

# Laser Cutting Theory

In order to understand what makes a laser suitable for cutting, one must distinguish its unique features in comparison to ordinary light.

Conventional light produces waves, which radiate out in all directions to fill up and illuminate a wide area. The energy intensity rapidly decreases as waves move away from the source, just as the sun's intensity is diminished when it finally reaches the earth.

The laser on the other hand provides a stream of collimated, coherent light waves which give it exceptional intensity and direction ability. Lacking the dispersion of conventional light, a laser can be easily projected as a beam over relatively long distances while maintaining nearly all of its useful power output.

The use of lasers for cutting can be thought of in the same way as that of focusing sunlight with a magnifying glass to produce a concentrated source of heat energy. While this method only results in a few burned holes in paper, it gives us an illustration that light is indeed a source of energy with potential material processing capabilities.

A laser can be used for cutting by exposing material to the intense heat energy developed by its beam. If that heat input to the material is greater than that material's ability to reflect, conduct, or disperse the added energy, it will cause a sudden rise in temperature of the material at that point. If the temperature rise is substantial enough, the input heat is capable of initialising a hole by vaporizing the material. The linear movement of this intense heat energy with respect to the material provides cutting action.

In most cases the "raw" (unfocused) beam of even high power (multi-kilowatt) industrial lasers has inadequate energy to do much more than slowly heat a surface. Therefore, the beam is directed through a focusing lens. This allows the energy to be concentrated into a spot of less than 0.25 mm thus producing power densities of over a million watts per centimeter squared, capable of vaporizing many materials.

While intense heat is capable of vaporising material, the control of that heat is essential in determining quality. The key performance features of a laser are those beam characteristics that affect the resultant power density as it is directed onto the workpiece.

## **Mode**

A cross-section of a laser's beam profile is commonly referred to as mode. Described in terms of TEM (Transverse Electromagnetic Mode) mode relates to the beam's ability to be focused. It is also comparable to the degree of sharpness of a cutting tool. The lowest order or reference mode is TEM<sub>00</sub>, of which the beam's profile simulates a Gaussian distribution curve. Modes that approach this energy distribution can be focused down to the laser's theoretical minimum spot size and give the sharpest energy density.

Higher order or multi-mode beam profiles are characterised by a tendency to spread out the energy distribution away from the centre of the beam. The resultant spot is large with this mode causing lower energy concentration. Therefore, higher order mode lasers are considered to be duller cutting tools than low order mode lasers of equivalent power output.

## **Power Output**

Lasers are rated by their power output in terms of watts. Since laser cutting is a thermal process, the amount of heat produced relates to its capabilities. Whereas a 300 watt laser with a high quality output is more than adequate for the cutting of paper products, it lacks the heat producing capabilities to effectively couple into aluminium. Given all other considerations

being equal (eg power distribution, spot size, etc), increased power allows for faster processing speeds and the ability to cut thicker sections of materials.

### **Stability**

Since quality results are obtained by the application of consistent energy, the stability of the laser's output is a key feature in cutting. This includes maintaining unwavering output energy (power stability), consistent beam quality (mode stability), and fixed energy concentration (pointing stability). Should the power increase or decrease by more than a few percent over the short term operation, the beam quality oscillate between a Gaussian and multi-mode profile, or the location of the beams direction shift more than a few tenths of a milliradian due to the outputs instability, there will result a noticeable change in the available power density for cutting.

### **Polarisation**

Particularly evident in metal cutting and ceramic processing, studies have shown that random occurrences of inconsistent edge quality, namely variations in kerf, edge smoothness, and perpendicularity, are attributable to the effects of polarisation. Uncontrolled or random polarisation is characteristic of most standard material processing lasers. It can unpredictably affect the relative degree of absorption of the beam's energy that is coupled into the material at a given moment. To correct this inconsistency, lasers can be equipped with optical packages that either fix the polarisation to be aligned in the same direction of the cutting action or circularly polarise the output to give equivalent coupling regardless of the direction travel.

An important asset of laser cutting is the high level of control, which is available over the variables affecting the process. The cut can be tailored to meet the exact requirements of the job and the results can be readily duplicated. The principle parameters are:

### **Speed**

Laser cutting feedrates have been found to fit empirical formulas based on the available laser power density and the properties of the material to be cut. Above a threshold amount, the feedrates are directly proportional to available power density, which takes into account the laser's performance features (eg power, mode) in addition to the focusing system's characteristics (eg spot size). Cutting rates are likewise inversely proportional to the materials density and thickness. Therefore, given all other parameters are constant, feedrates will increase with:

- Additional power (1700 watts vs 3500 watts)
- Improved mode (TEM<sub>00</sub>, vs multimode)
- Smaller focused spot size (2.5 vs 5" F.L lens)
- Lower required energy to initiate vaporisation (plastic vs steel)
- Lower material density (white pine vs hickory)
- Decreased thickness (1.25" vs .250")

Feedrates can be varied for a particular set of parameters in order to obtain different edge quality results, particularly for metals, the plot of cutting speed versus thickness for a material has two curves. The upper curve reflects the top speed at which through cuts are achieved while the lower curve shows the limit below which the material is self-burning. The resultant window of acceptable cut speeds is usually wider at the thinner range of a material.

## **Focusing Lens**

Since speed is a function of available power density, the choice of the focusing lens has a great impact on the resulting cut quality. Imaging of lasers beams is usually accomplished with transmissive lenses of focal lengths ranging from 2.5 to 10 inches. Because the focused spot size is proportional to the focal length, the power density that is produced is proportional to the square of that length. Short focal length lenses give very high energy densities, but are limited in their application due to a shallow working depth. They are appropriate for use with thin materials and in high-speed operations where the material can be held within the limited depth of field. Longer focal length lenses have lower power densities but are able to maintain those densities over a much broader range and therefore can be used for thicker cross sections of materials given that they have enough energy initially.

## **Focal Point Position**

During the laser cutting process, the focal point of the lens should be consistently positioned in order to provide the best cutting results. In most cases, the focal point is positioned at or slightly below the surface of the material. Above or below this point the power density will taper off until it is insufficient to produce an effective cut. Cutting systems that employ short focal length lenses must ensure constant monitoring of the lens-to-work piece distance.

## **Assist Gas**

Recall that assist gas is supplied coaxial with the focused beam to protect the lens and aid in the material removal process. Generally, compressed air or inert gas is used to purge melted and evaporated material from the cut zone while minimising any excess burning. For most metal cutting applications, a reactive gas assist can be employed to promote an exothermic reaction. The enhanced energy intensity from the use of oxygen can improve cutting speeds by 25% - 40% over the results obtained with use of air.

In addition to gas type, delivery pressure is an important consideration. Typically, pressures of 45-60 psi (3-4 bar) developed in the gas jet nozzle are used in cutting thin material at high speeds to help prevent the clinging of slag or dross to the back edge of the cut. The pressure is reduced as the material thickness increases or process speeds slow.

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## **LASER CUTTING PROCESS**

Laser cutting systems combine the heat of the focused beam with assist gas, which is introduced through a nozzle coaxial to the focused beam. The high velocity gas jet serves to:

- Aid in material removal by blowing out excess material through the backside of the work piece
- Protect the lens from spatter ejected from the cut zone
- Assist in the burning process.

The best example of the chemical effect of the assist gas is the use of oxygen for the cutting of steels where performances are increased by the exothermic reaction of combustion of iron in oxygen. Another example is clean cutting stainless steel with high-pressure nitrogen. As the laser beam cuts the stainless steel, the high-pressure nitrogen blows the melted material away.

While carbon dioxide lasers are capable of generating tremendous heat intensity, it is an incorrect assumption that they are capable of vaporising and cutting all known materials.

Rather, each material has its own unique response, some of which are not suitable, to the effects of CO<sub>2</sub> lasers. Therefore, the question of suitability of using a laser for cutting that material hinges on how well it handles the added energy input. That interaction is dependent upon three key factors of the material.

- Surface condition - how well it initially absorbs the energy
- Heat flow properties - its coefficients of thermal diffusivity and conductivity
- Heat phase-change requirements - the amount of excess heat required to induce a change as a function of the materials density, specific heat, and latent heat of vaporisation.

The following information is intended to provide general inputs on the major categories of materials, keeping in mind these factors.

## **NON-METALS**

In general, non-metallic materials are good absorbers of infrared energy as produced by a CO<sub>2</sub> laser. Likewise, they are generally poor conductors of heat and have relatively low boiling temperatures. As such, the energy intensity of a focused beam is almost totally transmitted into the material at the spot and will instantly vaporise a hole.

### **Plastics (Polymers)**

Lasers have found their way into many plastic machining operations because of their ability to cut complex geometries, at high feedrates without contacting the work piece. Since the laser is an intense heat source, it uses its energy to vaporise the binder and quickly breaks down the material's polymer chains.

Thermoplastics with relatively low melting temperatures typically display clean cuts with fire-polished edges as a result of resolidified melting. Process control can be exercised to minimise or eliminate bubbling or the presence of small burrs on the backside of the cut.

As the tensile strength of the polymer increases, there is a correlation to a marked increase of charring present along the cut edge. Greater energy intensity per unit time is required to break the stronger chains and therefore leads to a burning action. Reasonable results have been obtained with polyester and polycarbonate while there is generally a substantial layer of decomposed material along the edge of phenolic, polyamides, and PVC.

As a caution, in the cutting of some polymers, specifically lucite, and PVC, careful attention must be directed at the containment and appropriate filtering of potentially hazardous and/or corrosive fumes that are generated as the result of burning.

### **Composites**

New lightweight, fibre reinforced polymers are difficult to machine with conventional, cutting tools. This has led many users to the non-contact cutting capabilities of a laser. Prior to the curing of laminates stacks, thin prepreg sheets in thicknesses up to 0.5mm can be trimmed or sized at speeds up to 40 metres per min without gumming up a cutting tool. The heat from the lasers cutting action fuses the edges, thus preventing fraying of the fibres.

For thicker sections and fully cured composites, particularly boron and carbon fibre material, there is a higher probability of charring, and thermal damage along the cut edge, thus reducing the acceptability of laser cutting for structural members. As with the cutting of polymers, care should be exercised in the removal of fumes.

### **Rubber**

Both natural gum and synthetic rubber materials in thicknesses up to 19mm readily vaporise from the heat of a focused laser beam. This allows precision sizing of items such as gaskets.

Material with fibre or steel cord reinforcement can be cut with a laser at considerably slower speeds due to the higher energy intensity per unit time necessary to sever the cords.

The advantage of laser cutting is the simplicity of handling without having to worry about stretching or distorting of the material due to the impact of a cutting tool. Fresh cut samples tend to exhibit slight stickiness along the edge so they require care in post-process handling. Additionally, some rubber, particularly those containing carbon black, may require a clean-up operation to wipe clean any edge charring.

### **Wood**

The laser offers a number of attractive advantages for the cutting of timber, plywood, and particleboard. In particular, it provides narrow kerfs of 0.3-0.8mm, the absence of sawdust, the ability to contour cut in any direction and no tool wear and noise. While the use of a laser likewise eliminates rough, torn-out, and fuzzy edges as evident with conventional sawing techniques, it is characterised by "burned" edges produced by the laser's heat. Greater amounts of charring will result when the material thickness is increased, thereby slowing the cutting feed-rates.

While lasers are routinely cutting slots in die boards for mounting of steel rule dies their acceptance for other industrial applications has been hampered by process limitations and relatively high initial cost. Since practical power outputs are limited to a few kilowatts, lasers are limited in their ability to cut up to 75mm thick for timber and 25mm for particleboard and plywood.

### **Other Organics**

Paper products and leather, as well as natural and synthetic textiles, can easily be cut with a laser. The lack of thickness; coupled with their high combustibility minimises the power output requirements of a laser to no more than a few hundred watts. The resultant edges are clean and free from fraying.

### **Quartz**

Since it has a relatively low co-efficient of thermal expansion, quartz responds well to the cutting action of a laser. Though there is the presence of a shallow heat affected zone adjacent to a cut, the resultant edges are crack-free and have a smooth appearance thereby eliminating clean-up operations required by saw cutting. Thicknesses up to 10mm can be cut at speeds that are a couple orders of magnitude greater than sawing and without imparting force to the work piece.

### **Glass**

As opposed to quartz, most types of glass are prone to thermal shock and are therefore generally not suitable candidates for laser cutting. The instantaneous heat of the laser's beam provides cutting action by both vaporisation and the blowing away of molten glass from the cut zone.

Some materials such as boro silicates have a low co-efficient of expansion and, with adequate head cycling, can tolerate the heat input from a laser. However, most other forms of glass including soda lime experience thermal shock that results in crack propagation along the cut edge. Also, based on the reflow characteristics of the particular glass, there will be varying degrees of resolidified material that will adhere to the edges and underside of the cut.

## **Stone & Rock**

While they tend to absorb the heat energy from a laser, granite, concrete, rock, stone and various minerals are not suited for laser cutting. The explosiveness from heating moisture within the materials can lead to undesirable cracking. Aside from the lack of uniformity in their structures, stone and rock are typically found in thicknesses greater than 25mm, far in excess of the practical depth of field of useable focussed laser energy.

## **Metals**

Although at room temperature, almost all metals are highly reflective of infrared energy, the CO<sub>2</sub> laser with its 10.6-micron wavelength (far infrared) is successfully employed on many metal cutting applications. The initial absorptivity can range from only 10% to as little as 0.5% of the incident energy. However, the focusing of a beam to provide power densities in excess of 1 million watts per square cm can quickly (in a matter of microseconds) initiate surface melting. The absorption characteristics of most metals in their molten states increase dramatically, raising the absorptivity of energy to as much as 60% - 80%.

## **Carbon Steel**

Conventional steels of up to 16 mm lend themselves reasonably well to oxygen assisted laser cutting. The kerfs are narrow (as little as 0.1 mm for thin material) and the resultant heat affected zones are negligible, particularly for mild and low carbon steel. At the same time, the cut edges are smooth, clean, and square.

It has been found that the presence of pockets of phosphorus and sulphur within mild steel can cause burnout along the cut edge, as such, the use of low impurity steels (eg cold rolled) will result in improved edge quality over results obtained with hot-rolled material. A higher carbon content within the steel does yield a slight improvement in edge quality yet will make the material subject to an increased HAZ.

## **Stainless Steel**

Lasers have been shown to be viable cutting tools for the fabrication of sheet metal components made from stainless. The controlled heat input of the laser beam serves to minimise the HAZ along the cut edge, thereby helping the material to maintain its corrosion resistance. Since stainless does not react with an oxygen assist as efficiently as does mild steel, cutting speeds for stainless are slightly slower than those for comparable thicknesses of plain steel. At the expense of up to 50% of the speed for oxygen-assisted cutting, an inert assist gas can be employed to obtain a "weld ready", oxide-free cut edge.

As for the resultant cut quality, martensitic and ferritic (400 series) stainless provide clean smooth edges. The presence of nickel within austenitic (300 series and precipitation hardened) stainless steels affects the energy coupling and transfer within the material. Specifically, the viscosity of molten nickel generated during the cutting action causes it to migrate and adhere to the backside of the cut. While the use of high velocity gas jets can effectively eliminate slag for material up to 1.0 mm thick, slag deposits up to 0.5mm are generally present on thicker cross sections.

## **Alloy Steel**

Since care is taken to control the amount and distribution of additives to the base iron, most alloy steels are considered ideal candidates for the laser cutting process. High strength materials such as AISI-SAE 4130 (chrome moly steel) and 4340 (chrome nickel moly steel) display exceptional laser cut edges that are square and clean.

## **Tool Steel**

Similar in many ways to alloy steels, most tool steels respond reasonably well to the cutting action of a laser. The most notable exceptions are the tungsten high speed (Group T) and tungsten hot work (part of Group H) materials that retain heat in a molten state, thereby resulting in burned out and sluggish cuts.

### **Aluminium Alloys**

Due to its high thermal conductivity and high reflectivity to a CO<sub>2</sub> laser's wavelength, aluminium requires considerably higher laser energy intensity in order to initiate cutting compared to steel. This means the need for a laser possessing exceptional beam quality and capable of outputting at least 500 watts, in addition to precise focus control. Due to the reduced coupling efficiency, even 1-2 kilowatt lasers are limited to cutting of thicknesses under 3.8mm.

During the cutting process, the assist gas serves primarily to blow the molten material from the cut zone. This helps to produce edge quality that is generally superior to that produced by a bandsaw. However, the melted material tends to flow along the edge and cling to the backside of the cut. While this slag is easily removable, there are intergranular cracks emanating from the cut surface on some alloys. Concern over the presence of this micro cracking has prevented the use of lasers for manufacturing structural components such as aircraft.

### **Copper Alloys**

Copper has less ability than aluminium to absorb energy from a CO<sub>2</sub> laser. Due to its high reflectance, copper generally cannot be cut. Brass on the other hand can absorb some energy. It essentially behaves like aluminium with slag adhering to the backside of the cut.

### **Titanium**

Pure titanium responds well to the concentrated heat energy of a focused laser beam. The use of an oxygen assist enhances the cutting speeds but tends to promote a larger oxide layer along the cut edge. Aircraft alloys such as 6AL-4V tend to exhibit some slag that adheres to the bottom side of the cut but is relatively easy to remove.

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## **Primary Considerations**

This section discusses the criteria that are important to successful cutting. It is intended as a guide only, since there is no substitute for operator experience.

These are the principal considerations with which the operator must concern himself at all times. Note that it is the combined effect of these adjustments that determines the result. The various items cannot be considered independently.

### **Laser Power Setting**

The most important point regarding laser power is that maximum power is not necessarily beneficial. Firstly, there is some trade-off between power and mode - the mode (or quality of the beam, which determines the fineness of the focus) is of significantly greater importance to cutting than the power level. Secondly, limiting the power is frequently beneficial in terms of reducing thermal input into the material - especially when cutting thin material, or materials which can be adversely affected by excess heat. It is simply wasteful to use more power than necessary.

### **Cutting Speed**

The actual feedrate in use for a job will directly affect the cutting results; the feedrate is decidedly a function of the type of material and material thickness to be used. In any particular case, there will be some feedrate that is too high and the cut will simply fail to penetrate the material fully; at the other extreme, excessive heat input is likely to damage the material adjacent to the cut. In general, some feedrate closer to the maximum limit will be optimum, but always the choice is made experimentally on the basis of cutting results; the operator, with a little experience, can make this determination quite readily, making use of the feedrate override control.

### **Focal Height**

Focus assemblies provide support for the lens in order to image the beam. These assemblies generally provide means to adjust the focal point in or at the part. Height sensing devices can be incorporated to automatically maintain the proper focal point position regardless of undulations in the work piece surface. These devices measure the lens-to-work piece spacing either through contact probes riding on the work piece surface or via a comparison of non-contact optical, acoustic, or electrical (inductance or capacitance measuring) signals bounced off the material. The feedback can trigger compensation of the vertical axis position.

For best results, the focal point of the beam must impinge on the surface of a work piece. This factor is of greater or lesser importance, depending on the material; in general, materials that have a high intrinsic reflectivity to the laser beam will be most critical of the focal height setting (eg. mild steel 45% reflective; stainless steel 66%; aluminium 99%). The focal point on aluminium and stainless steel should be approximately 4/5 buried into the material. Thicker carbon steel will cut better when the focal point is 1-2 mm above the material.

The operator may find that the focal point needs to be "tweaked" occasionally during a job; the precise focal point can change slightly owing to thermal effects in the lens.

### **Nozzle Lateral Adjustment (Spot)**

Gas jet nozzle assemblies are usually integrated with the focusing assembly below the lens in order to develop the desired gas assist. A properly designed nozzle tip is very important to the cutting process. It can promote higher feedrates, and better quality with minimum gas consumption.

Nozzle adjustment is an important factor, ensuring that the beam emanates centrally through the orifice. Misalignment of the nozzle normally causes noticeable variations in cut quality with respect to the direction of the cutting traverse. Severe misalignment results in the laser beam hitting the inner walls of the nozzle, with consequent poor cutting performance, and heating of the nozzle and surrounding assembly.

The nozzle adjustment must be made whenever a lens is changed, or even if a lens is removed temporarily for cleaning. During a working shift, the operator might "tweak" this adjustment a few times; the slight changes in pointing angle of the beam (through the external optical system) account for this requirement.

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### **Secondary Considerations**

These are considerations with which an operator must become concerned when cutting results are below expectations, and all primary considerations (listed above) have been checked.

### **Choice of lens**



As a general rule, the shortest focal length lens (5") produces the most sharply defined focal point. Thus, the 5" lens is used when maximum intensity is important - that is, cutting materials with high intrinsic reflectivity (metals). In practice, there is only a slight (but usually noticeable) difference between a 5" lens and a 7.5" lens in this respect.

The longer focal length is required, however, to achieve parallel-sided cuts in some materials when the material is reasonably thick. For example, to cut 1" thick acrylic, it is found virtually impossible to keep the sides of the cut parallel with the 5" lens, whereas the 7.5" lens makes this quite easy. Note that the choice of laser power, assist gas pressure, and feedrate all combine to influence the cut quality in this respect, apart from the lens itself.

### **Condition of the lens**

Cleanliness of the lens is of major importance, since any contaminants on its surfaces will cause it to absorb energy and become warm. Thermal distortion in the lens inevitably produces fuzziness in the focal point of the beam, and consequent reduction in cutting performance. Eventually, if a lens becomes excessively heated, thermal stress and gas pressure will cause it to shatter.

The operator should inspect the lens regularly (and clean as necessary). In fact, common sense is the rule here; the source of contamination is virtually always airborne particles produced by the cutting. Therefore, if material being cut produces contaminants (eg. sheet metal often has oil on the surface; rubber produces black smog when cut; etc.), the lens should be inspected as often as convenient. The assist gas greatly helps in keeping contaminants away from the lens, but the operator must be aware that this is by no means total protection. Lifting the focal height while piercing will also help protect the lens.

### **Condition of the nozzle**

The copper nozzle may become damaged or blocked in time, usually as a result of hot metal spatter thrown up from the work surface. The orifice can be cleared by a conventional oxy tip-cleaner.

After some usage, the orifice may become "out of round"; this causes swirling or vortex action in the assist gas jet, which usually produces highly directional effects in the cutting. Often, this can be rectified by carefully drilling the orifice; if the orifice is of large diameter then excessive assist gas will be consumed. Eventually, the nozzle will need replacement.

### **External Optical Alignment**

The optical system (set of mirrors) external to the laser cavity (including the mirror mounted at the top of the Beam Control Unit) should normally be checked and adjusted on a routine basis (say, once per month). However, if the integrity of the alignment is under suspicion in the meantime, it can be checked by using the cross-wire method of allowing the raw beam to pass through the system onto a target. The image produced by the cross-wire (its shadow) will indicate whether the beam passes through the position centrally.

Misalignment of the external beam will generally cause haphazard cutting results, with highly noticeable directionality.

### **Assist Gas Pressure**

Generally oxygen is used for metal cutting, and air is used for non-metal cutting. High-pressure nitrogen can be used to cut mild steel, stainless steel and aluminium. Using nitrogen as an assist gas leaves the cut edges clean and free of dross but is expensive because up to 25 bar is needed. The general rule with assist gas is: there must be sufficient flow (pressure) in each case, but an excessive amount is wasteful. Normally, high-pressure cutting requires increased pressure with increased material thickness and cutting with oxygen requires

decreased pressure with increased thickness. Of course, the type of material is also an influence; very low carbon steel, for example, will be adversely affected by excessive oxygen flow since it is highly reactive. In any particular case, the pressure used will be experimentally determined, and is usually not highly critical. Note that no material can be cut without any assist gas.