Laser cutting technology: applications, techniques – a review

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Abstract: Laser beam cutting is a highly efficient, non-contact method that offers production flexibility and enables precise shaping of various sheet materials. Due to these advantages, industries are increasingly adopting laser machining. This study investigates the effects of material type, workpiece thickness, cutting speed, and assistant gas pressure on cut quality in industrial applications using a CO_2 laser. The research focuses on AlMg3 aluminum alloy, St_37-2 low-carbon steel, and AISI 304 stainless steel, which represent common industrial materials and provide insights into different processes (such as inert-assisted fusion cutting and oxygen cutting) and their absorption behaviors with CO_2 laser wavelength. The research aims to enhance understanding of the interactions between laser cutting parameters and workpiece characteristics, with the goal of identifying general criteria and optimized process parameters for ensuring kerf quality. Cut quality assessment is based on kerf geometry, surface roughness, and cut edge quality. The study employs a systematic experimental design approach, with results validated through Analysis of Variance. Quality evaluation is presented and discussed, supported by visual inspections that confirm overall good quality and minimal laser cut imperfections. The experimental investigation demonstrates that various materials can be effectively processed across the range of tested values. Furthermore, optimal cutting conditions meeting quality standards for each material were determined. This research addresses both phenomenological and practical aspects of laser beam cutting.

Keywords: aluminum alloy; stainless steel; nitrogen; ANOVA; CO_2 laser

1. Introduction

Nowadays, Laser Beam Cutting (LBC) is the go-to industry choice for cutting various sheet materials. Laser machining can handle a wide range of materials, including metals, composites, and ceramics. This capability stems from the thermal nature of the laser process, which depends on the material's thermal behavior rather than its mechanical properties. The laser beam provides thermal energy, converting it into heat. The beam focuses on a small spot on the material's surface and, as electromagnetic radiation, it doesn't involve mechanical cutting force, tool wear, or vibration. Thus, LBC is suitable for cutting hard or brittle materials.

The laser beam interacts with the material's electrons, and some of the energy is absorbed, causing a highly localized rise in temperature up to melting, vaporization, or chemical state change. These physical phenomena mainly depend on the material's chemical and physical properties, as well as laser characteristics like wavelength and power density.

Melting cutting is the most common method for metal cutting, while vaporization cutting is used for materials with low vaporization energy and high irradiation lasers. Chemical state change cutting is used for some organic materials when temperature increase leads to the rupture of chemical bonds.

CO_2 gas lasers and solid-state lasers are the most established types for industrial metal cutting. CO_2 gas lasers are widely adopted for their high output power and good beam quality, while solid-state disk and fiber lasers offer advantages like high power efficiency, ease of beam guidance, high beam quality, and shorter wavelength. The choice depends on the material's absorption characteristics.

The main limitation of LBC is the high temperature reached during the process, causing thermal damage to the material, such as the formation of Heat Affected Zone, recast layer, drag line, and slag attachment.

2. Working Principle

Madic et. al. [4] stated that laser cutting is a thermal, non-contact and highly automated process well suited for various manufacturing industries to produce components in large numbers with high dimensional accuracy and surface finish. They also stated that high power density beam when focused in a spot melts and evaporates material in a fraction of second and the evaporated molten material is removed by a coaxial jet of assist gas from the affected zone as shown in Figure 1.

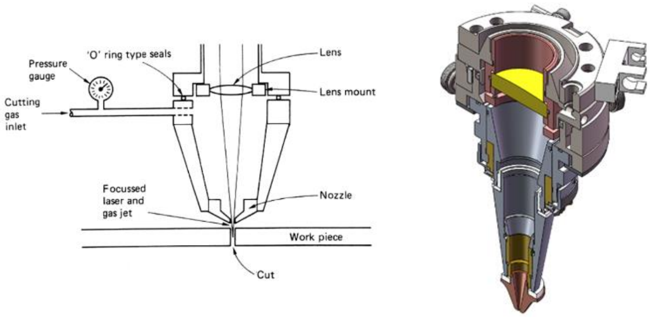


Figure 1. Classical gas assisted laser cutting

Before delving deeper into laser cutting, it's important to distinguish between conventional gas-assisted cutting and remote cutting. In conventional cutting, CO_2, fiber, disk, and Nd:YAG lasers—and more recently, direct diode lasers—serve as the energy sources to melt the material. An assist gas is then used to remove the molten material from the cut kerf. In contrast, remote cutting operates without an assist gas; instead, the evaporation pressure of the molten material generates thrust, ejecting the melt from the cutting zone. The rest of this discussion will focus on conventional gas-assisted laser cutting.

Key elements:

- Laser source: Commonly CO_2, Nd:YAG, and fiber lasers; recently, direct diode lasers are gaining use.
- Processing head: Consists of a gas nozzle and optical components, including a collimator and focusing lenses to concentrate the laser beam on the workpiece.
- Beam guidance: Mirrors for CO_2 lasers, while flexible optical fibers are used for fiber, disk, Nd:YAG, and direct diode lasers.
- Process gas: Nitrogen or argon as inert gases, and oxygen or air as reactive gases.
- CNC system: Used to displace the processing head and table in 2D flatbed cutting; for 3D structures, a robotic arm manipulator is employed.

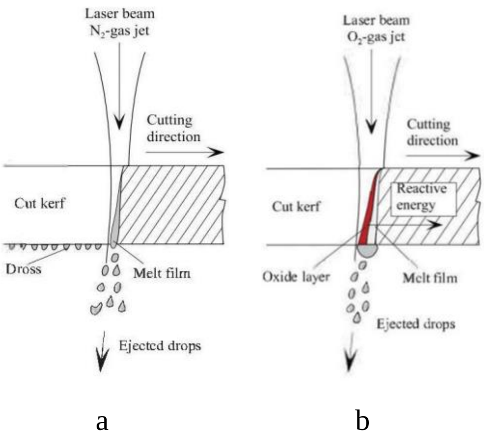


Figure 2 Sketch of the cutting front (side view) in (a) inert gas laser cutting and (b) oxygen gas laser cutting. (Kaplan (2009))

3. Process parameters

The laser cutting process has always been a major research area for achieving exceptionally good cut quality, such as reduced surface roughness, kerf width, and Heat Affected Zone (HAZ). The quality of the cut solely depends on the settings of process parameters like cutting speed, focal point, laser power, and assist gas pressure.

3.1 Surface Roughness:

Surface roughness is a critical parameter that effectively represents the quality of a machined surface. Studies have shown that:

- K.A. Ghany and M. Newishy [6] predicted that surface roughness decreases with an increase in cutting speed and frequency, while it is reduced by lowering laser power and gas pressure.
- Arun Kumar Pandey and Avanish Kumar Dubey [7] found that lower pulse frequency, higher cutting speed, and moderate gas pressure resulted in reduced surface roughness when laser cutting titanium alloy sheets.
- Riveiro et al. [8] illustrated the impact of laser power, gas pressure, pulsing frequency, and cutting speed on surface roughness (Figure 3). Their findings indicated that high cutting speeds and high laser power lead to improved quality.
- Stournaras et al. [9] also highlighted the significant influence of laser power and cutting speed on cutting quality, as their interplay determines the amount of heat introduced into the cutting regime.

In summary, the key factors affecting surface roughness are cutting speed, laser power, and gas pressure, which need to be optimized to achieve the desired cut quality.

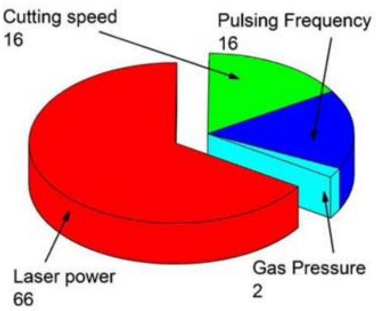
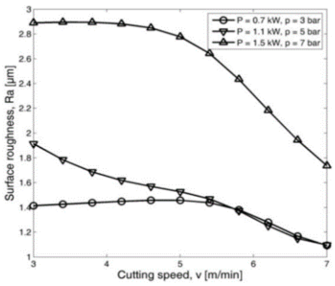


Figure. 3. Effect of each parameter on surface roughness [8]

Milos Madic and Miroslav Radovanovic [10] in their graph illustrated that surface roughness decreases with increase in cutting speed and increases with increase in assist gas pressure as shown in Figure 4 and Figure 5.



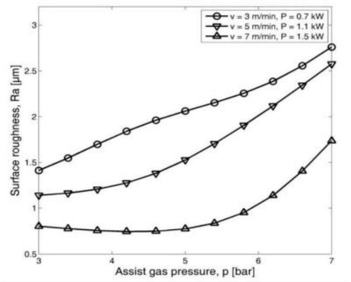


Figure 4. Surface roughness vs Cutting speed [10] **Figure 5**. Surface roughness vs Assist gas pressure [10]

Thawari et al. [11] observed that surface roughness decreases with an increase in cutting speed and frequency, as well as a decrease in laser power and gas pressure. Similarly, N. Rajaram et al. [12] concluded that high laser powers and lower feed rates resulted in better surface roughness. Milos Madic et al. [13] found that the optimal parameters for minimal surface roughness were: cutting speed at the highest level (7 m/min), assist gas pressure at the lowest level (3 bar), and laser power at an intermediate level (0.9 kW).

Sundar et al. [14] made the following conclusions regarding surface roughness:

- A decrease in assist gas pressure leads to a significant reduction in surface roughness.
- Higher cutting speeds produce lower surface roughness.
- There is a direct relationship between laser power and surface roughness, with the effect being more pronounced at lower power levels.
- The stand-off distance has a relatively minor impact on surface roughness.

Regarding kerf width, the kerf is a groove or slit where the lower and upper parts of the cut are typically not parallel, with the bottom being narrower than the top. Kerf width is measured along the entire cut line, and it is the difference between the starting width of the top profile and the ending width of the top profile. The same principle applies to the bottom surface (Figure 6).

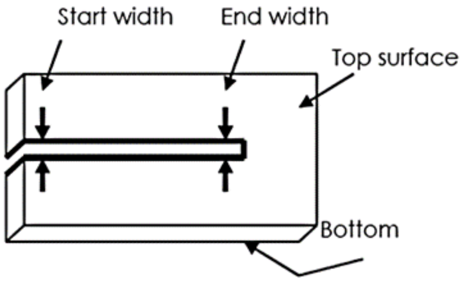


Figure 6. Kerf width measurements [14]

Thawari et al. [11] observed that the surface roughness value reduces with an increase in cutting speed and frequency, and a decrease in laser power and gas pressure. N. Rajaram et al. [12] concluded that high laser powers and lower feed rates resulted in good surface roughness. Milos Madic et al. [13] found that the optimal parameters for minimal surface roughness were: cutting speed at the highest level (7 m/min), assist gas pressure at the lowest level (3 bar), and laser power at an intermediate level (0.9 kW).

Sundar et al. [14] made the following conclusions regarding surface roughness:

- Decreasing the assist gas pressure shows a significant reduction in surface roughness.
- Higher cutting speeds produce lower surface roughness.
- There is a direct relationship between laser power and surface roughness, with the effect being more pronounced at lower power levels.
- The effect of stand-off distance on surface roughness is relatively minor.

Regarding kerf width, it is worth noting that in laser cutting, the cut edges will never be completely square, but the side walls tend to form a slight V-profile. The kerf width generally decreases along the cutting direction due to heat accumulation at the inlet of the laser beam. To consider the widening of the kerf, suitable measurements were taken at different heights starting from the upper surface of the specimens, as illustrated in Figure 7. In particular, six measurements of the kerf width were collected from the upper workpiece surface (top kerf, Tk) and the same number were acquired from the workpiece bottom surface (bottom kerf, Bk) proceeding in the beam direction. Additionally, the taper angle (Ta) and the section of material removed (S) were computed using Equations (1) and (2).

$$T_a = tan^{-1}[\frac{(T_k - B_k)}{2t}] \qquad [°] \qquad (1)$$

$$S = \frac{(T_k + B_k) \cdot t}{2} \qquad [\mu m^2] \qquad (2)$$

Kerf is a groove or a slit or a notch usually the lower and upper part of the cut is usually not parallel, it will be narrow at the bottom than the top. Kerf width is measured along the whole cut line of the width as shown in Figure 5. It is the difference of starting width of the top profile to the ending width of the top profile. This same applies to the bottom surface. [14]

Dhaval P. Patel and Mrugesh B. Khatri [15] identified that kerf width generally increases with higher assist gas pressure and laser power, while it decreases with increased cutting speed. Similarly, Ghany, K.A. and Newishy [16] observed that an increase in frequency leads to a reduction in kerf width.

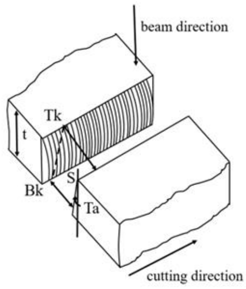


Figure 7. Schematic of kerf geometry.

Yilbas [17] examined the effects of laser output power and cutting speed on the resulting kerf size at the workpiece surface. Figure 8 illustrates the variation of kerf width with cutting speed and laser output power. As shown in Figure 9, kerf width increases with higher laser power but decreases with higher cutting speeds.

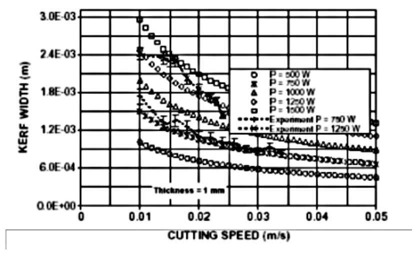


Figure 8. Variation of the kerf width with cutting speed [17]

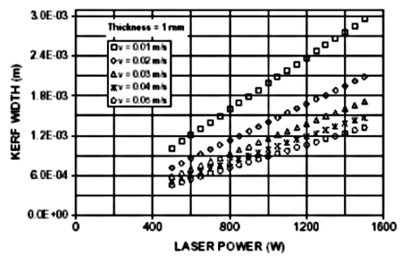


Figure 9. Variation of the kerf width with laser output power [17]

3.2 Heat Affected Zone (HAZ):

The thermal heat of the laser cutting process produces a heat-affected zone (HAZ) next to the cut edge. The heat-affected zone is the part of the material whose metallurgical structure is affected by heat but is not melted.

Rajaram et al. [11] investigated the combined effects of laser power and cutting speed on the size of the HAZ in CO_2 laser cutting of 4130 steel. It was found that an increase in cutting speed and a decrease in laser power resulted in a decrease in the width of the HAZ.

Sheng et al. [18] showed that the HAZ increases with increasing laser power, as shown in Figure 10. On the other hand, it was found that the HAZ decreases with increasing cutting speed, as shown in Figure 11.

In summary, the key factors affecting the size of the heat-affected zone are laser power and cutting speed. Increasing the cutting speed and decreasing the laser power can help reduce the width of the HAZ, which is desirable for achieving better cut quality.

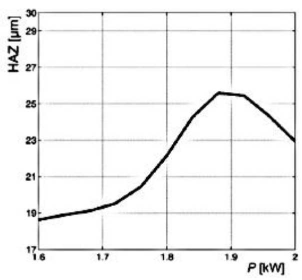


Figure 10. Effect of the laser power on the width of HAZ [18]

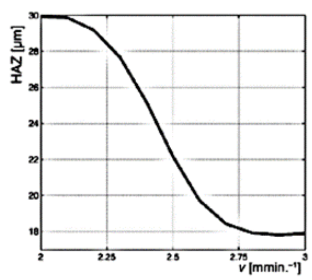


Figure 11. Effect of the cutting speed on the width of HAZ [18].

Paulo Davim et al. [19] conducted an experimental study on CO_2 laser cutting of polymeric materials and observed that the heat-affected zone (HAZ) increases with higher cutting speeds, as shown in Figure 12.

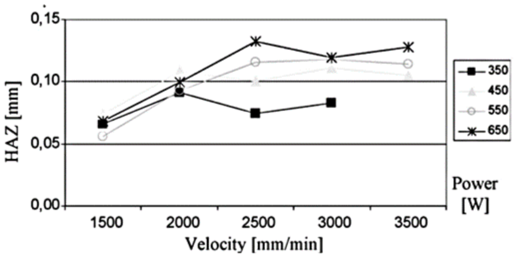


Figure 12. Dimension of HAZ (mm) of PMMA in function of cutting velocity for several power laser [19]

In contrast, Dhaval P. Patel and Mrugesh B. Khatri [15] performed an experimental investigation on CO_2 laser cutting of mild steel and stainless steel, and they identified that the size of the HAZ decreases with an increase in cutting speed, as illustrated in Figure 13.

So while the findings of Davim et al. showed that the HAZ increases with higher cutting speeds for polymeric materials, the work of Patel and Khatri revealed the opposite trend for mild steel and stainless steel, where the HAZ size decreased as the cutting speed was increased.

These contrasting results suggest that the relationship between cutting speed and HAZ size may depend on the specific material being cut, and further investigation may be needed to fully understand the underlying mechanisms.

Hanadi G. Salem et al. [20] found that the heat-affected zone (HAZ) width increases with higher laser power, but decreases with higher scanning speeds and gas pressures, as shown in Figure 14.

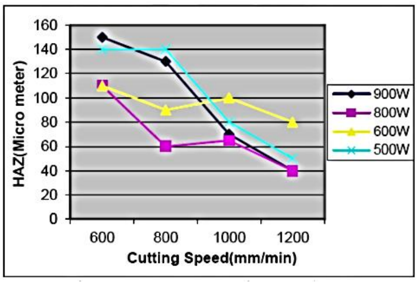


Figure 13 HAZ Vs Cutting speed [15]

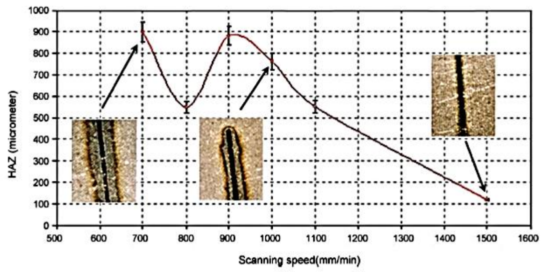


Figure 14. HAZ vs Speed [20]

4. Conclusion

The work presented here provides an overview of research on the laser cutting process. Based on the discussions above, the following key points can be concluded:

- The laser cutting process is capable of precisely and accurately cutting complex profiles in a wide range of materials.
- The performance of the laser cutting process is influenced by the input process parameters, such as laser power, cutting speed, and assist gas pressure, as well as the critical performance characteristics, including surface roughness, heat-affected zone (HAZ), and kerf width.
- This paper presents an overview of recent experimental investigations on laser cutting of various engineering materials, focusing on cut quality aspects like surface roughness, HAZ, and kerf width. It identifies the most common process parameters and cut quality characteristics studied in the research.
- The review highlights the importance of understanding the relationships between process parameters and the resulting cut quality to optimize the laser cutting process for different materials and applications.

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