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The geometry of the cutting front created by Fibre and CO_2 lasers when profiling stainless steel under standard commercial conditions

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ABSTRACT

Cutting fronts created by CO_2 and fibre lasers in stainless steel at thicknesses between 2 mm and 10 mm have been 'frozen' and their geometry has been measured. Standard commercial cutting parameters were used to generate the cuts for both types of laser. The resulting three-dimensional cutting front shapes have been curve fitted as polynomials and semicircles. Various features of the cutting front geometry are discussed including the lack of correlation of the cut front inclination with either the relevant Brewster angle or the inclination of the striations on the cut edge.

1. Introduction

Laser cutting is a well-established industrial process. Yet research is still ongoing, especially for 1 μm wavelength machines; fibre lasers [1–3], disk lasers [4] and direct diode lasers [5]. Lasers are versatile tools which can process a wide range of materials, from polymers [6] to titanium alloys [7] and ultra-high strength steels [8]. There are several methods by which a laser can cut materials but this paper will concentrate on laser fusion cutting, where the laser melts a volume of material, and a high velocity inert assist gas such as nitrogen ejects the melt from the cutting zone. The three dimensional geometry of the cutting zone created by the laser/gas jet combination is, of course, a major factor in understanding the laser cutting process and is the central subject of this paper. Throughout this work standard industrial cutting parameters were employed in order to concentrate on genuine commercial practice.

1.1. Theoretical modeling of the cutting front geometry

Any model of the laser cutting process requires a description of the cutting front geometry (inclination, width, curvature, surface waves etc.). This geometry is particularly important because the absorptivity of the surface is dependent on the angle of inclination of the cutting front [10–11]. Hirano and Fabbro [9] argue that laser absorptivity and its angular dependence is the cause for the differences in cut quality between 1 μm and 10 μm lasers (cut edge quality is a function of R_a and R_z roughness, levels of residual melt attached to the underside of the cut edge, and the inclination of the cut edge).

However, because of the difficulty of directly measuring the cutting front, most theoretical models have had to make assumptions about the cutting front geometry rather than relying on experimental data.

Pioneering work by Petring et al. carried out in the late 1980's [12] began by approximating the cutting front geometry to an inclined half-pipe (see Fig. 1). A second approach in the same paper calculated self-adjusting local variations in the cutting front inclination angle. At that time, Petring only took into account the Fresnel absorption depending on the local angle of incidence, and the local power demand for heating and melting the material. Bearing in mind this simplification the results were in surprisingly good agreement with longitudinal sections of experimental cutting fronts [12]. From this initial simplification Petring extended the theoretical approach to the much more sophisticated CALCut model, which allows for the balances of power, force and mass, as well as multiple reflections of the laser radiation along the cutting kerf and the self-adjusting local variation of cutting front inclination and kerf radius for lasers with wavelengths of both 10 μm and 1 μm [13,14].

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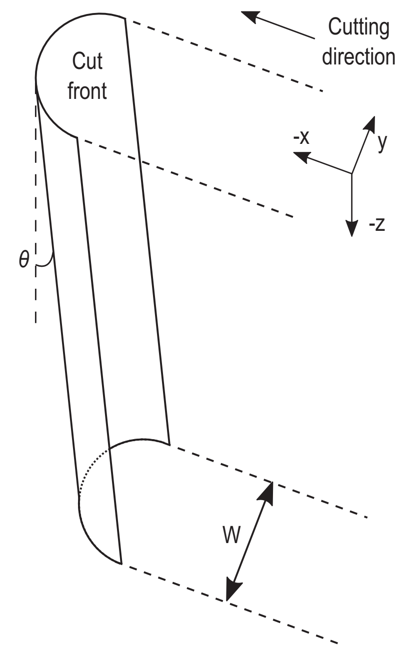

Fig. 1. The cutting front described as a half-pipe by Petring et al. [12]. (Kerf width denoted by W and inclination angle by Θ).

Duan et al. [15] presented a mathematical model which described the shape of the cutting front for CO_2 laser cutting as a truncated elliptical cone. Brügmann and Feurer [16] computed a two-dimensional cutting front geometry of the type shown in Fig. 2 and determined the absorptivity profile for CO_2 and disk laser cutting of steel. They concluded that the CO_2-laser absorptivity was higher than that of the disk laser for most parts of the cutting profile, except at the top and bottom of the front. The absorbed beam intensity (product of beam intensity and absorptivity) was found to be higher for the disk laser along the entire cutting profile. Brügmann and Feurer conclude that this could explain the higher cutting speeds associated with disk lasers when compared to CO_2 lasers.

Tamsaout and Amara [17] developed a numerical model to calculate the three-dimensional melt flow on the cutting front for Nd:YAG laser cutting. The cut zone was presented in two orientations, i.e., in the longitudinal direction, showing the melt inclination angle, and from the front, revealing the ripples on the melt surface.

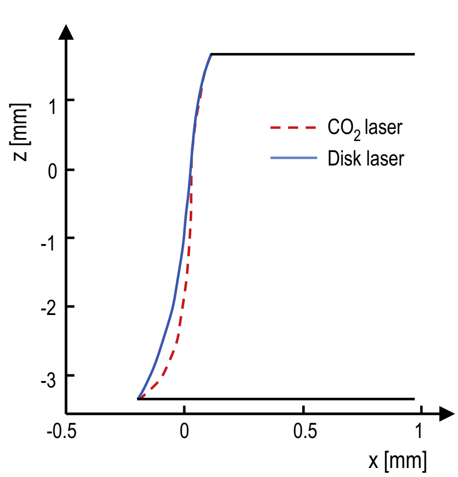

Fig. 2. Typical cutting front slopes of the type described by Niz'ev, Brügmann and Feurer [16].

The Finite Volume Method (FVM) was used to solve the hydrodynamic equations of the model. Tamsaout and Amara studied the effect of surface tension on the melt on the cutting front. They report that in the absence of surface tension, ripples or humps moved downwards on the melt surface. Ejection of molten metal droplets was also observed. They point out that the melt flow on the cutting front was unstable and of a cyclic nature. When surface tension was taken into consideration, the melt was more stable, and accumulated at the front exit.

Mahrle et al. [18] calculated the absorptivity for thick section CO_2 and fibre laser cutting. Their calculations were based on a two-dimensional geometrical model of the cut zone, which consisted of a straight, inclined cutting front.

Fallahi Sichani et al. [19,20] used FVM to calculate the melt temperature and cutting front inclination. They suggested that increased melt temperature enhances heat transfer to the processing gas, causing gas ionization and subsequent plasma formation which can defocus and absorb the laser beam. Kaplan [21] defined the cut zone as a control volume bounded by two inclined semi-circular cylinders, intersecting at the top. He determined average values of the macroscopic state of the cutting front, i.e. melt temperature, melt film velocity and melt thickness. Scintilla et al. [22] created a three-dimensional steady-state Finite Element Model (FEM) to calculate the cutting front temperature. They approximated the cutting front with the surface of an inclined cylinder. Scintilla et al. processed cold work tool steel ranging between 1 and 8 mm with both CO_2 and disk lasers. They suggested that cuts obtained with the disk laser had lower cut quality due to low cutting front temperature which increases the melt viscosity and leads to poor ejection of molten material.

Using 'CALCut', the most successful laser cutting model developed so far, Petring et al. [23] have simulated the cutting front for both 1 μm and 10 μm laser sources by taking into account multiple reflections of the laser beam in the cutting zone. This work revealed that the 1 μm wavelength laser cutting front has an expanded and irregular shape, with 'hot spots' (regions with elevated absorbed power density shown is red in Fig. 3). Petring et al. argue that the resultant irregular shape of the cutting front could be the cause of low cut edge quality associated with 1 μm laser cutting of thick sections. More recent results from Petring [24] have discussed the correlation between irregularities on calculated cut front geometries and the structure of striation patterns and kerf cross sections of the resulting cut edges.

1.2. Experimental observations of the laser cutting front

The cutting front geometry can be experimentally determined from observation of the 'frozen' cutting front at the end of the cut kerf, and from high speed imaging (HSI) techniques which allow observation of the processing front during cutting.

Petring et al. confirmed their calculated cutting front geometries for CO_2 laser cutting with longitudinal cross sections of experimental cutting fronts which were "frozen" by switching off the laser beam during cutting [12]. Some effects caused by multiple reflections of the laser beam were also identified in this early work.

Scintilla et al. [4] investigated the cutting front geometry created when cutting 5 and 8 mm thick tool steel with disk and CO_2 lasers. Longitudinal cross sections of the cutting front showed that parts of the cutting front are inclined towards the laser beam at the Brewster angle (the angle for maximum absorption) when processing with 1 μm and 10 μm wavelength lasers. Fallahi Sichani et al. [19,20] performed HSI to observe the cut zone in CO_2 laser cutting of stainless steel. Only one half of the beam interacted with the sheet edge, allowing HSI from the side to visualize the cutting front geometry. The HSI recordings show that the curvature of the