Fibre laser cutting of thin section mild steel; an explanation of the ‘striation free’ effect.

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Abstract

This paper presents the results of an experimental and theoretical investigation into the phenomenon of ‘striation free cutting’, which is a feature of fibre laser/oxygen cutting of thin section mild steel. The paper concludes that the creation of very low roughness edges is related to an optimisation of the cut front geometry when the cut front is inclined at angles close to the Brewster angle for the laser – material combination.

Key words: Laser cutting, Mild steel, Fibre laser, Fiber laser, Brewster angle, Striations, Oxygen, CO₂ laser.

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1. Introduction

Oxygen assisted laser cutting of mild steel is a highly successful industrial profiling method which has been under continuous development since its invention in 1967 [1]. The cut edge produced by this technique has, until recently, always featured parallel grooves (striations) similar to those pictured in figure 1. However, in recent years, results have been published [2, 3] which show that the distinctive striation pattern is minimized under certain processing conditions if a fibre laser is used instead of the more traditional CO₂ or Nd:YAG lasers. Figure 2 presents a photograph of such a ‘striation free’ cut edge produced by fibre laser/oxygen cutting. This paper investigates the laser-oxygen-steel interaction which results in striation free cutting.

Figure 1. Typical cut edges produced by CO₂ laser/oxygen cutting. The cut edges are covered in parallel grooves known as striations (samples are 12mm and 3mm thick).

Figure 3 presents a schematic diagram of laser/oxygen cutting of mild steel. The laser beam is focussed down onto the mild steel surface through a nozzle which also provides a low pressure jet of oxygen. The laser heats up the mild steel until it ignites in the stream of oxygen. The ensuing exothermic chemical reaction is then held in a thermodynamic balance between the heating effects of the laser/oxidation reaction and the cooling effect of thermal losses to the surrounding steel sheet. Even if the laser input to the cut zone is constant, this dynamic balance involves regular fluctuations in the burning reaction which result in the striation pattern on the cut edge [4, 5].

Figure 2. Under the correct process parameters a very smooth mild steel cut edge can be produced by a fibre laser in conjunction with an oxygen jet. Parameters; 1mm mild steel cut at 5.5 m/min, oxygen supply gauge pressure; 2 Bar, fibre laser power; 1000W.

Previously published work [2, 3] has studied fibre laser cutting of mild steel and suggested that ‘striation free’ cutting is a consequence of boiling within the cut zone. Work by the present authors [6] has demonstrated that this is unlikely to be the case because the entire surface of the melt in the cut zone is covered in FeO, which cannot boil and which has no gas phase.

Figure 3. A schematic of laser-oxygen cutting of mild steel.

‘Striation free’ cut edges are produced over a specific range of cutting speeds for a particular laser parameter – material combination. Above or below this range the cut edge is considerably rougher as a result of a number of effects which will be discussed later in this paper. Changing the speed of laser/oxygen cutting brings about changes in melt temperature, viscosity and mass flow rates as well as gas dynamics, cut front geometry and laser absorptivity. The aim of this paper is to identify which of these variables play the dominant role in producing very low roughness cuts.

2. Experimental procedure

The laser used in this investigation was an IPG YLR-2000 multi-mode Ytterbium Fibre machine with a maximum power of 2000 W and a wavelength of ~ 1070 nm. The laser was used in its continuous wave (cw) mode with an approximately top hat beam intensity distribution. The focusing optics consisted of a Precitec YK52 cutting head with a collimation lens of 125mm focal length and a 120 mm focal length objective lens. The process fibre used was 200 microns

in diameter and the focussed spot size was calculated to be 192 μm . The processing parameters used in the experiment are shown in table 1.

Table 1: Experimental Parameters.

The cut surface topography was examined using a Talysurf stylus profilometer. On each cut surface three (15mm long) Talysurf traces were taken along the cut face at distances of 0.25mm from the top and bottom of the cut edge. In each case the three results were then averaged to give an upper cut edge roughness and a lower cut edge roughness.

3. Results and Discussion

3.1 Cut edge roughness results

Figure 4 demonstrates that the average surface roughness of the cut edge decreased to a minimum as the cutting speed was increased up to approximately 5.5m/min. At higher speeds the roughness rose again until the cutting process broke down at the maximum cutting speed of just over 8.0m/min.

Figure 4: The average Ra roughness measurements of the cut edges as a function of speed.

Measurements were taken 0.25mm from the top or bottom of the cut face. Each point represents the average of three measurements, each 15mm long.

Figure 5: Cut edge at various speeds a) 2.0 m/min lower $R_a=3.0\mu\text{m}$, b) 4.0 m/min lower $R_a=2.0\mu\text{m}$, c) 5.5 m/min lower $R_a=0.2\mu\text{m}$, d) 7.0 m/min lower $R_a=1.4\mu\text{m}$.

Figure 5 supports figure 4 by presenting low magnification photographs of the cut edges at various speeds. The reduction of surface roughness as the cut speed approaches 5.5m/min is quite clear. The 5.5m/min sample is typical of a 'striation free' cut, but closer examination (see fig 6) reveals that the striations have not entirely disappeared. In the context of this paper this is an important point, but in general engineering use the term 'striation free' still has some validity as the roughness is extremely low.

One important feature of figure 4 is the difference in the roughness trend close to the top of the cut edge and close to the bottom. The roughness measurements near the bottom of the cut edge reduce to a very low value and then rise again with further increases in cutting speed. The roughness near the top of the cut edge continues to fall until the maximum cutting speed is reached. This trend is typical of fibre laser/oxygen cutting of thin section mild steel. To explain these results we need to consider the various factors which could influence the roughness of the cut edge.

Figure 6: A higher magnification view of a 'striation free' cut edge showing the presence of microscopic striations on the top part of the cut surface at 5.5m/min.

3.2 Factors which can influence the cut edge roughness as a function of cutting speed.

During laser cutting, liquid flows out of the cut zone - and the flow behaviour is reflected in the patterns of solidified melt on the cut edges. Turbulent flow will be reflected in the frozen turbulence of a rough and rippled surface. The smoothest cut edge will be created by the steadiest flow conditions. The clearest way to explain the observation that these 'steadiest flow

conditions' exist at an intermediate cutting speed, is to describe how the flow conditions change at speeds higher or lower than this optimum.

At very low cutting speeds we know that the laser/oxygen/steel interaction consists of a cyclic burning reaction. The cut front is almost vertical in this case and is only illuminated by the leading edge of the laser beam, so most of the laser power travels straight through the cut zone without interacting with the material (see figure 7a). Thus, the heating of the melt is primarily the result of the oxidation reaction and surface temperatures in the cut zone are low (approx 1900K – [6]) compared to those reached at higher cut speeds. At these low temperatures the viscosity of the FeO/Fe melt is high (see fig 8).

In summary, at low cutting speeds, the cutting process involves the expulsion of a relatively high viscosity melt at a fluctuating mass flow rate. This situation gives us the rather rough cut edge shown in figure 5a.

As cutting speeds increase, the process attains a quasi steady state and melt is ejected as a continuous stream of sparks (see fig. 3). The temperature of the melt surface rises with cutting speed and thus the viscosity of the melt decreases [6].

Figure 7: Cut front-laser beam interaction geometries at; a) slow cutting speeds, (the cut front is an almost vertical, straight line of fluctuating position), b) moderate cutting speeds (the cut front is straight line inclined at θ), c) higher cutting speeds (the cut front can be approximated to upper

and lower lines inclined θ_U and θ_L), d) very high cutting speeds (the cut front becomes extended in the direction of cutting and the reflected beam interacts more with the lower part of cut front).

Figure 8: The relationship between viscosity and temperature for iron and FeO. The experimental curve for FeO has been (Arrhenius type) extrapolated above 1900K [4].

This might lead us to expect a gradual reduction in cut edge roughness as speeds increase. However, there are two factors that have a disturbing effect on the melt flow as we approach the maximum cutting speed;

1. The cut front geometry becomes curved or kinked at high speeds.

It was mentioned above that at very slow speeds the cut front inclination is approximately vertical and it is eroded by contact with the leading edge of the laser beam and the oxygen jet. As the cutting speed is increased, the molten material cannot flow out of the cut zone quickly enough to allow the cut front to remain vertical. Thus, there will be a horizontal lag between the top and bottom of the cut front ('L' in figure 7). At intermediate speeds the cross section of the cut front can be approximated to an inclined straight line (see figs 5c and 7b). At higher speeds however, the lag between the top and bottom of the cut front increases and the profile of the cut front becomes curved or kinked (see fig 7c). This curvature or kink indicates a directional change on the melt part way down the cut front and the resultant melt deceleration increases turbulence and subsequent cut edge roughness (see fig 5d).

2. The melt thickness on the cut front increases with cutting speed.

In laser cutting, an increase in speed has only a minor effect on the kerf width and so the mass flow rate from the cut front is approximately proportional to cut speed. If, for example, the cutting speed is doubled then the mass flow rate will be approximately doubled. There are two mechanisms by which the flow rate can increase, either through higher melt velocity in the vertical direction, or greater flow cross-section. There is no reasonable mechanism by which increasing the cutting speed increases acceleration forces on the melt. However, there may be a minor increase in vertical flow speed as a result of decreased viscosity at higher temperatures, but the increasing angle of inclination and curvature of the cut front will prevent this from being a major factor. The main contribution to the increased flow rate must therefore be an increase in flow cross-section, which will result in a greater cut front melt thickness. This greater melt thickness will lead to an increase in melt turbulence and rougher cut edges.

This comparison of slow, intermediate and fast cutting speeds is summarised in table 2. From the cut zone behaviour at the extremes of slow and fast speeds, the physical characteristics of the cutting process at the optimal, intermediate cut speed can be inferred as is done in table 2.

Table 2: A summary of the phenomena controlling the surface roughness of laser cut edges at slow, optimum and fast cutting speeds.

Having established that irregular or highly turbulent flow occurs at slow and fast speeds respectively, it becomes clear that we should expect ‘striation free’ cutting to take place at intermediate speeds, it is now important to analyse the laser-material interaction involved.

3.3 Geometric aspects of the laser-material interaction

A laser/oxygen cut mild steel edge can generally be divided into two regions; an upper zone where the roughness is dominated by the laser-material interaction, and a lower zone where the roughness is dictated by the flow conditions of the melt as it leaves the cut front. In the following discussion these zones will be called ‘Laser dominated’ and ‘Melt-flow controlled’. The differences between these zones are particularly obvious at high speeds (eg figure 5d) and thick sections (eg. figure 1). The photos in figure 5 show;

- a. (2.0m/min) A rough surface produced by sporadic melting/oxidation.
- b. (4.0m/min) Melt-flow controlled surface towards the bottom of the edge.
- c. (5.5m/min) Optimum low roughness (‘striation free’ edge).
- d. (7.0m/min) Melt-flow controlled surface towards the bottom of the edge.

Figure 9: A simplified view of the laser-cut front interaction zone.

In the case of the 5.5m/min sample the cut edge shows minimal evidence of a change from a ‘laser dominated’ to a ‘melt-flow controlled’ surface – and this is the key to ‘striation free’ cutting. At certain combinations of melt viscosity and cut front geometry, it is possible for the whole of cut front to assume the approximate shape of an inclined, straight, half pipe, as shown in figure 9. Flow down this half pipe has minimal turbulence and the whole cut front can be said to be ‘laser dominated’. The creation of this type of cut front shape can be explained by a simple geometrical argument. For the purpose of this simplified discussion the kerf will be considered to

be parallel sided, with a semicircular cut front. The laser will be assumed to be a column of light of the same diameter as the cut front (figure 9).

Note; As the following discussion is centred around laser-material interactions at glancing angles, we will henceforth consider the ‘glancing angle’ between the laser beam and the plane of the workpiece rather than the more usual ‘angle of incidence’. The glancing angle is equal to 90 degrees minus the angle of incidence – as shown in figure 10.

The phenomenon of increased absorption of light over a specific range of glancing angles centred around a maximum value at the Brewster angle is well known [7] and a good examination of the subject in the context of laser cutting is provided in [8] and [9]. Figure 11 shows how the absorptivity of a molten iron surface changes with the angle of incidence at glancing angles for light from CO₂ lasers (10.6um wavelength) and fibre lasers (1.07um wavelength) [8, 9].

Figure 10: The relationship between the glancing angle (used throughout this paper) and the angle of incidence.

Figure 11: The absorptivity of light from CO₂ and fibre lasers of a liquid iron surface as a function of glancing angle (from [8] and [9]).

As we increase the cutting speed from zero, the change in inclination of the cut front has two effects;

1: As the cut front inclination increases, the proportion of the beam which interacts with the cut front increases (see fig. 12).

2: The cut front inclination and the glancing angle between the laser and the cut front are the same ($\theta = \gamma$), so any increase in inclination from zero up to the Brewster angle leads to an increase in the absorptivity of the cut front (see figures 9, 10 and 11).

Figure 12: The proportion of a (columnar) laser beam which illuminates the cut front as a function of the lag between the top and bottom of the cut front.

In the case of our experiment with 1.1mm thick mild steel, a cut front inclination equal to the Brewster angle for fibre laser light (10.4 degrees) gives a lag between the upper and lower parts of the cut front of 194 microns – which is approximately the diameter of the focussed beam (192 microns). Therefore, a cut front inclined at 10.4 degrees would have a high absorptivity and be fully illuminated by the total power of the direct beam (if the beam is collimated – as in figure 9). The straight line result given in figure 12 implies that the illumination of this sloping cut front would be uniform which would add to the stability of the flow pattern (at higher speeds and inclinations only the upper part of the melt is illuminated by the direct beam – the lower parts are heated by reflections from above).

In fact, the beam is not collimated and so the lag between the top and bottom of the cut zone might need to be extended in order to collect the entire beam – this would require an increase in the cut front inclination beyond the Brewster angle. However, figure 11 shows us that the absorptivity of the beam remains almost constant at the Brewster maximum from about 8 to 14 degrees.

From the above it would be expected that a straight cut front inclined at between 8 and 14 degrees would offer an optimum laser material interaction for thin section material. Figure 13 confirms that the average striation inclination at the optimum roughness speed of 5.5m/min is indeed within this range. Measurements made by ourselves on other ‘striation free’ cuts in thin section mild steel (including the relevant photo in [3]) have identified a generally close relationship between very low roughness cuts and almost straight striations inclined at angles of between 8 and 14 degrees. Another important point is that, even at higher speeds where the lower part of the cut edge is roughened by fluid flow, the striations on the upper part of the cut edge remain within this range of inclination. The observation that the roughness towards the top of the cut edge does not increase with cutting speed (see figure 4), is further evidence of the correlation between low roughness and cut front inclination.

Figure 13: Figure 5c with superimposed lines at 8 and 14 degrees, demonstrating that the striation inclination lies within these guidelines.

This link between ‘striation free’ cut quality and the Brewster angle is the reason why this type of ‘striation free’ result has not been seen in the context of CO₂ laser cutting. Figure 11 makes it clear that there are two main differences between the absorptivity curves for fibre and CO₂ lasers;

- a. The Brewster angle for CO₂ lasers is a much steeper glancing angle (approximately 3 degrees) than it is for fibre lasers.
- b. The value of absorptivity diminishes much more rapidly in the case of CO₂ lasers as we move away from the Brewster angle maximum; the ‘close to Brewster absorptivity’ range in this case is only from about 2 to 4 degrees.

The fact that the upper, laser dominated, part of the cut front is also linked to the Brewster angle in the case of CO₂ lasers is clear from the photos presented in figure 1. The upper part of the 3mm cut edge has striations inclined at approximately 3 degrees with more steeply inclined melt flow lines below. The 12mm thick material was cut at a much lower speed and has upper zone striations which incline from zero to three degrees before joining the more steeply inclined melt flow lines further down the cut face.

It must be noted that the above analysis disregards any effect of the presence of FeO on the absorptivity. This is equivalent to assuming that FeO is transparent to the laser wavelengths considered. This approximation is primarily due to the lack of data available in the open literature on the optical properties of molten FeO. However, it can reasonably be argued that the ionic bonding in FeO will result in a band structure that only produces high absorptivities for narrow ranges of frequencies, whereas the frequency dependence of absorptivity of metallic Fe varies more gradually, as can be seen from the Fresnel relations [8, 9]. The correlations observed in this work indicate that this approximation is valid.

4. Conclusions

- The lowest roughness mild steel cut edges are produced at intermediate speeds considerably lower than the maximum cutting speed. At lower speeds the roughness is higher because the viscosity of the melt is relatively high. At higher speeds the cut edge is rougher because the mass flow down the cut front is larger and the melt is thicker.
- ‘Striation free’ fibre laser cut edges are covered in microscopic striations.
- These low roughness striations are inclined at an angle between 8 and 14 degrees because this range of angles gives the optimum laser absorption at the fibre laser wavelength.

5. References

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Tables

Table 1: Experimental Parameters.

Parameter	Value
Speed	2-8 m/min
Power	1000 W
Oxygen Gauge Pressure	2 Bar
Nozzle Diameter	1mm
Stand Off Distance	1mm
Lens focal length	120 mm
Mild steel thickness	1.1 mm

Table 2: A summary of the phenomena controlling the surface roughness of laser cut edges at slow, optimum and fast cutting speeds.

Slow Speeds	Optimum Speed Range (for low roughness edges)	Fast Speeds
Vertical straight line cut front Intermittant reaction; irregular flow High viscosity melt; low temperature Fluctuating melt depth; high turbulence.	Inclined straight line cut front; low turbulence Minimum (stable) melt thickness; low turbulence.	Curved or kinked cut front; high turbulence. Increased mass flow, melt thickness; high turbulence.

Figure Captions

Figure 1. Typical cut edges produced by CO₂ laser/oxygen cutting. The cut edges are covered in parallel grooves known as striations (samples are 12mm and 3mm thick).

Figure 2. Under the correct process parameters a very smooth mild steel cut edge can be produced by a fibre laser in conjunction with an oxygen jet. Parameters; 1mm mild steel cut at 5.5 m/min, oxygen supply gauge pressure; 2 Bar, fibre laser power; 1000W.

Figure 3. A schematic of laser-oxygen cutting of mild steel.

Figure 4: The average Ra roughness measurements of the cut edges as a function of speed.

Measurements were taken 0.25mm from the top or bottom of the cut face. Each point represents the average of three measurements, each 15mm long.

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Figure 6: A higher magnification view of a ‘striation free’ cut edge showing the presence of microscopic striations on the top part of the cut surface at 5.5m/min.

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Figure 8: The relationship between viscosity and temperature for iron and FeO. The experimental curve for FeO has been (Arrhenius type) extrapolated above 1900K [4].

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Figure 13: Figure 5c with superimposed lines at 8 and 14 degrees, demonstrating that the striation inclination lies within these guidelines.