Laser cutting of variable thickness materials – Understanding the problem

Conference Paper · January 2006

DOI: 10.2351/1.5060831

Mohamed Sobih
Higher Colleges of Technology

Lin Li
The University of Manchester

Laser cutting of variable thickness materials – understanding the problem

Paper 408

M. Sobih, P.L. Crouse, and L. Li

Laser Processing Research Centre, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Sackville Street Building, PO Box 88, Manchester M60 1QD, United Kingdom.

Abstract

Laser cutting has been widely applied to materials with uniform thickness profiles. The aim of this study is to explore the problems and effects of cutting non-uniform metallic sheets. Mild steel sheets between 2-3 mm thickness with steps of 0.25 mm were cut using both CO_2 and Nd:YAG lasers with equivalent cutting parameters and in 4 different cutting arrangements: a) thin-to-thick from the flat side; b) thick-to-thin from the flat side; c) thin-to-thick from the stepped side; and d) thick-to-thin from the stepped side. Quality of cut was examined in terms of dross attachment, surface roughness, perpendicularity, kerf width, and striation height. The work shows that variation in workpiece thickness affects the cut surface quality due to several factors related to irradiance and assist gas flow. In some situations these effects can be minimized within certain tolerances.

Introduction

Since the invention of laser in 1960 it has played a distinctive role in industry due to its unique properties of monochromaticity and coherence. Laser applications in industry include welding, cutting, drilling, surface treatment and inspection. The most used types are CO_2 and Nd:YAG lasers. Although metal cutting application is widely used, it is still dominantly confined to cutting of uniform thickness material even if the existence of many applications that need cutting of variable thickness. These applications can be categorized into two classes, *viz.* cases where the quality of cut is not important, and where it is of critical importance. In the former class we typically find civil engineering and nuclear decommissioning and decontamination projects, where the *e.g.* pipes, construction beams, and metal vessels have to be cut. This paper addresses the second class of problem where a consistent, standardized quality of cut has to be maintained for more user friendly workpieces, such as steel sheets. Table 1 gives the tolerances on thickness of the cold rolled low carbon steel according to the British standards BS EN 10131:1991, [1]. The fact that nominally uniform thickness sheet are produced within certain tolerances, means that the operator is dealing with material of variable thickness, which causes variation in cut quality. Where very tight tolerances are required, this could become an untenable problem, [2].

Nearly all the reported laser cutting research has been carried out using uniform thickness materials. The early work done by Gonsalves and Duley in 1970s [3, 4] shows that the kerf width decreases with increasing cutting speed, while it increases with an increase of laser power, and that the maximum cutting speed increases with laser power and decreases with sheet thickness. They also showed that using oxygen as an assist gas will increase the maximum (critical) cutting speed due to the exothermic chemical reaction in the cutting zone. Here the cutting speed first increases with an increase in oxygen flow rate then decreases because of the cooling of the cutting zone due to the heat transfer to the impinging gas. There are many other studies that strongly agree with these findings. [5-9].

Table 1: Tolerances on thickness of low carbon cold rolled steel sheets (all dimensions in mm).

Normal thickness	Normal tolerances for a nominal width of :		
	≤1200	>1200 to ≤1500	>1500
≥0.35 to ≤0.40	±0.04	±0.05	----
>0.40 to ≤0.60	±0.05	±0.06	±0.07
>0.60 to ≤0.80	±0.06	±0.7	±0.08
>0.80 to ≤1.00	±0.07	±0.8	±0.09
>1.00 to ≤1.20	±0.08	±0.9	±0.10
>1.20 to ≤1.60	±0.10	±0.11	±0.11
>1.60 to ≤2.00	±0.12	±0.13	±0.13
>2.00 to ≤2.50	±0.14	±0.15	±0.15
>2.50 to ≤3.00	±0.16	±0.17	±0.17

The findings of Gonsalves and Duley [3, 4] which show that the kerf width decreases with an increase of workpiece thickness contradict those of Karatas *et al.* [10] which report that the kerf width increases with an increase of workpiece thickness. Karatas *et al.* concluded that laser beam waist position has a significant effect upon the kerf width; the minimum kerf width can be obtained for thin metals when the focus setting becomes similar to the nominal focal length of the focus lens while for thick metal it can be obtained if the beam waist position moves into the workpiece.

Bagger and Olsen [11] studied the effect of laser power, focal length, assist gas pressure and cutting speed on the cut surface perpendicularity. They concluded that: an average power of 2.0 kW gives more perpendicular cut surface than both 1.5 and 2.5 kW, an assist gas pressure of 10 bar gives more perpendicular cut surface than 13 and 16 bar and a relatively high cutting speed gives more perpendicular cut surface than a low cutting speed.

The aim of this work is to quantify the effect of workpiece thickness variation upon the characteristic values of the quality of the cut surface. This is a first step in determining the viability of cutting non-uniform thickness metals by laser with the same cutting parameters within certain limits of thickness variation, and to assess the problems involved with non-uniform thickness workpieces if we go outside these limits. The ultimate aim is then to find ways of solving these difficulties.

According to the British standards of thermal cutting BS EN ISO 9013:2002 [12] the characteristic values of the quality of the cut surface are: perpendicularity (u) which is the distance between two parallel straight lines between which the cut surface profile is inscribed, Figure 1 [12]; surface roughness; and the occurrence of dross or melt drops on the lower edge of the cut. In this study the dross existence, kerf width, surface roughness R_a, Figure 2 [13]., perpendicularity, and striation height are investigated.

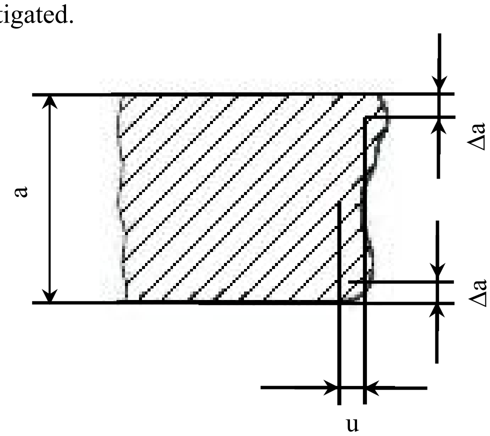
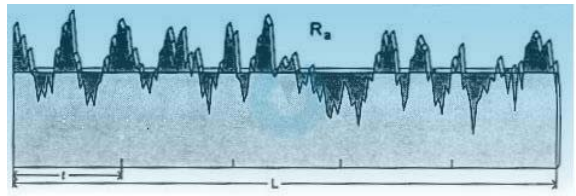


Figure 1. Cut surface perpendicularity. [12]



$$R_a = \frac{1}{L}\int_0^L |r(x)|\,\mathrm{d}x$$

Figure 2. Cut surface profile mean height. [13]

Experimental Procedures

The experiments were done on as-received EN43 annealed mild steel sheets sample stepped down from 3 mm to 2 mm, by steps of 0.25 mm, as shown in Figure 3. The samples were cut using both CO_2 and Nd:YAG lasers with equivalent cutting parameters and in four different cutting arrangements: thin-to-thick from the flat side; thick-to-thin from the flat side; thin-to-thick from the stepped side; and thick-to-thin from the stepped side, Figure 4. In all cases oxygen was used as an assist gas.

The first group of experiments was performed using a Rofin-Sinar 1 kW CO_2 laser with maximum laser power of 1200 W. It is coupled to a UNIMATIC CNC x-y table through a beam delivery system and a laser processing head. A 750 W laser beam was focused using a 127 mm (5") focal length lens and a simple conical cutting nozzle that had an exit diameter of 1 mm, using a nozzle-workpiece standoff distance of 1 mm. The cutting speed was 25 mm/sec and oxygen cylinder output pressure was 5 bar.

The second group of experiments was carried out using a fiber delivered Nd:YAG laser, with 600 µm core diameter fiber. The Scorpion Nd:YAG laser machine used has the following specifications: average laser power range 0-400 W; peak laser power range 0-7 kW; laser energy per pulse range 0-70 J; pulse frequency range single shot to 1 kHz; laser pulse width range 0.3 - 10 ms; and wavelength 1064 nm. The laser beam was focused using a 160 mm focal length lens and a simple conical cutting nozzle with an exit diameter of 1 mm was used, with a nozzle-workpiece standoff distance of 1 mm. The following cutting parameters were used: laser average power 360 W, peak power 1.2 kW, pulse frequency 75 Hz, pulse width 4 msec, cutting speed 15 mm/sec and oxygen cylinder output pressure 5 bar.

The kerf width and striation wavelength were measured using optical microscopy, while the surface roughness and perpendicularity were measured using a laser surface profile scanning system which was developed in-house by LPRC, Manchester University.

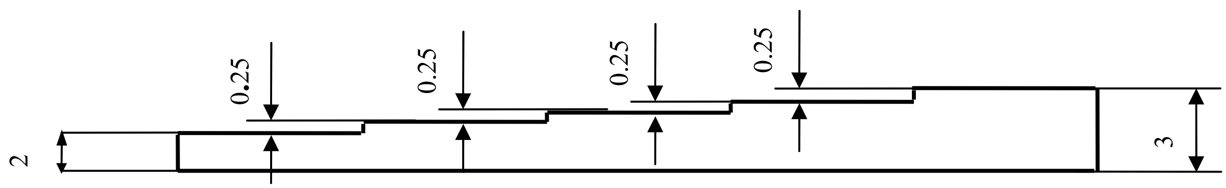


Figure 3. Dimensions of the used workpiece.

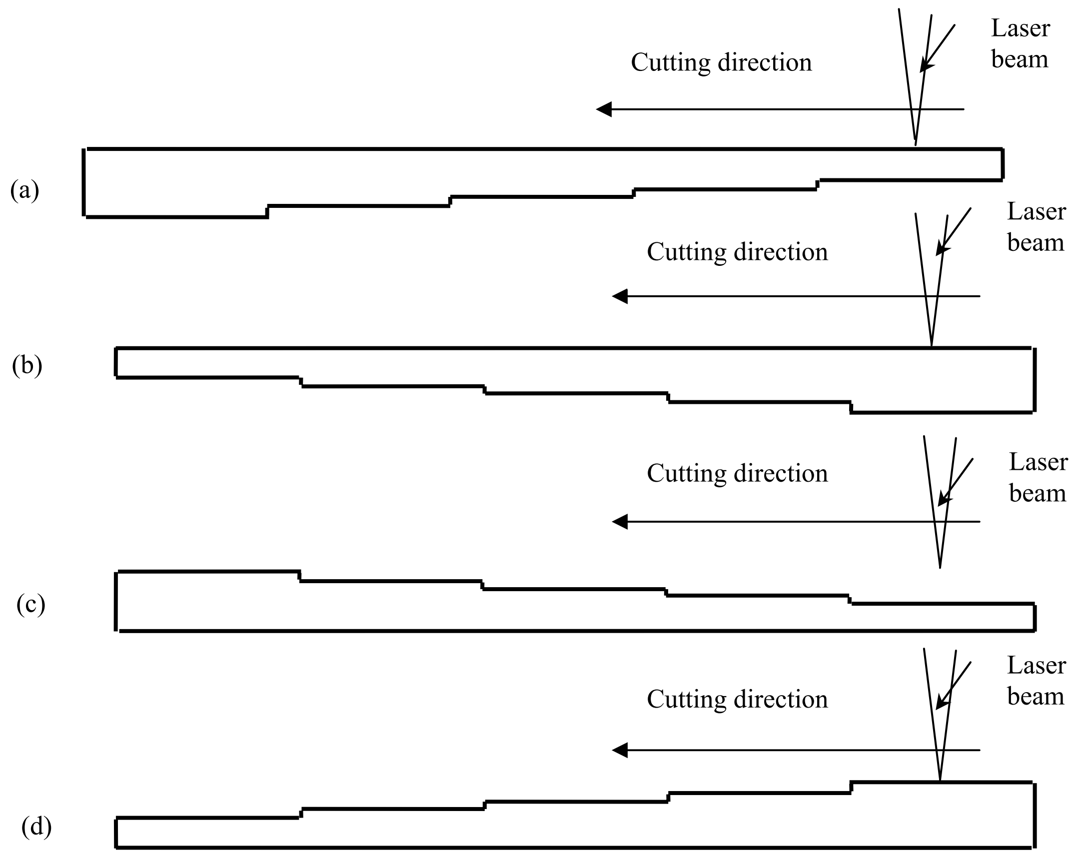


Figure 4. A schematic drawing showing the four cutting directions in the stepped mild steel sample (the diamensions are equivalent to Figure 1): a) Experiment 1; b) Experiment 2; c) Experiment 3; and d) Experiment 4.

Results and discussion

The experiments shows that when cutting a stepped sample with a CO_2 laser in any direction with its flat surface facing the laser beam we can get a nearly clean cut without dross attachment, Figure 5 (a, b) and Figure 6 (a, b). When the cut was done with the laser beam facing the stepped surface, with the focal plane on the highest surface, we obtained a massive dross attachment to the bottom edges and surrounding area in the 2.0 and 2.25 mm sections as the cut goes from thin to thick, Figure 5 (c) and Figure 6 (c). If the cut direction is reversed we get massive dross attachment at the 2.0 mm, 2.25 mm, and 2.5 mm sections and very little at the 2.75 mm section, Figure 5 (d) and Figure 6 (d). The results obtained cutting the same samples using the Nd:YAG laser display a few differences compared to the CO_2 results.

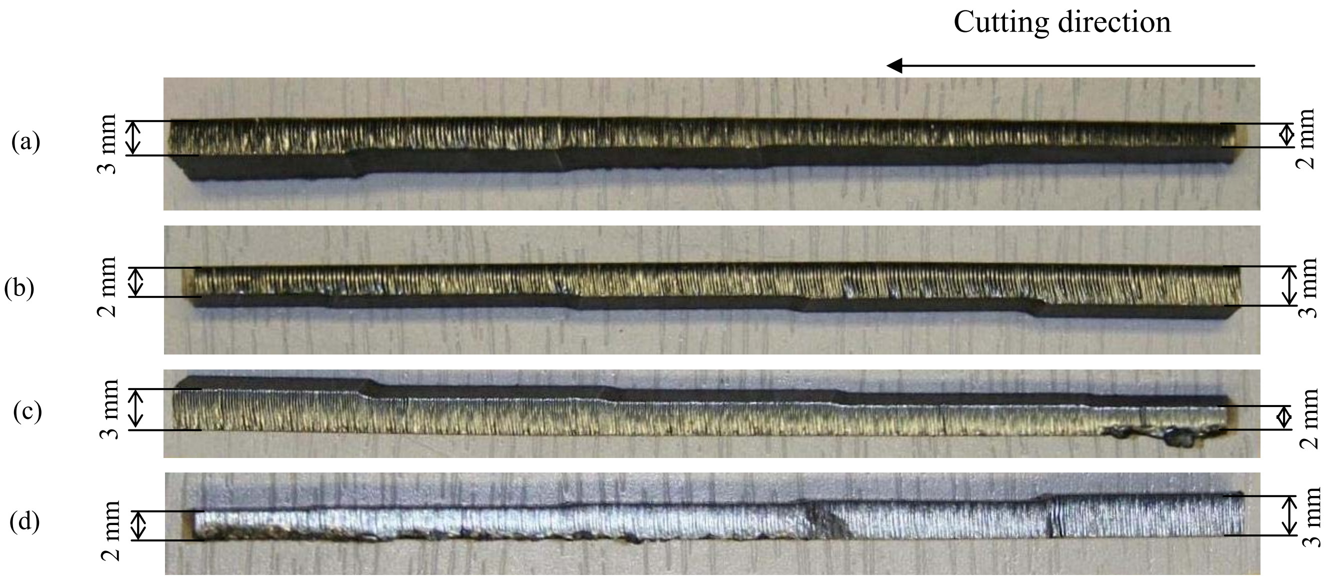


Figure 5. Cut surface of the four experiments were done using CO_2 laser: a) Experiment 1; b) Experiment 2; c) Experiment 3; and d) Experiment 4.

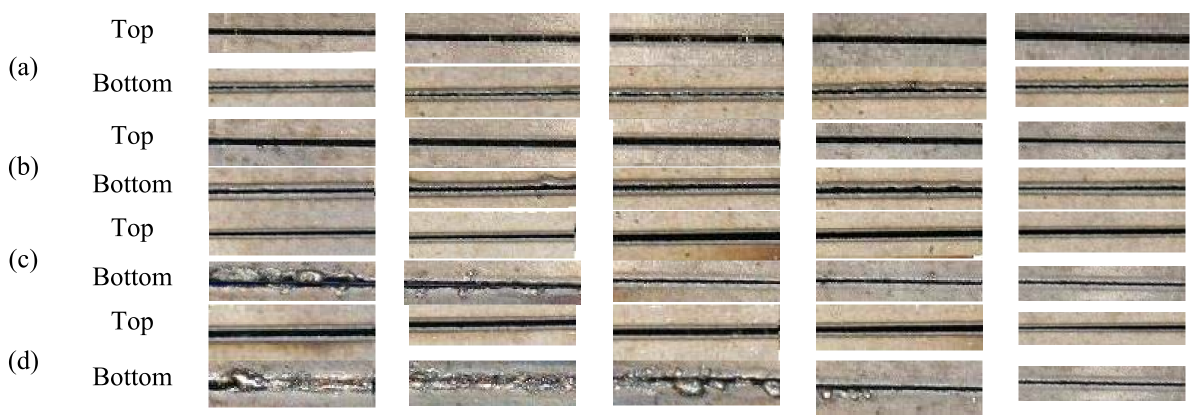


Figure 6. top and bottom view of the cut kerf when CO_2 laser cutting: a) Experiment 1; b) Experiment 2; c) Experiment 3; and d) Experiment 4.

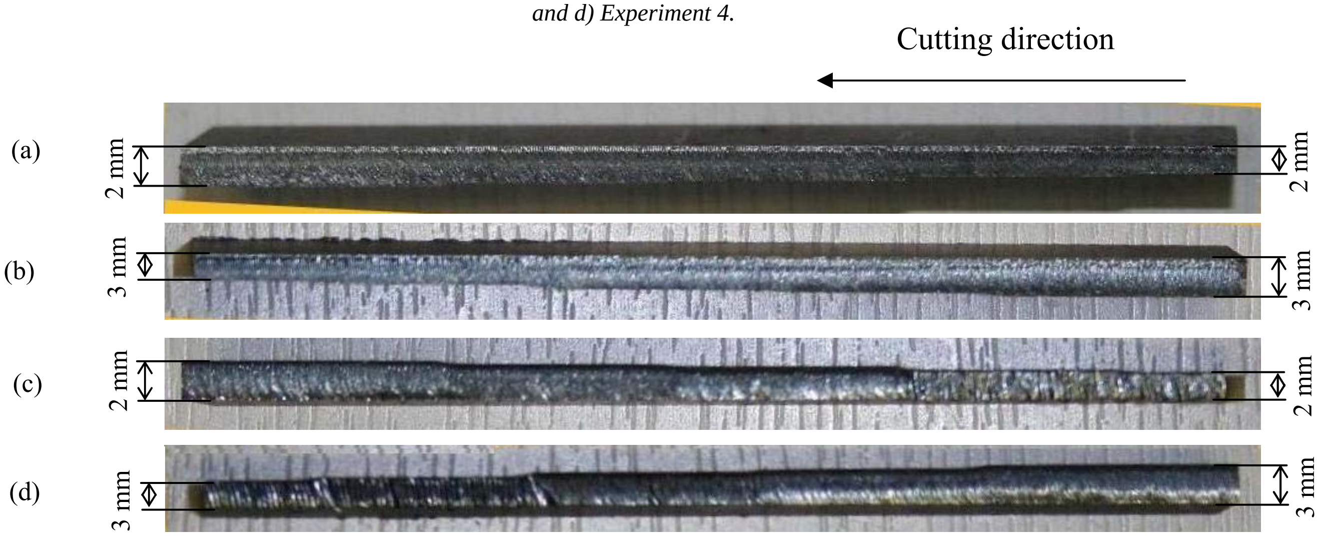


Figure 7. Cut surface of the four experiments were done using Nd:YAG laser: a) Experiment 1; b) Experiment 2; c) Experiment 3; and d) Experiment 4.

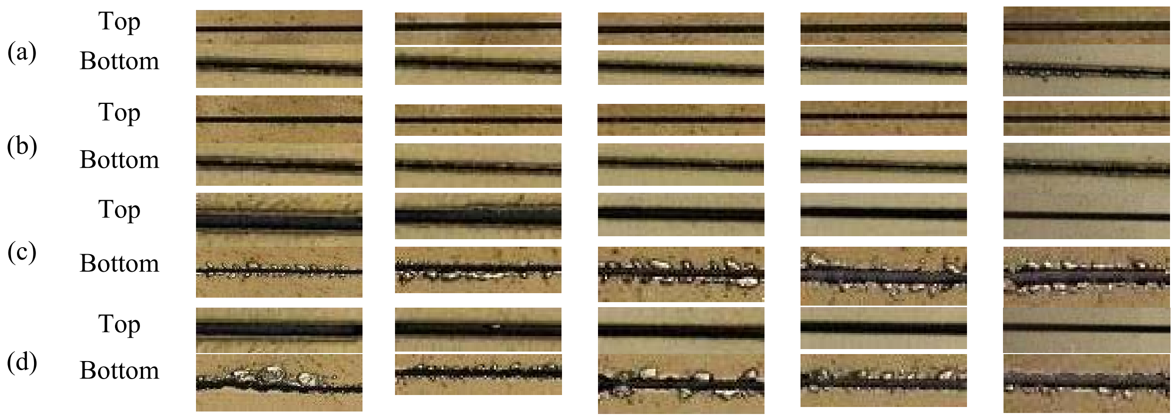


Figure 8. Top and bottom view of the cut kerf when Nd:YAG laser cutting: a) Experiment 1; b) Experiment 2; c) Experiment 3; and d) Experiment 4.

When cutting from the flat side, there is dross in the 3 mm section only, Figure 7 (a, b) and Figure 8 (a, b) while the CO_2 here cuts without dross formation. When cutting form the stepped surface, dross is present in all sections, Figure 7 (c, d) and Figure 8 (c, d).

Figure 9 and Figure 10 represent the experimental results of the kerf width, for both lasers, which show that the kerf width increases with increased workpiece thickness, when cutting from both direction and the laser beam facing the flat surface. This is because the increase of the amount of molten metal to be removed from the kerf, due to the increase in thickness, and hence the molten metal velocity decreases, so the time required to remove this molten metal from thick sections is long compared to thin one. Therefore the more heat will transfer to the side walls leading to the increase of molten metal. Moreover the exothermic reaction duration increases leading to more heat generation. The thermal erosion in the kerf increases hence with increase in workpiece thickness, consequently the kerf width increases with the increase of workpiece thickness. In the case of laser beam facing the stepped surface, with the focal plane fixed to the highest surface, the kerf width is more or less unchanging. This is may be due to the interaction between the effects of thickness change, laser spot size change, and assist-gas divergence.

Cutting of the stepped sample in all four cases using the CO_2 laser and in the first two cases using Nd:YAG laser shows improvement of the cut surface roughness as the workpiece thickness decreases, Figure 11 and Figure 12. This is because resolidification of the molten material on the side walls most likely occurs at the thicker sections. For the third and fourth experiments with Nd:YAG laser the cut at the 2.0 and 2.25 mm section the quality was too poor for the trend line to be considered meaningful.

The same is true for surface roughness; cutting of the stepped sample in all four cases using the CO_2 laser and in the first two cases using Nd:YAG laser shows improvement of the cut surface perpendicularity as the workpiece thickness decreases, Figure 13 and Figure 14.

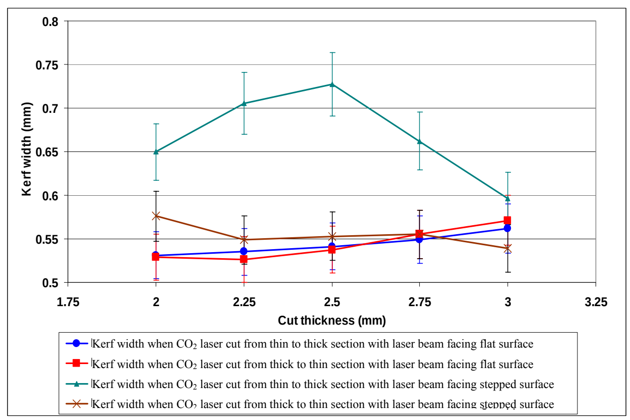


Figure 9. Effect of workpiece thickness variation upon the cut kerf width when CO_2 laser cutting.

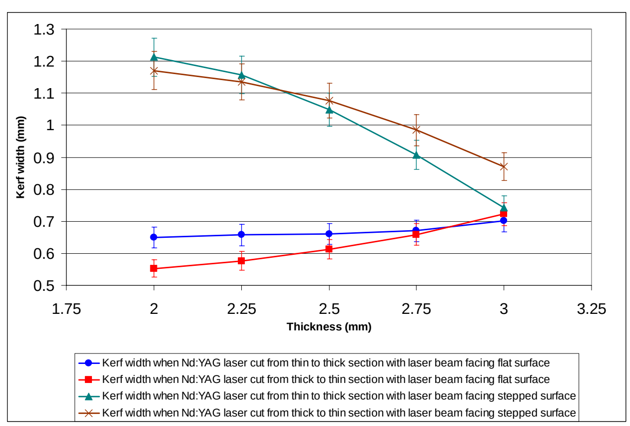


Figure 10. Effect of workpiece thickness variation upon the cut kerf width when Nd:YAG laser cutting.

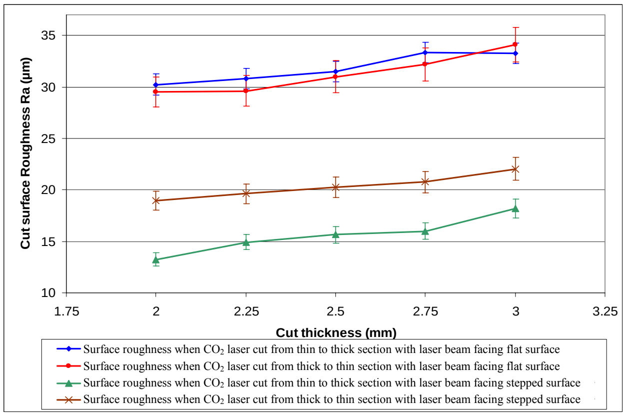


Figure 11. Effect of workpiece thickness variation upon the cut surface roughness when CO_2 laser cutting.

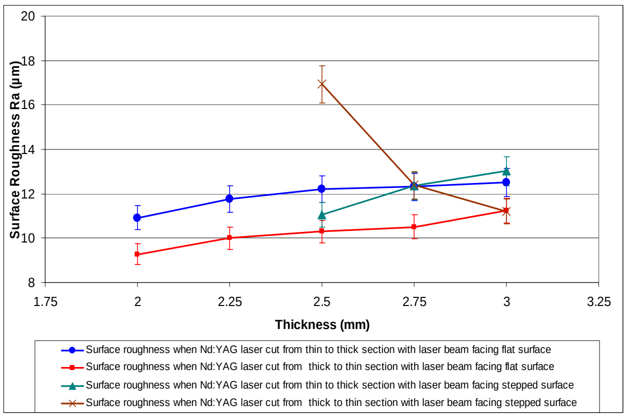


Figure 12. Effect of workpiece thickness variation upon the cut surface roughness when Nd:YAG laser cutting.

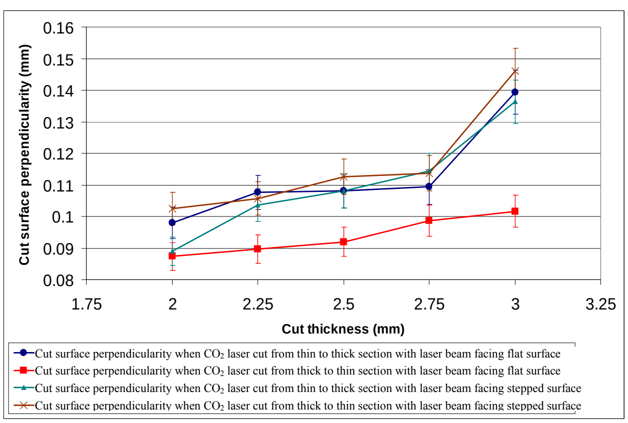


Figure 13. Effect of workpiece thickness variation upon the cut surface perpendicularity when CO_2 laser cutting.

The striation height seems to be proportional to the workpiece thickness, which reflects an improvement of the cut surface quality when the workpiece thickness becomes less, Figure 15 and Figure 16.

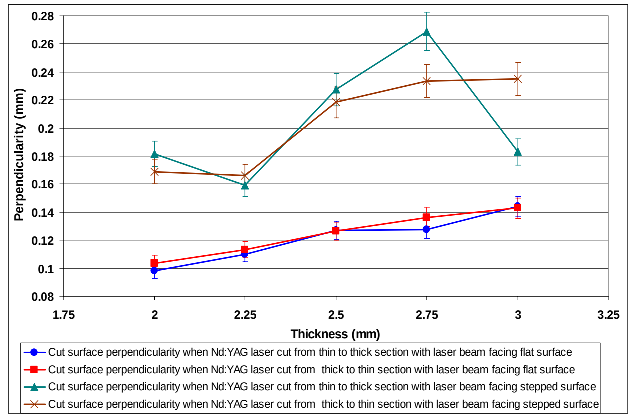


Figure 14. Effect of workpiece thickness variation upon the cut surface perpendicularity when Nd:YAG laser cutting.

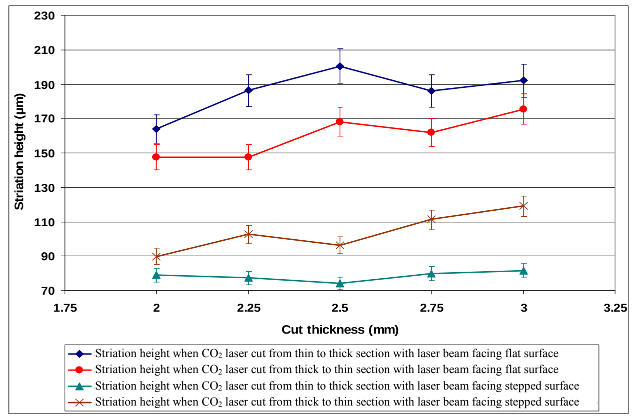


Figure 15. Effect of workpiece thickness variation upon the cut surface striation height when CO_2 laser cutting.

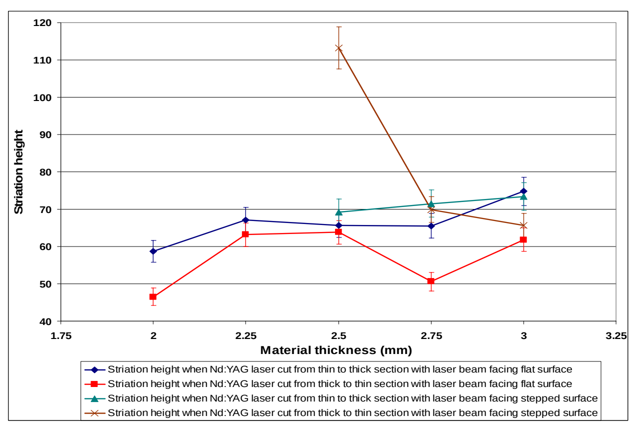


Figure 16. Effect of workpiece thickness variation upon the cut surface striation height when Nd:YAG laser cutting.

While standards for kerf width are not specified, those for both the cut surface perpendicularity and cut surface roughness are given in British standards document BS EN ISO 9013:2002 [12]. Tables 2 and 3 give these values and show that these tolerances are divided into distinct quality ranges. For the variation in workpiece thickness in the experiments presented here, it is clear that the Range 2 can be obtained for both perpendicularity and striation roughness.

Table 2. Perpendicularity tolerance.

Range	Perpendicularity tolerance (u), mm
1	0.05+0.003a*
2	0.15+0.007a
3	0.4+0.01a
4	0.8+0.02a
5	1.2+0.035a

* a is the sheet thickness in mm

Table 3. Mean height of the profile.

Range	Mean height of the profile, μm
1	10+0.6a*
2	40+0.8a
3	70+1.2a
4	110+1.8a

* a is the sheet thickness in

Conclusions

Cutting of non-uniform thickness metal sheet, with a thickness variation from +0 to -33%, with the stand-off distance between the cutting head and the workpiece kept fixed, can be done within British standards tolerance Range 2 for both perpendicularity and roughness. This applies to both CO_2 and Nd:YAG lasers. This variation is worse than the manufacturing tolerances of the *e.g.* cold rolled low carbon steel sheets, Table 1, which is of the order of ±10%. Cutting mild steel using an Nd:YAG laser is better than a CO_2 laser from the point of view of roughness. The variation in kerf width presents a more difficult problem. The lowest variation in kerf width was recorded using the CO_2 laser, cutting from thin to thick section with the beam facing the flat side of the workpiece; the thick section displaying a ~30 μm wider kerf. The worst case was obtained with the Nd:YAG, cutting from thin to thick, with the beam facing the stepped side. Here the thin section is wider by ~500 μm.

References

1. Institution, B.S., Cold-rooled uncoated low carbon and high yield strength steel flat products for cold forming-Tolerances on dimensions and shape. 1991. BS EN 10131:1991.

2. MacFarlane, J., Greatest Cock-up. The Industrial Laser User, 2005(38): p. 4.

3. Gonsalves, J.N. and W.W. Duley, Cutting Thin Metal Sheets with the CW CO_2 Laser. Journal of Applied Physics, 1972. v43(n 11): p. 4684-4687.

4. Duley, W.W. and J.N. Gonsalves, CO_2 Laser cutting of Thin Metal Sheets with Gas Jet Assist. Optics and Laser technology, 1974. v6(n2): p. 78-81.

5. Uslan, I., CO_2 laser cutting: Kerf width variation during cutting. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2005. 219(8): p. 571-577.

6. Kaplan, A.F.H., An Analytical Model of Metal Cutting with a Laser Beam. Journal of Applied Physics, 1996. v95(n5): p. 2198-2208.

7. Yilbas, B.S., The analysis of CO_2 laser cutting. Proceedings of the institution of mechanical engineers, Part B: Journal of engineering manufacture, 1997. v 211(n B3): p. 223-32.

8. Wang, J., An Experimental Analysis and Optimization of the CO_2 Laser Cutting Process for Metallic Coated Sheet Steels. International Journal of Advanced Manufacturing Technology, 2000. v16(n5): p. 334-340.

9. Rajaram, N., J. Sheikh, and S.H. Cheraghi, CO_2 Lasers Cut Quality of 4130 Steel. International Journal of Machine Tool and Manufacture, 2003. v43: p. 351-358.

10. Karatas, C., Keles, O., Uslan, I. and Usta, Y., Laser cutting of steel sheets: Influence of workpiece thickness and beam waist position on kerf size and stria formation. Journal of Materials Processing Technology, 2006. 172(1): p. 22-29.

11. Bagger, C. and F.O. Olsen, Pulsed mode laser cutting of sheets for tailored blanks. Journal of Materials Processing Technology, 2001. 115(1): p. 131-135.

12. Institution, B.S., Thermal Cutting - classification of Thermal Cuts - Geometrical product specification and quality tolerances. British Standard, 2002. BS EN ISO 9013:2002.

13. Surface metrology guide. http://www.predev.com/smg/index.html.

Meet the Authors

Mohamed Sobih is a PhD student in Laser Processing Research Centre, School of MACE, University of Manchester. He did his undergraduate studies at MTC, Egypt.

Philip Crouse is a Research Fellow at the Laser Processing Research Centre, the University of Manchester.

Lin Li is the Director of the Laser Processing Research Centre at The University of Manchester, is author/co-author of over 300 publications, one book and inventor and co-inventor of 30 patents on laser processing