

# Laser Beam Machining Techniques and Applications: A Review

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## Abstract

*Laser beam machining (LBM) is the most common thermal energy-based non-contact, non-conventional machining process. The non-conventional manufacturing processes are used to remove extra material using a variety of mechanical, thermal, electrical, chemical, or combinations of these energies without the use of sharp cutting tools as is required for conventional manufacturing. With innovative approaches to manufacturing processes, it has transformed a number of industries. It is frequently used to machine a nearly complete classification of materials. The metal materials include carbon steel, titanium, stainless steel, copper, aluminum, and alloys of these metals, whereas a majority of non-metal materials are plastics, ceramics, rubber, and wood. A laser beam is directed during this procedure to melt and vaporize the undesirable material from the base material. This method works well for cutting geometrically challenging shapes. On sheet metal, a variety of machining operations, such as micromachining, cutting, and drilling, are readily and precisely performed. By examining several process parameters that have an impact on the quality characteristics, researchers have recently investigated a variety of strategies to enhance the performance of the LBM process. The proper selection of material parameters (type, thickness, optical and thermal properties), operating parameters (assist gas pressure and cutting speed), and laser parameters (power, pulse width, frequency, modes of operation, pulse energy, wavelength, and focal position) can all greatly improve process performance, according to experimental studies. The primary factors influencing laser cutting quality are the laser power, pulse frequency, cutting speed, and focus location. In this paper detailed review of available literature is carried out to study the effect of LBM on different metallic materials like AISI 304, advanced high-strength steels (AHSS), EN43, mild steel, stainless steel, EN 1.4301, titanium alloy, alloy steels 1.4571, mild steel, alumina, and 22MnB5 steel.*

**Keywords:** Laser beam machine, process and performance parameters, micromachining, LBM process, AHSS

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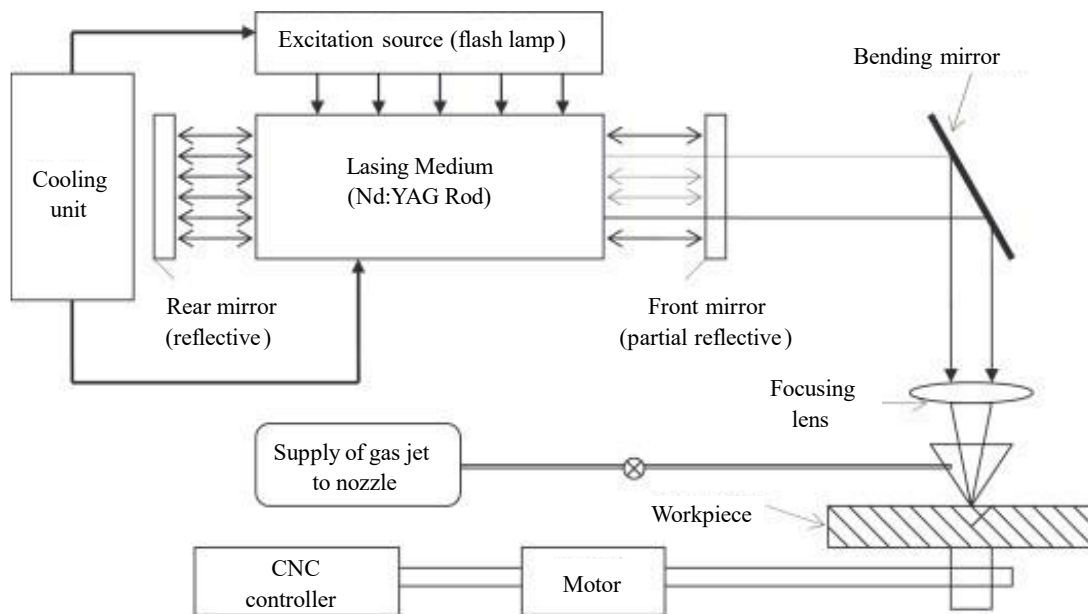
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## INTRODUCTION

A sophisticated machining technique, known as laser beam machining (LBM), uses heat energy. It involves the removal of the material through (a) melting, (b) vaporization, (c) sublimation, and (d) chemical deterioration, which results from the broken chemical bonds of the materials. Thermal energy is absorbed when a high-energy-density laser beam is directed onto the work surface. When a high-pressure assist gas jet is used to remove the heated work volume, it becomes molten, evaporates, or undergoes chemical changes that facilitate the removal. The gas jet accelerates the converted material and forces it out of the machining zone. The LBM focuses on material processing and machining, including heat treatment, sheet metal bending, alloying, and cladding.



**Figure 1.** Schematic of Nd laser beam-cutting system [1].

One of the AMPs used to shape practically every type of engineering material is LBM. Laser beams are frequently used for cutting, drilling, welding, marking, sintering, and heat treatment [1]. Although lasers can also be used for turning and milling tasks, their primary purpose is to cut sheets made of metal and non-metal. Figure 1. Schematic of the Nd laser beam-cutting system [1].

## APPLICATIONS

LBM is widely used in the fields of transportation, aerospace, electronics, civil engineering, nuclear energy, and home appliances. Stainless steel, a distinctive technical material used in cars and home appliances, is ideal for cutting using laser beams. Advanced high-strength steels (AHSS) are employed in the car industry and boiler operations. Lasers are utilized to cut the titanium alloy sheets used in the aerospace sector to create the front compression section of jet engines. One of the most promising materials for laser machining implantation is the aluminum alloy used in aeronautics.

## LITERATURE REVIEW

Research has been conducted on the joint effect of power and feed rate on surface roughness, striation frequency, kerf width, and size of the heat-affected zone (HAZ) using samples of 4130 steel cut using a CO<sub>2</sub> laser cutting system. Models that explain how independent process parameters affect the quality of laser cuts were created using regression analysis. Power was found to have a significant impact on the kerf width and size of the HAZ for a variety of operational circumstances evaluated, whereas feed rate effects were secondary [2]. Stainless steel has a high melting point and produces oxides that have low viscosities, which are important technical materials that are challenging to cut using oxy-fuel techniques. However, they can be cut using a laser. Using a pulsed and continuous-wave (CW) Nd:YAG laser beam, as well as nitrogen or oxygen as assistance gases, Ghany et al. analyzed the optimum laser cutting parameters for 1.2 mm austenitic stainless steel sheets. The primary factors influencing the laser cutting quality are the laser power, pulse frequency, cutting speed, and focus location [3]. Steel sheets cut with a CO<sub>2</sub> laser were taken into consideration, and the effect of the thickness of the workpiece and beam waist position on the formation of striations was investigated. The kerf width was modeled using a lump parameter analysis. The cut surfaces were examined by scanning electron microscopy (SEM) and optical microscopy. It was discovered that the placement of the beam waist had a considerable impact on the size of the kerf, and when the thickness of the workpiece decreased, the relative location of the beam waist changed for the minimal kerf width [4]. Two laser cutting processes, fusion cutting of stainless steel with a neutral assist gas and oxygen-assisted cutting of low carbon steel, were examined to compare

the fiber and CO<sub>2</sub> lasers. The amount of material removed was assessed in relation to the absorbed laser energy for the cutting parameters that corresponded to the lowest roughness of the cut surface. When cutting stainless steel using a fusion process, the minimum roughness is attained at the highest cutting speed [5]. Using laser cutting, complicated geometries can be achieved in a variety of dimensions with great precision, as well as a high degree of process parameters and cut-material-type flexibility. The two more competitive laser cutting technologies are based on the use of CO<sub>2</sub> and active fiber sources, which generate visibly distinct samples with uneven surfaces and varying striation depths [6].

This paper presents work on process optimization for cutting thick stainless steel (AISI SS304) sheets with pulsed Nd:YAG lasers in dry air and underwater environments. A 500 W average power long pulse Nd:YAG laser system with fiber-optic beam delivery was used in laser cutting experiments. Compared to conventional dismantling techniques, these findings will be helpful in the laser-based deconstruction of ancient steel structures in radioactive and underwater environments to reduce radiation dose consumption and save time [7]. The flow properties of the 10 mm stainless steel AISI 304 (EN 1.4301) laser-cut fronts were analyzed using high-speed imaging (HSI). Laser-cut samples were generated using a 6 kW fiber laser and nitrogen gas assist. The findings indicate that a thin layer of liquid is present on the bumps that cover the cut front created while cutting stainless steel using a fiber laser and nitrogen assist gas [8]. Using the design of experiments, the variation in the laser-cut quality with varied process parameters was investigated within the operational zone. By utilizing a three-level Box-Behnken design, the response surface methodology (RSM) is utilized to reduce the variation in cut quality and identify ideal process parameters for the required quality [9]. The laser-cut fatigue behavior of metastable austenitic stainless steel AISI 304 sheet-like samples was investigated by Pessoa et al. Based on these investigations, it was determined that three types of macroscopic defects were produced by laser beam-cutting: a burr on the underside of the cut edge, pores within the recast layer or at the interface between it and the base material, and a conspicuous relief-like pattern along the cut surface [10]. Maximum speeds of 150 m/min were used to cut the thicknesses of the electrical, aluminum, and high-strength steel sheets. The cutting quality was analyzed in terms of the kerf width, burr development, and cutting-edge look [11].

When cutting a sheet of 3 mm stainless steel (SS) (ASTM 304), Dhrupal et al. performed a parametric analysis of the process parameters for the fiber laser cutting system on the surface characteristics of the cut portion. The workpiece surface roughness and top kerf width, such as the gas pressure, cutting speed, and laser power, were considered when analyzing and optimizing the factors for laser cutting. All three parameters were examined using the design of experiments (DOE) method. It was shown that laser power, rather than the cutting speed and gas pressure, had a greater impact on the responses [12]. Using a Taguchi-Grey relational approach, Muthuramalingam et al. investigated the impact of process variables on the surface performance of titanium alloys. Owing to the relevance of plasma energy, it has been discovered that laser power has a significant influence on the taper angle and surface roughness quality measurements. Because of the emergence of microcraters with less particle adhesion, the lower nozzle distance and higher laser power produce surfaces with lower surface roughness [13]. To assess the impact on the taper angle, surface roughness (Ra), and HAZ, researchers used a hard die steel plate (EN-31, 10 mm thick) and investigated the effects of process variables such as cutting speed, laser power, frequency, duty cycle, and gas pressure. Second-order mathematical models with RSM were developed and compared to experimental results. The main effect plot shows that the taper angle is significantly influenced by cutting speed, laser power, and frequency [14].

An experiment was conducted in a manner similar to the simulation settings. Morphological and metallurgical alterations in the laser-treated region were investigated using optical and SEM. The residual stress generated in the radiation-damaged area was measured using the X-ray diffraction (XRD) technique. It was discovered that the predicted residual stress and the measurement results agreed. High von Mises stress levels are caused by rapid heating and cooling of the surface area [15]. Using nitrogen as an assist gas, Cekic et al. employed mathematical models to forecast the surface roughness and the

width of the heat-influenced zone when cutting alloy steels 1.4571 and 1.4828 with a laser. Four independent variables were utilized in a multiple regression analysis to create proper mathematical models. The cutting process is not significantly affected by minor variations in the assist gas pressure, and the cutting speed is inversely related to material thickness [16].

The workpiece surface roughness was considered during the examination and adjustment of the laser cutting parameters, such as the gas pressure, cutting speed, and laser power. The ideal surface roughness value was ascertained by utilizing the RSM, DOE, and analysis of variance (ANOVA) techniques on the laser cutting components. The analysis revealed that the laser power, rather than the cutting speed and gas pressure, has a greater impact on the responses [17]. Lum et al. studied a laser-processed medium-density fiberboard (MDF). Results for cutting in both pulse mode (PM) and CW are presented, and the implications on cut quality that accompany them are discussed. Laser-cut MDF can achieve small kerf widths [18]. Hastelloy-X sheet with a thickness of 1 mm was cut using a pulsed Nd:YAG laser. A typical cutting regime was created, and the extent of spot overlap was discussed. The investigation and correlation with the established processing regime were performed on the features of single holes that were drilled using the same process parameters as those used for cutting. Spot overlap is a key factor in pulsed Nd:YAG laser cutting that significantly influences the cut quality characteristics, including kerf width, surface roughness, and surface morphology [19]. To achieve the striation-free laser cutting of EN43 mild steel sheets with a thickness of 2 mm, Lin et al. In this experiment, a 1 kW single-mode fiber laser was employed. High-speed striation-free laser cutting is possible under certain operating conditions. A theoretical model was used to determine the threshold cutting speed at which the striation-free cutting occurred. It is also noted that the surface roughness and striation return increase with speed when cutting at speeds higher than the critical cutting speed, a hitherto unrecognized phenomenon [20].

Grum et al. used a photodiode to measure infrared light emissions from the cutting front, statistically assessed the temperature data, and optimized the laser cutting procedure based on a critical cutting speed. Based on calibration, the temperature signal from the observed infrared radiation was translated into a temperature that was associated with the development of macro- and microstructures, as well as the change in microhardness in the surface layer of the cut. Experimental data demonstrated that the heat effects in the cutting front significantly affected the quality of the cut [21]. The dynamic behavior of melt ejection during laser cutting of a 1 mm thick titanium sheet was investigated by Rao et al. to obtain dross-free cuts with a minimal heat-impacted zone. The titanium sheet was cut using a CO<sub>2</sub> laser in CW and pulsed modes using a variety of shear gases, including argon, helium, and nitrogen. For laser cutting, dross-free cuts with no appreciable HAZ were produced by the laser's high-frequency and low-duty-cycle PM operation. [22]. Pramanik et al. investigated the relationship between process parameters, such as duty cycle, cutting speed, pulse frequency, power setting, sawing angle, and the surface roughness of stainless steel. The experimental validation of the suggested model demonstrates that the desired surface roughness can be produced by optimizing appropriately chosen controllable process parameters [23].

Zhang et al. developed an adaptive neural fuzzy inference system (ANFIS) model that combines the neural network's adaptive learning capacity and the fuzzy inference system's experience-based knowledge. Accurate forecasting of the level of laser cutting roughness and raising the standard of laser cutting. The effect of the process parameters on the laser cutting roughness was investigated to compare the predictions generated using laboratory data with those made using the BP neural network model. The findings demonstrate that the convergence speed of the ANFIS model is faster, and its prediction values are consistent with its observed values [24]. The Taguchi method was used to design the tests, after which some of them were performed and others were approximated using a backpropagation neural network (BPNN) method. Finally, the optimal robust data envelopment analysis (RDEA) model is used to choose the best combination of quality parameters. Trials were carried out using CO<sub>2</sub> laser cutting equipment to demonstrate the potential of the suggested approach [25].

An attempt was made to reduce the kerf width and kerf ratio when cutting mild steel with a CO<sub>2</sub> laser. The cutting speed, power, and gas pressure were considered when using the Box-Behnken design to conduct the trials. In comparison with other elements, power was shown to be the most significant factor. 1 kW of power, 0.15 bar of gas pressure, and 1.3 m/min of cutting speed were the best operating parameters [26]. The improvement in the flexural strength of 0.63 mm thick alumina during single-mode fiber laser cutting for electrical applications was presented by Adelman et al. The position of the focus has the greatest impact on the strength, according to the results of the optimization through the DOE [27]. The cutting speed affects the HAZ and surface roughness of AISI316L stainless steel laser cutting. While keeping the other process variables constant, the test samples were cut at various cutting speeds. The surface roughness of each test sample was measured at multiple points along the cutting depth. Images of the cut surfaces were captured using a stereoscopic microscope with a camera. The impact of cutting speed on the surface roughness and HAZ was examined and discussed, and conclusions were drawn [28].

A 3.5 kW CO<sub>2</sub> laser source was able to cleanly cut commercial black granite boards that were 10 mm thick. Statistically designed trials were used to evaluate the cutting quality in terms of kerf width and cut wall roughness. The findings show that with the use of a supersonic nozzle, cutting granite boards could be a new usage for CO<sub>2</sub> laser cutting equipment [29]. The cutting characteristics of austenitic stainless steel were examined using AGF laser cutting with a 2 kW CO<sub>2</sub> laser. To investigate the effect of these parameters on the cutting characteristics, the laser power and cutting speed were varied. As a result, AGF laser cutting was able to cut austenitic stainless steel without producing any dross [30]. To choose the best operational settings, the impact of laser power, gas pressure, cutting speed, and focal point position on the CO<sub>2</sub> laser cutting of polymethylmethacrylate (PMMA) sheets of various thicknesses was investigated. Therefore, to determine the influence of each element and establish the ideal ranges of process parameters for producing flat kerfs without streaks or surface flaws, a design experiment (DOE) of the response surface type was conducted. The value of KPD is predicted using an artificial neural network (ANN)-based model that considers all the factors affecting cutting as well as other classification criteria used to categorize the stage of profile deviation. This study demonstrated that ANN, and more specifically, the MLP-based model, is a reliable way to forecast the value and trend of KPD when various cutting and status characteristics are considered [31].

The effects of cutting power, speed, and assisting gas pressure during the continuous CO<sub>2</sub> laser cutting process on the burr and roughness of the workpiece were investigated. Statistical tools were used to conduct analyses. To assess the level of influence of the parameters and any potential interactions, factorial arrangements based on the gathered data were created using the experimental design methodology. In conclusion, the key variables influencing burr and roughness formation in the laser cutting of ABNT 1045 steel are cutting speed and assist gas pressure [32]. The simulation test findings in this study demonstrate that the simulated material removal rate (MRR) values utilizing neural network models are reasonably close to the values computed using theoretical equations. An ANN approach was built for the vertical laser cutting position to represent the relationship between cutting quality and cutting specification. ANN produces excellent results for adjusting parameters, analyzing cutting results, and predicting fresh cutting data [33]. The optimal working and cutting conditions for a variety of AHSS are discussed in this article. The results of a study on the elements that affect the cutting sheet metal were divided into two significant groups with thicknesses of more and less than 1 mm. The effects of the material and, more importantly, the coating was both considered. These findings indicate that the thinnest and thickest sheets act differently, but the influence of the material on the change in cutting parameters is less significant. The ideal cutting zones and quality were assessed using various factors. Under the sheet, was determined to be the ideal spot for the laser beam [34]. In cutting 22MnB5, very high-strength steel, this study examined the kerf width and HAZ. A 4 kW Carbon Dioxide (CO<sub>2</sub>) laser system with a 10.6 m wavelength and a 0.2 mm laser spot size was used to cut the samples using a three-level Box-Behnken design of the experiment. Peak power, cutting speed, and duty cycle were the three components that developed RSM. The settings were optimized for

HAZ formation and the lowest kerf width. A MITUTOYO TM 505 gadget was used to visually measure the kerf width and HAZ.

This research suggests that, after the cutting speed and laser power, the laser duty cycle plays a significant role in influencing the cut quality of ultra-high-strength steel. The smallest HAZ region and narrowest kerf width generation are caused by low power intensity with continuous waves [35].

### Process Parameters

The wavelength, power intensity, spot size, pulse or CW laser power, focal position, process gas pressure, nozzle diameter, stand-off distance, and cutting speed are some of the process parameters.

### Performance Parameter

MRR, surface roughness, surface hardness, kerf width, and HAZ are critical LBM performance attributes.

### CONCLUSION

In this work, an effort was made to review LBM research on advanced materials. The conclusions of the LBM review are as follows:

- One of the most popular non-conventional machining techniques is LBM, which can produce complicated and exact geometries with a very small tolerance.
- The LBM performance is influenced by the laser, material, and process parameters.
- Important performance parameters for LBM investigation include the kerf width, HAZ, kerf taper, surface roughness, recast layer, and dross adherence.
- In-depth studies are needed because not much work is available for machining thick materials.
- For future research, more focus should be given to optimizing the laser cutting parameters to reduce HAZ, kerf width, dross, and surface roughness.

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