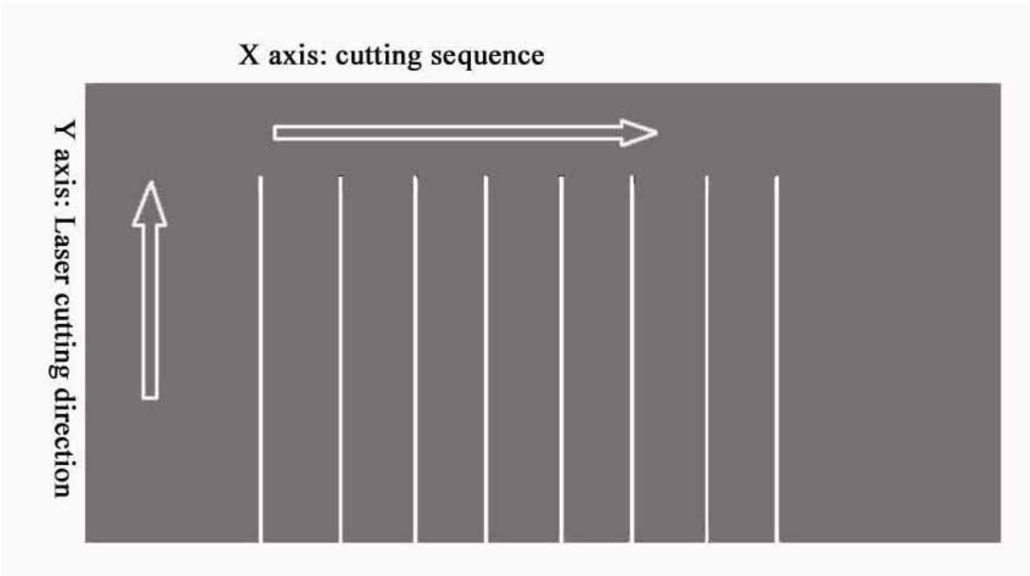


Figure 8.3 Schematic diagram of test procedure.

In the whole experiment, the only one thickness was used is 3 mm and the length of cut piece is 200mm. And the assist gas is chose as oxygen due to the mild steel as material. Thus, there are just 7 parameter left as variables: power level, cutting speed, focal length, focal point position, working distance, oxygen pressure and nozzle diameter. In each experiment, different parameter combination was used to find out the best cutting result. And when the focus position locates insider the workpiece, it is marked with symbol "-", and symbol "+" means above the upper surface. The details of the cutting parameters are contained in Appendix.

In order to analysis the cutting result conveniently, a numerical grade system for the cut quality was used in the experiment. The quality assessment of cut edge can be graded into a 5 score system: 0 corresponds to no cut and 5 represents the best cut quality. The judgment of these grades is based on the eye observation of the surface cut quality, striation pattern, dross attachment, burrs and over burning. In the following, four pictures are shown about the cut quality with different numerical grades.

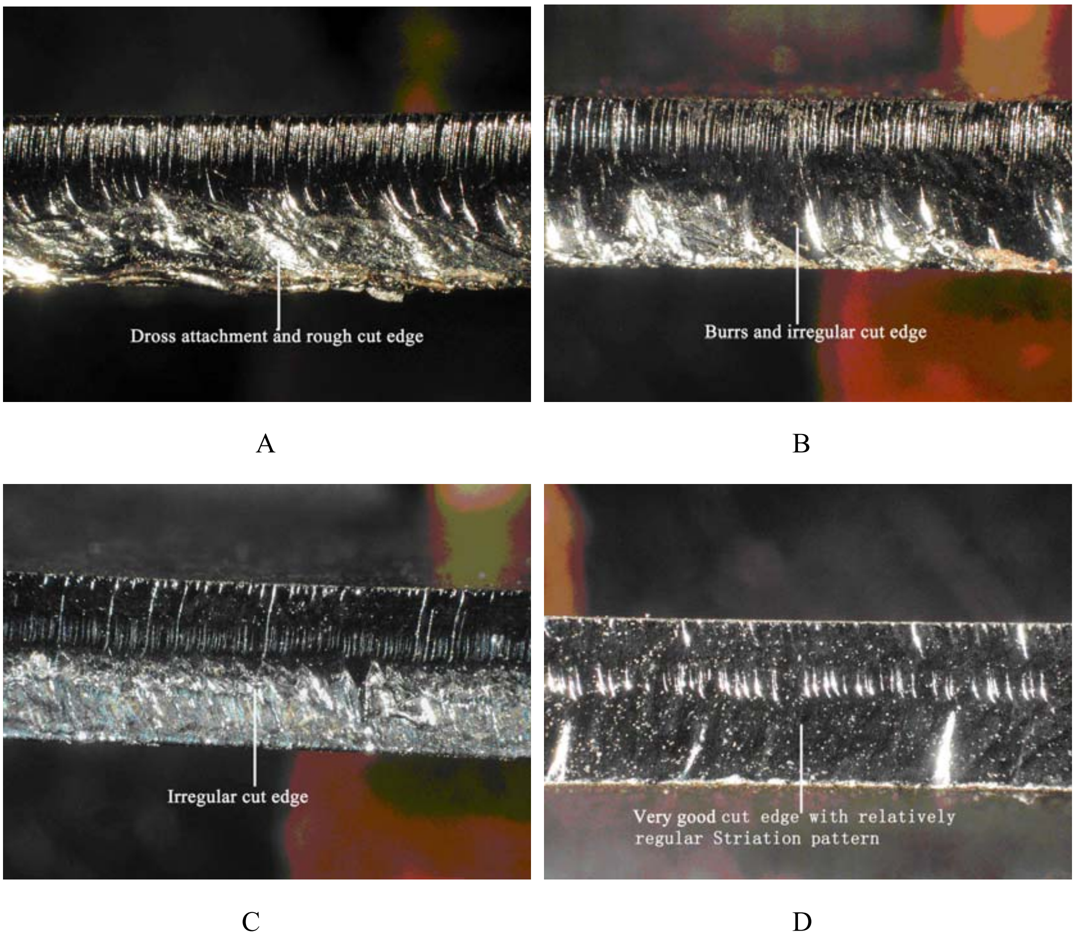


Figure 8.4 Examples for the cut quality with different numerical grades:

A. cut piece with grade 1. B. cut piece with grade 2.

C. cut piece with grade 3. D. cut piece with grade 4.5.

After the measurement of the cut quality by professional equipment, the validity of the numerical grade system was checked based on the measured result. It can be found that. And the measured result of surface roughness was taken into consideration as shown in

Figure 8.5. It can be noticed that the grade value decreased nearly linearly as the increasing of the roughness Ra value. It is proved that this numerical grade system is basically accordant with the measured result. Therefore it can be concluded that the numerical grade can basically reflect the cut quality objectively.

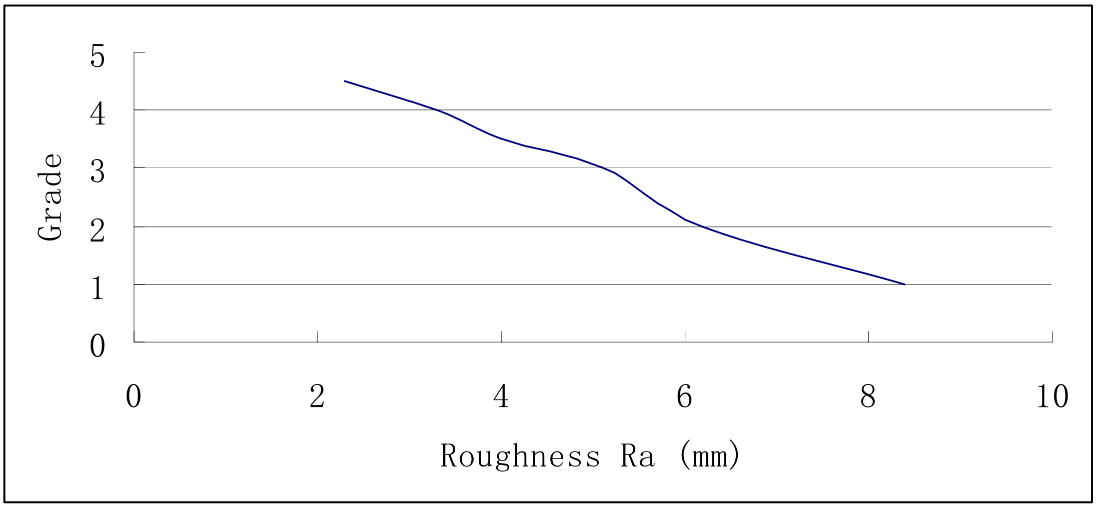


Figure 8.5 the numerical grade Vs Surface roughness Ra

8.4 Measurement equipment

To decide the cut quality, the kerf width, perpendicularity of the cut edges, the surface roughness and the striation pattern are measured in the experiment.

8.4.1 Kerf width measurement

The kerf width measurement was done by equipment including a Leica M25 microscope, an Olympus digital camera and the UTHSCSA ImageTool Version 3.0 program.

First, the Olympus digital camera was used to take the photographs through the Leica M25 microscope about both the top and the bottom cut kerf of the test piece. And a ruler is put beside the workpiece as a calibration for the measurement, as shown in

Figure 8.6. And also the illumination is kept constant for the samples. After that, the photographs were transmitted into the computer. The UTHSCSA ImageTool program was used to do the measurement on the computer.

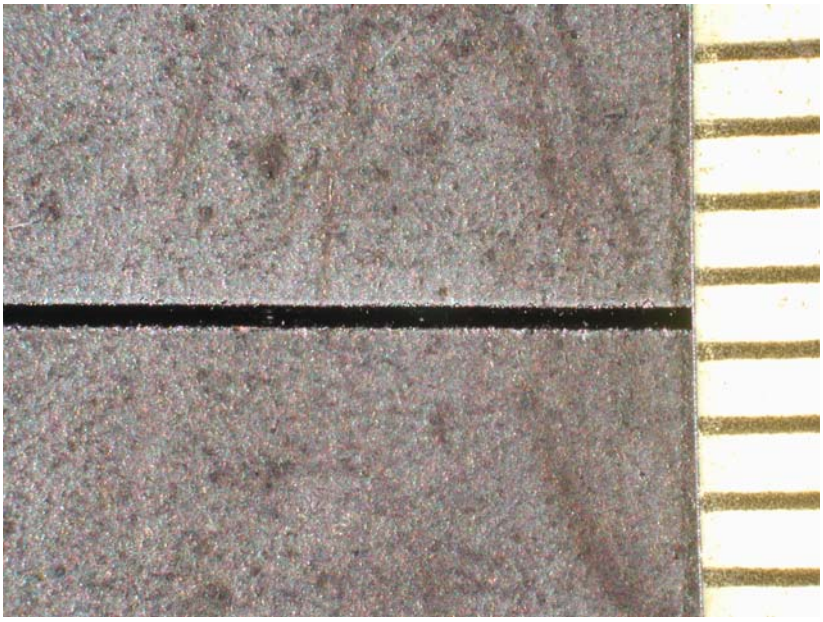


Figure 8.6 A sample of digital photograph about kerf width measurement.

8.4.2 Perpendicularity measurement

The perpendicularity measurements were done with the workpiece cut through to reveal the cut surface profile variation. First the digital photographs of the cut surface profile were made as same as the kerf width measurement. Then the PhotoShop software was used to edit the background of the photographs in order to make these more clearly to do measurement. As illustrated in the Figure 8.7, the photograph after edition work in PhotoShop become very clear even the heat affect zone can be clearly identified in a different color. After that, the measurements were done by using the UTHSCSA ImageTool program. At last, the EN ISO 9013:2002 standard was used to classify the cut edges based on the measured perpendicularity values. This international standard applies to materials suitable for oxyfuel flame cutting, plasma cutting and laser cutting, and it includes geometrical product specifications and quality tolerances.

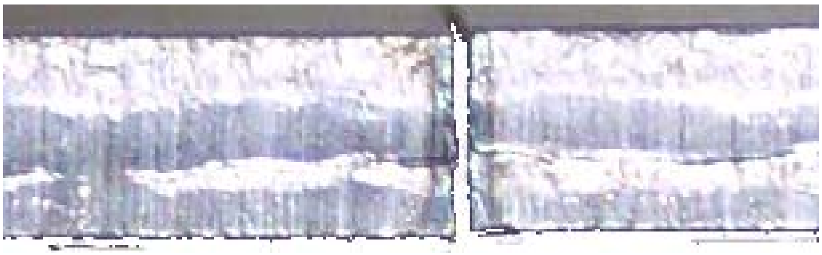


Figure 8.7 The cut surface profile after edition in Photoshop program

8.4.3 Surface roughness measurement

After the measurement of kerf width and perpendicularity, it comes to the surface roughness by measuring both the separated cut edges. As mentioned in the chapter, the surface roughness is measured in terms of the arithmetic average height parameter Ra.

The sampling length for each measurement was 15 mm. The measurement was taken at two positions along the cut width: one is located at the upper part and the other at the lower part, which is according to the location of the boundary layer separation point (BLS). And 5 times measurement is applied on each part. And the average value of these measurements was recorded as the surface roughness.

8.4.4 Striation pattern measurement

The measurement about striation pattern is focused on determining the location of the boundary layer separation point (BLS). The distance between the boundary layer separation point and the upper surface of the cut piece was measured in the UTHSCSA ImageTool. And then a line was drawn according to the position of the boundary layer separation point and beside the line remarked with acronym of Boundary Layer Separation.

9. Preliminary test

Because the fiber laser cutting of mild steel is a very young technology, there is almost no previous work which can be consulted in this study. Thus a preliminary experiment was carried out to investigate how the setting parameters affect the cutting result by using the material Fe 52D. And in the process of preliminary experiment, a lot of good suggestion was given by my supervisor and Mr. Vuorinen from company Prolaser. For example, sometimes three cutting speeds were used in one cutting process, in order to decrease the time to find out the best cutting speed range. In order to distinguish the cut piece with three speeds from those with one speed, an affiliated letter was added in the end of each number of cut pieces, which can be seen in Appendix. For example, one work piece (with number 116) is cut by three speeds: 3.7, 3.8, 3.9 m/min. Then N116A is used to represent the cut speed with 3.7 m/min and so on.

After analysis the preliminary cutting results with my supervisors and Mr. Vuorinen, the whole idea of fiber laser cutting mild steel become clear. Then the experiments were carried out by using S355 mild steel.

10. Experiment results and discussion

In this chapter, the optimum cutting speed, optimum gas pressure, the measured value of kerf width, perpendicularity tolerance, surface roughness and striation pattern are presented. And then an analysis about these results is given.

10.1 Optimum cutting speed

Unlike the inert gas laser cutting, in oxygen laser cutting the maximum cutting speed, which can penetrate the workpiece properly, always does not means the optimum cutting speed. When the maximum cutting speed is used in the experiment, it is very hard to achieve a high surface quality. That it is because the oxygen participates in an exothermic reaction with the mild steel. When a high pressure is used, it always causes over burning effect. Contrary, when a low oxygen pressure is applied, the cutting process does not get enough energy and results in a rough cut profile. Therefore, the optimum cutting speed in laser cutting mild steel with oxygen is always lower than the maximum cutting speed, as shown in Figure 10.1. And in this point, oxygen gas takes a more critical role in determining the cut surface quality than the inert gas in laser cutting. That is why lower oxygen pressure is used when cutting thicker material which is different from inert gas laser cutting.

Compared Figure 10.1 with Figure 6.3, it can be noticed the optimum cutting speed got in the experiment in the power level 2000 W is 4.5 m/min which is almost the same as the speed shown in Figure 6.3 with 3 mm thickness.

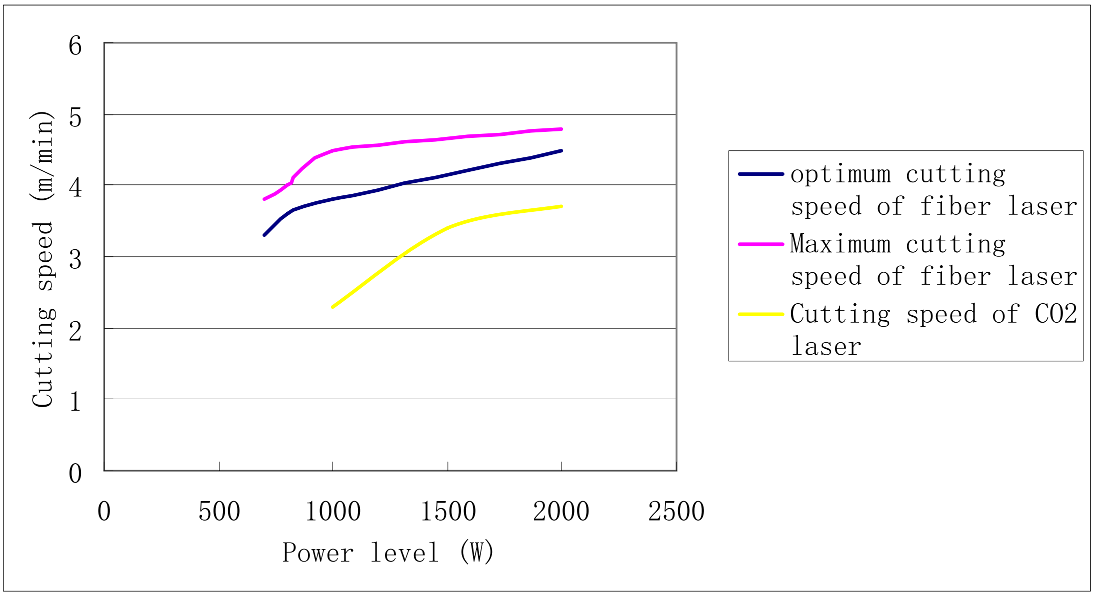


Figure 10.1 Optimum cutting speed and maximum cutting speed of fiber laser, and CO2 laser cutting speed in different power level

Compared with CO_2 laser

Because laser cutting mild steel is a very young technology, there is a little literature about it. And CO_2 laser is still the dominant laser in cutting mild steel nowadays. Therefore, a comparison between fiber laser and CO_2 laser about cutting mild steel becomes necessary.

It can be noticed from Figure 11.1 that the cutting speeds are higher for the fiber laser than for the CO_2 laser with the same power level. The enormous cutting speeds for the fiber laser compared to CO_2 can be attributed to its better beam quality. The higher absorption also might be the reason because of wavelength of fiber laser. The better beam quality and wavelength enable the laser beam focused into a smaller spot size compared to the CO_2 laser, and results in higher power density, hence higher cutting speeds. The typically cutting parameter of fiber laser and CO_2 laser were obtained in Table10.1

Table 10.1 compares the optimum cutting parameter with recommended parameter for a PRC CO_2 laser. /49/

	PRC	Fiber
Power	1000 W	1000 W
Focal length	125 mm	190 mm
Focal position	0 mm	0.5 mm below
Nozzle diameter	1.5 mm	1.25 mm
Nozzle standoff	1 mm	0.5 mm
Oxygen Pressure	1 Bar	1.8 Bar
Cutting speed	2.3 mm/min	3.8 mm/min

The table obviously shows that CO_2 laser and fiber laser have considerable difference in terms of the important parameter values. Due to the good beam quality of fiber laser, the cutting speed of fiber laser (3.8 m/min) is dramatically higher than the CO_2 laser (2.3 m/min) with the same power.

10.2 Optimum gas pressure

Figure 10.2 shows the gas pressure affection on the cut quality with nozzle diameter 1.25 mm. As mentioned in the above chapter, the cut quality is classified in a numerical grade system in order to make the result analysis process more convenient. It is noticeable that the highest score appears with the 1.8 bar gas pressure, which is just a little bit higher than the gas pressure can start the cutting process. The low gas pressure is always preferred in the industry application because that means less financial spending. It also can be noticed that the score precipitates when the gas pressure nearly reaches 3 bars. That is because the over burning effect become very apparently.

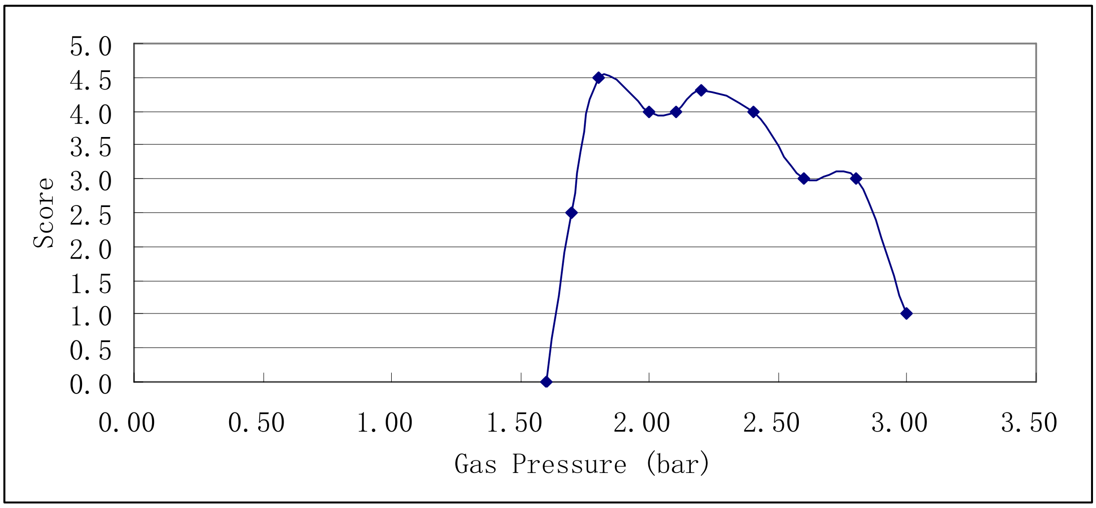


Figure 10.2 Effect of gas pressure on cut quality with nozzle diameter 1.25 mm, laser power 1000 W, focal length 190 mm, cutting speed 3.8 m/min, focal position -0.5 mm, working distance 0.5 mm.

Figure 10.3 shows the gas pressure effect on the cut quality with nozzle diameter 1.5 mm. Compared with the above figure, it can be noticed that for same quality score, the gas pressure required with 1.5 mm nozzle diameter is higher than it with 1.25 mm nozzle diameter. The reason can be clear that with a wider nozzle diameter, the speed and density of gas from the nozzle will decrease with the same pressure. Therefore, in order to maintain these, the gas pressure should be higher in wider nozzle diameter. In the view of industrial application, the nozzle diameter 1.25 is preferred, not only it can get a better cut quality, but also it consumes less gas in the process.

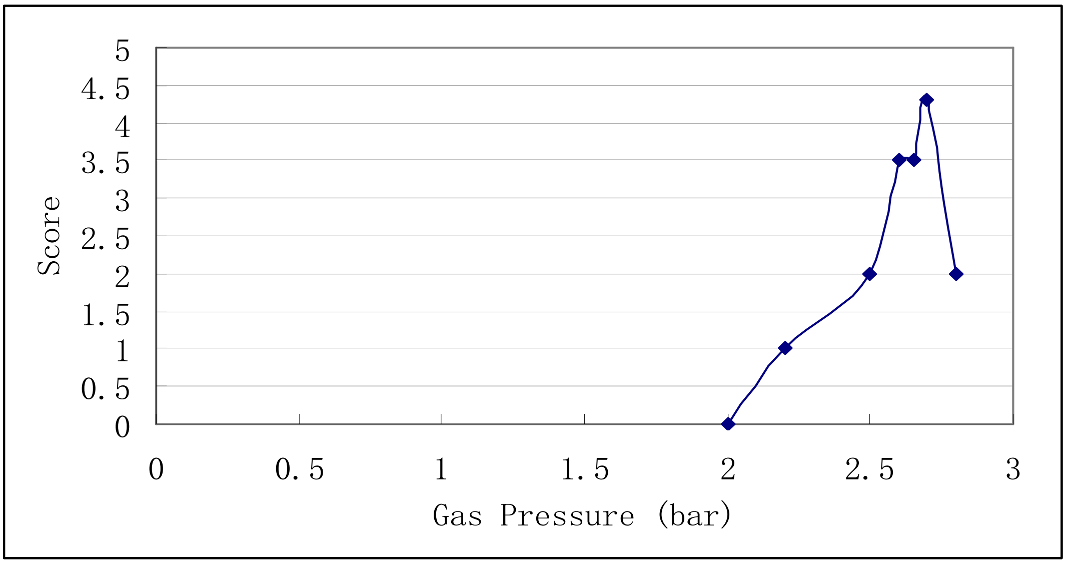


Figure 10.3 Effect of gas pressure on cut quality with nozzle diameter 1.5 mm, laser power 1000 W, focal length 190 mm, cutting speed 3.8 m/min, focal position -1.2 mm, working distance 0.4 mm.

The parameters with the best quality got with 1.25 and 1.5 mm nozzle diameter showing in the Table 10.2. They have the same value in terms of power level, focal length, cutting speed and with similar value of nozzle standoff. The only difference is focused on focal position, except for the gas pressure.

Table 10.2 Parameters for 1.25 mm and 1.5 mm nozzle diameter

Nozzle Diameter	**1.25 mm**	**1.5 mm**
Power	1000 W	1000 W
Focal length	190 mm	190 mm
Focal position	**0.5 mm below**	**1.2 mm below**
Nozzle standoff	0.5 mm	0.4 mm
Oxygen Pressure	1.8 Bar	2.7 Bar
Cutting speed	3.8 mm/min	3.8 mm/min
Score	4.5	4.3

10.3 Effect of focal length on cut quality

In the experiment, two kinds of length of focal lenses were used—127 mm (5”) and 190 mm (7.5”). The parameters of with the best quality for both of the focal lenses are outlined in Table 10.3.

Table 10.3 Comparison of parameters with different focal lenses

Focal length (mm)	127	190
Cutting speed (m/min)	3.7	3.8
Laser power (W)	1000	1000
Focal point position (mm)	-0.5	-0.5
Working distance	0.5	0.5
Gas pressure (bar)	2.4	1.8
Nozzle diameter (mm)	1.25	1.25
Score	2.5	4.5

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It can be noticed that the cut quality got by 127 mm focal lens was not satisfied which just has a score 2.5. The cutting speed is lower with a much higher gas pressure compared with the parameters of 190 mm focal lens. This can be explained by the Rayleigh lengths of different lenses. The Rayleigh length of 190 mm focal length is 2.25 times larger than the 127 mm focal length. Although the 190 mm lens has a larger focal point size than 127 mm focal length, which means a lower power density, the cutting speed is still higher. The reason is not clear completely. It is probably due to the high beam quality of fiber laser and this advantage of its Rayleigh length which enabled deeper cutting with relatively high power density. That also can explain the reason of rough bottom cut surface with 127 mm focal lens. And the reason also might be that there is certain minimum width for the cut kerf in this thickness that is required in order to be able to provide proper flow of oxygen to the root

10.4 Kerf width

Considering the overheating in the initiation and termination of cutting process, the beginning and end positions of the cutting slot are not took into the consideration for judging the kerf width. And in the following, the effect of power level, cutting speed and focus position on kerf width are discussed individually, at the end, a comparison and discussion about kerf width of CO_2 and fiber laser cutting is given.

Effect of power level on kerf width

Figure 10.4 shows the variation of kerf width with power in the condition of best quality. It can be noticeable the kerf width increased linearly as the power level increased. The reason can be clear that high power intensity enhances the material removal rate from the kerf. Therefore, the size of kerf width increased at high laser output power levels.

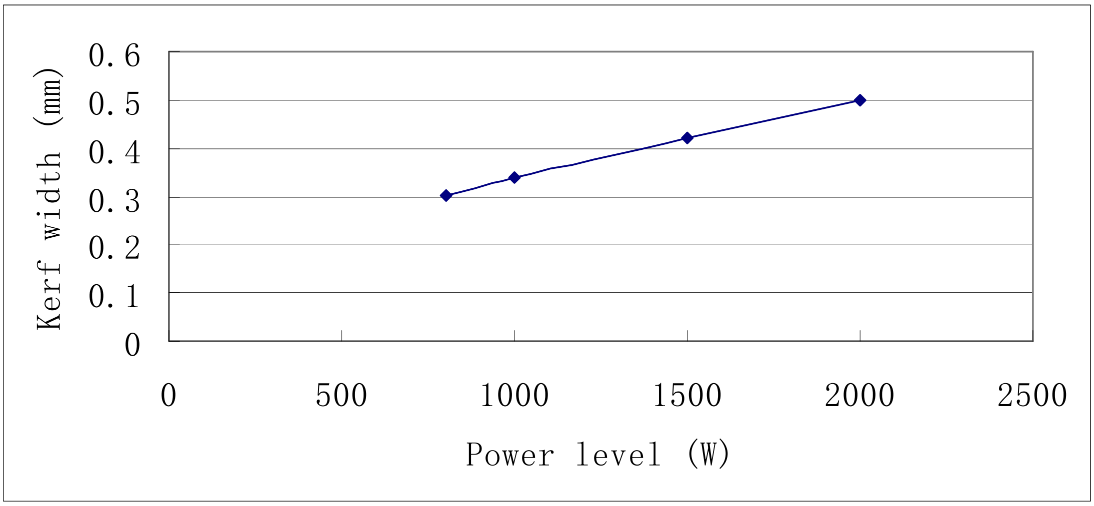

Figure 10.4 Effect of power level on kerf width

Effect of cutting speed on kerf width

Figure 10.5 illustrates the variation of kerf width with cutting speed in the condition of best quality. Obviously, the smallest kerf width is 0.34 mm with cutting speed 3.8 m/min. The reason can be clear that with 1000 W power, lowering laser beam speed than 3.8 m/min results in high material removal rate for the kerf. When the speed is higher than 3.8 m/min, in order to get better cut quality, the increase of gas pressure is required. Therefore, the increase of kerf width is mainly due to the increasing gas pressure when the speed is higher than 3.8 m/min.

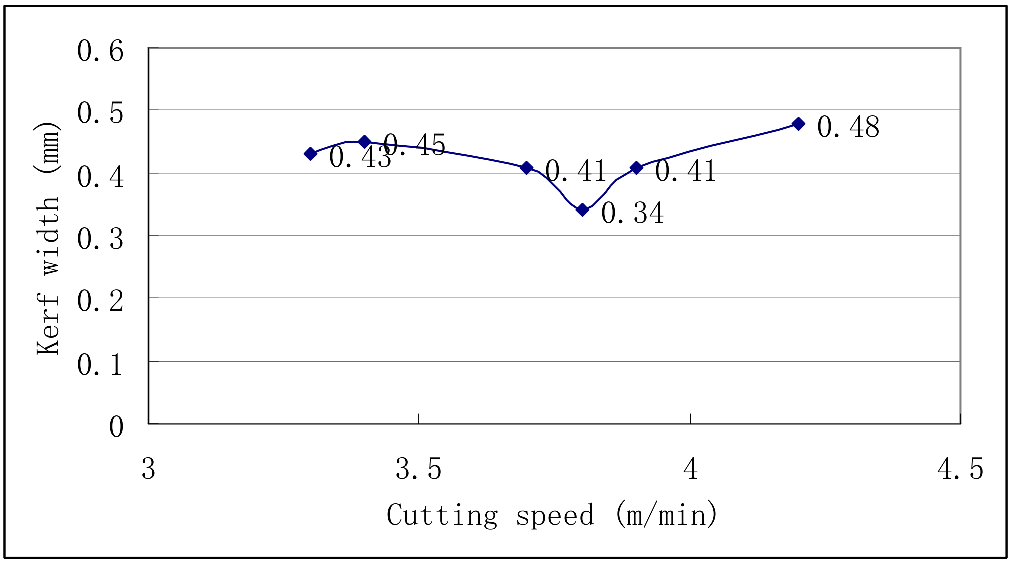

Figure 10.5 Effect of cutting speed on kerf width with focal length 190 mm and power 1000 W.

Effect of focal point position on kerf width

Figure 10.6 shows the top and bottom kerf width variation with focus position. The measured kerf width showed a strong correlation with the focus position. That is because the focus position is relative to the power intensity in the cutting process thus affecting the size of the kerf width. From the Figure 10.6, the kerf width has the smallest value when the focus position is nearly -0.5 mm. when the focus position lies between -0.3 and 0.2 mm, the red line in the figure locate below the blue one. It means the bottom kerf is smaller than the top one, which forms the tapered cut kerf as shown in Figure 10.7. This is due to that the beam divergence has significant influence on the kerf width. With the focus position located nearly the upper surface, the laser beam diameter below the focus point size become apparently bigger as the beam penetrates into the workpiece, thus decrease the beam intensity and also the pressure of gas flow is losing with the cut kerf goes deep.

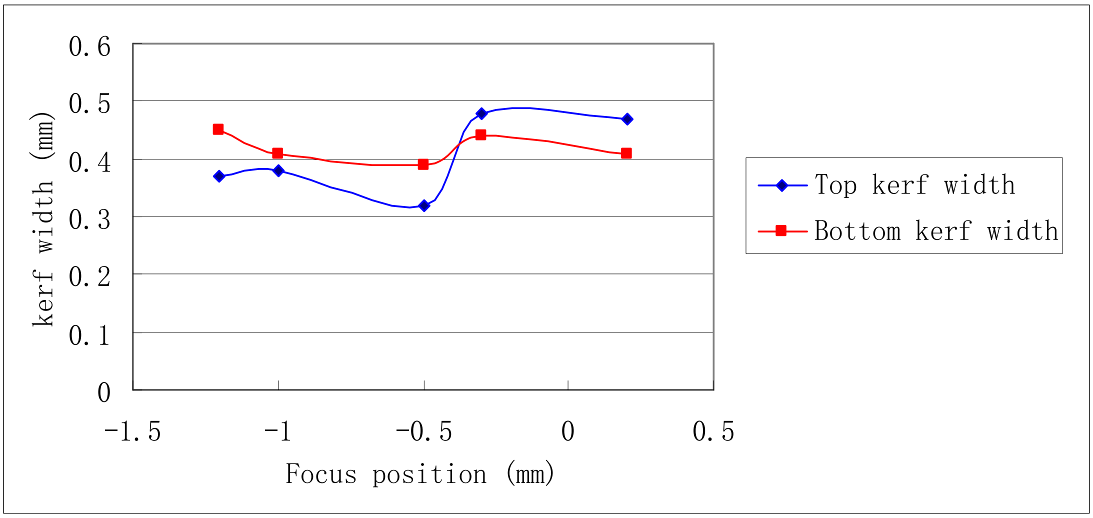

Figure 10.6 Kerf width variations with focus position, Focal length 190 mm, cutting speed 3.8 m/min, power 1000 W.

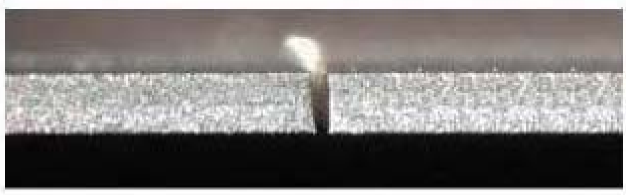

Figure 10.7 a tapered cut kerf

Contrarily, the red line lies below the blue one in the value of focus position below -0.3 mm. There might be two reasons caused this phenomena. With the laser beam focused deeply down the upper surface of the workpiece, the loss of beam intensity become much smaller in the top surface of workpiece compared to the beam focus nearly the upper surface even above the upper surface. On the other hand, the thermal conductivity makes the cut area below get more heating energy from the top part.

Compared with CO_2 laser

Typically, the kerf width of CO_2 laser cutting mild steel lies between 0.15 and 0.2 mm (Data got from Data collection TLC 105, TC L5005, TRUMPF). Compared with CO_2 laser, the kerf width of fiber laser cutting mild steel is wider.

As mentioned in Chapter 4, the kerf width represents the material removed in the cutting process and it is desirable to keep the kerf width to a minimum. The kerf width always correlates to the focused spot size, which is determined by the laser beam quality and focus optics. In the term of laser beam quality, the fiber laser is superior to the CO_2 laser; hence it results in a smaller spot size. In this point, the fiber laser cutting should have a smaller kerf width than the CO_2 laser. However, the experiments show an opposite result. The reason might be that the high intensity of fiber laser gives a so high energy density in the cutting process as to melt the material near the focal point beam by the heating conduction. A longer focal length is recommended in the future experiment to get a smaller kerf width.

10.5 Perpendicularity tolerance

Because only one thickness is involved in the measurement, the ranges for the perpendicularity *u* is calculated based on the cut thickness *a* equal to 3 mm according to EN ISO 9013:2002, which are shown in Table 10.4. In the perpendicularity tolerance ranges, range 1 corresponds to the best quality and range 5 is the worst quality.

Table 10.4 Perpendicularity tolerance value in different range with 3 mm thickness. /15/

Range	Perpendicularity tolerance, *u* (mm)
1	0.05+0.003a=0.059
2	0.15+0.007a=0.171
3	0.4+0.01a=0.43
4	0.8+0.02a=0.86
5	1.4+0.035a=1.505

In this measurement, the piece with the best cut quality was chose. And the maximum measured value for perpendicularity of this piece is 0.12 mm. This value is bigger than the value of Range 1 (0.059 mm) and is smaller than the value of Range 2 (0.171 mm). Therefore, a conclusion about the perpendicularity tolerance can be made: the best quality of workpiece made in this thesis's experiments is in the Range 2 of perpendicularity tolerance.

10.6 Surface roughness

In our experiment result measurement, only the surface roughness Ra is taken into roughness analysis, because Ra is the most important parameter in surface roughness judgment. And compared to Rz, it is more commonly used.

Figure 10.8 illustrates the variation of surface roughness Ra (include the surface roughness at the top and bottom of the cut thickness, and the average roughness) with the cutting speed with nozzle diameter 1.25 mm. The value of surface roughness is varied consistent with the cutting speed. That is because the laser power, gas pressure, focal length, and focus position were kept constant. Obviously, the minimum average roughness value is about 2.1 μm with cutting speed around 3.8 m/min. with the decrease of cutting speed from 3.8 m/min, the roughness increase slowly, while the roughness increases sharply with the increase of cutting. The reason can be clear that relatively less energy input in high speed situation caused roughly cut result. It also shows there is a big difference between the surface roughness at the top of the cut thickness and that at the bottom of the cut thickness. That is because the boundary layer separation point (BLS) exists in the cut kerf. From observing the pictures shown in the section of striation pattern, the striation pattern below the BLS location appears very chaotic. This explains why the top part of the cut kerf has a better roughness condition compared with the bottom part.

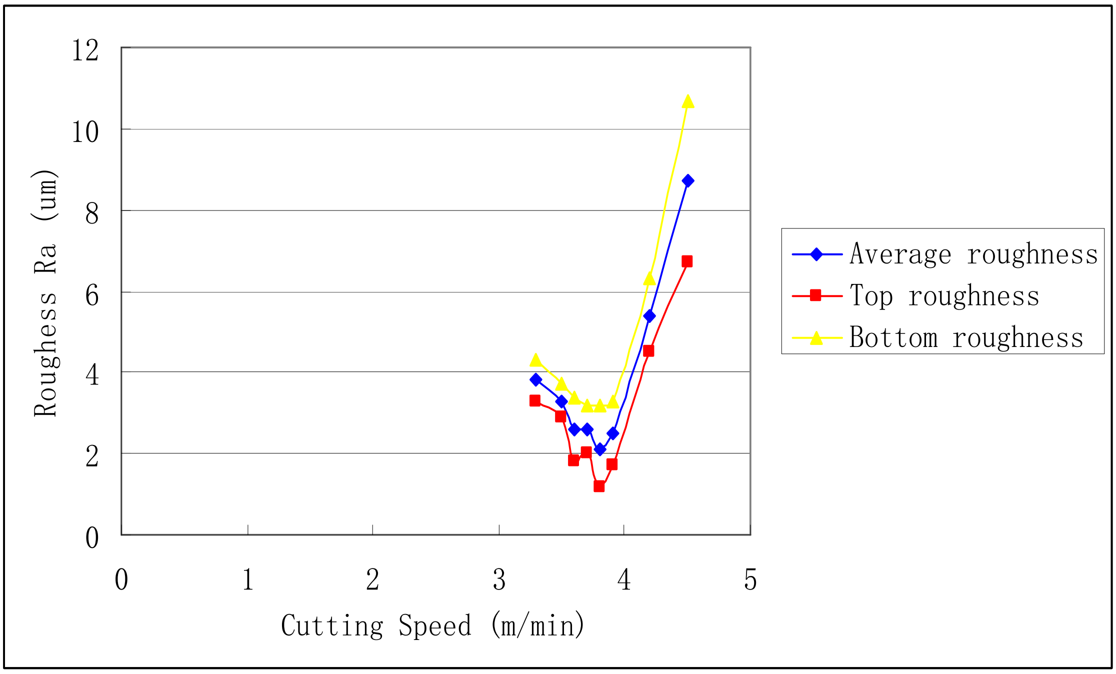

Figure 10.8 Surface roughness with cutting speed variation with nozzle diameter 1.25 mm, power 1000 W, Gas pressure 1.8 bar, focus position -0.5 mm, working distance 0.5 mm and focal length 190 mm.

Compared with the above figure, the variation of surface roughness with cutting speed was not consistent in Figure 10.9, probably because of the variation in other cutting parameters such as assist gas pressure. For example, the two lowest values of surface roughness lies in the speed of 3.65 and 3.8 m/min, the gas pressure for 3.65 m/min cutting speed is 2.6 bar and the other is 2.7 bar. It is undoubted that the variation in cutting speed as well as the variation in assist gas pressure has a combined effect on the surface roughness variation.

Figure 10.9 Surface roughness with cutting speed variation with nozzle diameter 1.5 mm.

10.7 Striation pattern

Striations followed regular patterns. As mentioned in Chapter 4.4, these have been classified in a non-standard way called the boundary layer separation point (BLS), which is the most noticeable visible effect on the cut edge.

In the following, a typical mild cutting edge with the boundary layer separation points located at 1/3 of the thickness is shown in Figure 10.10, and Figure 10.11 and Figure 10.12 illustrate that BLS located at 1/2 and 2/3 of the thickness. In Figure 10.13, a relative regular striation pattern through the cut thickness is illustrated. And the cutting parameters for each figure are outlined in Table 10.5.

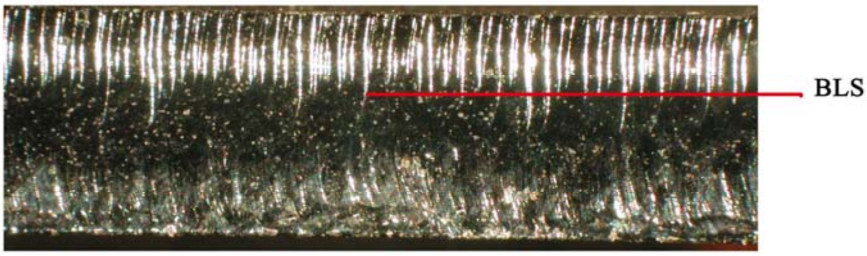

Figure 10.10 The boundary layer separation points (BLS) located at 1/3 of the thickness.

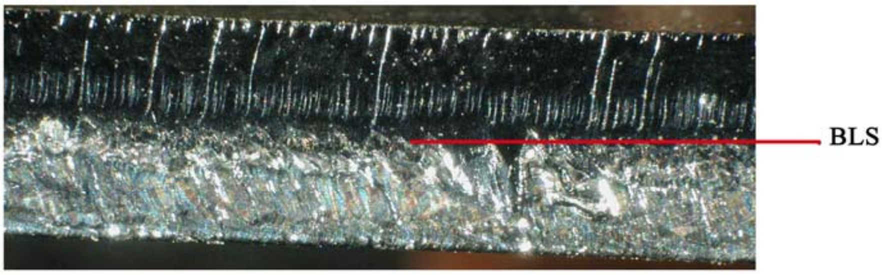

Figure 10.11 The boundary layer separation points (BLS) located at 1/2 of the thickness

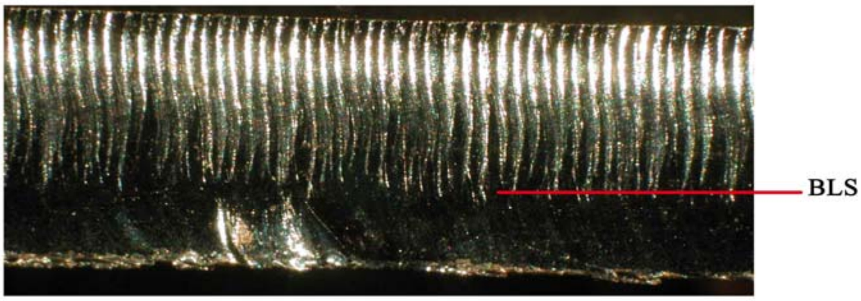

Figure 10.12 The boundary layer separation points (BLS) located at 2/3 of the thickness.

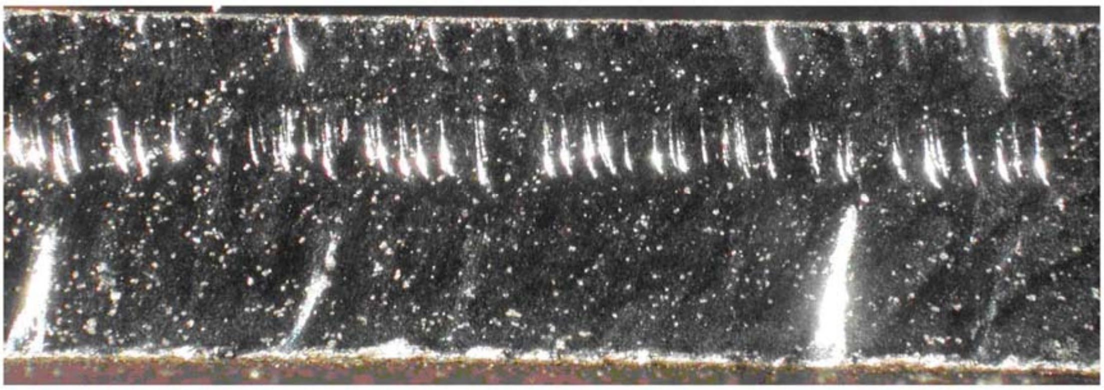

Figure 10.13 A relative regular striation pattern

Table 10.5 Corresponding cutting parameters for the above four figures

	Figure 10.10	Figure 10.11	Figure 10.12	Figure 10.13
Cutting speed(m/min)	**3.8**	**4**	**3.8**	**3.8**
Laser power (W)	1000	1000	1000	1000
Focal length (mm)	190	190	190	190
Focal point position(mm)	**-0.4**	**-0.4**	**-0.5**	**-0.5**
Working distance(mm)	0.5	0.5	0.5	0.5
Assist Gas	Oxygen	Oxygen	Oxygen	Oxygen
Gas pressure (bar)	**1.8**	**1.8**	**2**	**1.8**
Nozzle diameter (mm)	1.25	1.25	1.25	1.25

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From the above table, the difference of these four group parameters are focused on the cutting speed, focus position and gas pressure. Compared the first group parameters with the second ones, we can find the only difference is the cutting speed. This indicated that the cutting speed has effect on the striation pattern. Similarly, from the comparison of the first with the fourth group parameters and the third one with the fourth, the focus position and gas pressure also play an important role in the striation pattern. In inert gas laser cutting, an increase in pressure consistently pushed the position of the separation point further down the cut front. However, this theory can not be applied to the oxygen laser cutting. For example, compared with third group, the fourth group parameters used a lower gas pressure and got a relative regular striation pattern. Therefore, we can conclude the depth of the separation point and the striation pattern in fiber laser oxygen cutting mild steel is affected by cutting speed, focus position, gas pressure and nozzle diameters.

11. Conclusion, recommendation and future study

This thesis studied the performance of fiber laser cutting mild steel. The experiment was made by using 3 mm thickness S355 steel with oxygen as assistant gas cut by the YLR 5000S fiber laser system and Precitec HP 1.5” cutting head. After the experiment, the cut quality was investigated by mainly focusing on the surface roughness, kerf width perpendicularity tolerance and striation pattern and then it was analyzed according to some standard criterions.

The best result got in the experiment is not perfect as predicted, such as there is still little irregular striation on the cut edge and a wider cut kerf compared with CO_2 laser cutting, which means more material was remove in the fiber laser cutting process. However, the whole result of the test can be accepted, such as a relatively higher cutting speed compared with CO_2 laser cutting, a relative uniform cutting kerf (Perpendicularity tolerance is in the range 2), a good surface profile with Ra 2.1 and a regular striation patter, and so on. Therefore, the experiment basically achieved the purpose of this study which is to reveal the cutting performance and how cutting parameters affect fiber laser cutting mild steel.

The power level, cutting speed and gas pressure are the most critical parameters involved in the cutting performance. The test has proved the prediction about a relatively high cutting speed (3.8 m/min) with a low power level (1000W), which is mainly contributed by the better beam quality with Beam Parameter Product (BPP) equals 4.2 mm*mrad, resulting a small focus spot size (52.3μm for 5” focal length and 72.4μm for 7.5” focal length), and by the high absorption due to the wavelength of Yb fiber laser (1070 nm). The optimum gas pressure (1.8 bar) is just a little bit higher than the pressure which can start the cutting process. From the view of industrial application, it is no doubt that the fiber laser has a potential for mild steel cutting technology and it might be challenging the dominate position of CO_2 laser cutting in future.

A further improvement about the cut quality might be possible by proper selection of process parameters, especially on the combination of the focal point position, working distance, the nozzle diameter and gas pressure. Due to the limited time, only one thickness with linear cutting is performed in the experiment. Because the laser cutting mild steel is a very young technology, the whole cutting performance of fiber laser is still not clear as traditional laser system. A future study might be able to be focused on cutting different thickness mild steel in order to investigate the cutting performance more clearly. And after that, a 2D cutting such as circular and angular shape even 3D cutting can be investigated in future study. A longer focal length is recommended to improve the cut quality especially for the thickness more than 3 mm mild steel.

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Appendices

Appendix 1. Preliminary test parameters

Appendix 2. Formal test parameters

APPENDIX 1 Preliminary test

Appendix 1.1

Num.	Cutting speed (m/min)	Laser power (W)	Focal length (mm)	Focus point position (mm)	Working distance (mm)	Gas pressure (bar)	Nozzle diameter (mm)	Score	Remark
N1	4	2000	127	0	0.8	2	1	1	
N2	4	2000	127	0	0.8	4	1	1	
N3	4	900	127	0	0.8	4	1	1	
N4	4	900	127	0	0.8	4.9	1	2	
N5	4	800	127	0	0.8	4.9	1	0	No cut
N6	4	900	127	0	0.8	5.5	1	2	
N7	3.5	900	127	0	0.8	5.5	1	3	Good
N8	3.5	900	127	0	0.5	5.5	1	3	Good
N9	3.2	900	127	0	0.5	5.5	1	2	
N10	3.8	900	127	0	0.5	5.5	1	2	
N11	3.8	900	127	0	0.5	6	1	2	
N12	3.8	800	127	0	1	4	1	0	No cut
N13	3.8	900	127	-0.3	1	5.5	1	3	
N14	3.8	900	127	-0.7	1	5.5	1	3	
N15	3.8	900	127	-0.5	1	5.5	1	1	
N16	3.5	900	127	0	0.5	5.5	1.5	1	
N17	3.5	900	127	0	1	5.5	1.5	1	
N18	3.5	900	127	-0.5	0.5	5.5	1.5	4	The best of preliminary test
N19	3.5	900	127	-0.6	0.5	5.5	1.5	4	
N20	3.5	1000	127	-0.6	0.5	5.5	1.5	3	
N21	3.5	1100	127	-0.6	0.5	5.5	1.5	2.5	

Appendix 1.2

N22	3.5	1200	127	-0.6	0.5	5.5	1.5	2.5	
N23	3.5	1000	127	-0.6	0.5	6	1.5	2.5	
N24	3.5	1000	127	-0.7	0.5	6	1.5	2.5	
N25	3.5	1000	127	-0.7	0.5	4	1.5	2	
N26	2.5	700	127	-0.7	0.5	2	1.5	1	
N27	2.8	700	127	-0.7	0.5	2	1.5	0	No cut
N28	2	700	127	-0.7	0.5	2	1.5	1	
N29	1.5	700	127	-0.7	0.5	2	1.5	1	
N30	1.5	700	127	-0.7	0.5	5	1.5	1	rougness is too high
N31	3.5	900	127	-0.8	0.5	5.5	1.5	1	
N32	3.5	900	127	-0.8	0.5	5.5	1.5	2	
N33	3.5	900	127	-0.8	0.5	4.5	1.5	1	
N34	3.5	900	127	-0.8	0.5	4.8	1.5	1	
N35	3.5	900	127	-1	0.5	5	1.5	1	
N36	3.5	850	127	-0.8	0.5	5	1.5	2	
N37	3.5	800	127	-0.8	0.5	5	1.5	1.5	
N38	3.5	950	127	-0.8	0.5	5	1.5	2	
N39	3.5	1000	127	-0.8	0.5	5	1.5	2	
N40	3.5	1000	127	-0.5	0.5	5	1.5	2	
N41	3.5	1000	127	0	0.5	5	1.5	2	
N42	3.5	975	127	-0.8	0.5	5	1.5	2	
N43	3.5	975	127	-0.8	0.8	5	1.5	2	
N44	4.5	2000	127	-0.8	0.5	3	1.5	0	No cut
N45	4	2000	127	-0.8	0.5	3	1.5	1	
N46	4	2000	127	-0.8	0.5	3	1.5	1	

Appendix 1.3

N47	4	2000	127	-0.8	0.5	4	1.5	1	
N48	3.8	2000	127	-0.8	0.5	4	1.5	1	
N49	3.5	2000	127	-0.8	0.5	4	1.5	1	
N50	4	2000	127	-0.8	0.5	5	1.5	1	
N51	4	2000	127	-0.8	0.5	2	2	0	No cut
N52	4	2000	127	-0.8	0.5	5	2	0	No cut
N53	4	2000	127	-0.8	0.5	7	1.5	1	
N54	4	2500	127	-0.8	0.5	5	1.5	1	
N55	4	3000	127	-0.8	0.5	5	1.5	1	
N56	4	2500	127	-0.8	0.8	5	1.5	1	
N57	3.3	900	127	-0.5	0.5	5.5	1.5	3	
N58	3.3	900	127	-0.5	0.5	6	1.5	2	
N59	3.3	900	127	-0.5	0.5	5.5	1.25	2	
N60	3.3	900	127	-0.5	0.5	5	1.25	3	
N61	3.4	900	127	-0.5	0.5	5	1.25	3	
N62	3.5	900	127	-0.5	0.5	5	1.25	3	
N63	3.5	900	127	-0.5	0.5	4.5	1.25	3	
N64	3.5	900	127	-0.5	0.5	4.8	1.25	3	
N65	3.5	900	127	-0.5	0.5	4.9	1.25	3	
N66	3.4	900	127	-0.5	0.5	4.9	1.25	3	
N67	3.4	900	127	-0.5	0.5	5.2	1.25	3	
N68	3.4	900	127	-0.5	0.5	5.1	1.25	3	
N69	3.4	900	127	-0.6	0.5	5.1	1.25	3	
N70	3.4	900	127	-0.6	0.5	4.9	1.25	3	
N71	3.4	900	127	-0.6	0.5	4.8	1.25	3	

Appendix 1.4

N72	3.4	900	127	-0.6	0.5	4.6	1.25	3	
N73	3.4	900	127	-0.6	0.5	4.4	1.25	3.5	
N74	3.4	900	127	-0.6	0.5	4.4	1.25	3.5	
N75	3.4	900	127	-0.6	0.5	4.2	1.25	3.5	
N76	3.4	900	127	-0.6	0.5	4	1.25	3.5	
N77	3.4	900	127	-0.6	0.5	3.8	1.25	3	
N78	3.4	900	127	-0.7	0.5	4	1.25	2	
N79	3.4	900	127	-0.6	0.6	4	1.25	3	
N80	3.4	900	127	-0.6	0.7	4	1.25	2	
N81	3.4	900	127	-0.6	0.4	4	1.25	3	
N82	3.4	900	127	-0.5	0.4	4	1.25	3	
N83	3.4	900	127	-0.5	0.4	4.2	1.25	3	
N84	3.4	900	127	-0.5	0.4	4.2	1.25	3	
N85	3.4	900	127	-0.5	0.4	4.4	1.25	3	
N86	3.4	900	127	-0.5	0.4	4.3	1.25	3	
N87	3.4	900	127	-0.5	0.4	4.8	1.25	3	
N88	3.4	900	127	-0.5	0.4	3.5	1.25	3	
N89	3.4	900	127	-0.5	0.4	4.2	1.25	3	
N90	3.5	900	190	-0.5	0.5	4	1.25	1	
N91	3.5	900	190	-0.5	0.6	4.2	1.25	1	
N92A	3	900	190	-0.5	0.7	4.2	1.25	1	
N92B	3.1	900	190	-0.5	0.7	4.2	1.25	1	
N92C	3.2	900	190	-0.5	0.7	4.2	1.25	1	
N93A	3.3	900	190	-0.5	0.8	4.2	1.25	1	
N93B	3.4	900	190	-0.5	0.8	4.2	1.25	1	

Appendix 1.5

N93C	3.5	900	190	-0.5	0.8	4.2	1.25	1	
N94A	3.3	900	190	0	0.8	4.2	1.25	1	
N94B	3.4	900	190	0	0.8	4.2	1.25	1	
N94C	3.5	900	190	0	0.8	4.2	1.25	1	
N95A	3.3	900	190	0	0.8	5	1.25	1	
N95B	3.4	900	190	0	0.8	5	1.25	1	
N95C	3.5	900	190	0	0.8	5	1.25	1	
N96A	3.3	900	190	-0.5	0.8	5	1.25	1	
N96B	3.4	900	190	-0.5	0.8	5	1.25	1	
N96C	3.5	900	190	-0.5	0.8	5	1.25	1	
N97A	3	900	190	-0.5	0.8	5	1.25	1	
N97B	3.1	900	190	-0.5	0.8	5	1.25	1	
N97C	3.2	900	190	-0.5	0.8	5	1.25	1	
N98A	3.6	900	190	-0.5	0.8	5	1.25	1	
N98B	3.7	900	190	-0.5	0.8	5	1.25	1	
N98C	3.8	900	190	-0.5	0.8	5	1.25	1	
N99A	3.3	900	190	-0.5	0.8	5	1.25	1	
N99B	3.4	900	190	-0.5	0.8	5	1.25	1	
N99C	3.5	900	190	-0.5	0.8	5	1.25	1	
N100	3.6	850	190	-0.5	0.8	5	1.25	1	
N101	3.7	850	190	-0.5	0.8	4.5	1.25	1	
N102	3.8	850	190	-0.5	0.8	4.8	1.25	1	

APPENDIX 2 Formal experiment parameters

Appendix 2.1

Num.	Cutting speed (m/min)	Laser power (W)	Focal length (mm)	Focus point position (mm)	Working distance (mm)	Gas pressure (bar)	Nozzle diameter (mm)	Score	Remark
N103	3.40	1000	190	-0.5	0.5	4.4	1.25	1.0	
N104	3.40	1000	190	-0.5	0.5	4	1.25	1.0	
N105	3.40	1000	190	-0.5	0.5	3.5	1.25	1.0	
N106	3.40	1000	190	-0.5	0.5	3	1.25	1.0	
N107	3.40	1000	190	-0.5	0.5	2.5	1.25	1.0	
N108	3.40	1000	190	-0.5	0.5	2	1.25	2.0	
N109	3.40	1000	190	-0.5	0.5	1.8	1.25	2.0	
N110	3.40	1000	190	-0.5	0.5	1.6	1.25	2.0	
N111	3.40	1000	190	-0.5	0.5	1.7	1.25	2.0	
N112A	3.00	1000	190	-0.5	0.5	1.90	1.25	2.0	
N112B	3.20	1000	190	-0.5	0.5	1.90	1.25	2.0	
N112C	3.40	1000	190	-0.5	0.5	1.90	1.25	2.0	
N113A	3.40	1000	190	-0.5	0.5	1.80	1.25	2.0	
N113B	3.70	1000	190	-0.5	0.5	1.80	1.25	2.0	
N113C	4.00	1000	190	-0.5	0.5	1.80	1.25	2.5	
N114A	4.00	1000	190	-0.5	0.5	1.80	1.25	2.0	
N114B	4.25	1000	190	-0.5	0.5	1.80	1.25	2.0	
N114C	4.50	1000	190	-0.5	0.5	1.80	1.25	1.0	the maximum cutting speed for 1000 W
N115	4.00	1000	190	-0.4	0.5	1.80	1.25	3.0	
N116A	3.50	1000	190	-0.5	0.5	1.80	1.25	3.5	
N116B	3.75	1000	190	-0.5	0.5	1.80	1.25	4.0	

Appendix 2.2

N116C	4.00	1000	190	-0.5	0.5	1.80	1.25	4.3	
N117A	3.70	1000	190	-0.5	0.5	1.80	1.25	4.3	
N117B	**3.80**	**1000**	**190**	**-0.5**	**0.5**	**1.80**	**1.25**	**4.5**	**The best quality**
N117C	3.90	1000	190	-0.5	0.5	1.80	1.25	4.3	
N118A	3.70	900	190	-0.5	0.5	1.80	1.25	3.5	
N118B	3.80	900	190	-0.5	0.5	1.80	1.25	3.5	
N118C	3.90	900	190	-0.5	0.5	1.80	1.25	3.5	
N119A	3.70	1000	190	-0.4	0.5	1.80	1.25	3.5	
N119B	3.80	1000	190	-0.4	0.5	1.80	1.25	3.0	
N119C	3.90	1000	190	-0.4	0.5	1.80	1.25	4.2	
N120A	3.80	950	190	-0.5	0.5	1.80	1.25	4.0	
N120B	3.80	1200	190	-0.5	0.5	1.80	1.25	4.0	
N120C	3.80	1500	190	-0.5	0.5	1.80	1.25	3.0	
N121A	3.70	1000	190	-0.5	0.5	2.00	1.25	4.0	
N121B	3.80	1000	190	-0.5	0.5	2.00	1.25	4.0	
N121C	3.90	1000	190	-0.5	0.5	2.00	1.25	4.2	
N122	3.90	1000	190	-0.5	0.5	2.00	1.25	4.2	
N123A	3.70	1000	190	-0.5	0.5	2.20	1.25	4.0	
N123B	3.80	1000	190	-0.5	0.5	2.20	1.25	4.3	
N123C	3.90	1000	190	-0.5	0.5	2.20	1.25	4.3	
N124A	3.80	1000	190	-0.5	0.5	2.20	1.25	4.0	
N124B	3.85	1000	190	-0.5	0.5	2.20	1.25	4.0	
N124C	3.90	1000	190	-0.5	0.5	2.20	1.25	4.0	
N125A	3.80	1000	190	-0.5	0.5	2.10	1.25	4.0	
N125B	3.85	1000	190	-0.5	0.5	2.10	1.25	4.0	

Appendix 2.3

N125C	3.90	1000	190	-0.5	0.5	2.10	1.25	4.0	
N126A	3.80	1000	190	-0.5	0.5	2.40	1.25	4.0	
N126B	3.85	1000	190	-0.5	0.5	2.40	1.25	4.0	
N126C	3.90	1000	190	-0.5	0.5	2.40	1.25	4.0	
N127	3.85	1000	190	-0.5	0.5	2.20	1.25	3.0	
N128	3.85	1000	190	-0.3	0.5	2.20	1.25	2.5	
N129	3.85	1000	190	-0.1	0.5	2.20	1.25	2.5	
N130	3.85	1000	190	0.1	0.5	2.20	1.25	2.5	
N131	3.85	1000	190	-0.8	0.5	2.20	1.25	2.3	
N132	3.85	1000	190	0	0.8	2.20	1.25	2.0	
N133	3.85	1000	190	-0.5	0.8	2.20	1.25	2.0	
N134	3.85	1000	190	-0.5	0.6	2.20	1.25	2.0	
N135	3.85	1000	190	-0.5	0.4	2.20	1.25	2.0	
N136A	3.70	1000	190	-0.5	0.5	1.80	1.5	2.0	
N136B	3.80	1000	190	-0.5	0.5	1.80	1.5	2.0	
N136C	3.90	1000	190	-0.5	0.5	1.80	1.5	2.0	
N137A	3.70	1000	190	-0.5	0.5	2.00	1.5	2.0	
N137B	3.80	1000	190	-0.5	0.5	2.00	1.5	2.0	
N137C	3.90	1000	190	-0.5	0.5	2.00	1.5	2.0	
N138A	3.70	1000	190	-0.5	0.5	2.50	1.5	3.0	
N138B	3.80	1000	190	-0.5	0.5	2.50	1.5	3.5	
N138C	3.90	1000	190	-0.5	0.5	2.50	1.5	4.0	
N139A	3.70	1000	190	-0.5	0.5	2.80	1.5	3.0	
N139B	3.80	1000	190	-0.5	0.5	2.80	1.5	4.0	
N139C	3.90	1000	190	-0.5	0.5	2.80	1.5	4.0	

Appendix 2.4

N140A	3.70	1000	190	-0.5	0.5	3.00	1.5	3.0	
N140B	3.80	1000	190	-0.4	0.5	3.00	1.5	4.0	
N140C	3.90	1000	190	-0.5	0.5	3.00	1.5	4.0	
N141A	3.70	1000	190	-0.5	0.5	3.50	1.5	3.0	
N141B	3.80	1000	190	-0.5	0.5	3.50	1.5	3.0	
N141C	3.90	1000	190	-0.5	0.5	3.50	1.5	3.5	
N142A	3.70	1000	190	-0.5	0.5	4.00	1.5	2.5	
N142B	3.80	1000	190	-0.5	0.5	4.00	1.5	2.5	
N142C	3.90	1000	190	-0.5	0.5	4.00	1.5	2.5	
N143A	3.70	1000	190	-0.5	0.5	4.50	1.5	2.0	
N143B	3.80	1000	190	-0.5	0.5	4.50	1.5	2.0	
N143C	3.90	1000	190	-0.5	0.5	4.50	1.5	2.0	
N144	3.70	1000	190	-0.5	0.5	2.50	1.5	3.0	
N145A	3.70	1000	190	-0.5	0.5	2.60	1.5	3.0	
N145B	3.80	1000	190	-0.5	0.5	2.60	1.5	3.0	
N145C	3.90	1000	190	-0.5	0.5	2.60	1.5	3.5	
N146A	3.70	1000	190	-0.5	0.5	2.30	1.5	2.5	
N146B	3.80	1000	190	-0.5	0.5	2.30	1.5	2.5	
N146C	3.90	1000	190	-0.5	0.5	2.30	1.5	2.5	
N147A	3.70	1000	190	-0.5	0.5	2.70	1.5	3.0	
N147B	3.80	1000	190	-0.5	0.5	2.70	1.5	3.5	
N147C	3.90	1000	190	-0.5	0.5	2.70	1.5	3.5	
N148	4.60	1000	190	-0.5	0.5	2.50	1.5	0.0	
N149	4.50	1000	190	-0.5	0.5	3.00	1.5	1.0	
N150	4.00	1000	190	-0.5	0.4	2.50	1.5	3.0	

Appendix 2.5

N151	4.00	1000	190	-0.5	0.4	2.20	1.5	2.0	
N152	4.00	1000	190	-0.5	0.4	2.00	1.5	2.0	
N153	4.00	1000	190	-0.5	0.4	1.80	1.5	1.0	
N154	3.80	1000	190	-0.5	0.4	2.70	1.5	4.0	
N155	3.80	1000	190	-0.5	0.4	2.70	1.5	4.0	
N156	3.80	1000	190	-0.5	0.4	2.60	1.5	4.0	
N157	3.80	1000	190	-0.5	0.4	2.40	1.5	2.0	
N158	3.80	1000	190	-0.5	0.4	2.30	1.5	2.0	
N159	3.80	1000	190	-0.5	0.4	2.10	1.5	2.0	
N160	3.80	1000	190	-0.5	0.4	2.80	1.5	3.0	
N161	3.85	1000	190	-0.5	0.4	2.80	1.5	2.5	
N162	3.80	1000	190	-0.6	0.4	2.80	1.5	3.0	
N163	3.80	1000	190	-0.6	0.4	2.70	1.5	2.5	
N164	3.80	1000	190	-0.8	0.4	2.70	1.5	2.5	
N165	3.80	1000	190	-1	0.4	2.70	1.5	4.0	
N166	**3.80**	**1000**	**190**	**-1.2**	**0.4**	**2.70**	**1.5**	**4.3**	**The best quality with nozzle diameter 1.5 mm**
N167	3.80	1000	190	-1.2	0.4	2.70	1.5	4.1	
N168	3.80	1000	190	-1.1	0.4	2.70	1.5	4.2	
N169	3.80	1000	190	-1.3	0.4	2.70	1.5	3.5	
N170	3.85	1000	190	-1.1	0.4	2.70	1.5	2.5	
N171	3.75	1000	190	-1.1	0.4	2.70	1.5	2.5	
N172	3.80	1000	190	-1.2	0.4	2.60	1.5	3.5	
N173	3.80	1000	190	-1.2	0.4	2.65	1.5	3.5	
N174	3.80	1000	190	-1.4	0.4	2.75	1.5	3.5	
N175	3.80	1000	190		0.4	2.60	1.5	3.5	

N176	3.80	1000	190	-1.1	0.4	2.40	1.5	3.5	
N177	3.80	1000	190	-1.2	0.4	2.20	1.5	1.0	
N178	3.80	1000	190	-1.2	0.4	2.00	1.5	0.0	
N179	3.80	1000	190	-1.1	0.4	2.65	1.5	3.5	
N180A	3.70	1000	190	-0.5	0.5	1.80	1.5	1.0	
N180B	3.80	1000	190	-0.5	0.5	1.80	1.5	1.0	
N180C	3.90	1000	190	-0.5	0.5	1.80	1.5	1.0	
N181A	3.70	1000	190	-0.5	0.5	1.70	1.5	1.0	
N181B	3.80	1000	190	-0.5	0.5	1.70	1.5	1.0	
N181C	3.90	1000	190	-0.5	0.5	1.70	1.5	1.0	
N182A	3.70	1000	190	0	0.5	1.70	1.5	1.0	
N182B	3.80	1000	190	0	0.5	1.70	1.5	1.0	
N182C	3.90	1000	190	0	0.5	1.70	1.5	1.0	
N183A	3.70	1000	190	0	0.5	1.80	1.5	1.0	
N183B	3.80	1000	190	0	0.5	1.80	1.5	1.0	
N183C	3.90	1000	190	0	0.5	1.80	1.5	1.0	
N184A	3.70	1000	190	0	0.5	1.90	1.5	1.0	
N184B	3.80	1000	190	0	0.5	1.90	1.5	1.0	
N184C	3.90	1000	190	0	0.5	1.90	1.5	1.0	
N185A	3.70	1000	190	0	0.5	2.00	1.5	2.0	
N185B	3.80	1000	190	0	0.5	2.00	1.5	2.0	
N185C	3.90	1000	190	0	0.5	2.00	1.5	2.0	
N186A	3.70	1000	190	0	0.5	2.10	1.5	2.0	
N186B	3.80	1000	190	0	0.5	2.10	1.5	2.0	
N186C	3.90	1000	190	0	0.5	2.10	1.5	2.0	

N187A	3.70	900	190	0	0.5	2.10	1.5	1.0	
N187B	3.80	900	190	0	0.5	2.10	1.5	1.0	
N187C	3.90	900	190	0	0.5	2.10	1.5	1.0	
N188A	3.90	1000	190	0	0.5	2.10	1.5	1.0	
N188B	4.00	1000	190	0	0.5	2.10	1.5	1.0	
N188C	4.10	1000	190	0	0.5	2.10	1.5	1.0	
N189A	3.40	1000	190	0	0.5	2.10	1.5	2.0	
N189B	3.50	1000	190	0	0.5	2.10	1.5	2.0	
N189C	3.60	1000	190	0	0.5	2.10	1.5	2.0	
N190A	3.10	1000	190	0	0.5	2.10	1.5	2.0	
N190B	3.20	1000	190	0	0.5	2.10	1.5	2.0	
N190C	3.30	1000	190	0	0.5	2.10	1.5	2.0	
N191	3.00	1000	190	0	0.5	2.10	1.5	2.0	
N192	3.80	1000	190	-1.2	0.4	2.80	1.5	2.0	
N193A	3.60	1000	190	-1.2	0.4	2.70	1.5	2.5	
N193B	3.70	1000	190	-1.2	0.4	2.70	1.5	2.5	
N193C	3.80	1000	190	-1.2	0.4	2.70	1.5	2.0	
N194A	3.60	1000	190	-1.2	0.4	2.50	1.5	4.0	
N194B	3.70	1000	190	-1.2	0.4	2.50	1.5	3.5	
N194C	3.80	1000	190	-1.2	0.4	2.50	1.5	2.0	
N195A	3.50	1000	190	-1.2	0.4	2.30	1.5	3.0	
N195B	3.60	1000	190	-1.2	0.4	2.30	1.5	3.0	
N195C	3.70	1000	190	-1.2	0.4	2.30	1.5	1.0	
N196A	3.50	1000	190	-1.2	0.4	2.10	1.5	2.0	
N196B	3.60	1000	190	-1.2	0.4	2.10	1.5	2.0	

N196C	3.70	1000	190	-1.2	0.4	2.10	1.5	1.0	
N197A	3.50	1000	190	-1.2	0.4	2.00	1.5	2.5	
N197B	3.50	1000	190	-1.2	0.4	2.00	1.5	2.5	
N197C	3.50	1000	190	-1.2	0.4	2.00	1.5	1.0	
N198	3.60	1000	190	-1.2	0.4	2.00	1.5	2.0	
N199A	3.65	1000	190	-1.2	0.4	2.50	1.5	4.0	
N199A	3.60	1000	190	-1.2	0.4	2.50	1.5	3.0	
N199A	3.70	1000	190	-1.2	0.4	2.50	1.5	3.0	
N200	3.65	1000	190	-1.2	0.4	2.50	1.5	4.0	
N201	3.65	1000	190	-1.2	0.4	2.40	1.5	3.5	
N202	3.65	1000	190	-1.2	0.4	2.30	1.5	2.5	
N203	3.65	1000	190	-1.2	0.4	2.60	1.5	4.2	
N204	3.65	1000	190	-1.2	0.4	2.70	1.5	4.0	
N205A	3.60	1000	190	-1.2	0.4	2.70	1.5	4.0	
N205B	3.65	1000	190	-1.2	0.4	2.70	1.5	4.0	
N205C	3.70	1000	190	-1.2	0.4	2.70	1.5	3.5	
N206	3.70	1000	190	0	0.4	2.50	1.5	3.0	
N207	3.70	1000	190	0	0.4	2.70	1.5	2.5	
N208	3.70	1000	190	0	0.4	2.30	1.5	2.0	
N209	3.70	1000	190	0	0.4	2.00	1.5	2.0	
N210	3.70	900	190	0	0.4	2.00	1.5	2.0	
N211	3.60	900	190	0	0.4	2.00	1.5	2.0	
N212	3.60	900	190	0	0.4	1.80	1.5	2.0	
N213	3.60	900	190	0	0.4	2.10	1.5	2.3	
N214	3.60	800	190	0	0.4	2.10	1.5	2.0	

N215	3.60	850	190	0	0.4	2.10	1.5	1.5	
N216	3.60	850	190	0	1	2.10	1.5	1.5	
N217	3.60	850	190	0	1	2.20	1.5	2.0	
N218	3.60	850	190	0	1	2.00	1.5	2.0	
N219	3.60	850	190	0	1	1.90	1.5	1.0	
N220	3.60	850	190	0	1	1.80	1.5	1.0	
N221	3.60	850	190	0	0.8	2.10	1.5	1.5	
N222	3.60	900	190	0	0.8	2.10	1.5	1.5	
N223	3.60	1000	190	0	0.8	2.10	1.5	2.0	
N224	3.60	1100	190	0	0.8	2.10	1.5	1.5	
N225	3.80	1000	190	-0.5	0.5	1.70	1.25	2.5	
N226	3.80	1000	190	-0.5	0.5	1.60	1.25	0.0	No cut
N227	3.80	1000	190	-0.5	0.5	2.60	1.25	3.0	
N228	3.80	1000	190	-0.5	0.5	2.80	1.25	3.0	
N229	3.80	1000	190	-0.5	0.5	3.00	1.25	1.0	Over burning
N230	3.80	1000	190	-0.3	0.5	2.20	1.25	3.0	
N231	3.80	1000	190	0	0.5	2.20	1.25	3.0	
N232	3.80	1000	190	0.2	0.5	2.20	1.25	3.0	
N233	3.40	1000	190	-1.2	0.4	2.70	1.5	3.0	
N234	4.00	1000	190	-1.2	0.4	2.70	1.5	1.5	
N235	3.7	1000	127	-0.5	0.5	2.20	1.25	1.0	
N236	3.7	1000	127	-0.5	0.5	2.10	1.25	1.0	
N237	3.7	1000	127	-0.5	0.5	2.40	1.25	2.5	The best qualtiy for 127 mm focal lens
N238	3.7	1000	127	-0.5	0.5	2.60	1.25	2.0	
N239	3.7	1000	127	-0.5	0.5	2.80	1.25	2.0	

N240	3.7	1000	127	-0.5	0.5	3.00	1.25	1.0	
N241	3.7	1000	127	-0.5	0.5	3.20	1.25	1.0	
N242	3.7	1000	127	-0.5	0.5	2.70	1.25	1.0	
N243	3.7	1000	127	-0.5	0.5	2.80	1.25	1.0	
N244	3.8	1000	127	-0.5	0.5	2.80	1.25	1.0	
N245	3.8	1000	127	-0.5	0.5	2.20	1.25	1.0	
N246	3.8	1000	127	-0.5	0.5	2.00	1.25	1.0	
N247	3.8	1000	127	-0.5	0.5	2.50	1.25	1.0	
N248	3.8	1000	127	-0.5	0.5	2.40	1.25	1.0	
N249	3.8	1000	127	-0.5	0.5	2.30	1.25	1.0	
N250	3.8	1000	127	-0.5	0.5	2.60	1.25	1.0	
N251	3.8	1000	127	-0.5	0.5	2.30	1.25	1.0	
N252	3.9	1000	127	-0.5	0.5	2.30	1.25	1.0	
N253	3.9	1000	127	-0.5	0.5	2.00	1.25	1.0	
N254	3.9	1000	127	-0.5	0.5	2.50	1.25	1.0	
N255	3.9	1000	127	-0.5	0.5	2.20	1.25	1.0	
N256	3.9	1000	127	-0.5	0.5	2.40	1.25	1.0	
N257	3.9	1000	127	-0.5	0.5	2.80	1.25	1.0	
N258	3.9	1000	127	-0.5	0.5	2.20	1.25	1.0	
N259	3.9	1000	127	-0.5	0.5	2.80	1.25	1.0	
N260	3.8	1000	127	-1.2	0.4	2.70	1.25	2.0	
N261	3.8	1000	127	-1.2	0.4	2.50	1.25	1.0	
N262	3.8	1000	127	-1.2	0.4	2.30	1.25	1.0	
N263	3.8	1000	127	-1.2	0.4	2.90	1.25	1.0	
N264	3.8	1000	127	-1.2	0.4	3.10	1.25	1.0	

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N265	3.8	1000	127	-1.2	0.4	3.30	1.25	1.0	
N266	3.8	1000	127	-1.2	0.4	2.10	1.25	1.0	
N267	3.8	1000	127	-1.2	0.4	2.70	1.25	2.0	
N268	4.5	2000	190	-0.5	0.5	2.20	1.25	1.0	
N269	4.6	2000	190	-0.5	0.5	2.20	1.25	1.0	
N270	4.7	2000	190	-0.5	0.5	2.20	1.25	1.0	
N271	4.8	2000	190	-0.5	0.5	2.20	1.25	1.0	Maximum cutting speed for power 2000 W
N272	4.9	2000	190	-0.5	0.5	2.20	1.25	0.0	
N273	5	2000	190	-0.5	0.5	2.20	1.25	0.0	
N274	3.8	800	190	-0.5	0.5	2.20	1.25	1.5	
N275	3.9	800	190	-0.5	0.5	2.20	1.25	1.5	
N276	4	800	190	-0.5	0.5	2.20	1.25	1.0	Maximum cutting speed for power 800 W
N277	4.1	800	190	-0.5	0.5	2.20	1.25	0.0	
N278	3.8	700	190	-0.5	0.5	2.20	1.25	2.0	
N279	3.9	700	190	-0.5	0.5	2.20	1.25	0.0	No cut
N280	3.8	700	190	-0.5	0.5	2.00	1.25	2.0	
N281	3.8	700	190	-0.5	0.5	1.80	1.25	2.0	Maximum cutting speed for power 700 W
N282	3.8	750	190	-0.5	0.5	2.00	1.25	2.0	
N283	3.8	650	190	-0.5	0.5	2.00	1.25	1.0	
N284	3.9	700	190	-0.5	0.5	2.00	1.25	0.0	No cut
N285	3.9	700	190	-0.5	0.5	2.40	1.25	0.0	No cut
N286	3.7	700	190	-0.5	0.5	2.00	1.25	1.0	
N287	3.5	700	190	-0.5	0.5	2.00	1.25	1.0	
N288	3.4	700	190	-0.5	0.5	2.00	1.25	2.0	
N289	3.3	700	190	-0.5	0.5	2.00	1.25	2.0	

Appendix 2.12

N290	3.2	700	190	-0.5	0.5	2.00	1.25	2.0	
N291	3.2	700	190	-0.5	0.5	1.60	1.25	2.0	
N292	3.3	700	190	-0.5	0.5	1.60	1.25	2.0	
N293	3.3	700	190	-0.5	0.5	1.80	1.25	2.0	
N294	3.3	700	190	-0.5	0.5	2.00	1.25	2.0	
N295	3.3	700	190	-0.5	0.5	2.20	1.25	2.0	
N296	3.3	700	190	-0.5	0.5	2.40	1.25	2.0	
N297	3.3	700	190	-0.5	0.5	1.40	1.25	2.0	
N298	3.3	700	190	-0.5	0.5	1.20	1.25	2.0	
N299	3.3	700	190	-0.5	0.5	1.00	1.25	2.0	
N300	3.3	700	190	-0.5	0.5	0.80	1.25	2.0	
N301	3.3	700	190	-0.5	0.5	0.70	1.25	2.0	
N302	3.3	700	190	-0.5	0.5	2.60	1.25	2.0	
N303	3.3	700	190	-0.3	0.5	1.00	1.25	0.0	No cut
N304	3.3	700	190	-0.7	0.5	1.00	1.25	0.0	No cut
N305	3.3	700	190	-1	0.5	1.00	1.25	0.0	No cut
N306	3.3	700	190	0	0.5	1.00	1.25	1.0	
N307	3.3	700	190	0.1	0.5	1.00	1.25	2.0	
N308	3.3	700	190	0	0.8	1.00	1.25	2.0	
N309	3.3	700	190	0	0.3	1.00	1.25	2.0	
N310	3.3	700	190	0	1	1.00	1.25	2.0	
N311	3.3	700	190	0	0.3	1.20	1.25	2.0	
N312	3.3	700	190	0	0.3	1.40	1.25	2.0	
N313	3.3	700	190	0	0.3	1.60	1.25	2.0	
N314	3.3	700	190	0	0.3	1.80	1.25	2.0	

N315	3.3	700	190	0	0.3	2.00	1.25	2.0	
N316	3.3	700	190	0	0.8	1.40	1.25	2.0	
N317	3.3	700	190	0	0.8	1.60	1.25	2.0	
N318	3.3	700	190	0	0.8	1.80	1.25	2.0	
N319	3.3	700	190	0	0.8	2.00	1.25	2.0	
N320	3.3	700	190	0	0.8	2.20	1.25	2.0	
N321	3.3	700	190	0	0.8	1.20	1.25	0.0	
N322	3.3	700	190	0	1	1.60	1.25	2.0	
N323	3.3	700	190	0	1	1.80	1.25	2.0	
N324	3.3	800	190	0	1	1.80	1.25	3.0	
N325	3.3	800	190	0	1	1.60	1.25	3.0	
N326	3.3	800	190	0	1	1.40	1.25	3.0	
N327	3.3	800	190	0	1	1.30	1.25	3.0	
N328	3.3	850	190	0	0.8	1.40	1.25	3.0	
N329	3.3	850	190	0	1	1.40	1.25	3.0	
N330	3.3	850	190	0	1.2	1.40	1.25	3.0	
N331	3.3	850	190	-0.5	1	1.40	1.25	3.0	
N332	3.3	850	190	0.1	1	1.40	1.25	3.5	
N333	3.3	850	190	0.2	1	1.40	1.25	4.0	
N334	3.3	700	190	0.3	1	1.40	1.25	3.0	
N335	3.3	700	190	0.4	0.8	1.40	1.25	3.0	
N336	3.3	700	190	0.2	0.8	1.40	1.25	3.0	
N337	3.3	700	190	0.2	1	1.40	1.25	3.0	
N338	3.3	800	190	0.2	1	1.40	1.25	3.5	
N339	3.3	900	190	0.2	1	1.40	1.25	3.5	

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N340	3.4	900	190	0.2	1	1.40	1.25	4.0	
N341	3.5	900	190	0.2	1	1.40	1.25	3.5	
N342	3.6	900	190	0.2	1	1.40	1.25	3.5	
N343	3.4	850	190	0.2	1	1.40	1.25	3.5	
N344	3.2	850	190	0.2	1	1.40	1.25	3.5	
N345	3.2	850	190	0.2	1	1.20	1.25	3.5	
N346	3.3	850	190	0.2	1	1.20	1.25	3.5	
N347	3.3	850	190	0.2	1	1.00	1.25	3.5	
N348	3.3	850	190	0.3	1	1.20	1.25	3.5	
N349	3.3	850	190	0.4	1	1.20	1.25	3.5	
N350	3.3	850	190	0.5	1	1.20	1.25	3.5	
N351	3.3	850	190	0.5	1	1.40	1.25	3.5	
N352	3.3	850	190	0.5	1	1.60	1.25	3.5	
N353	3.3	850	190	0.5	1	1.80	1.25	3.5	
N354	3.3	850	190	0.5	1	2.00	1.25	3.0	
N355	3.3	850	190	0.5	1	2.20	1.25	3.0	
N356	3.3	850	190	0.5	1	2.40	1.25	3.0	
N357	3.3	850	190	0.5	1	2.60	1.25	3.0	
N358	3.3	850	190	0.4	1	1.60	1.25	3.5	
N359	3.3	850	190	0.4	1	1.80	1.25	3.5	
N360	3.3	850	190	0.4	1.1	1.80	1.25	3.5	
N361	3.3	850	190	0.4	1.2	1.80	1.25	3.0	
N362	3.3	850	190	0.4	1.1	1.60	1.25	3.5	
N363	3.3	850	190	0.3	1.1	1.60	1.25	3.5	
N364	3.3	900	190	0.2	1.1	1.40	1.25	3.5	

Appendix 2.15

N365	3.3	900	190	0.2	1.1	1.40	1.25	3.5	
N366	3.3	900	190	0.2	1	1.40	1.25	3.5	
N367	3.3	900	190	0.2	1	1.50	1.25	3.5	
N368	3.3	800	190	0.2	1	1.40	1.25	3.5	
N369	3.3	800	190	0.2	1	1.60	1.25	2.0	
N370	3.3	800	190	0.2	1	1.80	1.25	2.0	