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CUTTING OF STAINLESS STEEL WITH FIBER AND DISK LASER

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Abstract

Laser cutting is a major application of laser materials processing. The cutting is usually performed with CO_2-laser due to its good beam quality and its relatively low costs of ownership. Ever since entering the market the high power solid state lasers have been expected to achieve a dominating role also in cutting applications. This has not happened mainly due to the fact that beam quality has not been sufficient. The introduction of new generation of solid state lasers has raised the interest of use of them in cutting application. This study was concentrated on use of fiber and disk lasers, the new laser types with a high beam quality, in cutting of austenitic stainless steel. The performance of these new lasers at power level of 4 kW was compared with CO_2-laser in respect of cutting speed, kerf width, kerf edge roughness and perpendicularity (squarness) in order to validate the potential of both of the new lasers against traditional CO_2-laser. The results showed that the new lasers offer a great potential in improving the productivity of cutting phase with an acceptable edge quality. This is emphasized in thin sheets of 1.3 and 2.3 mm thickness. In that case the width of the cut kerf is considerably narrow especially when using a fiber laser. In case of thicker sections (4.3 and 6.2 mm) the focal length was increased in order to reach an acceptable cut quality still providing a competitive cutting speed in comparison to a CO_2-laser. The fiber laser was the fastest cutting laser in case of each thickness. The results were very promising and it can be stated that these new laser types have a great potential in cutting and will probably gain a considerable market share not only in 3D cutting applications but also in ordinary flat sheet cutting.

Introduction

Stainless steel is used extensively in a number of everyday applications in the home, industry, hospitals, food processing, farming, aerospace, construction, chemical, electronics, and energy industries. Cutting of stainless steel sheets is one of the primary requirements in the fabrication of most of the components. Laser cutting offers several advantages: high productivity, thanks to the high cutting speeds, narrow kerf width (minimum material lost), straight cut edges, low roughness of cut surfaces, minimum metallurgical distortions, easy integration with computer numerically controlled (CNC) machines for cutting complex profiles and it is a non contact process suitable for cutting in areas with limited access. [1,2,3,4]

Despite the Nd:YAG laser (solid-state laser) advantages of higher absorptivity of its wavelength by metal surfaces and use of optical fibers for beam delivery, the CO_2-laser is the more commonly used laser for cutting applications especially for cutting of thick sections because of its better beam quality and availability of high output powers as compared to the Nd:YAG laser beam quality which becomes poorer with increase in output power. However, the high power fiber laser and thin disk laser – the new solid-state laser technologies – offer a combination of high beam quality and a wavelength that is easily absorbed by metal surfaces. The output powers of the fiber laser and thin disk laser are scalable to the kilowatt range without much detrimental effect on the beam quality. These systems are promising for cutting applications and are expected to challenge the CO_2-laser in thick section metal cutting because their high beam quality enables focusing of the laser beam to a small spot producing high power density that is essential for cutting of metals and enhances higher cutting speeds. [5,6,7]

With the aim of investigating the potential of the fiber and disk laser for metal cutting of thick sections, this paper presents the stainless steel cutting experiments of the fiber, disk and CO_2 lasers to investigate the cutting performance and cut quality obtained.

Literature review

The high power fiber laser and thin disk laser are the new diode pumped solid-state laser (DPSSL) technologies with output powers that are scalable to the kilowatt range without much detrimental effect on the beam quality. [5,6,7]

The fiber lasers had been primarily used in communications but the development of the double-clad high power fiber lasers for materials processing promise to disrupt existing technology bases such as the Nd:YAG laser, opening an opportunity for fiber lasers in significant non-telecommunications markets such laser welding, cutting and marking. [8] The primary material processing fiber lasers are at the Ytterbium (Yb) 1070nm wavelength, consistent with the wavelength of YAG lasers. [9] The ytterbium fiber (Yb:glass) lasers with output powers upto 20kW far exceed the laser powers that are available using Nd:YAG laser technology, while also offering a better beam quality. The single mode Erbium fiber (Er:glass) lasers with wavelengths from 1530nm to 1600nm are available at output powers of 1 – 100 W and beam quality (BPP) less than 1.1 mm*mrad. [10,11,12] The fiber laser output power is easily scalable such that output power in the kW-range can be achieved by incoherent coupling of several fiber lasers. The beam delivery fiber for a 4-kilowatt system is 50 microns and for a 10-kilowatt system is 300 microns, which allows for longer working distances and more consistent processing than conventional Nd:YAG lasers with fiber delivery. The reliability remains high, due to the module construction, with no additional component stress as power is increased. [5,9]

The thin disk laser concept allows the realization of lasers with high output power, having very good efficiency and also excellent beam quality by minimization of the optical distortion of the laser beam through surface cooling of the disk. [5,6] The thin disk laser configurations have a capacity for continuous wave (cw) output powers exceeding 4 kW and enable the generation of high average power by minimizing the distance over which waste heat is transported. With each disk producing kilowatts of power, power scaling by the thin disk laser concept can be achieved by increasing the pump diameter on the disk or use of several disks arranged along a folded resonator axis. Alternatively, power scaling can be achieved by polarization coupling of two different resonators. [5]

During laser cutting a characteristic temperature has to be reached in the material for melting and evaporation to occur while some energy is lost by heat conduction away from the interaction zone. High power intensity is required in order to yield a safe process and this is more easily reached when the focused diameter (d_f) is smaller for a given power.

The maximum achievable speed for cutting also roughly scales with the power intensity such that at a given value of traverse speed, v, the cut thickness can be raised proportionally to the power intensity. [5]

The Beam Parameter Product (BPP), the standard measure of beam quality used for the comparison of laser beams from different laser systems because it includes the wavelength effects, is defined by the relationship in equation 1 below.

$$BPP = \Theta d_0 / 4 = \lambda M^2 / \pi \quad \text{.....................} (1)$$

(Θ - the full divergence angle, d_0 - the waist diameter, λ - wavelength and M^2 - times diffraction limit factor, which tells how much larger is the BPP of the laser under consideration compared to the physically lowest value of λ/π for a beam in the TEM_{00} mode (diffraction limit))

The beneficial effect of high beam quality (low value of BPP or M^2) is in achieving a smaller focused diameter, which reduces the necessary power for doing a particular job. The focus diameter (d_f) achievable with a given focusing number (F - focal length divided by the beam diameter on the optic) is directly proportional to the BPP as illustrated in equation 2 below.

$$d_f = (\Theta d_0) F = (4\lambda/\pi) M^2 F = 4F \cdot BPP \quad ..(2)$$

The depth of focus (z) set sort of tolerance of optimum focal point position and describes the distance within which the beam's cross-section and hence its power density varies up to a factor of 2, also directly depends on the BPP as equation 3 illustrates.

$$z = d_f F = (\Theta d_0) F^2 = (4\lambda/\pi) M^2 F^2$$
$$= 4F^2 \cdot BPP \quad \text{...} (3)$$

[5]

Experimental method

Three sets of cutting experiments were done with the disk laser, fiber laser and CO_2-laser. Because of the numerous parameters that affect the laser cutting process, a procedure of trial and error was used to choose a range of parameters that could produce a reasonable cut at the highest cutting speeds possible for each laser type and the different material thickness considered.

Test material

The test material used in the cutting experiments was austenitic stainless steel (AISI 304 and AISI 316), which was available in the form of sheets. Since some of the material was from different deliveries the material thicknesses between experiments were slightly different. Nominal thicknesses were 1, 2, 4 and 6 mm. Thickness of each material used was measured and they area summarized in table 1. All of the material had normal 2B surface quality. After cutting trials the cut kerfs were cut out of sample sheet by laser cutting prior further sectioning, grinding and polishing.

Table 1. The test material thickness

Test material	**Sheet thickness (mm)**		
	Fiber laser	Disk laser	CO_2 laser
AISI 304	1.30	1.30	1.30
AISI 316 (Fiber and Disk) AISI 304 (CO_2)	2.30	2.30	1.85
AISI 304	4.30	4.30	4.40
AISI 304	6.20	6.20	6.40

Fiber laser experiments

A 2D-laser cutting machine with linear drives (Arnold GmbH & Co. KG) and a fiber laser YLR 4000W (IPG Laser GmbH) with a maximum laser power output of 4000 W, beam quality of 2.5mm.mrad and a light conducting cable with a fiber diameter of 50 µm for the transfer of the laser beam to the focusing optics was used for the fiber laser cutting experiments. The focusing optics consisted of a HP 1.5" cutting head with a collimation of focal length 50mm and lens of focal lengths 5" (127mm) and 7.5" (190.5mm). Thus, for a fiber diameter of 50 µm, the imaging ratio was 1:2.54 for 5" focal length and a theoretical focus diameter of 127 µm. For the 7.5" focal length, the imaging ratio was 1:3.8 and consequently a theoretical focus diameter of 190.5 µm.

Nitrogen was used as assist gas. While increasing the cutting speed, five identical linear cuts of 150mm length were made for each sheet thickness until a point when the cutting speed employed could not produce a cut. The cuts were kept at sufficient distance from each other and from the workpiece edges in order to avoid interference. The cutting parameters were optimized in order to achieve the best cut quality at the highest cutting speeds.

The procedure of optimization was demonstrated with the cutting of 1.3mm sheet thickness. The validation was started at a cutting speed of 10 m/min for the focal length of 5" (127mm) and the parameters were varied in such a way that the feed rate could be increased step-by-step with the result that the cutting could be done in a process safe way. This was successful for a sheet thickness of 1.3mm at a laser power of 4000 W and with a cutting speed of up to 55 m/min (12 bar cutting gas pressure and a nozzle of 2.0 mm).

Disk laser experiments

A Trumpf disk laser (HLD 4002) was used for the disk laser cutting experiments. This system has a beam quality of 8 mm*mrad with a maximum laser power output of 4 kW at the workpiece and utilizes an optic fiber with core diameter of 200 µm for beam delivery.

The variables in the cutting experiments included material thickness, cutting speed and the focus position. The pressure of the nitrogen gas, employed as the assist gas, was varied from 6 to 30 bar depending on the material thickness so as to ensure effective ejection of the molten material during the cutting process.

While increasing the cutting speed, linear cut slots, 100mm long, were made for each thickness until a maximum cutting speed beyond which the cut quality was poor or no cut was produced altogether. The cuts were kept at sufficient distance apart from each other and from the workpiece edges in order to avoid interference. In another cutting condition, the focus position was varied with steps of -6mm, -3mm, 0, +3mm and +6mm from the workpiece surface for material thickness of 1.3mm and 2.3mm.

CO_2-laser experiments

A CO_2-laser machining center with a maximum output power of 6000 W was used to conduct the CO_2-laser cutting experiments. The cutting experiments were performed with the laser power of 4000 W with nitrogen as assist gas.

For each sheet thickness, linear cuts of 100mm length were made while increasing the cutting speed until a maximum cutting speed was reached beyond which the cut quality was poor or no cut was obtained.

Results and Discussion

The maximum cutting speeds and cut quality obtained were investigated. The cut quality was investigated by measuring the kerf width, cut edge perpendicularity (squarness) and surface roughness (R_a and R_z). The cut edge perpendicularity and surface roughness values were compared to valid cut kerf quality standard EN ISO 9013:2002 standard. [13]

Maximum cutting speeds

Generally, the fiber laser cutting speeds were highest compared to the disk laser and CO_2-laser cutting speeds especially at smaller sheet thickness (thickness less than 3mm) as figure 1 shows. The disk laser cutting speeds were also higher than the CO_2-laser cutting speeds.

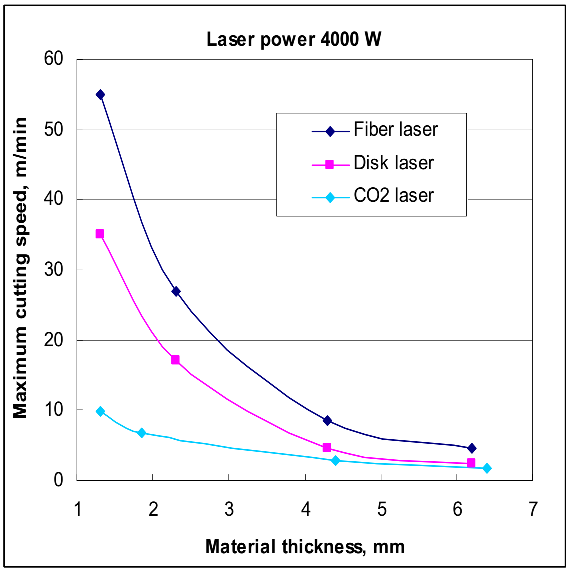


Figure 1. Maximum cutting speeds for the Disk, Fiber and CO_2 lasers

The fiber and disk laser cutting speeds were much lower when thicker sheets (thickness greater than 4mm) were cut. However, there was still a considerable percentage increase in cutting speeds of the fiber and disk lasers for the sheet thickness greater than 4mm compared to the cutting speeds of the CO_2-laser for similar sheet thickness (see table 2).

Table 2. Comparison of maximum cutting speeds of the disk and fiber lasers with the CO_2-laser cutting speeds at similar sheet thickness

	Sheet thickness (mm)	Max. cutting speed m/min	Percentage increase in cutting speeds compared to CO_2-laser cutting speeds at similar sheet thickness
Fiber laser BPP = 2.5 mm*mrad λ = 1.07µm	1.3	55	461%
	2.3	27	294%
	4.3	8,5	204%
	6.2	4.5	143%
Disk laser BPP = 8 mm*mrad λ = 1.07µm	1.3	35	257%
	2.3	17	148%
	4.3	4.7	68%
	6.2	2.3	24%
CO_2-laser BPP = 6.14 mm*mrad λ = 10.6µm	1.3	9.8	
	1.85	6.85	
	4.4	2.8	
	6.4	1.85	

The higher cutting speeds of the fiber and disk lasers especially at smaller sheet thickness can be attributed to their beam quality and wavelength advantage. The beam quality of the fiber laser used (2.5 mm*mrad) was better than the disk laser beam quality (8 mm*mrad) and CO_2-laser beam quality (6.4 mm*mrad) and this could explain why the fiber laser cutting speeds were much higher than the disk laser cutting speeds.

The high beam quality and shorter wavelength of the fiber laser and disk laser enable focusing of the laser beam to a smaller spot resulting into higher power densities and hence higher cutting speeds.

The high beam quality also enables use of longer focusing optics which increases the working distance thus reducing the risk of spatters damaging the focusing optics. A larger working distance is also advantageous when cutting is done in areas that are not easily accessible.

Kerf width

The kerf width represents the amount of material melted during cutting and correlates to the focused spot size. A small kerf width can have advantages when small details are to be made and when cutting sharp corners. The size of the focused spot is determined by the laser beam quality and focusing optics.

A shorter focal length resulted in a smaller kerf width as shown in figure 2. This is because the focal length is directly proportional to the focus spot size with a shorter focal length giving a smaller focused spot size and hence a smaller kerf width.

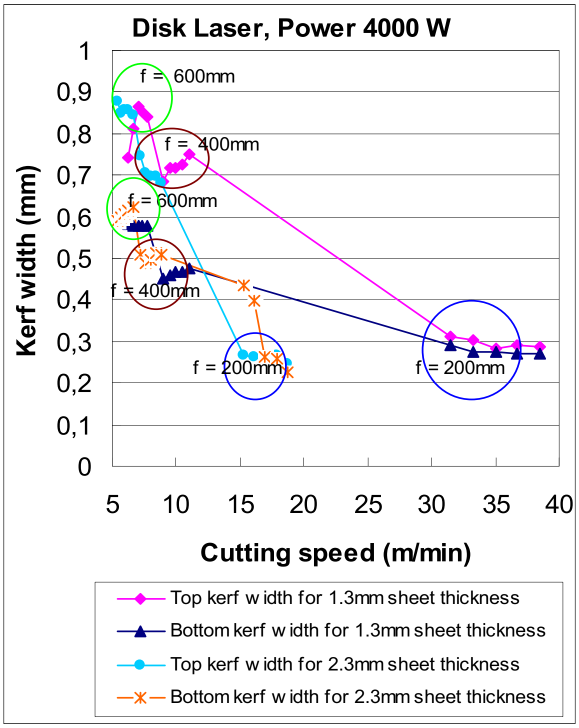


Figure 2. Kerf width variation with focal length and cutting speed for the 1.3mm and 2.3mm sheet thickness (Disk laser)

Changing the beam waist position relative to the sheet surface modifies the power intensity at the sheet surface thus affecting the size of the kerf as shown in figure 3.

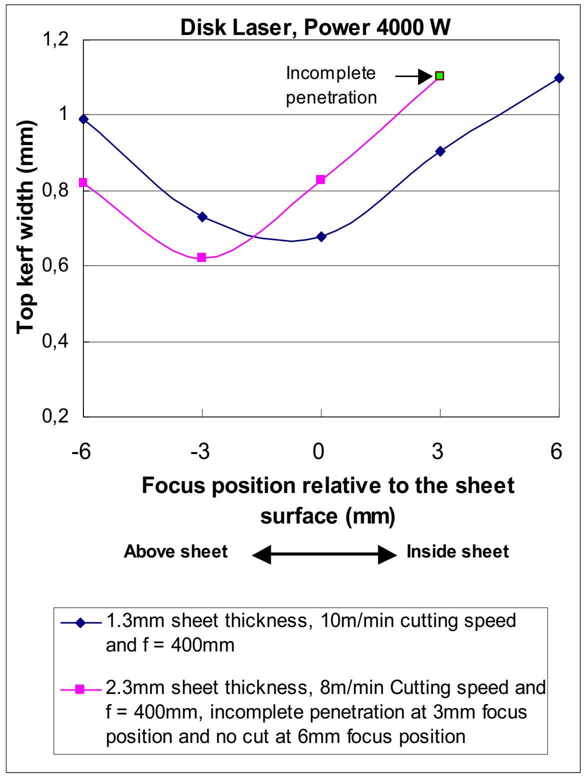


Figure 3. Kerf width variation with focus position for the 1.3mm and 2.3mm sheet thickness (Disk laser)

The disk and fiber laser cut kerfs had a narrower kerf width than the CO_2-laser cut kerfs. The smaller kerf widths can be attributed to the smaller focused spot size that is associated to the better beam quality and wavelength of the fiber and disk lasers as compared to the CO_2-laser beam quality and wavelength.

The top kerf widths were generally wider than the bottom kerf widths for most of the cutting conditions indicating the tapered nature of laser cutting as caused by the loss of beam intensity due to widening of the focused spot size below the focus point and loss of gas pressure across the thickness of the cut especially for the larger sheet thickness (more than 4mm).

Fiber laser Figure 4 shows the top and bottom kerf widths of the fiber laser cut kerfs. The difference between the top and bottom kerf widths was smaller for the 1.3mm and 2.3mm thickness but was larger for the 4.3mm and 6.2mm sheet thickness. The larger difference between the top and bottom kerf widths for the thicker sheets could also be caused by defocusing of the laser beam and the cutting speeds were lower during cutting of thicker sheets leading to accumulation of heat in the workpiece during the slow cutting process.

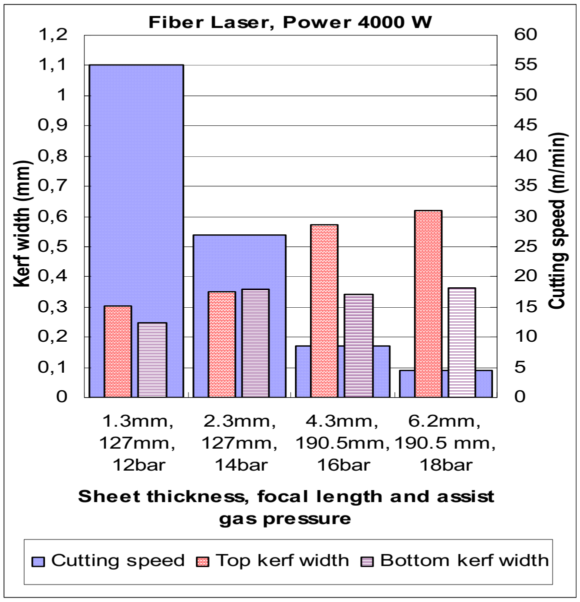


Figure 4. Fiber laser kerf widths for the 1.3mm, 2.3mm, 4.3mm and 6.2mm sheet thickness

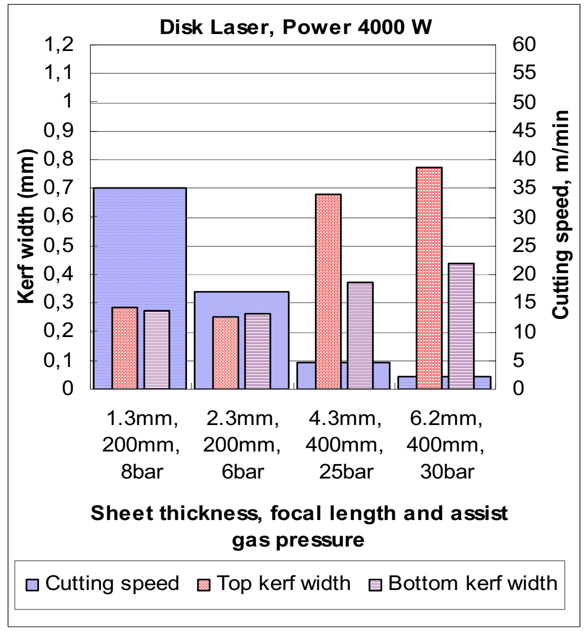


Figure 5. Disk laser kerf widths for the 1.3mm, 2.3mm, 4.3mm and 6.2mm sheet thickness

Disk laser The top and bottom kerf widths of the disk laser cut kerfs are shown in figure 5. The kerf widths for the 1.3mm and 2.3mm sheet thickness were narrower than for the 4.3mm and 6.2mm sheet thickness and the difference between the top and bottom kerf width was larger at 4.3mm and 6.2mm sheet thickness. This is expected based on the fact that the focal length of 200mm was used for cutting of 1.3mm and 2.3mm sheet thickness and a focal length of 400mm was used when the 4.3mm and 6.2mm sheet thickness was cut. It has already been shown in figure 2 that the kerf width is smaller when the focal length is shorter because the focal length determines the achievable focused spot size that defines the width of process front edge and hence the size of the kerf.

CO_2-laser The CO_2-laser cut kerfs also showed a larger difference between the top and bottom kerf widths as the sheet thickness increased as shown in figure 6. This trend can also be attributed to the widening of the laser beam after the focused spot and accumulation of heat in the workpiece during the cutting process.

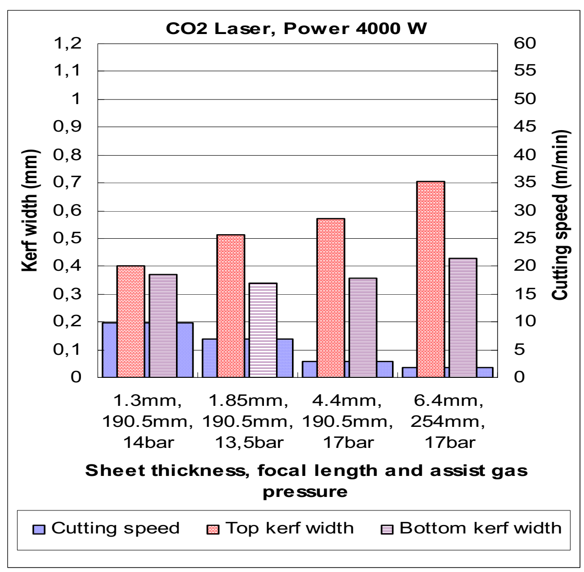


Figure 6. CO_2-laser kerf widths for the 1.3mm, 1.85mm, 4.4mm and 6.4mm sheet thickness

Defocusing of the laser beam and accumulation of heat in the workpiece as the cut progresses could be the cause of the large difference between the top and bottom kerf widths for the thicker sheets (sheet thickness more than 4 mm).

Perpendicularity deviation of cut edges

The perpendicularity deviation for each cut kerf made at maximum cutting speed for each sheet thickness was classified in the tolerance fields of the EN ISO 9013:2002 standard for thermal cuts. In the perpendicularity tolerance limits of this standard, range 1 corresponds to the best quality and range 5 the worst quality.

Figure 7 shows the perpendicularity deviation classification of the fiber, disk and CO_2 laser cut kerfs made at maximum cutting speed for the sheet thickness considered. Each of the laser cut kerfs – fiber, disk and CO_2 laser cut kerfs – were classified within ranges 1 and 2.

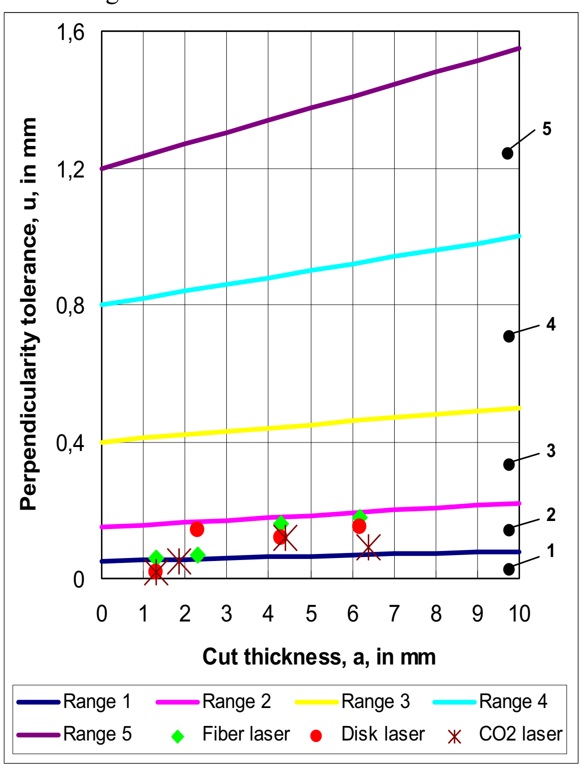


Figure 7. Perpendicularity tolerance classification of the laser cut edges made at maximum cutting speeds for each sheet thickness (fiber, disk and CO_2 lasers)

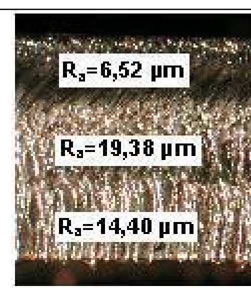
Generally, the CO_2-laser cut surfaces had the lowest perpendicularity deviation in these cutting experiments. Probably, the cutting speeds do not have a significant effect on the cut edge perpendicularity since the CO_2-laser cut kerfs were made at the lowest cutting speeds compared to the fiber and disk laser cutting speeds. However, in these particular cutting experiments the cutting speed was varied as well as the assist gas pressure, focal length and focus position. Therefore, the effects of the gas pressure, focal length and focus position on the perpendicularity deviation of the cut edges could not be established. This could be investigated further by keeping all the other processing conditions constant while varying only the cutting speed.

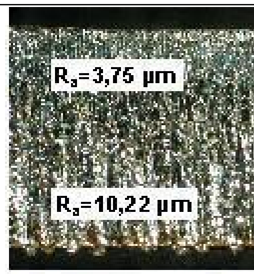
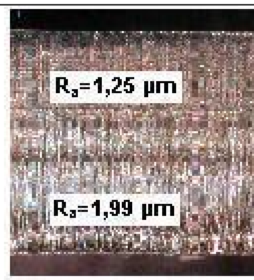
Surface roughness

The surface roughness varied along the cut thickness especially for thicker sheets. Therefore the roughness measurements were done at locations along the cut thickness where the maximum roughness values were expected. For the 1.3mm, 1.85mm and 2.3mm sheet thickness, the roughness measurement was done at the middle of the cut thickness and roughness measurements for the 4.3mm, 4.4mm, 6.2mm and 6.4mm sheet thickness were done at two positions along the cut thickness – one measurement position at the upper part and the other at the lower part of the cut thickness. The surface was rougher at the lower part of the cut thickness than at the upper part. For the 6.2mm sheet thickness fiber laser cut surface, a third roughness measurement position was selected from the middle of the cut thickness, as three different regions of surface roughness were visible with the roughest region being at the middle of the cut thickness.

Table 3 shows the roughness profile of the 6.2mm sheet thickness cut with the fiber and disk lasers and 6.4mm sheet thickness cut with the CO_2-laser. The fiber laser cut surface showed the highest roughness at the middle of the cut thickness, the disk laser cut sample had roughest surface at the bottom of the cut thickness. CO_2 laser cut surface in turn showed the lowest roughness which was relatively uniform along the cut thickness.

Table 3: Surface roughness profile along the cut thickness

FIBER LASER Thickness: 6,2mm Power: 4000W Speed: 4,5m/min Focal length: 190,5mm Assist gas: Nitrogen Pressure: 18bar	

DISK LASER Thickness: 6,2mm Power: 4000W Speed: 2,3m/min Focal length: 600mm Assist gas: Nitrogen Pressure: 30bar	
CO_2 LASER Thickness: 6,4mm Power: 4000W Speed: 1,85m/min Focal length: 254mm Assist gas: Nitrogen Pressure: 17bar	

The cut quality revealed a higher surface roughness for the cuts of 4.3mm and 6.2mm sheet thickness made with the disk and fiber lasers and the roughness varied along the cut thickness. The CO_2 laser cuts had a relatively low surface roughness even at 4.4mm and 6.4mm sheet thickness and the roughness was uniform along the cut thickness. Previous studies [2] have shown that there is a critical cutting speed beyond which the surface roughness increases and this critical cutting speed is dependent on the power level.

The cut surface roughness for each sample cut at maximum cutting speed for each sheet thickness was classified in the tolerance fields of the EN ISO 9013:2002 standard for thermal cuts as shown in figure 8. Range 1 of the mean height of the profile, R_z5, tolerance limit corresponds to the best quality while range 4 corresponds to the worst quality.

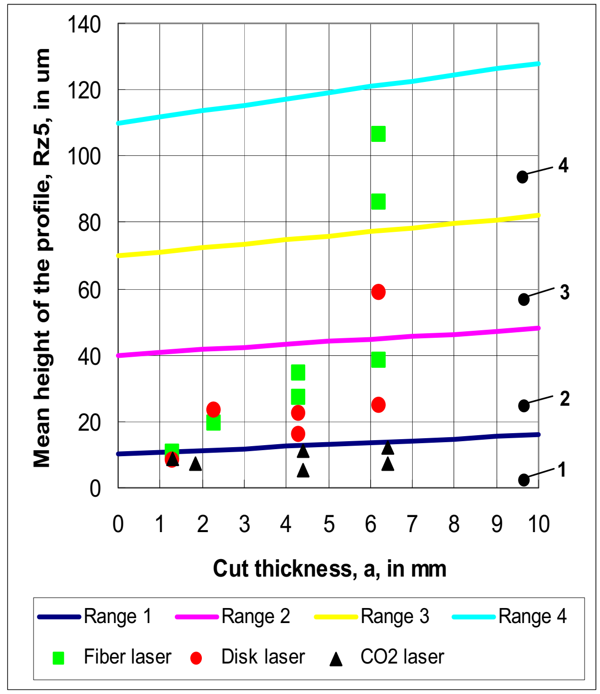


Figure 8. Roughness classification of the laser cut edges made at maximum cutting speeds for each sheet thickness (fiber, disk and CO_2 lasers)

Generally, the CO_2-laser cut surfaces showed a lower surface roughness than the fiber laser and disk laser cut surfaces. The fiber laser cut surface of 6.2mm sheet thickness that was cut at the maximum cutting speed of 4.5m/min and focal length of 7.5" (190.5mm) generally had the highest roughness and there was increased surface roughness at the middle of the cut thickness. Laser cutting of this sheet thickness with the cutting speed of 4.5m/min might be the threshold case for cutting with a focal length of 7.5" (190.5mm). Better results could probably be achieved by using a longer focal length, say 10" (254mm).

High surface roughness of the 4.3mm and 6.2mm sheet thickness cut using the fiber and disk lasers suggest that probably the fiber and disk laser cutting experiments for the 4.3mm and 6.2mm sheet thickness did not have the appropriate combinations of focal length, focus position, cutting speeds and assist gas pressures for achievement of minimum surface roughness.

For the case of fiber laser cutting of 6.2mm sheet thickness, it could be possible that the surface roughness can be reduced by the use of a longer focal length that would give a wider kerf for efficient ejection of melt material. As it has been shown in equations 2 and 3 above that both the focus spot size and depth of focus are directly proportional to the Beam Parameter Product (BPP), the high beam quality (BPP = 2.5mm.mrad) of the fiber laser gives a smaller spot size and a smaller depth of focus which limit the effective cutting of thicker sheets. A smaller depth of focus limits the length along the cut thickness for effective cutting to take place and a smaller spot size results in a smaller kerf width that limits the effective removal of the large amount of molten material generated in thick section cutting. Therefore, cutting of thicker sheets requires a larger depth of focus for effective cutting throughout the whole sheet thickness and a wider kerf that would allow a larger part of the gas flow to penetrate the kerf and eject the molten material satisfactorily. The use of a longer focal length in this case would give a wider kerf and a larger depth of focus. The focus position can also be adjusted appropriately so as to achieve a wider kerf.

Conclusion

The cutting speeds for the fiber and disk laser cutting experiments were enormous at sheet thickness less than 4mm as compared to the cutting speeds for the CO_2-laser cutting experiments at similar sheet thickness. These high cutting speeds are a direct effect of the high power densities facilitated by the high beam quality. The cutting speeds for the fiber and disk lasers were lower at 6.2mm sheet thickness but there was still a considerable relative increase compared to the CO_2-laser cutting speeds at this thickness.

The fiber and disk cutting experiments in this study achieved the objective of maximum cutting speeds, which is a good parameter for higher productivity. However, optimization of the cut quality in relation to the maximum cutting speeds was not achieved for the 4.3mm and 6.2mm sheet thickness as seen by the high values of the surface roughness of the fiber laser and disk laser cut surfaces for the 4.3mm and 6.2mm sheet thickness. The classification of the cut surfaces revealed that the fiber laser and disk laser cutting experiments did not achieve the anticipated smooth cut surfaces (low surface roughness). The cut surface quality of the CO_2-laser cut surfaces was better than that of the fiber laser and disk laser cut surfaces.

The cutting results showed that the disk laser and fiber laser have a potential for cutting applications and are capable of competing favorably with the CO_2-laser. It might be possible that the defects observed for thick sheets can be avoided by proper selection of process parameters, especially focus position, cutting speed and gas pressure. The appropriate cutting parameters for the fiber laser and disk laser cutting of larger sheet thickness (thickness more than 4mm) could not be established in this study.

Future studies on cutting of stainless steel with the fiber laser and disk laser could cover optimization of the cut quality by ensuring minimum surface roughness and minimum perpendicularity deviation. The main focus could be on improving the surface quality for the thicker sheets.

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