CHAPTER 6

SOME OF THE SCIENTIFIC ASPECTS OF LASER CUTTING

This chapter is aimed at students, engineers and scientists who would like to have a more in-depth grasp of the science behind laser cutting. The first section discusses the factors that affect the efficiency of the laser cutting process and contains a discussion presented in more detail in the following paper:

J. Pocorni, D. Petring, J. Powell, E. Deichsel & A.F.H. Kaplan.
The effect of laser type and power on the efficiency of industrial cutting of mild and stainless steels.
J. Manufacturing Science and Engineering (2016). 138(3), 031012

The second section looks at the rather complicated physical and chemical interactions that take place during laser-oxygen cutting. Once again the discussion is presented in more detail in the paper:

J. Powell, D. Petring, R.V. Kumar, S.O. Al-Mashikhi, A.F.H. Kaplan & K.T. Voisey.
Laser-oxygen cutting of mild steel: the thermodynamics of the oxidation reaction.
J Phys D: Appl. Phys. 42 (1) (2009) 015504 (11pp)
doi: 10.1088/0022-3727/42/1/015504.

6.1 Factors Affecting the Efficiency of Laser Cutting

The subject of the efficiency of laser cutting can be boiled down to one question:

"How much cut edge is produced for each kilojoule of laser energy?"

This measure of efficiency can be described by the following simple equation:

$$\alpha = \frac{v \cdot t}{P_{laser}} \left(\frac{mm^2}{kJ}\right) \qquad [1]$$

Where:

α	: cutting efficiency	(mm^2/kJ)
v	: cutting speed	(mm/s)
t	: material thickness	(mm)
P_{laser}	: laser power	(kW)

For example, if a laser cuts 3mm stainless steel at 95mm/s with a laser power of 5kW it is producing (3x95)/5 = 57mm^2 of cut edge per kilojoule of laser energy. Although the laser cutting process produces two cut edges (one on each side of the beam) only one of these is part of the finished product – and so only the useful cut edge is considered here.

The following discussions will show that cutting efficiency changes with laser type, material type, laser power and material thickness.

To create the following graphs a large number of laser cuts were created using standard commercial parameters rather than the maximum cutting speeds that might be investigated in laboratory conditions. These industrial conditions produce a stable, reliable, standard quality cut. Also, as the rest of this section is only concerned with comparing trends, the results have been normalized (i.e., the maximum value in any graph or group of related graphs has been given a value of 1 and all other values are relative to this) rather than giving actual efficiency figures.

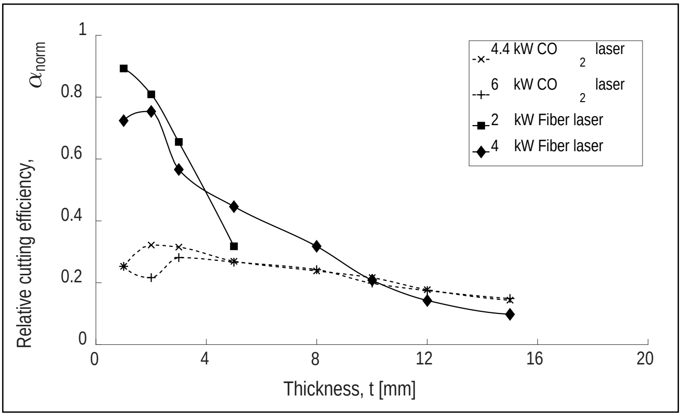

Figure 6.1 Relative cutting efficiency results for fusion cutting stainless steel (Nitrogen cutting gas).

Figure 6.1 shows the relative cutting efficiency of typical industrial CO_2 and fiber lasers when fusion cutting stainless steel with nitrogen assist.

A number of conclusions can be drawn from the results given in Figure 6.1:

- **As material thickness increases the cutting efficiency decreases.**
  Several effects may contribute to this trend. For all thermal cutting processes an increase in material thickness results in a decrease in cutting speed. A decrease in cutting speed increases the laser-material interaction time in any one area along the cut line and this allows a greater proportion of the heat to be carried away by conduction. This increase in conductive losses per unit length of cut results in a decrease in process efficiency. A drop-off in efficiency of this sort is accentuated when lower powers are used (because lower powers mean even lower cutting speeds), which is why the efficiency reduction (as material thickness increases) in Figure 6.1 is more extreme for the 2kW fiber than it is for the 4kW fiber. Other possible reasons for the decrease in efficiency with thickness are: a. reduced absorptivity, and b. the creation of wider kerfs as the material thickness is increased (cuts which have wider kerfs require more energy because a greater volume of melt is created per mm^2 of cut edge produced).

- **At thinner sections fiber lasers are more efficient than CO_2 machines.**
  Differences in absorptivity provide the main explanation of this result. The differences in absorptivity between the two types of laser will be discussed later in this section.

- **At thin sections the higher power lasers of both wavelengths tend to have slightly lower efficiencies than the lower power machines.**

Increased power and reduced material thickness are linked to higher cutting speeds. The temperature of the cutting zone rises as cutting speeds rise, and the cutting speeds (and therefore the cutting front temperatures) are highest at the thinnest sections. At these temperatures a proportion of the laser energy is consumed in boiling some of the liquid in the cut zone. As far as laser cutting is concerned, boiling is a far less energy efficient material removal mechanism than melting and so the overall process efficiency is reduced.

Also, as mentioned earlier, these experiments were carried out under commercial parameters which often involve a deliberate reduction of speed (and power) at thin sections and high powers in order to optimize the stability and productivity of the process. This deliberate reduction in speed also reduces cutting efficiency.

- **As material thickness increases, the efficiency of the fiber lasers falls off more rapidly than that of the CO_2 lasers.**

- **At thicker sections the CO_2 lasers are more efficient than the fiber lasers.**

These final two conclusions will be explained later in this section.

Figure 6.2 shows the results for laser cutting mild steel with oxygen as the assist gas. In this case the difference between the fiber and CO_2 laser performance is very much reduced compared to Figure 6.1. The reason for this similarity in performance is that the oxidation reaction contributes a considerable proportion of the energy to the process for both types of laser (see section 6.2) and this helps to even out the differences between the laser-material interactions.

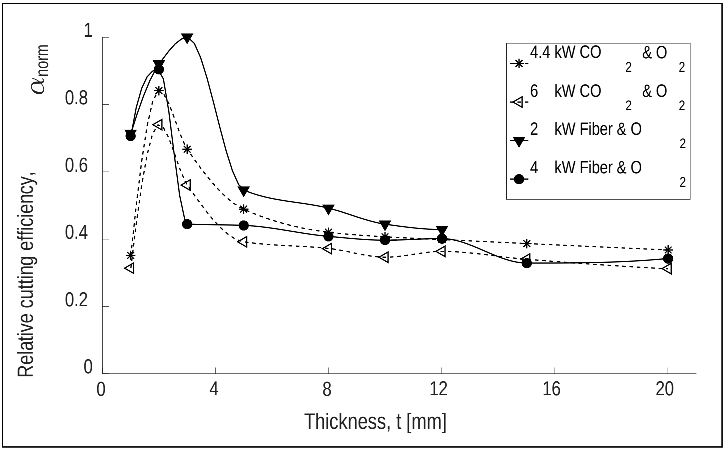

Figure 6.2 Relative cutting efficiency results for mild steel cut with oxygen assist gas. Note: Powers given here are the nominal maximum powers of the lasers in question. When cutting thin sections, the laser power is often automatically reduced (see notes below).

As was the case for cutting with nitrogen, a fall off can be seen in cutting efficiency at the lowest thickness. In this case the mechanism which results in this reduction in efficiency is not simply boiling of the melt. As for fusion cutting, thinner sections mean higher cutting speeds and higher cutting front temperatures. However, if the full power laser was allowed to generate very high temperatures within the melt during oxidation cutting then the oxidation reaction would be disrupted [1] (see section 6.2). For this reason, very high melt temperatures are avoided by an automatic reduction of the laser power when cutting thin section mild steel with oxygen. Because the laser is operating at a lower power it appears to be cutting less efficiently in Figure 6.2.