LASER CUTTING PARAMETERS

The laser cutting parameters are dependent on the beam characteristics, the cutting rate required, the composition and thickness of the material to be cut, and the desired cut edge quality. The laser cutting process and cut quality depend upon the proper selection of laser and workpiece parameters. Deficiencies in cutting quality may be related to the slow process drifts and disturbances that are caused by velocity fluctuations, variation in power and spatial intensity distribution as well as optical integrity perturbations. The effects of the beam parameters, process parameters and material parameters are described in the following sections.

Beam parameters

These are parameters that characterize the properties of the laser beam and include the wavelength, power and intensity, beam quality and polarization. Prior to significant heating of the workpiece, the incident laser beam is reflected, scattered and absorbed in proportions determined by the wavelength of the irradiation, the state of polarization of the laser beam, the angle of incidence and the optical properties of the surface.

Wavelength

Reflectivity of metallic materials to laser light is a function of laser wavelength whereby metals are highly reflective to long infrared wavelengths (CO_2 laser wavelength) than the shorter infrared wavelengths (Nd:YAG laser wavelength). An Nd:YAG beam can be focused to a smaller diameter than a CO_2 laser beam, providing more accuracy, a narrower kerf width and low surface roughness. Figure 1 shows the absorption phenomena of some frequently used metals over a range of different laser wavelengths.

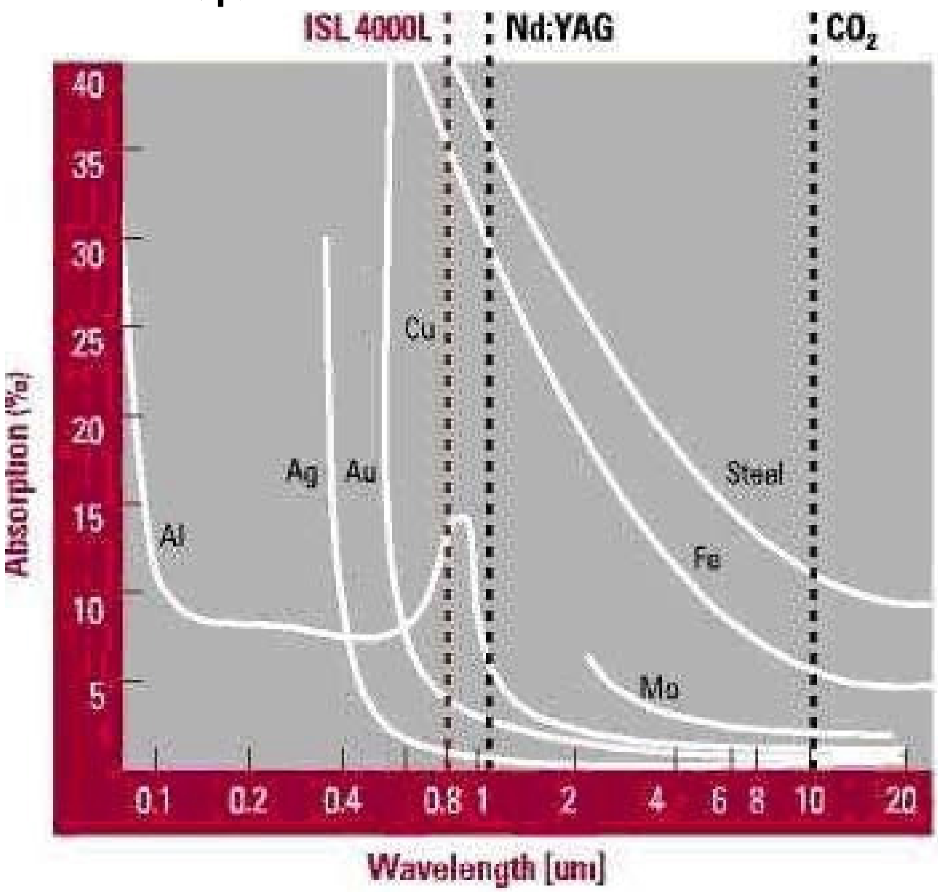


Figure 1: Absorption phenomena of typical metals over a range of different laser wavelengths.

Absorption of the longer infrared wavelength of a CO_2 laser (10.6µm) is governed by the electrical conductivity of the material. At room temperature, highly conducting metals such as gold, silver, aluminium and copper absorb only a very small amount of CO_2 laser radiation and reflect the large majority of it, medium conductors such as steel show an absorption of around 10% and insulators such as plastics and wood-based materials show a perfect absorption. On the other hand, the absorption of the shorter infrared wavelength of the Nd:YAG laser (1.06µm) is governed by the lattice atoms. For metals, this mechanism leads to good absorption that is higher than in the case of CO_2 laser wavelength. However, insulators show only negligible absorption and nearly perfect transmission of radiation at the Nd:YAG wavelength because insulators require large energy to be ionized in order for absorption of radiation to take place. Nevertheless, the suitability of a particular laser for an application than others is more often attributed to other laser parameters such as peak power, pulse length and focusability other than wavelength characteristics. Both Nd:YAG and CO_2 lasers can overcome the high initial reflectivity of many metals provided the intensity of the focused beam is sufficiently high.

Metals that are highly reflective to the CO_2 laser light at room temperature become better absorbers when they are heated. After a cut has been started, the cut acts as a black body and the incident laser light is strongly absorbed by the thin molten layer. The reflectivity of the laser light impinging on the melt surface is dependent on the angle of incidence of the laser beam, plane of polarization of the laser light and the optical properties of the molten material.

The heating - increased absorption - heating cycle is difficult to set up in the very highly reflective non-ferrous metals such as copper and aluminium. This is because these metals combine a high reflectivity with a high thermal conductivity, which reduces the efficiency of the cutting process.

Power and intensity

Laser power is the total energy emitted in the form of laser light per second while the intensity of the laser beam is the power divided by the area over which the power is concentrated. High beam intensity, obtained by focusing the laser beam to a small spot, is desirable for cutting applications because it causes rapid heating of the kerf leaving little time for the heat to dissipate to the surrounding which results into high cutting speeds and excellent cut quality. Additionally, reflectivity of most metals is high at low beam intensities but much lower at high intensities and cutting of thicker materials requires higher intensities. The optimum incident power is established during procedure development because excessive power results in a wide kerf width, a thicker recast later and an increase in dross while insufficient power cannot initiate cutting.

High power beams can be achieved both in pulsed and continuous modes; however, high power lasers do not automatically deliver high intensity beams. Therefore, the focusability of the laser beam is an important factor to be considered.

Beam quality

The laser beam quality is characterized by the mode of a laser beam, which is the energy distribution through its cross section. A good beam mode having uniform energy distribution is essential for laser cutting because it can be focused to a very small spot giving high power density, which leads to high cutting speeds and low roughness. Higher order modes with zones of elevated energy density outside the major spot may result in a poor cut quality due to heating of the material outside the kerf.

Theoretically, the lowest order mode, TEM_{00}, refers to a gaussian intensity distribution about a central peak. The TEM_{00} mode gives the smallest focused spot size with very high intensity in comparison with higher order beam modes. The TEM_{00} mode also has the largest depth of focus and therefore gives the best performance when cutting thicker materials. The highest edge quality can be obtained if the Rayleigh length (depth of focus) is equal to the sheet thickness. However, in practice, high power lasers usually deliver higher order modes that give a larger focused spot size than the TEM_{00} mode. The laser beam quality is measured by factors K or M^2 (K1$_2$=M) and the TEM_{00} mode has a beam quality factor, K, close to 1 while higher order modes have lower K-values. An M^2 value of 1 corresponds to a 'perfect' gaussian beam profile but all real beams have M^2 values greater than 1.

The K or M^2 value is sufficient for the comparison of laser beams from similar laser systems having the same wavelength. The Beam Parameter Product (BPP) is the standard measure of beam quality that is used for the comparison of laser beams from different laser systems because it includes the wavelength effects.

Beam polarization

In laser cutting, the laser light is coupled into the material on the cut front where light absorption takes place in a thin surface molten layer. The reflectivity of the laser light impinging on the melt surface is dependent on the angle of incidence of the laser light, plane of polarization of the laser light and optical properties of the molten material.

Laser beam polarization can be linear (also called plane polarization), circular, elliptic or random. Linear polarization exists in two possibilities, either parallel or perpendicular to the plane of incidence, and the two options are absorbed differently in different directions during the cutting process. The material is a good absorber of parallel-polarized light at an irradiation angle known as Brewster's angle, which is about 80°. On the other hand, the perpendicularly polarized light is reflected more strongly.

The influence of beam polarization during cutting is basically related to the inclination of the cut kerf resulting from the relationship between the polarization surface and the cutting direction. The polarization influence becomes larger as the plate thickness increases and is most significant on cutting of materials with a high reflectivity for normal incident radiation i.e. metallic materials than when cutting materials with a low reflectivity for normal incident radiation i.e. nonmetals. When cutting of materials with a high reflectivity for normal incident radiation is performed with a linear polarized laser, the absorption of energy in the cutting kerf depends upon the angle, ψ, between the plane of polarization, p, and the cutting direction, c, as shown in figure 2.

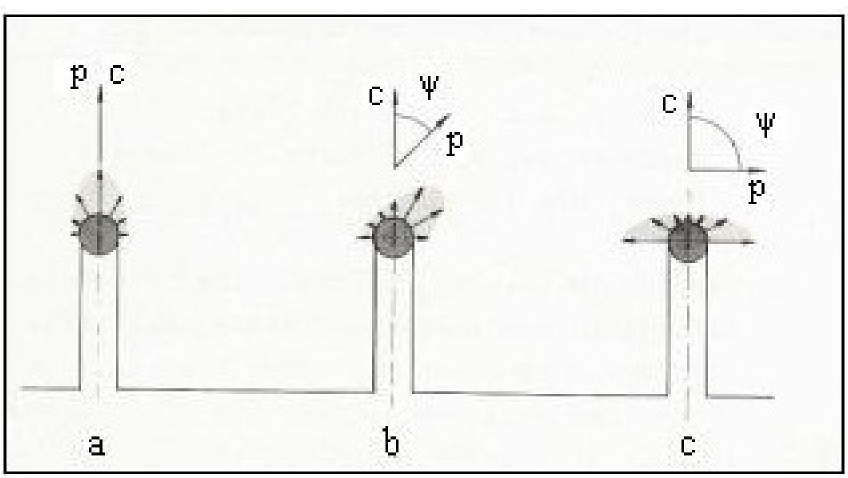


Figure 2: The relative absorption of energy for different orientations of the cutting direction and direction of polarization, whereby ψ is the angle between the plane of polarization, p, and the cutting direction, c.
When the angle ψ, is 0°, the front of the cutting kerf absorbs more energy than the sides but when the angle, ψ, is 90°, the front of the cutting kerf absorbs less energy than the sides. Therefore, the cutting speed can be higher when cutting in the same direction as the plane of polarization than when cutting in a direction perpendicular to the plane of polarization. The energy absorption is asymmetric when ψ is between 0° and 90° causing an asymmetric cutting profile. A smaller cut kerf width is obtained when cutting in the direction of polarization than when cutting in the perpendicular direction.

The perfectly circularly polarized light achieves nearly uniform cut kerfs in every direction but the linearly or elliptically polarized light produces a variation on the inclination of the cut kerf. Metal cutting with a linear polarized beam is an advantage if cutting can be done in direction of the polarization but curve cutting with a linear polarized beam causes variation in the cutting profile as shown in figure 20 in which the cut edges are not square in some positions. When cutting is to be performed in more than one direction, circular or random beam polarization is favorable in order to get a uniform cut of a high quality.

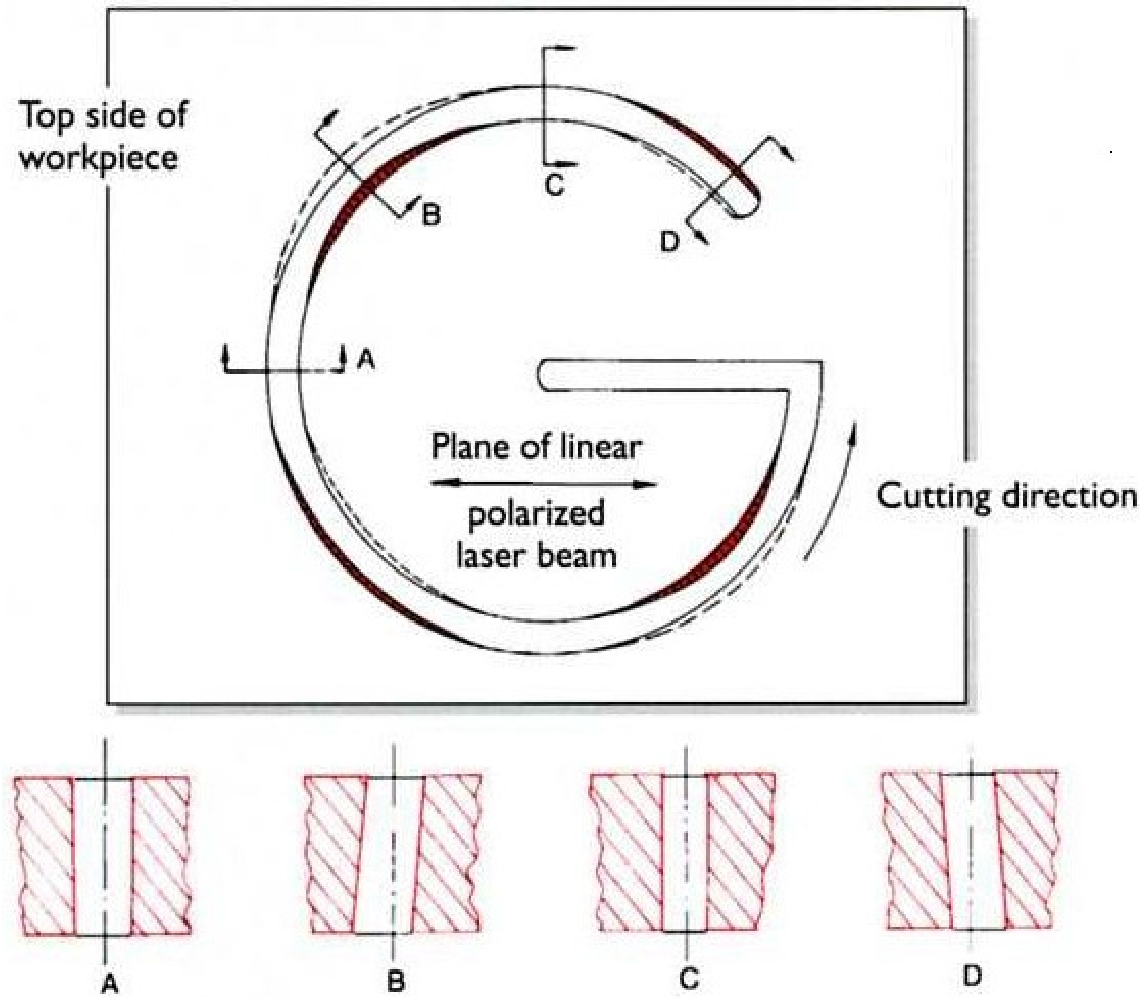


Figure 3: Effects of polarization in cutting
Beam polarization is of concern for CO_2 laser cutting since the light from a CO_2 laser is linearly polarized but light from Nd:YAG lasers is randomly polarized and so cutting performance is not affected by direction. A phase-shift mirror is used in cutting machines with CO_2 lasers to change light with linear polarization into circular polarization.

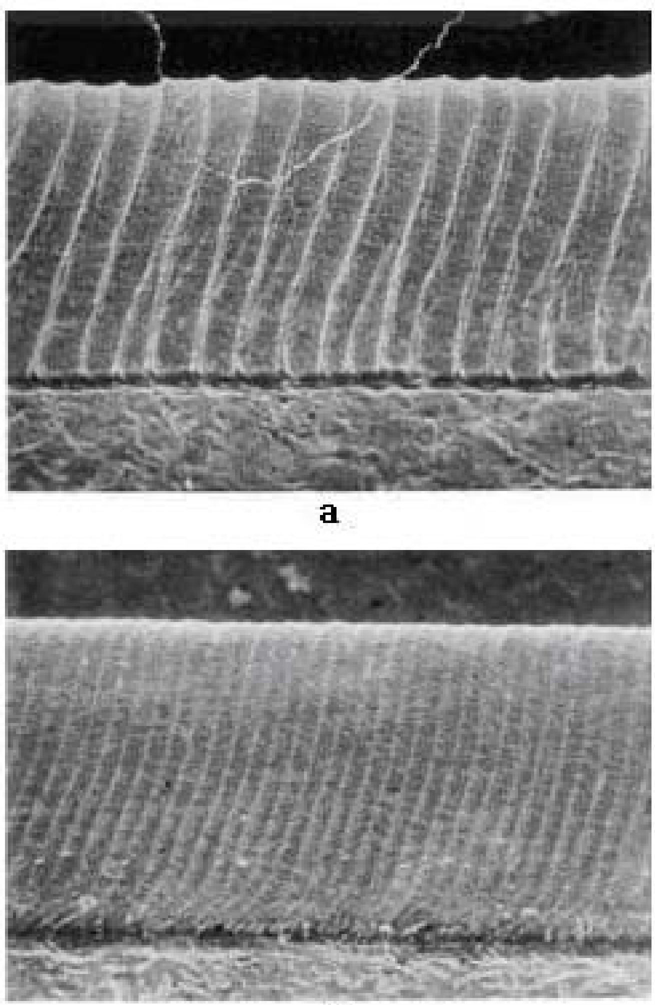
Process parameters

The process parameters include those characteristics of the laser cutting process that can be altered in order to improve the quality of the cutting process and achieve the required cutting results. However, some process parameters are normally not altered by the operator.

Continuous wave (cw) or pulsed (p) laser power

High intensity can be achieved in both pulsed and continuous beams. The peak pulse power in pulsed cutting or the average power in continuous cutting determines the penetration. A high power CW laser beam is preferred for smooth, high cutting rate applications particularly with thicker sections because the highest cutting speeds can be obtained with high average power levels. However, the removal of molten or vaporized material is not efficient enough to prevent some of the heat in the molten/vaporized material from being transferred to the kerf walls causing heating of the workpiece and deterioration of the cut quality. A lower energy pulsed beam is preferred for precision cutting of fine components producing better cuts than a high power CW laser because the high peak power in the short pulses ensures efficient heating while the low average power results in a slow process with an effective removal of hot material from the kerf reducing dross formation. A pulsed beam of high peak power is also advantageous when processing materials with a high thermal conductivity and when cutting narrow geometries in complex sections where overheating is a problem.

The striations formed during pulsed cutting are finer than those formed during continuous wave cutting (see figure 4). Additionally, cutting at sharp corners is better achieved with pulsed cutting than continuous wave cutting as illustrated in figure 5.



a

b

Figure 4: A comparison of (**a**) continuous wave laser cutting and **(b)** pulsed laser cutting

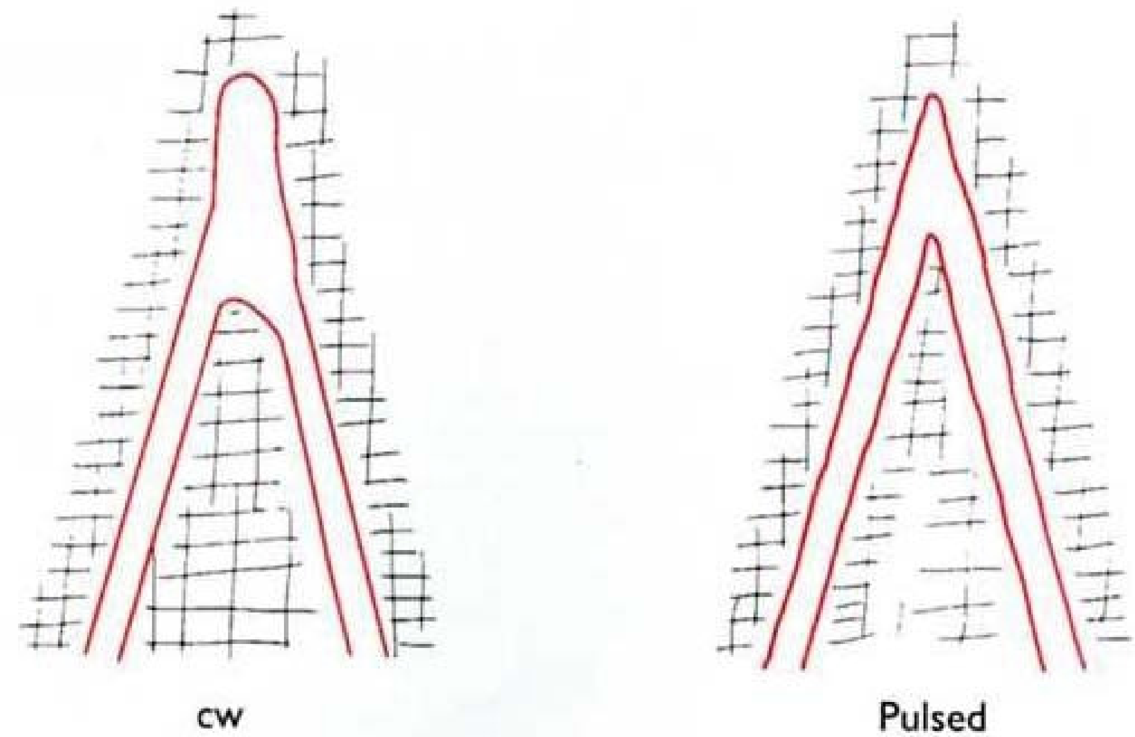


Figure 5: Effect of pulsing at a sharp corner

Focal length of the lens

Solid-state lasers usually utilize fiber optics for beam delivery and a collimator is used to form the divergent laser beam emitting from the light cable into a parallel laser beam. After the laser beam has passed the laser light cable and the collimator, the focusing lens then focuses the parallel laser beam onto the workpiece.

CO_2 lasers do not utilize fiber optics for beam delivery; therefore, the beam emitted by the laser is directly focused onto the workpiece using a focusing lens. The laser cutting process requires focusing a high-power laser beam to a small spot that has sufficient power density to produce a cut through the material. The focal length of the focusing lens determines the focused spot size and also the depth of focus which is the effective distance over which satisfactory cutting can be achieved.

The focusability of laser beams is illustrated in figure 6 in which is the depth of focus (Rayleigh length) shows the parameters that determine the focused spot size The depth of focus is also dependent on the same parameters as the focused spot diameter; generally a small spot size is associated with a short depth of focus.

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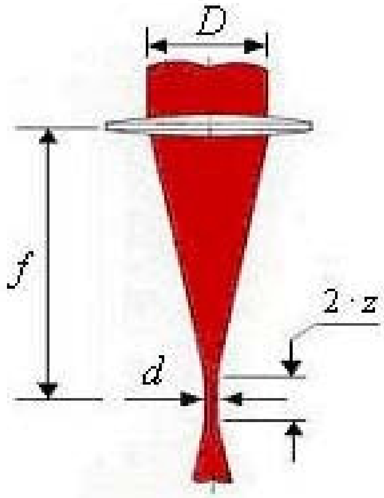

Figure 6: Focusability of laser beams

For cutting of thin materials (less than 4mm in thickness), a short focal length - typically 63mm - gives a narrow kerf and smooth edge because of the small spot size. A longer focal length is preferred for thick section cutting where the depth of focus should be around half the plate thickness. The use of long focal length lenses enlarges the working distance, minimizes the contamination of the lens and increases the depth of focus. A high quality laser beam would enable the use of longer focusing optics without compromising on the focused spot size. The critical factors that determine the selection of the lens for a cutting application are the focused spot diameter and the depth of focus so the focal length has to be optimized with respect to the material thickness to be cut.

Focal position relative to the material surface

The focal position has to be controlled in order to ensure optimum cutting performance. Differences in material thickness may also require focus alterations and variations in laser beam shape.

When cutting with oxygen, the maximum cutting speed is achieved when the focal plane of the beam is positioned at the plate surface for thin sheets or about one third of the plate thickness below the surface for thick plates. However, the optimum position is closer to the lower surface of the plate when using an inert gas because a wider kerf is produced that allows a larger part of the gas flow to penetrate the kerf and eject molten material. Larger nozzle diameters are used in inert gas cutting. If the focal plane is positioned too high relative to the workpiece surface or too far below the surface, the kerf width and recast layer thickness increase to a point at which the power density falls below that required for cutting.

Cutting speed

The energy balance for the laser cutting process is such that the energy supplied to the cutting zone is divided into two parts namely; energy used in generating a cut and the energy losses from the cut zone. It is shown that the energy used in cutting is independent of the time taken to carry out the cut but the energy losses from the cut zone are proportion to the time taken. Therefore, the energy lost from the cut zone decreases with increasing cutting speed resulting into an increase in the efficiency of the cutting process. A reduction in cutting speed when cutting thicker materials leads to an increase in the wasted energy and the process becomes less efficient. The levels of conductive loss, which is the most substantial thermal loss from the cut zone for most metals, rise rapidly with increasing material thickness coupled with the reduction in cutting speed.

The cutting speed must be balanced with the gas flow rate and the power. As cutting speed increases, striations on the cut edge become more prominent, dross is more likely to remain on the underside and penetration is lost. When oxygen is applied in mild steel cutting, too low cutting speed results in excessive burning of the cut edge, which degrades the edge quality and increases the width of the heat affected zone (HAZ). In general, the cutting speed for a material is inversely proportional to its thickness. The speed must be reduced when cutting sharp corners with a corresponding reduction in beam power to avoid burning.

Process gas and gas pressure

The process gas has five principle functions during laser cutting. An inert gas such as nitrogen expels molten material without allowing drops to solidify on the underside (dross) while an active gas such as oxygen participates in an exothermic reaction with the material. The gas also acts to suppress the formation of plasma when cutting thick sections with high beam intensities and focusing optics are protected from spatter by the gas flow. The cut edge is cooled by the gas flow thus restricting the width of the HAZ.

The choice of process gas has a significant effect on the productivity and quality of the laser cutting process. The commonly used gases are oxygen (active gas) and nitrogen (inert gas) with each having its own advantages and potential disadvantages. Although nitrogen is not purely inert, it is the most commonly used gas for inert gas cutting because it is relatively cheap. Purely inert gases, argon and helium, are common choices when cutting titanium since they prevent the formation of oxides or brittle titanium nitrides.

Nitrogen gas is the preferred gas for the cutting of stainless steel, high-alloyed steels, aluminium and nickel alloys and it requires higher gas pressures to remove the molten material from the cut kerf. The high gas pressure provides an extra mechanical force to blow out the molten material from the cut kerf. When high-pressure nitrogen cutting is used to cut stainless steel, it produces a bright, oxide free cut edge but the processing speeds are lower than in oxygen assisted cutting. The main problem associated with the inert gas cutting is the formation of burrs of resolidified material on the underside of the kerf. Burr-free cutting conditions are achieved by optimization of the principle processing parameters; nozzle diameter, focal position and gas pressure. The nitrogen pressure lies in the range of 10-20 bar and the pressure requirement increases with increasing material thickness. Nitrogen gas purity should be above 99.8%.

Oxygen is normally used for cutting of mild steel and low-alloyed steels. Use of oxygen causes an exothermic reaction, which contributes to the cutting energy resulting into high cutting speeds and the ability to cut thick sections up to 12mm. However, oxygen cutting leads to oxidized cut edges and requires careful control of process parameters to minimize dross adherence and edge roughness. The oxygen gas nozzle pressure usually lies in the range of 0.5-5 bar. The oxygen pressure is reduced as plate thickness is increased to avoid burning effects and the nozzle diameter is increased. High gas purity is important – mild steel of 1mm thickness can be cut up to 30% more quickly using 99.9% or 99.99% purity oxygen in comparison with the standard oxygen purity of 99.7%.

Figure 7 shows the typical cutting speeds for high pressure nitrogen cutting of stainless steel and oxygen assisted cutting of mild steel with 2 kW CO_2 laser. The cutting speeds and maximum material thickness cut are relatively higher for the oxygen assisted cutting than for high pressure nitrogen cutting.

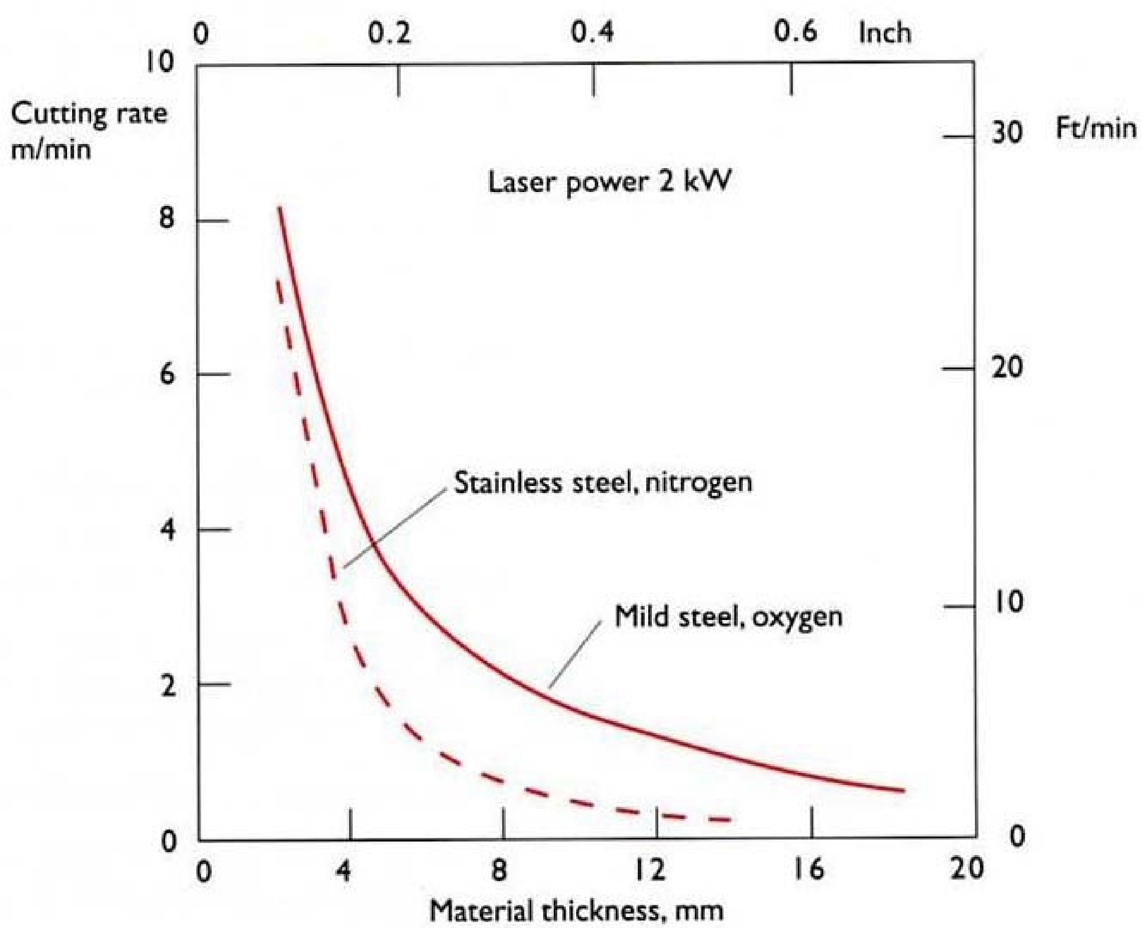

Figure 7: Cutting speed for a 2kW CO_2 laser. Oxygen is used as cutting gas for mild steel. High pressure nitrogen (20 bar) is used for stainless steel

Nozzle diameter and standoff distance

The nozzle delivers the cutting gas to the cutting front ensuring that the gas is coaxial with the laser beam and stabilizes the pressure on the workpiece surface to minimize turbulence in the melt pool. The nozzle design, particularly the design of the orifice, determines the shape of the cutting gas jet and hence the quality of the cut. The diameter of the nozzle, which ranges from 0.8 mm and 3 mm, is selected according to the material and plate thickness. Due to the small size of the focused laser beam, the cut kerf created during laser cutting is often smaller than the diameter of the nozzle. Consequently, only a portion of the gas jet formed by the nozzle penetrates the kerf, which necessitates the use of a high gas pressure. Off-axis nozzles have also been used in mirror focusing applications but the cutting pressure is limited to 200Kpa.

The stand-off distance is the distance between the nozzle and the workpiece. This distance influences the flow patterns in the gas, which have a direct bearing on the cutting performance and cut quality. Large variations in pressure can occur if the stand-off distance is greater than about 1mm. A stand-off distance smaller than the nozzle diameter is recommended because larger standoff distances result in turbulence and large pressure changes in the gap between the nozzle and workpiece. With a short standoff distance, the kerf acts as a nozzle and the nozzle geometry is not so critical. Figure 8 shows the nozzle geometry definitions.

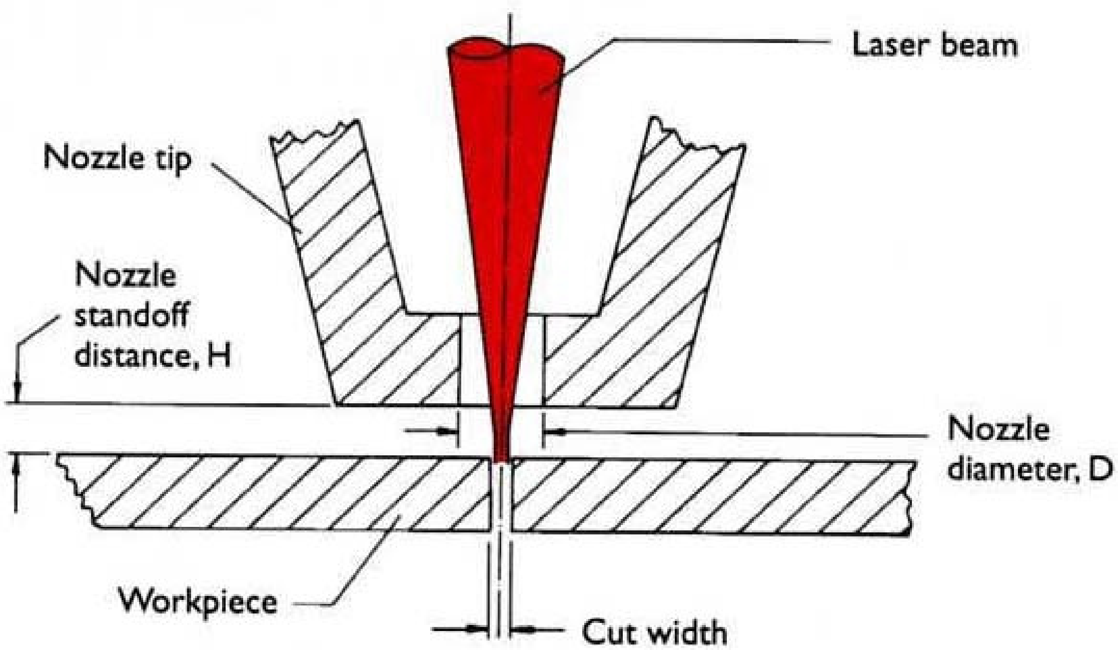

Figure 8: Nozzle geometry – definitions

Kai Chen et al examined the effects of processing parameters such as gas pressure and nozzle standoff distance on cut quality. Their numerical simulations and laser cutting experiments revealed that the fluctuation of pressure gradient and shear force at the machining front has detrimental effects on the removal capability of the gas jet, which often results in poorer cut quality.

The structure of shocks present in supersonic flow from laser cutting nozzles results in a reduction of the stagnation pressure accross the shock. The interaction of the shocks with a workpiece result in a cutting pressure that shows large variations as a function of nozzle standoff distance. For higher nozzle pressures, the cutting perfomance is impaired by the formation of a strong normal shock (the Mach Shock disk, MSD). The flow downstream of the MSD is subsonic having suffered a large drop in stagnation pressure and results in a low laser cutting pressure. Besides causing a significant reduction in the cutting pressure, the MSD also encourages the formation of a stable stagnation bubble on the surface of the workpiece. The stagnation bubble could result in ineffective debris removal and plasma formation due to absorbtion of laser radiation by trapped debris.

Nozzle Alignment

Nozzle misalignment may cause poor cutting quality, as the process is extremely susceptible to any discrepancy in the alignment of the cutting gas jet with the laser beam. The gas flow from the nozzle generates a pressure gradient on the material surface, which is coaxial with the nozzle itself. If the nozzle and the focused laser beam are coaxial, the cutting zone established by the beam will lie directly under the central core of the gas jet and there will be uniform lateral gas flow. Figure 9 (a) illustrates the equilibrium set up if the gas jet and laser beam are coaxial. However, nozzle-laser beam misalignment (see figure 9 (b)) leads to an overall directional gas flow across the top of the cut zone which can lead to unwanted cut edge burning and dross adhesion.

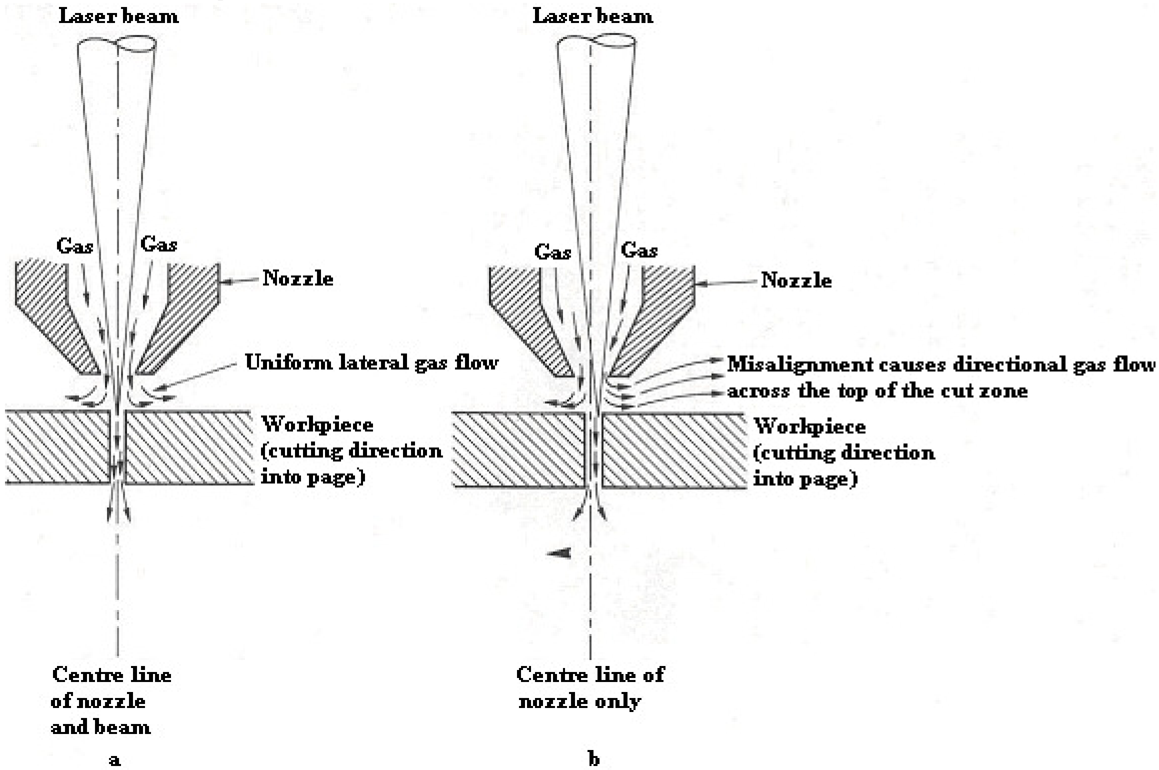

Figure 9: (a) The equilibrium set up when the gas jet and laser beam are coaxial
(b) Nozzle-laser beam misalignment.

However, previous studies have shown that an off-axis nozzle arrangement has some considerable advantages over the coaxial nozzle-laser beam arrangement. When coaxial gas nozzles are applied, the nozzle diameter is considerably larger than the cut kerf therefore the pressure losses in the kerf are larger than those in the nozzle. Since the preferable nozzle standoff distance should be in the range of 0.3mm or more, most of the gas flows out in between the nozzle and the workpiece and expands uniformly in all directions. The radial velocity of the gas is zero in the centerline of symmetry and then increases as the gas is expanding. The radial flow affects the gas flow down into the kerf so that the flow down into the kerf is largest if the laser beam is in front of the centerline of the nozzle and smallest if the laser beam is behind the centerline. Therefore, a nozzle arrangement where the laser beam is in front of the centerline of a coaxial nozzle is more efficient than a normal coaxial nozzle-laser beam alignment. It has been shown that the cutting range wherein good cut qualities can be obtained is expanded by utilizing off-axis beam arrangement compared to co-axial laser beam and gas jet. Additionally, the gas consumption is lower for off-axis cutting than for on-axis cutting.

Material properties

The laser is used to cut a wide range of engineering materials, which include metals such as mild steel, titanium and stainless steel, as well as nonmetallic materials like ceramics, glass, wood, paper and plastics. Cutting of metals requires higher power densities to melt the material but lower power densities are required for cutting of non-metals. The focused laser radiation that strikes the metal surface is partly absorbed and partly reflected by the metal surface. The fraction of the incident laser power absorbed, determined by the reflectivity of the metal surface, varies as the material heats up partly due to the temperature dependence of the optical properties of the material and partly due to the changes in the surface appearance, metallurgical phase and interaction of the incident light with ejected particulate and gaseous material near the surface. The thermal and physical properties of the material are important in choosing the right laser-material combination as well as the process parameters.

Thermal properties

The efficiency of laser cutting depends on efficient energy coupling into the material; therefore, the thermal characteristics of the material play a vital role in determining both the ability of the laser to cut and the quality of the cutting process.

The high reflectivity of some metals to infrared laser light can lead to difficulties with initiation and maintenance of the cutting process. During cutting of metals with high thermal conductivity, the heat is transported rapidly from the cutting front therefore high power levels or low cutting speeds are required to maintain a cutting front. However, reducing cutting speed causes instabilities that can result in abnormal molten regions, blowouts and poor edge quality. Greater amount of energy is required for cutting of materials with high values of specific heat capacity and those materials with high latent heats of melting and vaporization.

Physical properties

The surface conditions such as presence of grease or paint may interfere with the cutting process resulting in unpredictable performance. Changes in scale thickness or the presence of rolled-in defects and grooves are detrimental to edge quality. However, the presence of a thin, uniform oxide layer can facilitate absorption of the laser beam and improve cutting performance.

Molten materials with high values of surface tension and low viscosity are more difficult to remove from the cutting front by the assist gas resulting into adherent dross on the underside of the cut. The plate thickness determines the relationship between the rate at which cutting can be performed and the incident beam power for a given set of processing parameters.