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LASER CUTTING: FROM FIRST PRINCIPLES TO THE STATE OF THE ART

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Abstract

This paper presents an overview of the subject of laser cutting. Subjects covered include; Laser-materials interactions, different laser types, the technical and commercial growth of laser cutting and the state of the art.

First Principles

Most laser cutting is carried out using CO_2 or Nd:YAG lasers. The general principles of cutting are similar for both types of laser although CO_2 lasers dominate the market for reasons, which will be discussed later in the paper.

The basic mechanism of laser cutting is extremely simple and can be summarised as follows:

1. A high intensity beam of infrared light is generated by a laser.

2. This beam is focused onto the surface of the workpiece by means of a lens.

3. The focused beam heats the material and establishes a very localised melt (generally smaller than 0.5mm diameter) throughout the depth of the sheet.

4. The molten material is ejected from the area by a pressurised gas jet acting coaxially with the laser beam as shown in fig 1. (N.B. With certain materials this gas jet can accelerate the cutting process by doing chemical as well as physical work. For example, Carbon or mild steels are generally cut in a jet of pure oxygen. The oxidation process initiated by the laser heating generates it's own heat and this greatly adds to the efficiency of the process.)

5. This localised area of material removal is moved across the surface of the sheet thus generating a cut. Movement is achieved by manipulation of the focused laser spot (by CNC mirrors) or by mechanically moving the sheet on a CNC X-Y table. 'Hybrid' systems are also available where the material is moved in one axis and the laser spot moved in the other. Fully robotic systems are available for profiling three dimensional shapes. Nd:YAG lasers can utilise optical fibres rather than mirrors but this option is not available for the longer wavelength CO_2 laser.

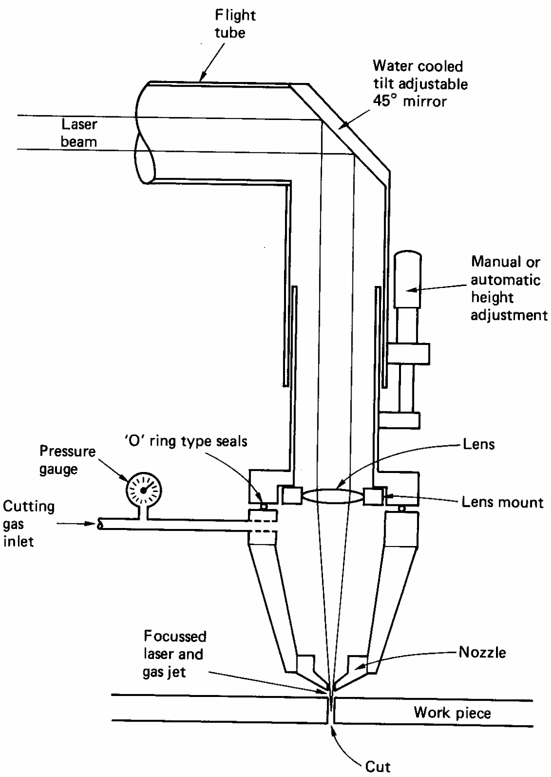


Figure 1. A schematic of laser cutting. The lens mount or the nozzle (or both) can be adjusted from left to right or into and out of the plane of the sketch. This allows for centralisation of the focused beam with the nozzle. The vertical distance between the nozzle and the lens can also be adjusted.

Before moving on to a more detailed description of the cutting process, now is a good time to summarize the benefits of laser cutting.

A. The process cuts at high speed compared to other profiling methods. For example a 1500W CO_2 laser will cut 2mm thick mild steel at $7.5 mmin^{-1}$. The same machine will cut 5mm thick acrylic sheet at $\sim 12 mmin^{-1}$.

B. In most cases (e.g. the two examples given above) the cut components will be ready for service immediately after cutting without any subsequent cleaning operation.

C. The cut width (kerf width) is extremely narrow (typically 0.1 to 1.0mm). Very detailed work can be carried out without the restrictions of a minimum internal radius imposed by milling machines and similar mechanical methods.

D. The process can be fully CNC controlled. This, combined with the lack of necessity for complex jigging arrangements, means that, a change of job from cutting component 'A' out of steel to cutting component 'B' out of polymer can be carried out in seconds. (Note Nd:YAG lasers cannot cut most plastics because they are transparent to Nd:YAG laser light).

E. Although laser cutting is a thermal process, the actual area heated by the laser is very small and most of this heated material is removed during cutting. Thus, the thermal input to the bulk of the material is very low, heat affected zones are minimized and thermal distortion is generally avoided.

F. It is a non-contact process, which means that material needs only to be lightly clamped or merely positioned under the beam. Flexible or flimsy materials can be cut with great precision and do not distort during cutting, as they would when cut by mechanical methods.

G. Owing to the CNC nature of the process, the narrowness of the keft width and the lack of mechanical force on the sheet being cut, components can be arranged to 'nest' very close together. Hence, material waste can be reduced to a minimum. In some cases this principle can be extended until there is no waste material at all between similar edges of adjacent components.

H. Although the capital cost of a laser-cutting machine is substantial, the running costs are generally low. Many industrial cases exist where a large installation has paid for itself in under a year.

I. The process is extremely quiet compared to competing techniques, a factor which improves the working environment and the efficiency or the operating staff.

J. Laser cutting machines are extremely safe to use in comparison with many of their mechanical counterparts.

A Comparison of CO_2 and Nd:YAG Laser Cutting.

CO_2 and Nd:YAG lasers both generate high intensity beams of infrared light which can be focused and used for cutting.

Far fewer Nd:YAG lasers are sold as cutting machines compared with CO_2 lasers. This is because for general cutting applications, CO_2 lasers are most effective. Nd:YAG lasers are only preferred:

A. If very fine detailed work is required in thin section material.

B. If highly reflective materials such as copper or silver alloys are to be cut on a regular basis,

OR

C. If an optical fibre is to be used to transport the laser beam to the work piece.

Although both CO_2 and Nd:YAG lasers generate infrared light, the wavelength of the CO2 laser light is ten times that of the Nd:YAG machines (10.6 microns and 1.06 microns respectively). Because the Nd:YAG laser light has a shorter wavelength it has three advantages over CO_2 laser light:

1. Nd:YAG laser light can be focused down to a smaller spot* than CO_2 laser light. This means that finer, more detailed work can be achieved (e.g. ornamental clock hands).

2. Nd:YAG laser light is less easily reflected by metal surfaces. For this reason Nd:YAG lasers are suited to work on highly reflective metals such as silver.

3. Nd:YAG light can travel through glass (CO_2 light can not). This means that high quality glass lenses can be used to focus the beam down to a minimum spot size*. Also, quartz optical fibres can be employed to carry the beam relatively long distances to the workpiece. This has led to the widespread use of Nd:YAG lasers on automobile production lines where available space on the lines is at a premium.

***Note:** If an optical fibre is used, the ability of the Nd:YAG laser light to be focused down to a very small spot may be lost if the average power is above 100 Watts. The focused spot size after travelling through an optical fibre may be larger than a CO_2 laser spot.

The shorter wavelength Nd:YAG laser light also has one major disadvantage:

1. Most organic materials (e.g. plastics, wood based products, leather, natural rubbers, etc.) are transparent to Nd:YAG laser light. For this reason they cannot be cut by Nd:YAG lasers. If the laser power is low or the focused spot size is large, the light passes through the material without heating it enough to cut it. If the intensity of the laser beam is increased, by increasing the power or reducing the spot size, the material will eventually respond with a localised explosion that may produce a tear or hole.

The situation with inorganic non-metals (e.g. ceramics, glasses, carbon etc.) is rather complex. CO_2 lasers can be used to cut a large proportion of these materials but, once again, Nd:YAG machines can run into problems of materials transparency (this is true of glass and quartz for example). One success story for both types of laser is the profiling of ceramic substrates for the electronics industry. In some cases the inorganic fillers which are used to colour or harden plastics can make them suitable to Nd:YAG cutting. Generally, however, the cutting of polymers is carried out only by CO_2 lasers.

In summary, Nd:YAG lasers can be used to cut fine detail, or they can be used with an optical fibre in which case fine detail will not be possible (except when cutting foils or thin masks at lower power). They are particularly suited to cutting high reflectivity alloys but cannot cut many non-metals.

CO_2 lasers, on the other hand, are usually a cheaper production route and are therefore favoured for general engineering purposes. CO_2 lasers also have the advantage that they can cut a wider range of materials from metals to polymers and wood.

Cutting Mechanisms

Cutting Mechanisms can laser cut materials by a variety of different mechanisms which are described below. The sub heading to each cutting mechanism includes a mention of the groups of materials cut and which of the lasers is involved.

Melt Shearing or Fusion Cutting (most metals and Thermoplastics – CO_2 and Nd:YAG lasers)

Figure 2 Melt Shearing or Fusion cutting

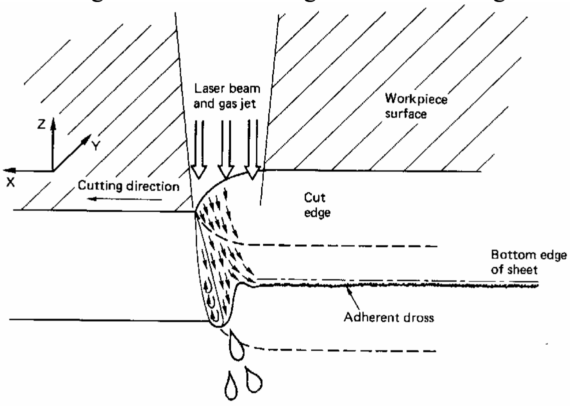


Figure 2 is a schematic of the process of melt shearing or fusion cutting. (Also referred to as 'inert gas cutting'). [1] In this case the focused laser beam melts the workpiece and the melt is ejected from the bottom of the cut by the mechanical action of the cutting gas jet. Materials which are cut in this way include the majority of those that can be melted i.e. metals and thermoplastics. To laser cut these materials successfully we need to choose our cutting gas type and pressure carefully.

The cutting gas type is chosen depending on the reactive nature of the material being cut, i.e.

- Molten thermoplastics do not chemically react with nitrogen or oxygen and so compressed air can be used as the cutting gas.

- Molten stainless steel reacts with oxygen but not with nitrogen and so nitrogen is used in this case.

- Molten titanium reacts with oxygen or nitrogen and so argon (which is chemically inert) is used as the cutting gas.

The pressure of the gas employed also depends upon the materials being cut, i.e. The removal of molten polymer from the cut zone (when cutting for example, nylon) does not require a high pressure gas jet and so the supply pressure to the cutting head may be of the range 2–6 bar. Molten stainless steel, on the other hand, requires considerably more mechanical thrust to remove it from the cut zone and so the supply pressures employed will be in the range 8–14 bar (the required pressure increases with the thickness of the steel).

Chemical Degradation Cutting (Thermoset Polymers and Wood Products - CO_2 Lasers)

Thermoset plastics and wood products are not cut by the melt shearing mechanism for the simple reason that they cannot melt. In this case the laser burns the workpiece, reducing the plastic or wood to a smoke made up of carbon and the other constituents of the original material.

This process is known as cutting by chemical degradation. Because this process takes more energy than simple melting, cut speeds and maximum thicknesses for thermosets are lower than for thermoplastics, the cut edge of such materials is generally flat, smooth and covered with a thin layer of carbon.

Evaporation Cutting (Acrylic and Polyacetal – CO_2 Lasers)

For metals the idea of laser cutting by evaporation is not at all attractive because evaporation consumes far more energy than the simple melting needed for melt shear cutting. For certain polymers however, evaporation cutting does take place because the melting and boiling points of the materials are very close together. The most common material which is cut in this way is Polymethylmethacrylate which is better known as acrylic or by its trade names; Perspex, Plexiglass etc.

This material is used extensively for sign and display work and it is fortunate that, because of its capacity to boil away during laser cutting, a glossy, polished cut edge can be produced.

Scribing (ceramics – CO_2 or Nd:YAG Lasers)

Scribing is a process by which very fast cutting speeds can be achieved on brittle, thin section ceramics (e.g. AL_2O_3) for the electronics industry. The laser is used in its pulsed mode to evaporate a line of shallow holes across the surface of the sheet of the material. The material is subsequently snapped along these lines of weakness. For obvious reasons the process is only appropriate to the production of straight lines.

Oxidation Cutting (Mild Steels and Carbon Steels – CO_2 or Nd:YAG Lasers)

Mild steel and carbon steels can be cut by the melt shearing process using nitrogen but they are more commonly cut using oxygen as the cutting gas. The oxygen chemically reacts with the iron in the cut zone and this has two advantages for the cutting process:

1. The reaction generates heat, which accelerates the cutting process and thus improves cutting speeds and increases the maximum thickness which can be cut.

2. The reaction produces an oxidised melt, which has a low viscosity and does not adhere well to the solid steel on either side of the cut. This means that the liquid is easily blown out of the cut zone and there is no residual melt (dross) attached to the lower edge of the cut.

The chemical reaction also has two drawbacks:

1. The sensitivity of the process is increased as far as the following process parameters are concerned;
    - The laser beam must be precisely centred on the hole in the cutting head nozzle (See Figure 1).
    - The laser beam must have an energy distribution which is axially symmetrical.

2. The chemical reaction leaves a thin (~100µm) skin of iron oxide on the cut edge. This oxide layer is brittle and not securely attached to the underlying steel. This is generally not a problem but it can flake off in service after a part has been painted, taking the paint with it. For this reason some customers insist on nitrogen cut mild steel components.

Case Study

It is misleading to choose a single component and then demonstrate why laser cutting is the preferred production method. In order to give a wider picture let us consider a *type* of component, i.e. a flat, approximately rectangular plate with ten holes, three slots and some edge detail. Let us assume an overall size of 200mm x 300mm.

The route to the manufacture will be determined by a number of factors:

> Material type and thickness, number of components required, accuracy required, edge quality required, hole/slot sizes, etc.

The decision will depend upon the costs associated with producing parts of the appropriate quality and the cheapest method will then be chosen. In many cases laser cutting will be the cheapest route but it is interesting to provide a few different examples of the product to demonstrate when an alternative method would be chosen:

1. Material – 3mm thick steel

    CO_2 laser cutting would be chosen except for the following conditions.

    - If we require more than 100000 components. For large batch production the initial costs associated with fixed tool punching could be justifiable.
    - If the overall contour involved no complex profiles and only one or two pieces were required then plasma or flame cutting followed by machining might be a competitor.
    - If the size tolerances on the holes or slots had to be much better than the ± 0.1mm typical of commercial CO_2 laser cutting. In this case Nd:YAG laser

cutting, CNC punching or electric discharge machining may be preferred.

2. Material – 15mm thick metal:

   In this case CO_2 laser cutting would generally be chosen as the cheapest option if the metal in question was steel. However, commercial laser cutting cannot be used to profile aluminium or copper alloys at this thickness and the usual alternative would be abrasive water jet cutting.

3. Material – 5mm Titanium:

   CO_2 laser cutting would be employed in this case if the heat-affected zone created along the cut edge is not important to the finished product. In fatigue life critical applications the heat–affected zone would be problematic and so mechanical machining, abrasive water jet or electric discharge machining might be used.

4. Material – 10mm polymer:

   In this case CO_2 laser cutting would be employed unless the number of components involved justified the use of injection moulding techniques.

The State of The Art

The state of the art of a topic as diverse as laser cutting is not a single subject. The performance of a machine dedicated to a single application may be very different from that of a more versatile job shop type installation.

For this reason the state of the art is best discussed under a number of headings:

Job Shop Laser Cutting

Since the inception of laser cutting as an industrial process in the early 1970's, machine manufactures have steadily increased the power of the lasers involved. The power used for cutting has always lagged behind the maximum powers available because laser cutting requires a high quality beam, which can be focused down to a small spot with axially symmetric energy density (this symmetry is necessary if the beam is to cut equally well in all directions).

Modern (2004) cutting machines often employ powers between 3.5kW and 5.5kW that are capable of very high production rates. Two important parameters from the point of view of a job shop are the maximum thickness of a particular material which can be cut and the cutting speeds available. Table 1 gives the approximate maximum thickness, which can be cut at 4 and 5 kW by CO_2 lasers.

Table 1. Approximate maximum thickness of materials for CO_2 lasers.

Material	Laser Power	
	4 kW	5kW
Mild Steel	20mm	25mm
Stainless Steel	12mm	20mm
Aluminium	10mm	12mm

Cutting Speeds

The Subject of cutting speeds is open to a lot of interpretation and keen sales people have published a lot of misleading information over the past three decades. In recent years the machine manufactures have realized two important points;

1. It is not just the linear maximum cutting speed that is important; it is the cycle time for the component.

2. It is often better to turn down the power of a multi-kilowatt machine to cut thinner section materials. (So your 4 kW machine may automatically reduce its power to 2kW to cut 2mm thick mild steel).

In order to maximize production the machine manufactures have recently concentrated on machine acceleration and inter-cut movement speeds. Improvement in these fields and related subjects such as piercing times and head retraction rates have made the laser cutting speed only a small component in a complicated calculation to estimate component cycle times. Nowadays the only accurate way of comparing the performance of two machines is to carry out trials on actual components. However, table 2 presents some typical cutting speeds.

Table 2. Typical laser cutting speeds for straight lines of several hundred millimeters in length at a power of approximately 5kW. (Average figures calculated from those given by Bystronic and Trumpf)

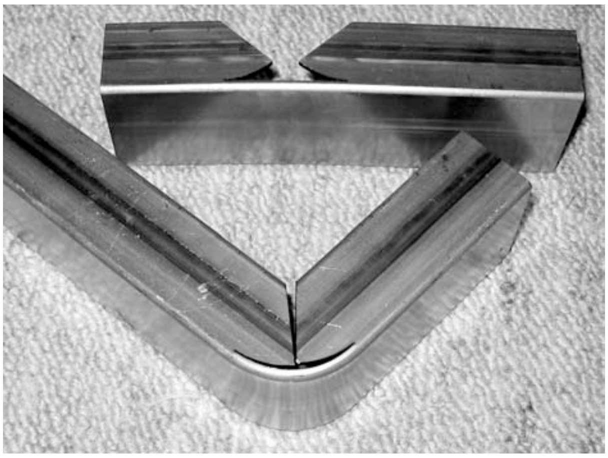
Materials Thickness (mm)	Cutting Speed (m/min)		
	Mild Steel (O_2)	Stainless Steel (N_2)	Aluminium (O_2)
2	5.85	7.25	8.60
5	4.00	3.00	3.10
10	2.35	1.30	0.82
15	1.58	0.70	-
20	1.10	0.42	-
25	0.80	-	-

Specialist Applications

No overview of the state of the art would be complete without a look at some specialist applications. Two such applications are the development of high speed slitting and thick section cutting developed at the Fraunhofer Institute fűr Lasertechnik in Aachen, Germany. By careful control of the process parameters the Aachen teams have cut stainless steel in excess of 40mm thick. The development of a laser-slitting machine for thin section steel is even more interesting because it involves an unusual type of laser-material interaction in the cut zone. It was mentioned earlier that evaporation is generally to be avoided when cutting metals as it consumes a lot of energy. However, when cutting thin sections at high speed the evaporative process can assist in the cutting process by applying a localized pressure in the cut zone which helps to eject the melt. By employing this principle the Aachen team, have achieved cutting speeds in excess of 145m/min for a steel sheet thickness of 0.23mm [2].

One recent area of advancement, which has become very popular in the past two or three years, is the development of laser tube cutting machines. Machines are now available which can process tube of almost any cross section, with diameters up to a couple of hundred millimeters. The advent of such machines has encouraged new attitudes to design. Instead of making, for example, two support legs and a cross piece from three pieces, the whole assembly can be laser cut out of one length of tube and simply bent into shape prior to welding– see figure 3.

Figure 3. A specially designed profile for the production of curved bends



Also, woodworking tongue and groove type joints can be employed to assist in final welding fit up or fabrication, see figure 4.

Figure 4. Design for laser cutting can involve the use of woodworking type tongue and groove joints. (Sample courtesy of BLM:Adige)

Another area of recent interest is the growth of laser micro machining. This area of application is becoming increasingly popular in the electronics and biomedical fields. The lasers involved usually need to have smaller focused spots than are possible using infrared CO_2 and standard Nd:YAG lasers. For this reason, lasers that generate visible or ultraviolet light are employed and the cutting process is one of evaporation or ablation rather than the type of profiling discussed in this article.

Conclusion

Since its beginnings in the early 1970s laser cutting has continually expanded to fill an ever increasing market share. The cost effectiveness of the process is clearly evident in its wide scope of application. It is clear that incremental improvements in both software and hardware will ensure the continuing success of the process.

Acknowledgements

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