Appl. Phys. A 90, 171–174 (2008)
DOI: 10.1007/s00339-007-4247-7

**Applied Physics A**
**Materials Science & Processing**

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# Striation-free fibre laser cutting of mild steel sheets

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**Received: 17 July 2007/Accepted: 19 July 2007**

**ABSTRACT** High-power laser cutting is extensively used in many industrial applications. An important weakness of this process is the formation of striations, i.e. regular lines on the cut surface, which lowers the quality of the surfaces produced. The elimination of striation formation is thus of considerable importance, since it could open a variety of novel high-precision applications. This study presents the initial results of a laser cutting study using a 1 kW single-mode fibre laser, a relative newcomer in the field of laser metal cutting. Striation-free laser cuts are demonstrated when cutting 1 mm thick mild steel sheets.

**PACS** 42.62.Cf; 81.05.Bx; 81.20.Wk; 42.55.Wd; 89.20.Bb

## 1 Introduction

Laser cutting of sheet-metal profiles has taken its place as one of the most frequently used industrial laser applications, due to its distinguishing advantages, viz. high processing speed, low running cost, and ease of automation [1–3]. The technology also has some drawbacks, among them the formation of striations on the cut surface. Striations are relatively regular straight lines with a slight inclination from the laser beam axis. Although striations strongly affect the cut surface quality and have been widely studied, a fully consistent explanation of the dynamic behaviour of the entire system, which leads to understanding the striation formation, is still not available [4–12]. The explanation of e.g. Ivarson et al. [11] is fairly typical. They demonstrated that the striation formation mechanism in the case of oxygen-laser cutting of mild steel is *not* one of the following: resolidification, gas instability, melt boiling, optical effects or time-based fluctuations of the power input. They hold that the mechanism, when oxygen is used, is cyclic in nature. This cycle consists of three stages: ignition, lateral combustion, and extinction. The most likely cause of striation formation is considered to be the cyclic variation in the driving force of the oxidation reaction, the viscosity, and the surface tension of the molten metal [11]. Unlike the postulates of Arata et al. [5], Powell [12] and Chen et al. [13], Ivarson et al. are unambiguous that no high-speed striation-free cutting regime exists. Laser cutting using inert gases also produces striations, however, but oxygen-assisted laser cutting is preferred because of its superior surface finish and higher cutting speed [14].

The continuous-wave (cw) $CO_2$ laser has most commonly been used for metal cutting over the last two decades and more. A recent newcomer to the industry is the fibre laser. The advantages of fibre laser over the $CO_2$ laser include: a small physical size, high stability of power output, high brightness and good beam quality, a narrow focus, significantly higher cutting speeds, smaller kerf widths, and higher beam absorption in metals due to its shorter wavelength [15–17]. This communication reports results on the quality of the cut surfaces using a 1 kW single-mode fibre laser. Striation-free surfaces were demonstrated for the first time when cutting 1 mm thick mild steel sheets, with average roughness ($R_\mathrm{a}$) values of less than 1 μm.

## 2 Experimental procedures

The experiments were performed on as-received 1 mm thickness sheets of EN43 annealed mild steel. Experiments were conducted using a continuous-wave IPG YLR-1000-SM ytterbium single-mode fibre laser with the following specifications: 1 kW maximum output power, 1.07 μm wavelength, 14 μm output fibre core diameter, mode $\mathrm{TEM}_{00}$ and $M^2 = 1.1$. The laser beam was focused using a 7.5 inch focal length lens, which achieved a beam diameter of nominally 50 μm. General striation features and heat-affected zones (HAZ) were examined using optical microscopy, while surface roughness was inspected using a Veeco–Wyko NT1100 optical profiling system.

## 3 Results

The experimental conditions used for cutting the 1 mm thick mild steel are given in Table 1. Figure 1 summarizes the variation of surface roughness as a function of cutting speed, at power values of 600, 800 and 1000 W. It shows that the surface roughness decreases as the cutting speed increases until an optimum cutting speed is reached. Beyond this the

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| Parameter | Value |
|---|---|
| Laser power | 600, 800, 1000 W |
| Measured focused beam diameter (approx.) | 73 µm |
| Focal plane position | 11 mm above the top surface |
| Measured beam diameter at this level (approx.) | 300 µm |
| Irradiance | 8.5 to 14 × $10^9$ W $m^{-2}$ |
| Assist gas type | $O_2$ |
| Assist gas pressure | 2 bar |
| Cutting speed | 30 mm $s^{-1}$ – variable maximum |
| Nozzle diameter | 1.5 mm |
| Stand off distance | 1 mm |

**TABLE 1** Cutting conditions for mild steel sheets

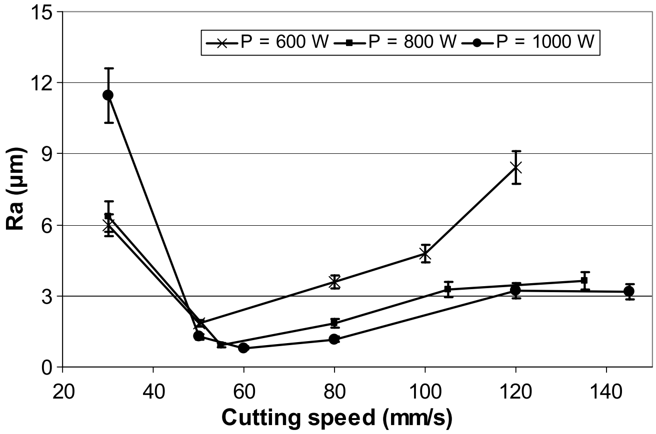

**FIGURE 1** The effect of cutting speed and power on surface roughness

surface roughness gradually increases again. This effect becomes more pronounced at higher powers.

Figures 2 and 3 show details of the cut quality at a constant power of 800 W. At this power there is a clear uniform striation pattern up to a speed of 35 mm $s^{-1}$ (Fig. 2a), which is similar to $CO_2$ laser cutting. As the speed increases up to roughly 40 mm $s^{-1}$ the striations gradually become wider and shallower. Beyond this the surface became almost flat, and the striations disappeared at around 50 mm $s^{-1}$. Here the surface is flat and generally free of striations, with only the slightest hint of grooving at the bottom edge, as shown in Fig. 2b. Above 60 mm $s^{-1}$ the cut surface is less homogeneous, with a relatively good surface at the top, but with some minor striations beginning to appear at the bottom (Fig. 2c). The striation frequency gradually increases and their initiation position moves upward until the maximum cutting speed of 135 mm $s^{-1}$ is reached. Figures 3a–c show interferometrically obtained surface profiles for 30, 55 and 80 mm $s^{-1}$, respectively, from which surface roughness was evaluated. The corresponding $R_a$ values are 5.94, 0.88 and 1.99 µm.

The kerf profile of the striation-free surface was observed to have a more regular profile, albeit still with a small taper. The heat-affected zones (HAZ) corresponding to low and optimal cutting speeds were examined after polishing and etching (Fig. 4). As is expected from its shorter laser interaction time, the striation-free cut has a less pronounced HAZ, about 10 µm shallower than that cut with striations.

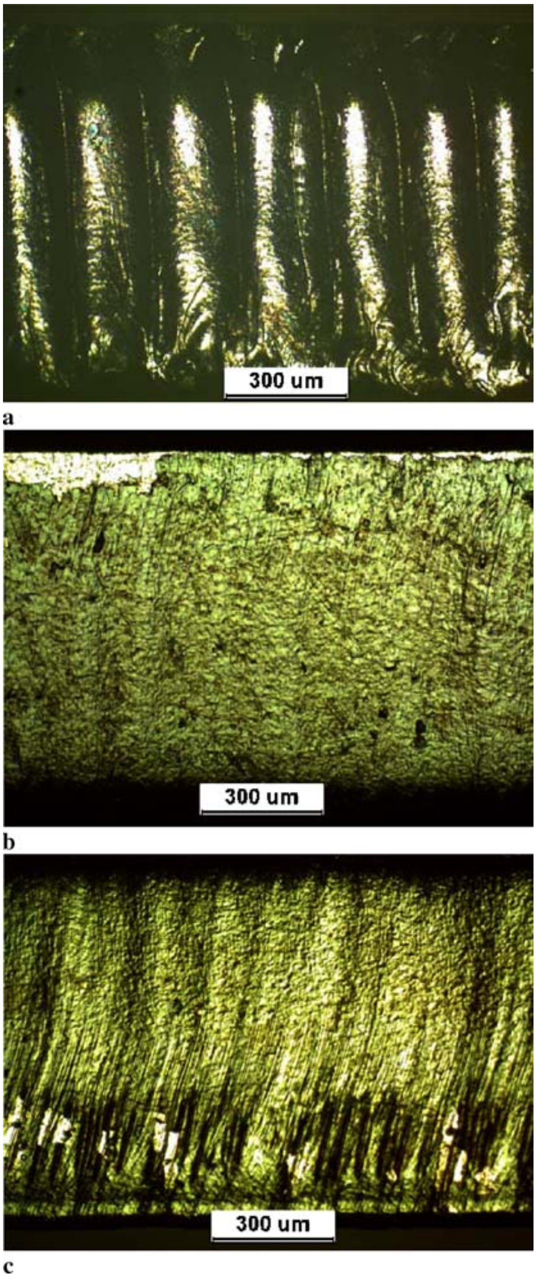

**FIGURE 2** Cut surface of mild steel sheet cut using fibre laser with cutting speed: (**a**) 30 mm $s^{-1}$, (**b**) 55 mm $s^{-1}$, and (**c**) 80 mm $s^{-1}$

## 4 Discussion

The instability of the oxygen-assisted laser cutting process of mild steel arises because of the fluctuation of the temperature during the cutting process [13]. The source of this temperature fluctuation is the behaviour of the molten layer, which in general is the metal oxide. As this oxide layer grows, the oxidation process, which is the dominant source of energy for $CO_2$ laser cutting, slows down because of its high resistance to oxygen diffusion, and the temperature starts to drop. Once the oxide layer has grown to a certain thickness, it is ejected down the kerf exposing a cleaner metal surface. The temperature again quickly increases due to the increased availability of oxygen and the

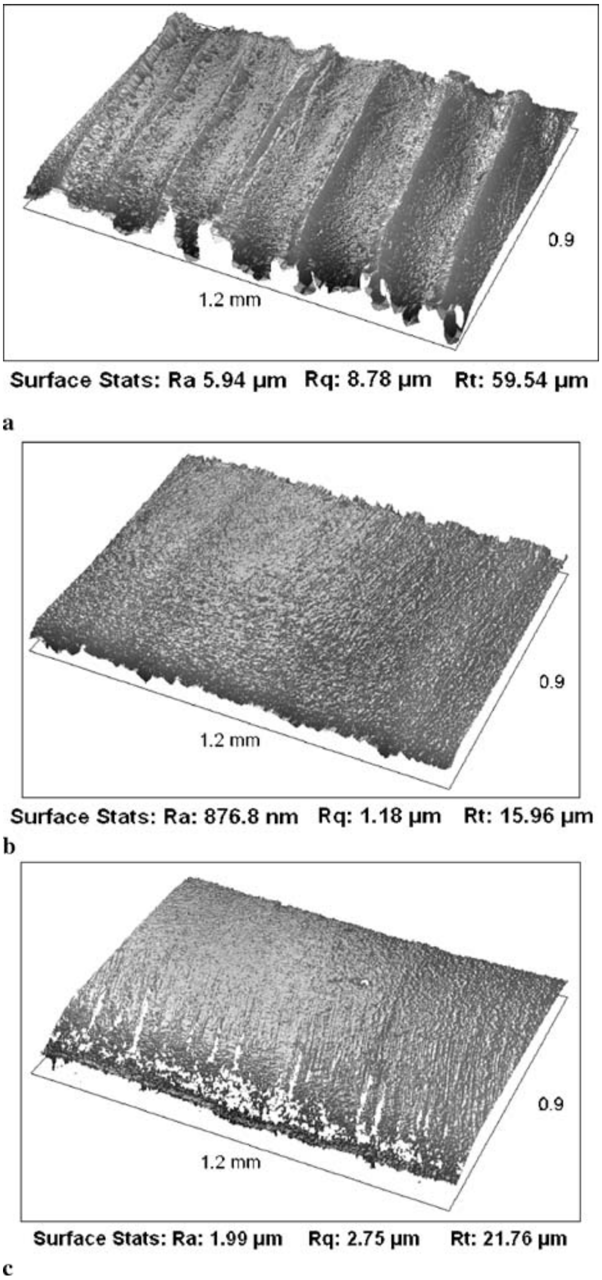

**FIGURE 3** Surface profile of mild steel cut using fibre laser at speed: (**a**) 30 mm $s^{-1}$, (**b**) 55 mm $s^{-1}$, and (**c**) 80 mm $s^{-1}$

resultant reaction energy. This instability in the behaviour of the oxide layer was postulated to be the cause of striation formation for oxygen-assisted laser cutting. This is valid below a critical speed, roughly 25 mm $s^{-1}$, beyond which the laser power becomes the major heat source and the variation in the laser beam is postulated to lead to the formation of striations [18, 19].

In this study, using a fibre laser with excellent beam quality, we appear to have easily reached a steady-state regime leading to striation-free cuts at more than double the abovementioned critical speed, i.e. at 50–60 mm $s^{-1}$. Our postulated reason for this phenomenon is that the low $M^2$ yields high irradiance values (8.5 to $14 \times 10^9$ W $m^{-2}$) at this power level, and a beam divergence substantially lower than typical $CO_2$ metal-cutting lasers. This allows more uniform irradiance down the kerf, higher cutting speeds at this power level, and hence lower laser material interaction times of 5 ms and less. This is short enough to largely prevent diffusion-controlled oxidation and the recession of the combustion front, and their concomitant cyclic effects. Below this optimum cutting speed, the interaction time is longer, and oxidative striation formation dominates. At speeds higher than optimum, the laser energy is not sufficient to achieve the steady state. Here undoubtedly the origin of the striations forming towards the bottom of the kerf is not cyclic oxidation, but rather flow phenomena resulting from lower melt viscosity and higher surface tension, causing flow instabilities and flow rippling.

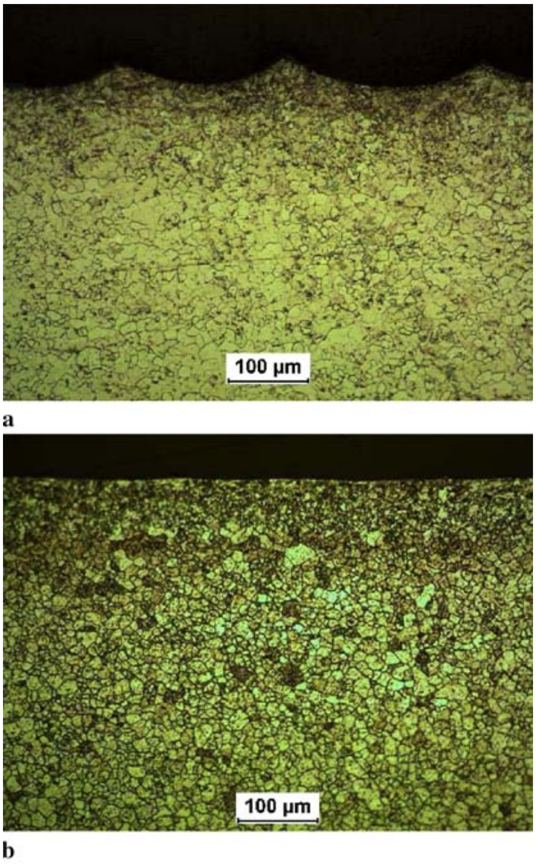

**FIGURE 4** Side view of the cut surface showing the microstructure of the HAZ and the bulk material when using fibre laser at speed: (**a**) 30 mm $s^{-1}$ and (**b**) 55 mm $s^{-1}$

## 5 Conclusion

The high irradiance resulting from the excellent beam quality of single-mode, a high-power fibre laser opens metal-cutting regimes previously unobtainable. The existence of a steady-state, striation-free cutting parameter window for the case of mild steel has been demonstrated experimentally. This finding can open the door to the use of laser cutting in many novel applications.

**ACKNOWLEDGEMENTS** Drs. Marc Schmidt, David Whitehead and Amin Abdolvand are thanked for experimental guidance and useful discussions. The UK Engineering and Physical Sciences Research Council is acknowledged for grant EP/C013352/1, which allowed the purchase of the single-mode, high-power fibre laser used here. The work presented in this paper was patent by The University of Manchester Intellectual Property Limited (UMIP), Application No. GB0713260.8; Filed 9th July 2007 and application No. GB0719287.5; Filed 2nd October 2007.

## REFERENCES

1 P. Di Pietro, Y.L. Yao, Int. J. Mach. Tools Manuf. **35**, 993 (1995)
2 B.S. Yilbas, Heat Mass Transf. **32**, 175 (1997)
3 P.S. Sheng, V.S. Joshi, J. Mater. Process. Technol. **53**, 879 (1995)
4 D. Schuocker, Appl. Phys. B **40**, 9 (1986)
5 Y. Arata, H. Maruo, I. Miyamoto, S. Takeuchi, Trans. Japan. Welding Institute **9**, 15 (1979)
6 M. Vicanek, G. Simon, H.M. Urbassek, I. Decker, J. Phys. D Appl. Phys. **20**, 140 (1987)
7 P. Di Pietro, Y.L. Yao, Int. J. Mach. Tools Manuf. **34**, 225 (1994)
8 T. Fushimi, H. Horisawa, S. Yamaguchi, N. Yasunaga, T. Fujioka, Proc. SPIE **3888**, 90 (2000)
9 T. Fushimi, H. Nakajima, H. Horisawa, S. Yamaguchi, N. Yasunaga, T. Fujioka, Proc. SPIE **4088**, 284 (2000)
10 C. Karatas, O. Keles, I. Uslan, Y. Usta, J. Mater. Process. Technol. **172**, 22 (2006)
11 A. Ivarson, J. Powell, J. Kamalu, C. Magnusson, J. Mater. Process. Technol. **40**, 359 (1994)
12 J. Powell, $CO_2$ *Laser Cutting* (Springer, Berlin Heidelberg New York, 1993)
13 K. Chen, Y.L. Yao, V. Modi, Int. J. Adv. Manuf. Technol. **15**, 835 (1999)
14 J.F. Ready, *LIA Handbook of Laser Materials Processing* (Magnolia, Orlando, 2001)
15 W. Liu, W. Du, J. Liao, Proc. SPIE **5629**, 263 (2005)
16 K.F. Kleine, K.G. Watkins, Proc. SPIE **4974**, 184 (2003)
17 B. Shiner, Proc. SPIE **5706**, 60 (2005)
18 I. Decker, H. Heyn, H. Wohlfahrt, Proc. SPIE **2062**, 50 (1993)
19 A.F.H. Kaplan, O. Wangler, D. Schuocker, Lasers Eng. **6**, 103 (1997)