International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating: 5.29
IJABR 2024; 8(2): 757-762
www.biochemjournal.com
Received: 15-01-2024
Accepted: 27-02-2024

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Laser technology applications in agricultural machinery design: A comparative study with conventional methods

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DOI: https://www.doi.org/10.33545/26174693.2024.v8.i2i.4185

Abstract
Laser technology has emerged as a transformative tool in modern manufacturing, offering high precision, speed, and versatility. In the context of agricultural machinery design, lasers provide significant advantages over traditional manufacturing techniques especially in cutting, welding, engraving, and shaping metal components used in equipment production. This paper explores the application of laser-based processes such as CO_2 laser cutting and laser welding in fabricating parts for agricultural machines. It also compares these processes with conventional methods like CNC routing, particularly in terms of material efficiency, operational cost, sustainability, and processing time. The non-contact nature of laser operations reduces tool wear and minimizes maintenance requirements, making it ideal for continuous production cycles. However, achieving optimal results requires careful selection of parameters such as laser power, focal length, gas pressure, and cutting speed since each metal or alloy used in agricultural machinery has unique physical and chemical properties. This review emphasizes the potential of laser technology to enhance the manufacturing process in agricultural equipment design while also addressing its limitations and future scope.

Keywords: CO_2 Laser, CNC machining, laser cutting, agricultural machinery, precision manufacturing, laser welding, sheet metal fabrication, sustainable design, material efficiency, manufacturing technology

Introduction

Since its inception in the mid-20th century, laser technology has undergone substantial evolution, progressively finding applications in various industries such as medical devices, electronics, textiles, and precision manufacturing. Over the last few decades, the integration of laser systems in manufacturing processes has significantly enhanced productivity, precision, and automation. Among these applications, the furniture manufacturing sector has notably benefited from laser-based techniques, particularly laser cutting and engraving, both of which enable clean, accurate, and flexible processing of a wide range of materials.

Laser engraving, a non-destructive technique used to inscribe text or decorative patterns, and laser cutting, which employs high-powered beams to slice through materials, have revolutionized the customization and production capabilities of both wooden and metallic furniture components. As demonstrated by Amaral *et al*. (2019) [29], optimized parameter control in fiber laser cutting directly enhances cut surface quality, promoting its adoption in precision-demanding applications. This becomes particularly relevant when dealing with metallic materials, which were traditionally expensive to process due to the complexity of machining and finishing. With advancements in laser processing enabling arbitrary pattern generation, variable depths and dimensions, high-speed performance, and burr-free edges these challenges are increasingly mitigated (Cristina Anghel *et al*., 2019) [31].

One of the critical motivations for using laser technology in furniture manufacturing is the growing demand for product diversification and personalization. Traditional mass production systems often fall short of accommodating the preferences of modern consumers who value uniqueness and multifunctionality in products. Laser systems allow for such customization at scale without compromising production efficiency, thereby bridging the gap between personalization and industrial throughput

Despite these advantages, laser processing is not universally applicable. Limitations arise based on material thickness, thermal conductivity, moisture content, and reflectivity. Additionally, laser systems must be meticulously calibrated to suit specific material characteristics to avoid undesirable thermal effects, such as charring or warping. This necessitates a hybrid approach where both conventional and laser-based technologies are strategically employed, depending on the material and design requirements.
Laser cutting can be broadly classified into three primary techniques: fusion cutting, flame cutting, and remote cutting. Fusion cutting employs inert gases like nitrogen to expel molten material, thereby ensuring clean edges with minimal oxidation. Flame cutting introduces oxygen to enhance thermal energy and cutting speed. Remote cutting, on the other hand, is utilized for thin sheet materials and does not require assist gases, making it suitable for contactless precision cutting.
Laser cutting typically involves focusing a high-power laser beam through lenses of specific focal lengths onto a precise location on the workpiece. This beam either melts or vaporizes the material in its path, with the beam or the workpiece moved under computer numerical control (CNC) to achieve desired geometries. Modern systems often integrate CAD/CAM software with multi-axis robotic setups, offering high degrees of automation and consistency in production (Choudhury & Shirley, 2009) [30].
Given these capabilities, laser technology is anticipated to progressively replace traditional machining methods, especially in the context of thin sheet materials and complex furniture geometries. This paper aims to present a comparative analysis of laser-based and conventional manufacturing techniques in the production of wooden and metal furniture, with a particular focus on thermal laser cutting versus mechanical vector cutting. Considering ongoing technological advancements and shifting consumer expectations, it is expected that the use of laser processing will continue to grow, particularly in the domain of sheet metal furniture manufacturing.

Laser Cutting
Laser cutting is a highly precise and adaptable thermal advanced machining process that removes material by means of intense localized heating. This technique utilizes a high-powered, coherent laser beam, which is focused along a predetermined cutting path, causing either melting or vaporization of the workpiece material. As the material is locally heated beyond its melting or boiling point, an assisting gas jet removes the molten or vaporized substance from the kerf, enabling clean and narrow cuts with minimal mechanical stress on the substrate. The method is applicable across a wide range of materials, including metals, polymers, ceramics, and composites, and is particularly valued for its high accuracy, minimal distortion, and automation compatibility.
The primary laser sources used in industrial cutting applications are CO_2 lasers and solid-state lasers, including Nd: YAG, fiber, and disc lasers (Powell, 1998) [11]. Each type has unique characteristics that determine its suitability for specific materials and configurations (Figure 1).

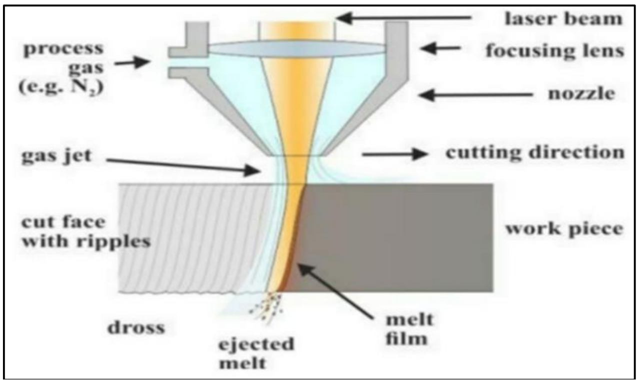


Fig 1: Laser Cutting Process

Types of Laser Sources and Their Characteristics
CO_2 lasers, operating at a wavelength of 10.6 µm, have traditionally dominated industrial laser cutting. These gas lasers offer high beam quality and cost-efficiency at elevated power levels, making them suitable for cutting thick ferrous and non-metallic materials (Figure 2). Their longer wavelength, however, prevents them from being transmitted through optical fibers, which limits their use in flexible robotic or automated environments (Zhou *et al.*, 2007) [15].

Process Parameters Comparison		
Parameter	**Present Condition**	**Optimal Condition**
Cutting speed [mm/min]	3500	3500
Power [W]	2000	2000
Efficiency [%]	100	80
Gas pressure [N/m²]	39227.6	39227.6
SN Ratio Comparison		
Condition	**SN Ratio**	
Present condition	-2.44334	
Optimal condition	-2.03871	

Fig 2: Optimal Condition

In contrast, solid-state lasers, such as fiber and Nd:YAG lasers, operate at shorter wavelengths (~1.05-1.07 µm), which can be transmitted through optical fibers, enabling their seamless integration into robotic systems and automated production lines. Their shorter wavelength also results in higher absorption rates in reflective and non-ferrous materials such as aluminum, titanium, and nickel alloys, significantly expanding their application range (Guerra & De Cuirana, 2017; Marimuthu *et al.*, 2019) [3, 10].
Fiber lasers, in particular, exhibit high electrical efficiency, minimal maintenance, and excellent beam quality, making them ideal for high-speed, high-precision cutting applications in advanced manufacturing sectors.

Laser Cutting Mechanism and Head Configuration
The laser cutting mechanism involves focusing the laser beam through a collimating lens assembly located in the cutting head, which converges the beam into a small spot often < 0.2 mm in diameter. This produces an energy density of ~1.4×10^{10} W/m², sufficient to melt or vaporize virtually any material. A coaxial gas jet, aligned with the laser beam, serves to assist material ejection and improve cutting efficiency (Figure 3).

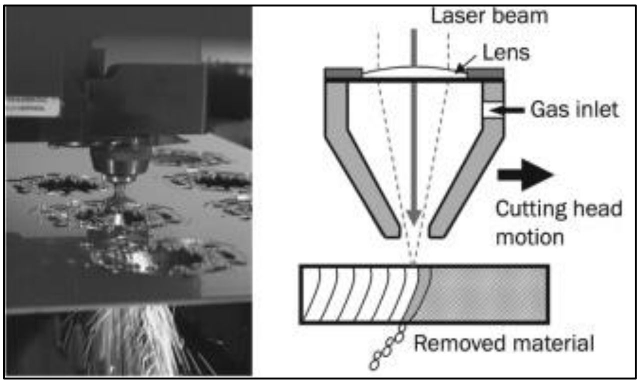


Fig 3: (a) Laser cutting of a stainless steel sheet; (b) scheme of a cutting head

In the case of ferrous metals, oxygen is commonly used as the assist gas. It reacts exothermically with the hot metal to generate additional heat, facilitating deeper and faster cuts. For non-ferrous metals and alloys, inert gases like nitrogen or argon are preferred to avoid oxidation and preserve material integrity (Yilbas, 2004; Boujelbene *et al*., 2018; Lim *et al*., 2006) [14, 2, 7].

Modern cutting heads incorporate capacitive sensors and feedback-controlled z-axes that maintain a constant stand-off distance between the lens and the workpiece, compensating for surface irregularities and ensuring a stable focal position (Ulrich Thombansena *et al*., 2014; Rodrigues *et al*., 2018) [13, 12].

Process Parameters and Control

Critical process parameters influencing laser cutting performance include:

- Laser power
- Cutting speed
- Focal position
- Assist gas pressure
- Beam mode (TEM_{00} vs multimode)

These parameters are intricately interconnected. For example, increasing laser power or reducing cutting speed generally leads to deeper penetration and wider kerf, but may also increase the heat-affected zone (HAZ) and surface roughness (Yilbas, 2004; Zhou *et al*., 2007) [14, 15].

Boujelbene *et al*. (2018) [2] analyzed the influence of power and speed on surface finish using the quadratic mean roughness (R_s) metric, reporting a direct relationship between energy input and roughness levels. Lim *et al.* (2006) [7] used the Taguchi method to optimize cutting parameters, identifying gas pressure as a dominant factor affecting edge quality and thermal load.

To address the multi-objective nature of laser cutting optimization, Madic *et al*. (2016, 2017) [8, 9] implemented multi-criteria decision-making (MCDM) techniques such as WASPAS, ANOM, OCRA, and Preference Selection Index (PSI). Their research demonstrates that optimal results are achievable only through balanced trade-offs between competing criteria such as material removal rate (MRR), kerf width, HAZ, and roughness.

Beam Configuration and Material Interaction

Recent innovations have introduced customized beam profiles, including annular and donut-shaped intensity distributions, which enable more uniform energy delivery along the cutting path. This leads to improved flank quality, reduced burr formation, and enhanced cutting efficiency, especially for thin-sheet applications (Hao Pang *et al*., 2020) [4].

Despite these advances, solid-state lasers may still underperform in surface smoothness compared to CO_2 lasers, especially when cutting thicker sections where the thermal profile is more complex (Rodrigues *et al*., 2018) [12]. Moreover, thermal lensing a phenomenon where the lens heats up during prolonged operation can cause a shift in focal position, leading to inconsistent kerf widths and reduced cut quality. Thombansena *et al*. (2014) [13] highlighted techniques to monitor and adjust for this focal shift in real-time to sustain process quality.

Energy and Environmental Considerations

Sustainability in laser cutting operations has gained attention due to the high energy demands and potential environmental impact of gas consumption and thermal emissions. Kellens *et al*. (2014) [6] proposed several strategies to enhance energy efficiency, including optimizing beam parameters, employing high-efficiency resonators, and reducing idle power consumption in machine tools.

Laser wavelength, beam polarization, and focusing strategies also affect energy utilization. Fine-tuning these parameters contributes to reduced energy waste, improved cutting precision, and lower carbon footprints (Rodrigues *et al*., 2018) [12].

Material-Specific Applications

Laser cutting is particularly beneficial for materials that are challenging to machine mechanically. For example:

- **Carbon Fibre Reinforced Plastics (CFRP):** Prone to delamination when machined conventionally, CFRPs respond well to laser cutting when parameters are carefully optimized. Xiong *et al*. (2012) [16] and Hasan *et al*. (2016) [5] demonstrated that lower power settings and controlled feed rates minimize defects.
- **Plastics, rubber, and wood:** CO_2 lasers offer excellent results for these non-metals, although issues such as fume generation, thermal charring, and edge discoloration must be managed (Zhou *et al*., 2007) [15].

Optimization Techniques

To achieve optimal cut quality and process efficiency, a variety of modelling and statistical optimization methods are used:

- Taguchi methods for robust design (Amaral *et al*., 2021) [1].
- MCDM techniques (Madic *et al*., 2016, 2017) [8, 9].
- Regression and artificial intelligence-based PSI modelling.

These methods enable precise tuning of parameters to achieve target objectives such as minimal HAZ, smoother surfaces, and faster processing times, ultimately leading to predictive capabilities for new material-laser combinations and enhanced sustainability.

Laser cutting technology in manufacturing

Laser cutting is a precise thermal process utilized to remove material by subjecting it to localized intense heating. This technique employs a high-powered, coherent laser beam that is focused onto a predetermined cutting path, where the material is either melted or vaporized. An assisting gas jet is used to remove the molten or vaporized material from the kerf, facilitating narrow, clean cuts with minimal mechanical stress on the substrate. The laser cutting process is highly versatile and can be applied to various materials, including metals, polymers, ceramics, and composites. It is particularly appreciated for its accuracy, minimal distortion, and compatibility with automated systems (Trumpf, 2000) [27].

The performance of laser cutting is influenced by various factors, including the type of laser used, the material properties, and the process parameters. The maximum cutting thickness achievable with CO_2 lasers, for example, varies depending on the power applied and the material being cut. Figure 4 & 5, illustrates the maximum thickness achievable at different CO_2 laser power settings for materials such as aluminium, stainless steel, and carbon steel (Trumpf, 2000) [27].

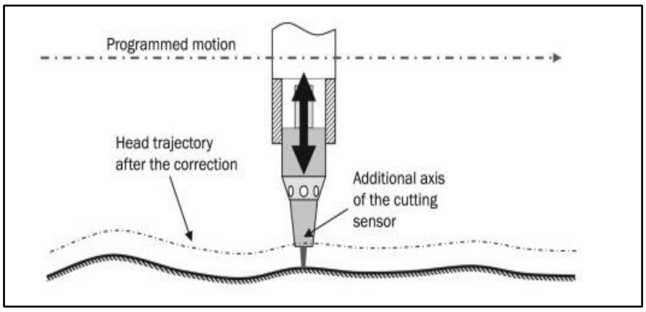


Fig 4: Compensation of the cutting head with capacitive sensor and additional axis

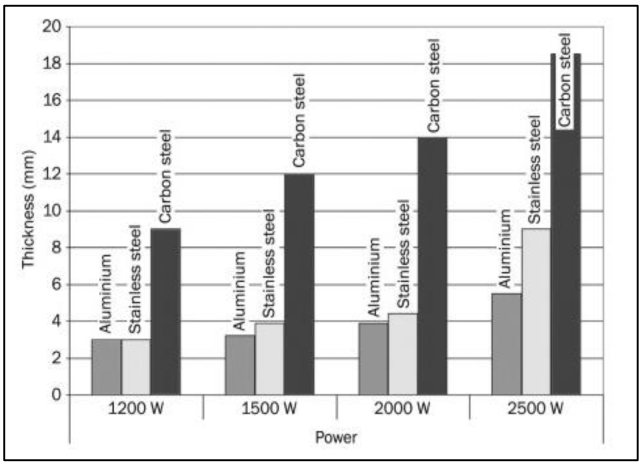
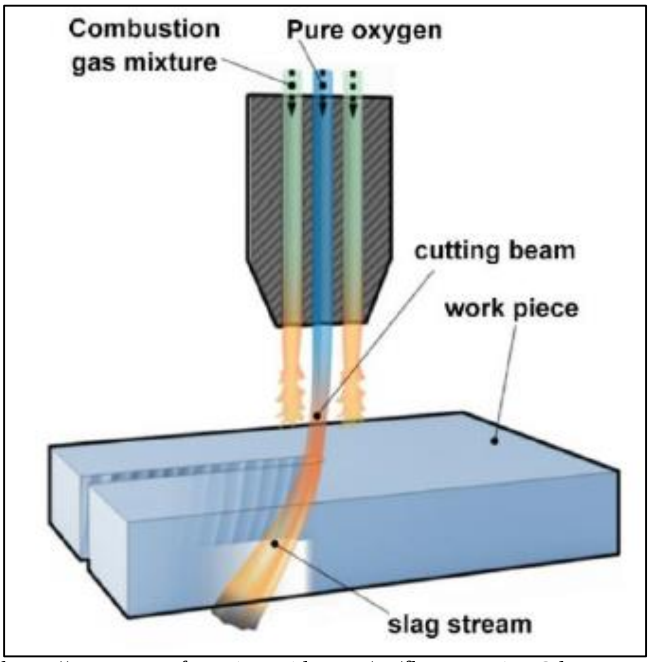


Fig 5: Maximum laser cutting thickness for different laser power

CNC Thermal Cutting Techniques

CNC thermal machines utilize focused beams from a nozzle to heat and manipulate materials for cutting, bending, or welding operations. These methods are predominantly employed in metal fabrication, with flame cutting being one of the most widely used techniques. Flame cutting, also known as oxy-fuel cutting, oxyacetylene cutting, or oxy-cutting, involves the use of a heated flame and an oxygen jet to ignite the material and cut through it (Development DO, 2007) [17]. The process operates in cold environments (below 10°C) and is particularly effective for cutting thick metal plates, ranging in thickness from 1 mm to 1000 mm. However, flame cutting is not suitable for materials like aluminium, bronze, and stainless steel, which resist oxidation (Figure 6).



https://www.manufacturingguide.com/en/flame-cutting-2d

Fig 6: Show flame-cutting system

Although flame cutting is efficient for cutting ferrous metals, it often results in residual strains and high tensile stresses along the cut edges, which necessitate additional treatments for achieving acceptable product quality (Jokiaho *et al*., 2020) [20]. Plasma cutting, which uses a jet of ionized gas to generate high temperatures, is an alternative that overcomes some of the limitations of flame cutting, particularly when working with metals such as aluminum or stainless steel (Nemchinsky, 2017) [24]. Plasma cutting operates at much higher speeds up to 10 times faster than oxy-fuel cutting while offering low noise and reduced heat exposure in the workplace. However, it may not be effective for processing very thin materials (Gani *et al*., 2021) [18].

One of the key advantages of plasma cutting is its ability to provide high-quality cuts with minimal heat-affected zones. For example, Liza *et al.* (2015) [21] used plasma cutting to create a coffee table from a 2-mm mild stainless-steel plate, achieving high accuracy with the help of a screw-type air compressor system and a high-capacity 120-ampere plasma generator.

Wire-Cut Electrical Discharge Machining (EDM)

Wire-Cut Electrical Discharge Machining (EDM) is another advanced cutting technique that uses eroding sparks from a continuously circulating wire as an electrode. The process, which occurs in a dielectric fluid, enables the removal of material along a programmed path. The wire anode can be made from materials such as copper, brass, molybdenum, steel-core, or tungsten, depending on the workpiece material, thickness, and required precision. EDM wire cutting is ideal for cutting thicker slabs and plates of metal with an excellent surface finish (Wasif & Tufail, 2022) [28]. However, controlling the accuracy of wire-cutting thickness can be challenging due to residual stresses and heating effects in the work piece (Figure 7 & 8), which may affect the accuracy of rough cuts (Nakagawa *et al*., 2020) [23].

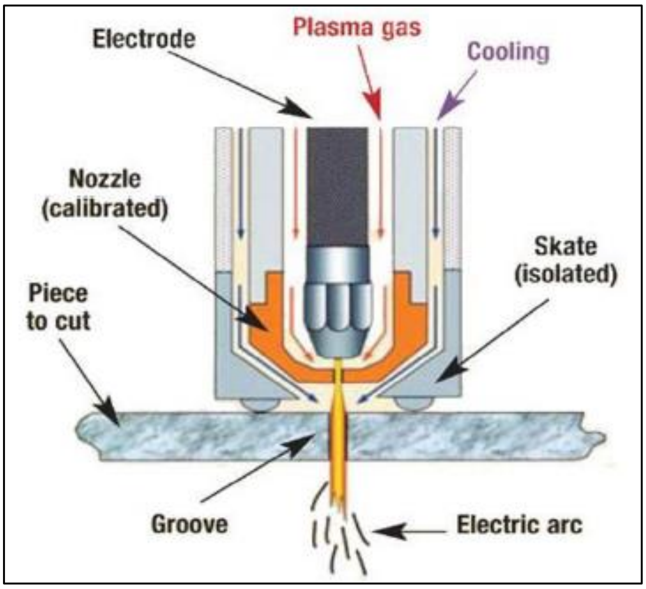


Fig 7: Plasma Arc Cutting system.

Fig 8: Stainless steel coffee table cut by plasma

Application of laser technology in the agricultural sector

Laser technology has revolutionized many industries, and its application extends to sectors such as agriculture, particularly for cutting wood and metal sheets. In the manufacturing sector, laser cutting is valued for its rapid processing times, clean edges, and ease of programming. Laser technology has captured a significant share of the material processing market, especially in metal parts and material handling applications (Schmidt, 2017) [25]. The ability of laser light to focus into a spot approximately the size of its wavelength enables it to achieve extremely high-power densities, facilitating efficient cutting, drilling, and etching operations (Sing *et al*., 2016) [26].

The advantages of laser cutting in the mechanical industry include not only fast processing and smooth cutting surfaces but also the ability to work with diverse materials such as sheet metal and tubes. This is particularly beneficial in agricultural equipment manufacturing, where precise and efficient material cutting is essential for developing complex, high-performance designs (Hong & Shin, 2017) [19]. CNC multi-axis machines, in particular, allow for the creation of intricate shapes and designs, enabling the production of innovative agricultural machine components (Figure 9). These machines, capable of operating on a variety of materials such as metal and wood, provide designers and manufacturers with the flexibility to utilize CAD/CAM operations without limitations.

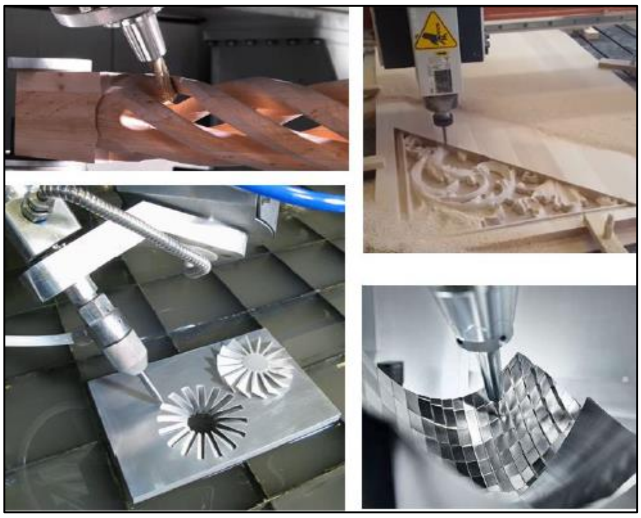


Fig 9: Reveals the application of 5 axis CNR in wooden and steel parts

Conclusion

The integration of laser technology into agricultural machinery design offers transformative advantages over conventional manufacturing methods, particularly in terms of precision, flexibility, and production efficiency. As demonstrated through comparative analysis, laser-based techniques such as thermal laser cutting enable the fabrication of complex geometries in both wood and metal materials with minimal post-processing requirements. This is especially valuable for producing customized, lightweight, and durable components suited for modern agricultural applications. While traditional methods still hold relevance for certain material types and economic constraints, ongoing advancements in laser systems combined with CAD/CAM and CNC automation are progressively bridging the gap between mass production and individualized design requirements. Consequently, laser technology is poised to become a pivotal tool in the next generation of agricultural machinery manufacturing, supporting both functional innovation and the evolving demands of sustainability and operational versatility.

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