AIP | Journal of Laser Applications
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Citation: Journal of Laser Applications **21**, 154 (2009); doi: 10.2351/1.3184429
View online: http://dx.doi.org/10.2351/1.3184429
View Table of Contents: http://scitation.aip.org/content/lia/journal/jla/21/3?ver=pdfcov
Published by the Laser Institute of America

JOURNAL OF LASER APPLICATIONS VOLUME 21, NUMBER 3 AUGUST 2009

Inert gas cutting of thick-section stainless steel and medium-section aluminum using a high power fiber laser

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(Received 13 November 2008; accepted for publication 17 April 2009; published 13 August 2009)

Inert gas assisted laser cutting of 10 mm stainless steel plate and 4 mm aluminum sheet was performed with a 5 kW fiber laser. The effects of laser power, cutting speed, focal point position, and assist gas pressure on the cutting performance and cut quality were investigated. Clean cut surfaces without or with minimal dross were achieved with some combinations of process parameters and attempts were made to define parameter windows in terms of cutting speed and laser power for good quality cutting. The maximum cutting speeds for acceptable cut quality were determined at different power levels. The range at which complete through cutting could be achieved (so-called parameter window) was limited upwards by insufficient power intensity to obtain through cutting at high cutting speeds and downwards by heat conduction at slow cutting speeds. The effects of focal point position and assist gas pressure on the striation pattern (cut surface roughness) were also examined. Low surface roughness was achieved with the focal point position inside the workpiece showing the need for a wider kerf for better melt ejection in thick-section metal cutting. There was also a reduction in surface roughness with increase in assist gas pressure, but there was no significant reduction in surface roughness above the gas pressure of 16 bar, which could be due to the gas flow dynamics inside the narrow cut kerf at high assist-gas pressures. © *2009 Laser Institute of America.*

Key words: Fiber laser cutting, thick-section, stainless steel, aluminum

I. Introduction

The trend toward very high laser beam quality with high output powers of the high brightness fiber laser—which results in performance gains for thick-section metal cutting—has increased the need for detailed knowledge on the cutting performance of the fiber laser and the resulting cut quality.[1–3] In principle, thick-section laser cutting can be facilitated by the high beam quality of the high brightness fiber laser which enables high power densities through focusing of the high quality laser beam to a small spot size, a large depth of field for processing when combined with long focal length optics, and utilization of longer beam delivery fibers when cutting is performed in remote locations.[4]

Material thicknesses can be divided into different thickness ranges by the applications. In this paper the thicknesses are divided into three categories: thin section (up to 2 mm), medium section (2–6 mm), and thick section above 6 mm. The potential of the high power fiber laser for thick-section cutting has been examined experimentally and promising results have been reported. All of the research of cutting stainless steel with modern lasers is carried out with high pressure nitrogen cutting, which is a logical choice combining high value added process to high value and performance material. In a comparison of the thick-section metal sheet cut quality and cutting performance of the CO_2 and fiber lasers, Himmer *et al.*[5] and Wandera[6] reported increased cutting speeds for the fiber laser cutting but the CO_2 laser produced a better cut surface quality for thick sheets. The high brightness sources (disk and fiber lasers) offer considerable process improvements on thinner section materials, but the performance of the CO_2 laser matches that of the high brightness lasers more and more as the section thickness increases.[7] The authors[6,8] as well as other researchers[9] have investigated experimentally the medium-section stainless steel cutting using a high power fiber laser. Higher cutting speeds have been reported for fiber laser cutting compared to CO_2 laser cutting speeds but difficulties in obtaining full melt eject through the narrow fiber laser cut kerfs have been noted. The first experimental work explaining the gas jet phenomena between the nozzle

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tip and workpiece surface was presented by Fieret *et al.*[10] The behavior of the gas jet inside the cut kerf has also been investigated.[11,12] Zefferer *et al.*[11] used the Schlieren optical method to investigate the cutting gas flow pattern inside the simulated cutting kerf models and reported the presence of shock structures within the cutting kerf. They also observed the dependence of the boundary layer separation position on the nozzle geometry, nozzle position, cutting gas pressure, and workpiece thickness. Gas dynamics is still an important topic in laser cutting today because of the continuously increasing possibilities for laser cutting. These possibilities are gained in terms of increased material thickness that can be cut due to the development of improved laser systems with better beam quality and higher output powers. Olsen's[13] theoretical prediction of a more coarse cut surface roughness without striation pattern in the middle zone of the cut surface was corroborated by experimental evidence from the work of Wandera *et al.*[8] in which a 6 mm stainless steel fiber laser cut surface showed the highest roughness in the middle section of the cut thickness.[7] The characteristic appearance of the thick-section cut surfaces having lower roughness at the upper part and increased roughness at the bottom part of the cut surface is attributed to the gas flow separation from the cutting front.[14] Beyer *et al.*[15] and Hammann[16] argued that the poor cut quality in thick-section metal cutting with the fiber laser is due to the greater absorption of the 1 μm radiation which results in increased melting capacity and the poor melt ejection compared to the melting capacity and melt ejection obtained with the 10 μm CO_2 laser radiation. The melting and melt ejection mechanisms have to be well balanced so as to achieve a high cut quality.

In view of the fact that the thick-section fiber laser cutting parameters have not yet been understood quite well as compared to the thick-section cutting with CO_2 laser which has been dominating this area for a long time, the present work investigates the fiber laser cutting performance and the cut quality of 10 mm stainless steel plate and 4 mm aluminum sheet. The maximum cutting speeds with different laser power levels and the effects of assist-gas pressure and focal point position on the cut surface roughness are examined.

II. Experimental setup

A. Experimental procedure

Cutting experiments were undertaken using an IPG YLR-5000 fiber laser which has a beam parameter product of 4.2 mm× mrad and a power range of 40–5000 W. The beam was delivered through a 100 μm fiber into a standard Precitec cutting head Hp1.5 YW50 for thick-section flat cutting and a conical nozzle tip was used. The cutting head is also suitable for high pressure cutting. The optical system consisted of a 100 mm collimation lens and focusing lenses with focal lengths of 127 and 190.5 mm, giving focal point diameters of 0.16 and 0.24 mm correspondingly. All tests were made with a CN-controlled workstation with a working area $(X \times Y \times Z)$ of $11.7\ \text{m} \times 2.7\ \text{m} \times 1.2$ m. The acceleration of the workstation is less than 0.5 G and the maximum achievable speed is 20 m/min.

TABLE I. Process parameter levels.

Laser power	(kW)	1–5
Gas pressure	(bar)	6–22
Focal length	(mm)	127, 190.5
Focal point position[a]	(mm)	+8 to −12
Cutting speed	(m/min)	0.1–10.8

[a] + focal point above the workpiece top surface; − focal point below the workpiece top surface.

The tested materials included stainless steel 1.4301 with plate thickness of 10 mm and aluminum 5754 with sheet thickness of 4 mm; the workpieces were prepared into sizes of 200 mm×150 mm. Nitrogen was used as the assist gas. The cutting tests examined the influence of variations in process parameters—laser power, assist-gas pressure, focal point position, and cutting speed—on the cutting performance and cut quality. The focal point position was defined relative to the workpiece surface as being positive when the focal point was above the workpiece top surface and negative for focal point below the workpiece top surface (i.e., above the material or inside it). The cutting was performed by cutting straight cuts beside each other. The cutting of curves or corners was not included in this paper. The process parameter ranges employed are given in Table I and the cutting sequence and experimental setup are shown in Fig. 1.

Within the ranges shown in Table I the actual experiments were performed with steps of 1 kW when testing the effect of laser power. With each power level the cutting speed was varied with steps of 0.1 m/min in case of stainless steel and 0.2 m/min in case of aluminum until the

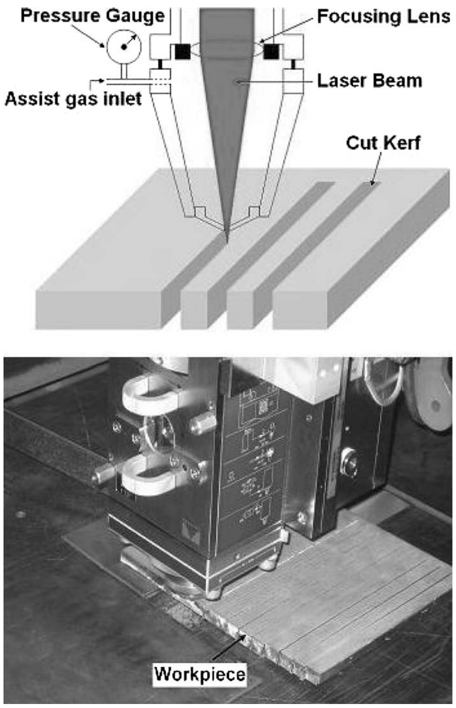
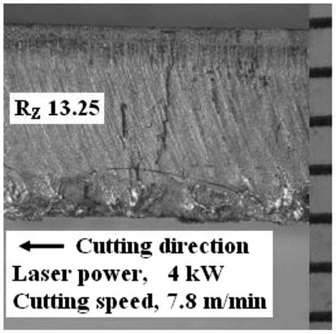


FIG. 1. Cutting sequence and experimental setup.


Aluminium (4 mm) cut surface

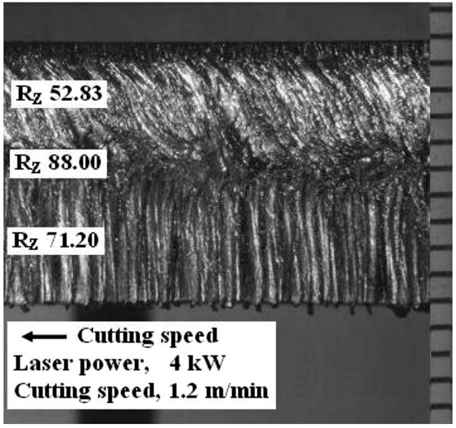

Stainless steel (10 mm) cut surface

FIG. 2. Cut edge quality at maximum cutting speed.

speed giving best quality was achieved. The gas pressure was studied in steps of 2 bar in both cases of stainless steel and aluminum.

The laser beam produced by the laser has random polarization, which is maintained also while transporting the beam with standard optical fiber used. Therefore the effect of polarization was not studied.

The maximum cutting speed was specified by testing the maximum cutting speed that could separate the material. The acceptable cut edge quality was then studied among the samples cut and the cut edge quality was specified by visual examination by optical microscopy and measurement of the surface roughness. The surface roughness was measured in Rz such as that suggested by the standard ISO/EN 9013:2002.[17]

III. Results and discussions

A. Physical observations

The quality of the cut edge can be evaluated by measuring the surface roughness. In practice the roughness will vary while studying it throughout the thickness. Typically the surface is smoother in the top part of the cut edge and rougher in the lower part of the cut edge. This means in practice that the roughness measurement should be supported by visual examination which gives the idea of the real shape of the cut edge. Some selected samples made at maximum cutting speed for the given laser power are shown in Fig. 2.

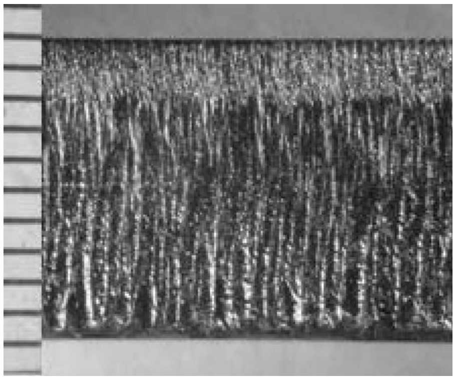


FIG. 3. The smooth cut surface with regular striation pattern on 10 mm stainless steel plate (laser power of 4 kW, cutting speed of 1 m/min, and nitrogen assist gas pressure of 20 bar).

1. Stainless steel

Stainless steel cutting was showing behavior typical to this material. With some parameter combinations the cut surface showed a chaotic striation pattern. The cut edge had adherent dross when cutting was performed with lower speeds and cleaner cut edges were obtained with higher cutting speed. The speed giving optimum quality was about 20–33 % lower than the maximum cutting speed. The cut quality at this point looks quite smooth and with regular striation pattern (see Fig. 3).

2. Aluminum

The aluminum cut surfaces showed a regular striation pattern in most of the cases. The striation pattern changed with speed such that with lower speed the striations were more spaced and with higher speed the striations were finer. Dross attachment was evident on the bottom of the aluminum cut surfaces showing an inefficient melt removal at the kerf exit.

B. Maximum cutting speed

When testing the maximum achievable cutting speed for each of the material there is a definition of quality to be made. Typically the cutting speed giving the best quality was lower than the maximum speed cutting through the material. The cutting speed giving the best cut quality can be referred to as the optimum cutting speed especially for applications where high quality is of paramount importance. If the cutting

TABLE II. Comparison of effect of power density on the required heat input for cutting through the material in case of stainless steel.

Power (kW)	Speed (m/min)	Heat input (kJ/mm)	Power density (W/mm^2)
1.0			2.2×10^4
2.0	0.2	0.60	4.4×10^4
3.0	0.8	0.23	6.6×10^4
4.0	1.2	0.20	8.8×10^4
5.0	1.5	0.20	1.1×10^5

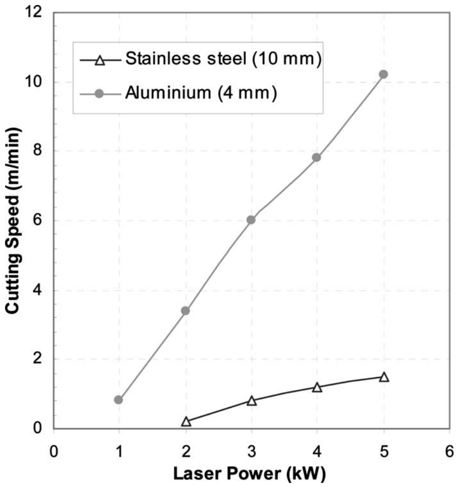


FIG. 4. Maximum cutting speeds with the corresponding required laser power.

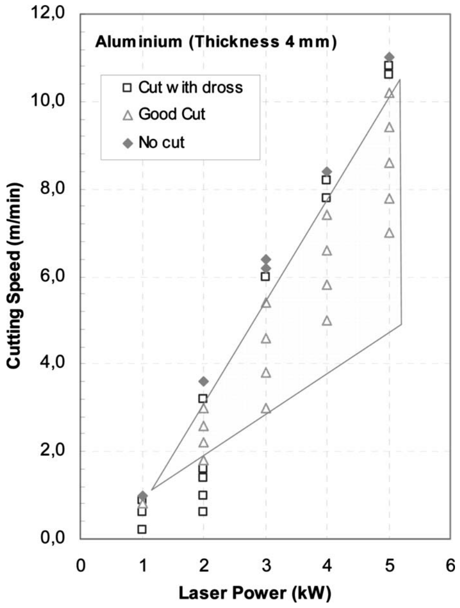


FIG. 6. Parameter window for good quality cutting of 4 mm aluminum (gas pressure of 14 bar, focal length of 190.5 mm, focal point position of −2 mm, working distance of 0.5 mm, and nozzle diameter of 1.5 mm).

speed was increased beyond this optimum cutting speed or lowered to too low a speed, there was dross formation in the bottom side of the cut edge.

The maximum cutting speeds with the corresponding required laser power levels—beyond which cutting was not possible—are presented in Fig. 4.

The cutting of 10 mm stainless steel plate was not possible with laser power of 1 kW because this power level is insufficient to produce complete cuts even at the lowest reasonable cutting speeds. In case of aluminum, cutting with the power of 1 kW was possible even though the parameter window was quite small.

The parameter windows for good quality process-safe cutting (Figs. 5 and 6) give the minimum and maximum cutting speeds for each laser power level for which complete cutting was possible. The combinations of laser power and cutting speed which produced clean dross free cuts are indicated as well as those combinations where cutting was not possible. The range at which complete through cutting could be achieved was limited upwards by insufficient power intensity to obtain through cutting at high cutting speeds and downwards by heat conduction at slow cutting speeds.

1. Stainless steel

At laser power of 5 kW, a clean cut surface was produced in 10 mm stainless steel plate at a maximum cutting speed of 1.5 m/min with gas pressure of 19 bar. The whole parameter window for stainless steel cutting is presented in Fig. 5.

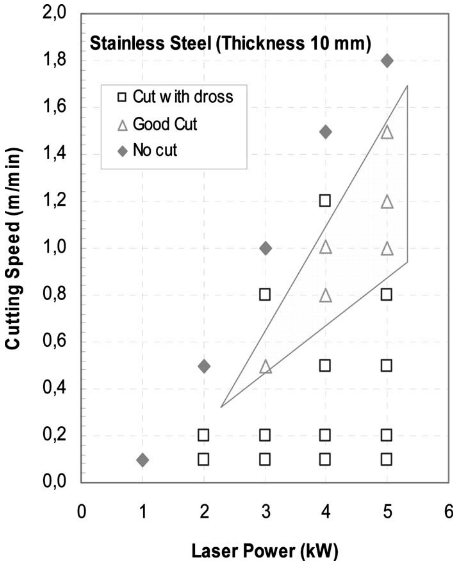


FIG. 5. Parameter window for good quality cutting of 10 mm stainless steel plate (gas pressure of 19 bar, focal length of 190.5 mm, focal point position of −8 mm, working distance of 0.5 mm, and nozzle diameter of 2.5 mm).

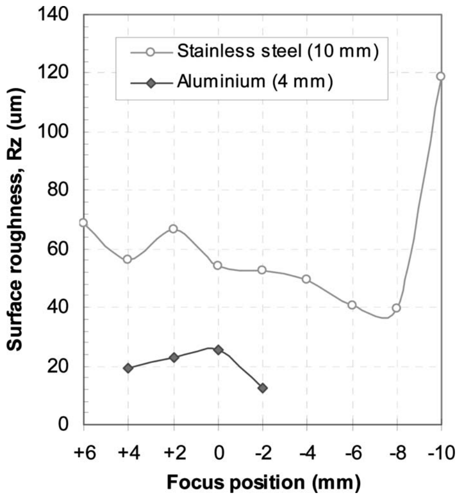


FIG. 7. The variation in surface roughness with focus position: laser power of −4 kW, focal length of −190.5 mm (stainless steel cutting speed is 1 m/min and assist gas pressure of 19 bar; and aluminum cutting speed is 7 m/min and assist gas pressure of 20 bar).

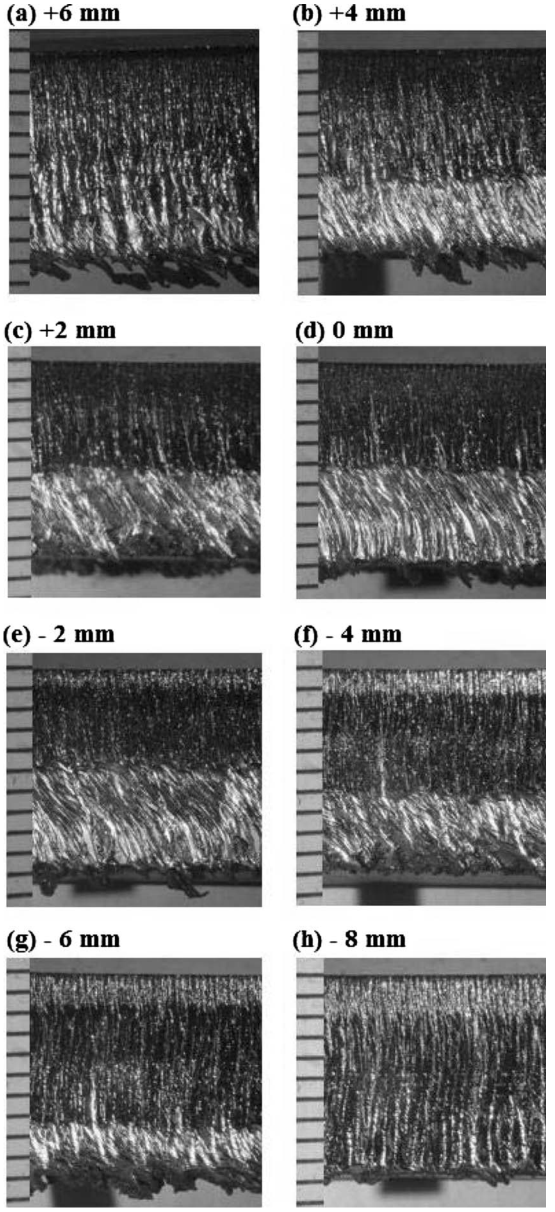

(a) +6 mm (b) +4 mm (c) +2 mm (d) 0 mm (e) - 2 mm (f) - 4 mm (g) - 6 mm (h) - 8 mm

FIG. 8. Effect of focal point position on striation pattern [stainless steel (10 mm): 4 kW, 1 m/min, and 19 bar nitrogen assist gas pressure].

Only a slight increase in cutting speed with laser power was realized in the stainless steel plate cutting. However, this seemingly slight increase in stainless steel plate cutting speed could be misleading in actual sense considering the thickness of the material being 10 mm.

2. Aluminum

Clean dross free cuts in 4 mm aluminum sheet were produced at a maximum cutting speed of 10.2 m/min with gas pressure of 14 bar. A sharp increase in cutting speed with increase in laser power was realized in the cutting of the 4 mm aluminum sheet (see Fig. 6).

In general when the cutting speed is increased high enough for a given laser power level, a maximum cutting speed is reached beyond which the laser power is insufficient to produce complete cutting and in that case a maximum cutting speed for that power level has been exceeded. However, there is a significant variation in cut quality even in combinations of laser power and cutting speed where complete through cutting is possible (see Figs. 5 and 6). The dross-free cutting range was larger at higher laser powers. The widening of the dross-free cutting range at higher laser powers is due to the increased incident intensity which enhances the cutting speeds and hence improves the thermal efficiency. As shown in Table II in the case of stainless steel, the power density of $2.2\times10^4\ \mathrm{W/mm^2}$ is not high enough to enable cutting through the 10 mm stainless steel plate. It can be seen from Tables II and III that the higher the intensity the lower the heat input required for cutting through the material.

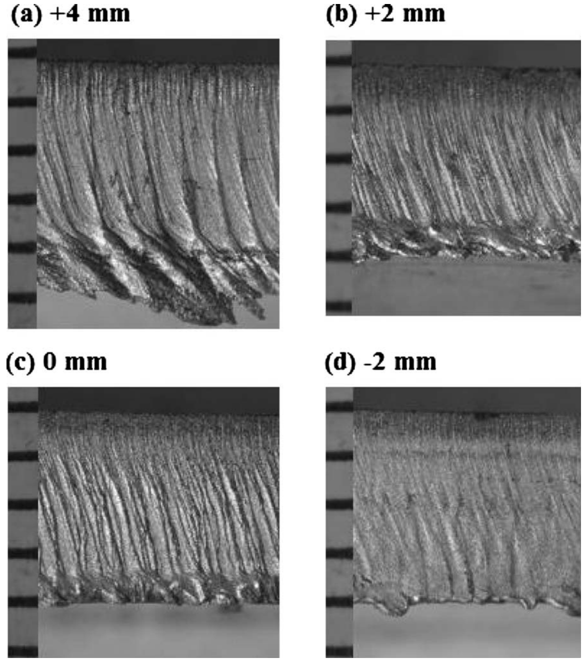

(a) +4 mm (b) +2 mm (c) 0 mm (d) -2 mm

FIG. 9. Effect of focal point position on striation pattern [aluminum (4 mm): 4 kW, 7 m/min, and 20 bar nitrogen assist gas pressure].

C. Variation in surface roughness with focal point position

The variation in surface roughness with focal point position (Fig. 7) shows that there is an optimum focal point position which produces minimum cut surface roughness while there are focal point positions where cutting through the material cannot be achieved.

TABLE III. Comparison of effect of power density on the required heat input for cutting through the material in case of aluminum.

Power (kW)	Speed (m/min)	Heat input (kJ/mm)	Power density ($\mathrm{W/mm^2}$)
1.0	0.9	0.07	2.2×10^4
2.0	3.4	0.04	4.4×10^4
3.0	6.0	0.03	6.6×10^4
4.0	7.8	0.03	8.8×10^4
5.0	10.2	0.03	1.1×10^5

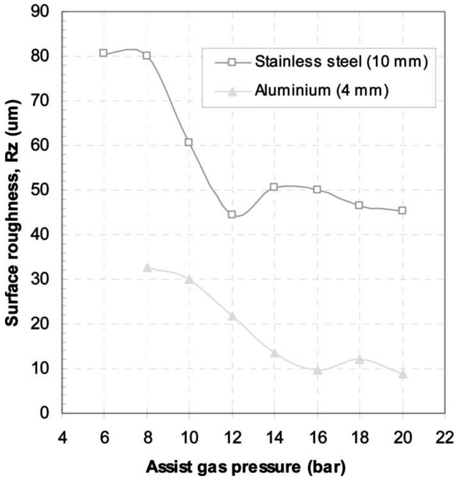


FIG. 10. The variation in surface roughness with assist gas pressure: laser power of −4 kW, focal length of −190.5 mm (stainless steel cutting speed is 1 m/min and focus position of −8; and aluminum cutting speed is 7 m/min and focus position of −2).

1. Stainless steel

The optimum focal point position that produced the best cut quality for the cutting of the 10 mm stainless steel plate was −8 (i.e.,8 mm below the workpiece top surface). Cutting of the 10 mm stainless steel plate was not possible with +8 and −12 focal point positions.

Depending on the focal point position, the stainless steel cut surfaces showed a visible separation point in which the striation pattern above the separation point was finer and regular while the striation pattern below the separation point was coarse and irregular. The separation point was pushed down the cut surface when the focal point position was located away from the workpiece top surface and it was not observable in the 10 mm stainless steel at the focal point position of 8 mm below the workpiece top surface revealing a uniform striation pattern throughout the whole cut surface (see Fig. 8). The variation in striation pattern with focal point position indicates the influence of the cut kerf size on the melt removal mechanism.

The size of the cut kerf is critical in thick-section laser cutting because it influences the efficiency of melt removal. The optimum focal point positions located below the workpiece top surface enhance the formation of a wider cut kerf which enables efficient removal of the molten material. The high power fiber laser with its high beam quality produces very high power intensity with a small spot size which enhances a small kerf width. Therefore, the improvement of the cut surface roughness at the focal point positions below the workpiece surface is as a result of the wider kerf produced for such focal point positions.

2. Aluminum

The optimum focal point position that produced the best cut quality in 4 mm aluminum sheet was −2 mm (i.e., 2 mm inside the workpiece) and cutting was not possible with the −4 (i.e., 4 mm inside the workpiece) focal point position. Figure 9 shows the variation in striation pattern of the aluminum cut surface with focus position. Unlike in the stainless steel cut surfaces where there was a visible separation point on the cut surface, the striation pattern on the aluminum cut surfaces was uniform throughout the workpiece thickness. There was adherent dross on the aluminum cut edge when the focal point position was located 4 mm above the workpiece top surface. This dross could easily be removed by a simple cleaning operation such as wire brushing.

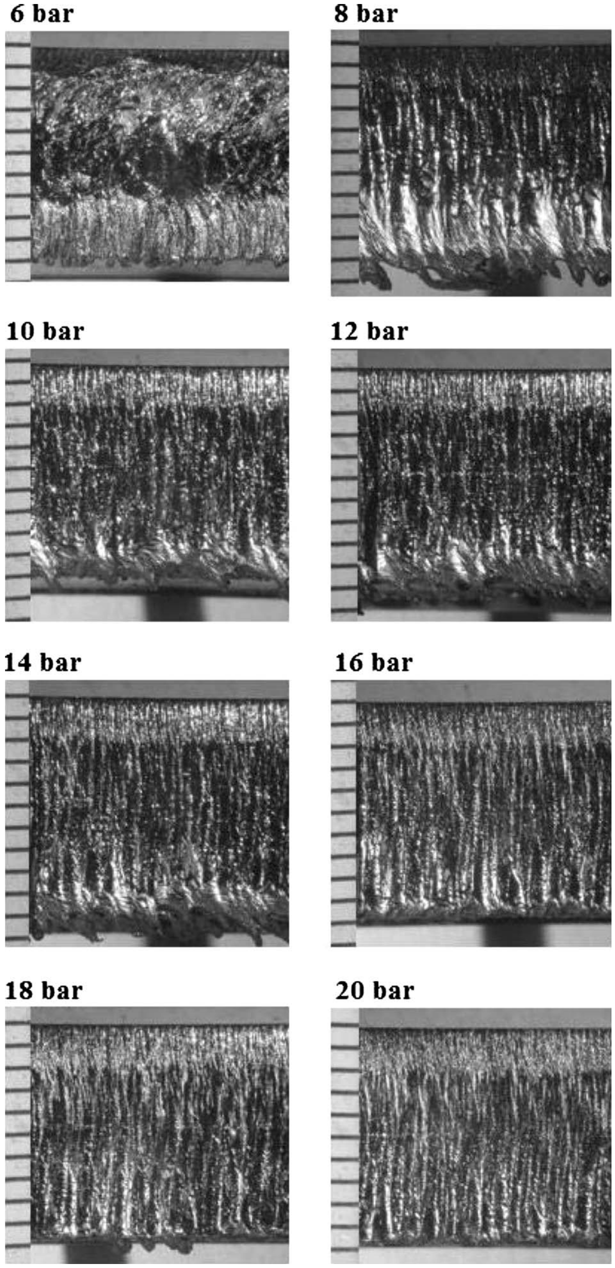


FIG. 11. Effect of assist gas pressure on striation pattern [stainless steel (10 mm): 4 kW, 1 m/min, and −8 focal point position].

D. Variation in surface roughness with assist-gas pressure

A noticeable reduction in surface roughness was realized with increasing assist-gas pressures (see Fig. 10) showing a significant influence of the assist-gas pressure on the quality of the cut surface. The reduction in surface roughness was

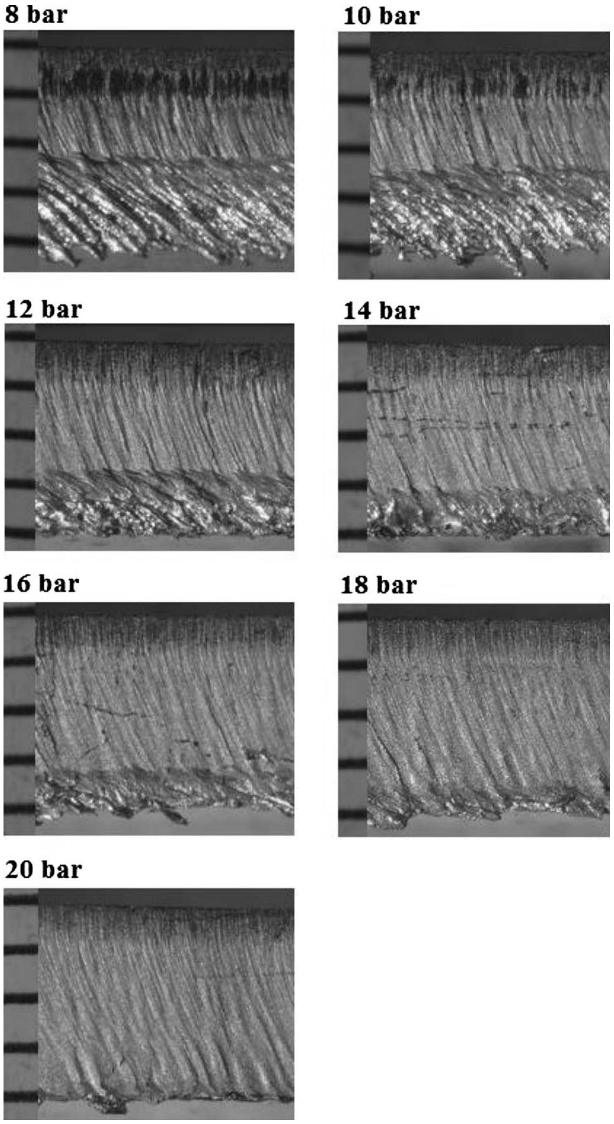


FIG. 12. Effect of assist gas pressure on striation pattern [aluminum (4 mm): 4 kW, 7 m/min, and −2 focal point position].

not much after the gas pressure of 16 bar and this could be due to the gas flow dynamics inside the narrow cut kerf at high assist-gas pressures. The gas flow dynamics inside the cut kerf is also influenced by other process parameters such as working distance, nozzle tip diameter, and the nozzle type (supersonic or subsonic).

1. Stainless steel

The striation pattern on the stainless steel cut surfaces was coarse and irregular at low assist-gas pressures but became smoother and regular with increase in assist-gas pressure (see Fig. 11). There was also some adherent dross at low assist-gas pressures but was cleared out as the assist-gas pressure increased. The higher assist-gas pressure provides the necessary force required to blow the molten material out of the kerf and produce clean cut edges.

2. Aluminum

The aluminum cut surfaces had a regular and uniform striation pattern even with lower assist-gas pressures; however, there was adherent dross on the cut edges made with low assist-gas pressures (see Fig. 12). The adherent dross was cleared with increasing assist-gas pressure such that the workpiece made with 20 bar assist-gas pressure was completely clean with no adherent dross showing that this pressure was able to provide the necessary force required to completely blow the molten material out of the cut kerf.

IV. Conclusions

The laser cutting of 10 mm stainless steel plate and 4 mm aluminum sheet with a high power fiber laser has been investigated in this paper. The maximum cutting speeds at different laser power levels were determined. The effects of focus position and assist-gas pressure on the cut surface roughness were also examined. Clean cut surfaces without dross or minimal dross were achieved with some process parameter combinations and it was possible to define process parameter windows—in terms of laser power and cutting speed—for good quality cutting. Acceptable cut quality was produced with the focal point position inside the plate showing the need for a wider cut kerf in thick-section metal cutting using the high power fiber laser.

ACKNOWLEDGMENTS

The authors would like to thank the company HT Laser-tekniikka Oy for funding this research project.

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