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Innovation in the Development of a CO_2 Laser Cutting Machine: Experimentation on Cutting Quality and Machine Precision

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ABSTRACT

In the era of Industry 4.0, CO_2 laser cutting technology has been increasingly adopted across manufacturing, creative industries, and vocational education due to its precision, flexibility, and non-contact process. However, wood-based composites such as Medium Density Fibreboard (MDF) present challenges in laser machining, including thermal deformation, carbonization, and surface damage, necessitating further investigation into process parameters. This study designed and developed a CNC CO_2 Laser Cutting Machine with a 60 W laser source, dimensions of 160 × 100 × 85 cm, and a working area of 110 × 72 × 2 cm, integrating mechanical, optical, and control systems to improve efficiency and precision. The research method involved prototype design, fabrication, assembly, and iterative trials on acrylic, plywood, and MDF, with adjustments made to optimize power, cutting speed, and control stability. Surface roughness tests showed significant variation across materials, with MDF achieving an average Ra value of 6.25 µm (smooth) and acrylic achieving 0.85 µm (very smooth), indicating that acrylic provides superior aesthetic and precision outcomes, while MDF remains suitable for applications with moderate tolerance. The findings highlight that laser parameter optimization is critical for cut quality, and further refinements through jigs/fixtures and the addition of a rotary axis are recommended to enhance structural accuracy and expand application versatility.

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1. Introduction

In the era of Industry 4.0, material processing technology using CO_2 laser machines has been increasingly adopted in various sectors such as manufacturing, creative industries, and vocational education. CO_2 lasers are well known for their ability to produce high-precision cutting and engraving, shape flexibility, and contactless processes that minimize mechanical damage to materials. In the context of wood-based and composite materials, the use of CO_2 lasers enables the creation of intricate and detailed patterns on material surfaces [1].

Wood composite materials such as Medium Density Fibreboard (MDF) are widely used in the furniture and decorative industries due to their homogeneity and relatively low cost. However, the thermal properties and composition of MDF—consisting of wood fibers bonded with resin—make the laser cutting or engraving process prone to thermal deformation, carbonization, and surface damage. Therefore, research on the influence of laser cutting parameters on the surface characteristics of MDF is essential to improve cutting quality [2].

National studies on the effect of CO_2 laser power variation on the surface roughness and color of particleboard and MDF have found that increasing laser power tends to raise surface roughness and cause material discoloration [3]. Another study on PMMA reported that laser power and cutting speed significantly affect average roughness (Ra) and dimensional accuracy of the cut products [4]. These findings strengthen the evidence that laser parameter variations are a decisive factor in determining the quality of surface finishing.

Furthermore, a study on sengon wood using the Response Surface Methodology (RSM) revealed that variations in laser power and cutting speed influence kerf width, cutting depth, and surface roughness [5]. This indicates that similar phenomena occur in other wood-based materials, making further investigation into MDF both relevant and urgent.

The literature review above highlights a research gap regarding the surface roughness characteristics of MDF in particular, especially when processed using innovatively developed CO_2 laser machines. Therefore, this study aims to experimentally investigate the influence of CO_2 laser parameters (power and cutting speed) on MDF surface roughness in order to determine the optimal parameters that yield smooth cutting surfaces applicable to both creative industries and vocational education.

2. Method

This research was conducted using the Research and Development (R&D) approach with a structured sequence of stages, starting from data collection to field testing. The initial stage involved collecting data related to existing CO_2 laser machine technologies available in the market, focusing on cutting efficiency and accuracy, as well as the operational parameters and control systems commonly implemented in commercial machines. The second stage was research planning, which included the preparation of technical specifications for the CO_2 laser machine to be developed, emphasizing improvements in energy efficiency and cutting precision. This plan also covered the selection of components and the design of a control system based on the Ruida controller.

In order to support the design and development process, several main components of the CNC CO_2 laser machine were identified and selected according to the required specifications. These components are critical to achieving system stability, precision, and efficiency. Table 1 presents the main components used in the construction of the prototype machine, including the laser source, optical system, cooling system, motion control, and controller unit, along with their respective specifications and functions.

The next stage was the development of the initial product draft, which involved designing the mechanical structure, optical system, and control system to achieve better efficiency and precision compared to commercial machines. Following the design, an initial field trial of the prototype was conducted to identify shortcomings in energy efficiency, control stability, and cutting accuracy. Based on the trial results, revisions were made to the machine’s design and control settings, particularly by adjusting parameters such as laser power and cutting speed. After revision, further field trials were carried out to measure machine efficiency and accuracy in greater detail. The prototype was tested on several materials, including acrylic, plywood, and MDF, in order to evaluate its performance across different conditions. Product refinement was then performed, consisting of mechanical strengthening and more precise control settings. The final stage was full-scale field testing, ensuring that the developed CO_2 laser machine was ready for industrial use and met the standards of efficiency, precision, and operational reliability.

Table 1. List of Components and Specifications of CNC CO_2 Laser Cutting Machine

Component	***Specification***
Frame	Hollow Steel 4x2, Thickness 1.4 mm
Y-Axis Rail	Aluminum Profile 2040
Linear Guide	15 mm L-3000 mm Linear Rail Slide Guide
Linear Block	Carriage Block for HGR15, 15 mm Linear Block
Laser Beam Guide	Laser Head
Transmission	Linear Rod SS 304, 8 mm
X-Axis Rail	Aluminum Profile 2020 T-slot
Tube Support	Tube Holder 50
Pulley	Pulley GT2 W10 20T B8 D16
Belt	Timing Belt GT2, Width 15 mm
Worktable	Aluminum U
Bolt	L Head Socket Bolt M4 x 8
Axis Support	Steel Plate, 3 mm
Rangka	Besi Hollow 4x2 Tebal 1,4mm
Bearing	Idler GT2 D18 B5 No Teeth
Power Supply	24 V Power Supply
Water Pump	DC 12V Water Pump
Sensor	Limit Switch Micro SPDT Roller Lever Arm
Control System	Ruida RDC6445G
Motor Driver	TB 6600 Motor Driver
Laser Tube	Puri 60 Watt Laser Tube

The research procedures began with the design of the CO_2 laser machine prototype, including considerations of optical and mechanical efficiency. Calculations and analyses were performed to determine the specifications of major components such as the laser source, cooling system, and mechanical assemblies. Technical drawings and component arrangements were then prepared, followed by the fabrication of machine parts according to the approved design. The components were assembled into a working prototype and subjected to initial testing to evaluate performance, efficiency, and cutting precision. Improvements were made based on test results to refine the prototype before broader testing.

After the development stage, experimental testing of the machine was carried out, focusing on cutting performance on different materials with varying parameter settings. Special attention was given to MDF as the primary material, where surface roughness was measured under different combinations of laser power and cutting speed. Previous experimental studies indicate that laser power, cutting speed, focal position, and assist gas pressure significantly influence kerf width, kerf taper, HAZ (heat-affected zone), and surface roughness for MDF and other wood-based materials — e.g., provide comprehensive parametric studies on MDF behavior under CO_2 laser cutting [6][10]. Other studies have modelled and optimized cutting parameters for wood and wood composites using statistical techniques such as Response Surface Methodology (RSM) and Taguchi methods, showing clear trade-offs between cut quality (surface roughness, kerf) and process productivity [11][12].

Understanding how laser energy is deposited and distributed is important for predicting cutting outcomes; foundational work on power distribution and laser–material interaction (continuous vs pulsed modes) provides the theoretical basis for selecting parameter windows and interpreting roughness/kerf observations [7]. In addition, investigations into surface cross-section irregularities after CO_2 laser cutting supply useful microstructural evidence on how process settings affect the cut edges and internal damage patterns relevant to MDF [13].

Energy consumption and process-level efficiency are also central to this research. Recent studies comparing beam strategies and optical setups show that dynamic beam shaping and optimized optics can substantially reduce specific energy consumption and assist-gas requirements while maintaining or improving cut quality — findings that guided our choices for optical layout and control strategies in the prototype [8][9][14]. Broader analyses of laser specific energy consumption across manufacturing processes highlight the relatively high energy intensity of laser cutting compared with some conventional methods, but also point to large improvement potential via parameter optimization and process scheduling [15].

To complement the machine trials, the MDF samples used in this study were characterized based on their material properties, including density, modulus of elasticity, thickness, and moisture content, as these significantly influence laser–material interaction and cutting results. Table 2 summarizes the key properties of MDF that served as input for parameter selection during testing.

Table 2. Material Properties MDF

Material Properties MDF		
Properties		***Values***
Bulk Modulus		2.6 GPa, or 0.37 10^6 psi
Maximum Temperatur	Typical Guideline	130 °C, or 260°F
Poisson's Ratio		2.5 Gpa, or 0,36 10^6 psi
Shear Modulus		1700 J/Kg-K
Specific Heat Capacity	Conventional	1200 10^3 J/m^3-K
	Volumetric	73 10^3 m/s, or 230 10^3ft/s
Stiffness to Weight Ratio	Bulk	3.5 MN-m/kg
	Shear	3.3 MN-m/kg
	Tensile	5.3 MN-m/kg
Strength to Weight Ratio	Compressive	13 kN-m/kg
	Tensile, Ultimate	24 kN-m/kg
Tensile Strenght	Ultimate	18 Mpa, or 2.6 10^3 psi
Thermal Conductivity	Ambient	0.3 W/m-k
Thermal Expansion	20 to 100	12 µm/m − k

3. Results and Discussion

This section presents the results of the research and development process of the CNC CO_2 laser cutting machine prototype. The discussion covers the analysis of design requirements, the calculation of major component specifications, fabrication, assembly, and preliminary testing. Each stage is explained systematically to demonstrate how the developed machine can meet the needs of small and medium industries (SMEs), especially in terms of efficiency, precision, and reliability.

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3.1. Analysis of Machine Geometry Requirements

The research began with an analysis of market segment needs, technical specifications including machine geometry requirements as shown in Fig. 1, and CNC laser cutting machine standardization. Considerations in this analysis were based on feedback from partner SMEs and machine users.

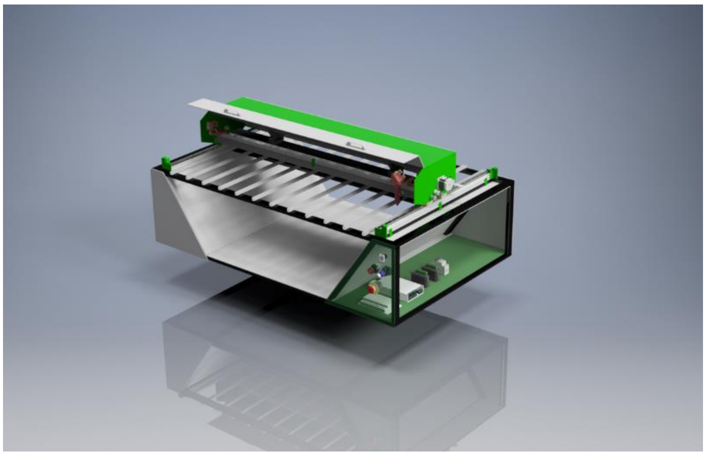

Fig. 1. Machine Geometry Requirements

3.2. Calculation of Major Component Specifications

In developing the CO_2 laser cutting machine for small and medium industries (SMEs), an important step was the calculation and analysis to determine the specifications of the main components. One of the main considerations was the selection of a 60-watt CO_2 laser tube, as this power level is considered ideal for SMEs to cut non-metallic materials such as acrylic, wood, and MDF of medium thickness. This tube is not only more affordable but also efficient enough for small to medium-scale production without compromising cutting quality.

For the machine frame, hollow steel was selected due to its strong structural properties, durability, and availability in the market, ensuring stability. The gantry was fabricated from 3 mm thick steel plate, as shown in Fig. 2, processed using laser cutting to achieve precision, strength, and vibration resistance during cutting operations. For the drive system, a NEMA 23 stepper motor was chosen because of its sufficient torque, high motion accuracy, and compatibility with the required axis movements of the laser cutting machine. This motor is also widely available in the industry, ensuring ease of procurement and maintenance. The Ruida controller was selected as the main control unit because it provides comprehensive features, user-friendly operation, and supports precise parameter adjustments. The use of Ruida also facilitates integration with design software, simplifying the operation for SME operators. With these specifications, the developed CNC CO_2 laser cutting machine is expected to balance production costs, cutting quality, and ease of operation to support SME productivity.

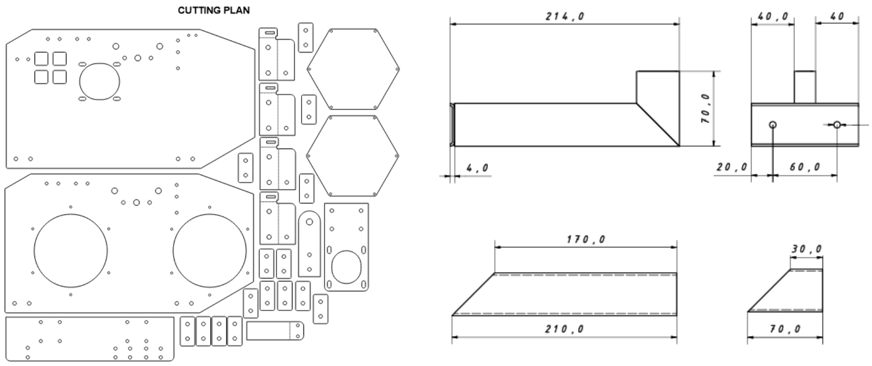

Fig. 2. Cutting Plan for 3 mm Steel Plate

3.3. Fabrication of Machine Components

The fabrication process of the CO_2 laser cutting machine components began with the construction of the main frame as shown in Fig. 3. Hollow steel was selected for its structural strength and easy availability. The material was cut according to the working drawings and welded using electric welding, ensuring dimensional accuracy and proper joint alignment to achieve a rigid and precise frame. After welding, the joints were ground to produce smooth surfaces, preparing them for subsequent assembly.

The gantry was then fabricated from 3 mm thick steel plates using laser cutting to ensure accuracy. Assembly focused on the alignment of linear rails and motor mounts as these components serve as the main supports for laser head movement. Precision at this stage was crucial as it directly influences the cutting quality.

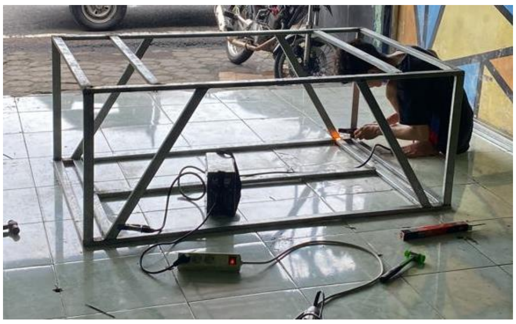

Fig. 3. Frame Welding

3.4. Assembly of Machine Components

The next step was the assembly of supporting mechanical components, including linear rails, pulleys, timing belts, and motor mounts, as shown in Fig.4. NEMA 23 stepper motors were installed to drive the X and Y axes with high accuracy. System integration was carried out by installing the 60-watt CO_2 laser tube along with the cooling system to maintain beam stability. In addition, lenses and mirrors were carefully positioned to direct the laser beam toward the cutting head.

Finally, the Ruida controller was installed and connected to all electrical components, enabling precise automatic control of cutting parameters through CNC software. With this sequence, the developed CNC CO_2 laser cutting machine was expected to have robust construction, high precision, and sufficient reliability to support SME production.

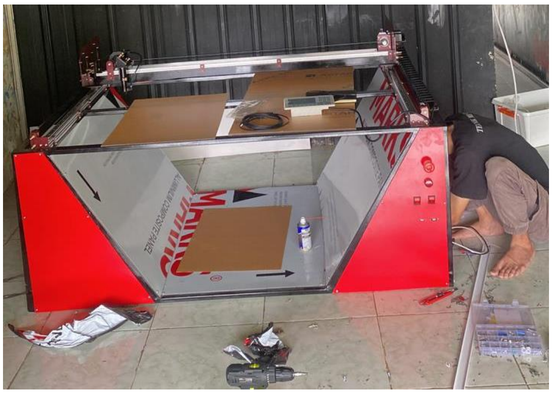

Fig. 4. Component Assembly

3.5 Initial Trial

The initial trial of the CNC CO_2 laser cutting machine was conducted after completing the mechanical assembly, electrical installation, and control system integration, as shown in Fig. 5. The trial began with functional checks, including the electrical circuits, cooling system, and the connection between the Ruida controller and CNC software. Next, the X and Y axes were tested to verify accuracy, smoothness of motion, and gantry alignment. The NEMA 23 motors were tested with simple movement commands, such as straight lines and basic geometric shapes, to identify excessive vibration, step loss, or misalignment.

Once the motion system was confirmed stable, the 60-watt CO_2 laser tube was activated. Initial cutting tests were performed on acrylic and wood samples of specific thicknesses to evaluate penetration, cutting quality, and beam intensity stability. Cutting parameters such as feed rate, assist gas pressure, and lens focus position were gradually adjusted to achieve optimal results. The cooling system was also monitored to ensure laser tube temperature stability and minimize overheating risks.

Based on the initial trials, the machine's performance was deemed satisfactory, allowing the process to continue to advanced testing and comprehensive evaluation.

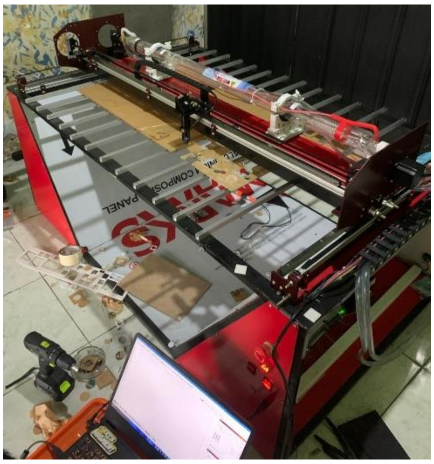

Fig. 5. Initial Trial

3.6. Performance Testing of CNC CO_2 Laser Cutting Machine

3.6.1. Cutting Speed Test

In the cutting speed test, the Material Test feature of the LightBurn software was used. This feature systematically generates a parameter variation matrix, allowing combinations of cutting speed and laser power to be tested in a single cutting process without requiring manual reset. This approach provides both efficiency and measurable outcomes. In this study, the test material was 3 mm thick MDF, with cutting speeds varied from low to high while adjusting the laser power to ensure consistent penetration of the material. The evaluation criteria included edge smoothness, completeness of the cut, and thermal defects such as burning or melting. From the Material Test matrix, optimal cutting speed parameters were identified, producing clean and precise results while maintaining processing efficiency. These parameters serve as a benchmark for further performance testing of the CO_2 laser cutting machine.

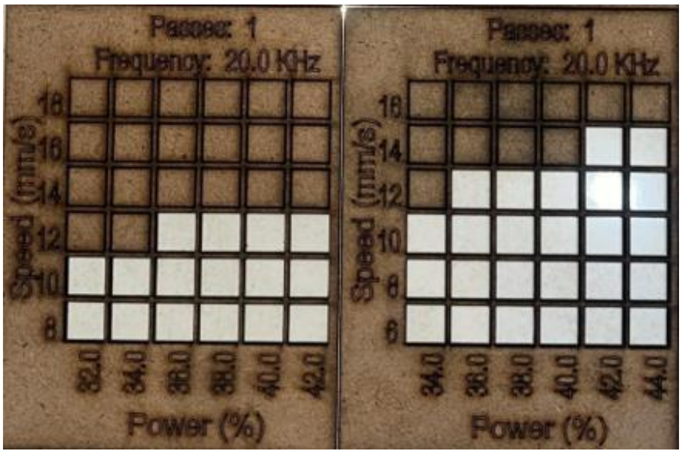

Fig. 6. Laser Cutting Results Using the Material Test Feature

Based on the results of the Material Test as shown in Fig. 6, the appropriate cutting parameter range for 3 mm MDF was found to be at cutting speeds between 6–18 mm/s with laser power set at 32–44%. This range produced complete cuts with flat surfaces and good edge quality. For operational efficiency, the selection of parameters was directed toward relatively higher cutting speeds with moderate laser power, which reduces energy consumption while shortening process time without sacrificing cut quality.

3.6.2. Optimal Cutting Capability by Measuring Kerf Width

The kerf width measurement test on 3 mm MDF cutting using the CO_2 laser was conducted with a digital microscope connected to a computer. The cut samples were placed on the microscope stage and magnified until the cutting area was clearly visible to identify the left and right edges of the kerf. Image analysis software integrated with the microscope was then used to measure kerf width dimensions accurately at the micrometer scale. This method provided higher measurement precision compared to conventional tools such as calipers, as it could detect irregularities in cut edges caused by material melting.

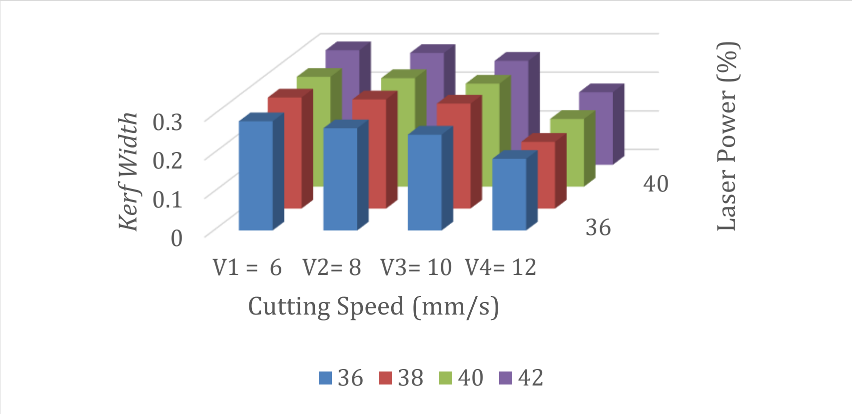

Fig. 7. Kerf Width Measurement Graph

The results, as shown in Fig. 7, indicated that kerf width consistently increased with higher laser power across all cutting speed variations. At lower speeds (e.g., 6 mm/s), the kerf width was relatively larger due to longer laser exposure on the material. Conversely, increasing the cutting speed to 12 mm/s produced narrower kerfs, though still influenced by the applied laser power. Thus, a combination of higher cutting speeds with moderate laser power yielded smaller and more uniform kerf widths. These findings suggest that such parameter combinations can achieve both precision and efficiency in the cutting process.

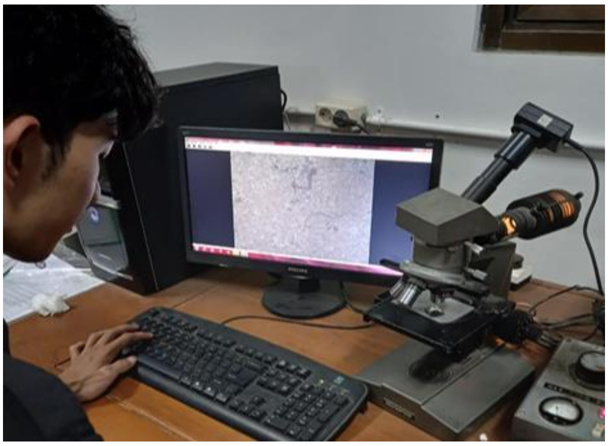

Fig. 8. Microscopic Observation of Cutting Results

The microscopic observations as shown in Fig.8 further confirmed these results by providing high-magnification images of the kerf. The images were analyzed using computer software to ensure precise measurement of the kerf width, offering detailed insights into the effect of laser parameters on cutting quality.

3.7. Surface Roughness Analysis

The surface roughness test in this study as shown in Fig. 9 was conducted to evaluate the cutting quality of the CNC CO_2 Laser Cutting Machine on 3 mm MDF. The test employed a Surface Roughness Tester SRT-6200, which is capable of measuring the average roughness value (Ra) with high accuracy. The objective of this test was to determine the degree of smoothness or roughness of the cut surfaces influenced by variations in cutting speed and laser power.

Fig. 9. Surface Roughness Testing Process

The measurement data were then analyzed to identify the combination of cutting parameters that could produce the best surface quality. This evaluation provided a comprehensive overview of the machine's performance in producing precise, clean cuts that meet the quality standards of material processing.

Table 3. Surface Roughness Results

Laser Power	Cutting Speed			
	V1	*V2*	*V3*	*V4*
	Surface Roughness (RA) µm	Surface Roughness (RA) µm	Surface Roughness (RA) µm	Surface Roughness (RA) µm
36	7.933	8.909	9.786	8.17
36	7.306	8.355	9.555	7.893
36	7.261	8.678	9.232	7.386
38	7.754	8.263	9.462	8.078
38	7.619	8.586	9.693	7.109
38	7.171	8.955	9.647	7.709
40	8.216	8.447	8.309	7.478
40	7.986	8.771	7.801	7.893
40	8.447	8.817	8.863	8.17
42	8.771	8.955	8.585	8.309
42	8.909	9.001	8.078	8.216
42	8.216	8.124	8.309	7.57

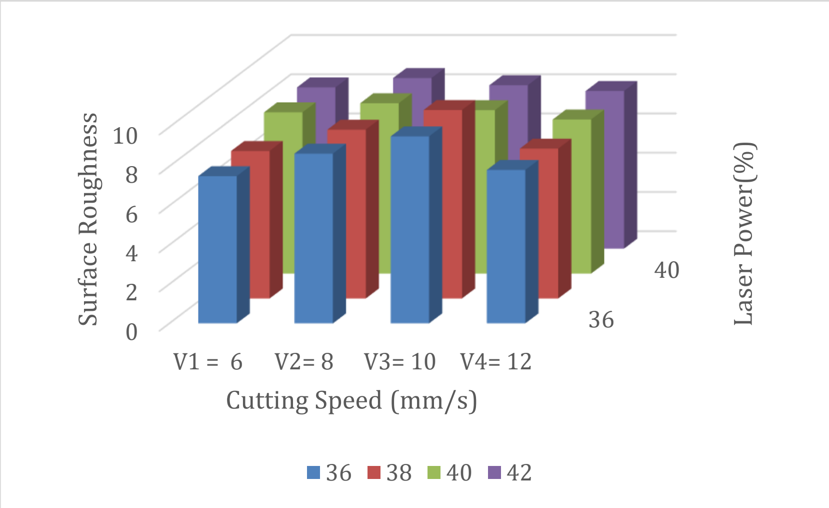

Fig. 10. Surface Roughness Testing on MDF

Fig. 10 shows the surface roughness test results for 3 mm MDF under variations of cutting speed (6, 8, 10, and 12 mm/s) and laser power (36%, 38%, 40%, and 42%). It shows that MDF generally exhibited higher roughness values compared to acrylic, ranging from 7–10 µm. This is due to the intrinsic characteristics of MDF, which is composed of wood fibers bonded with resin, making it more susceptible to burning, uneven melting, and resulting in rougher cut surfaces. At lower cutting speeds (6 mm/s) with laser power in the range of 36–38%, the roughness values tended to be lower, producing relatively smoother cut surfaces. However, as the cutting speed increased up to 12 mm/s with higher laser power (40–42%), the roughness values rose significantly, approaching 10 µm. This indicated instability in the cutting process caused by excessive thermal interaction with the wood-based material. Based on these findings, the most suitable cutting parameters for 3 mm MDF were determined to be at cutting speeds of 6–8 mm/s with laser power between 36–38%, as these conditions produced lower roughness values and better cut quality compared to other parameter combinations.

4. Conclusion

In this study, the design and development of a CNC CO_2 Laser Cutting Machine, along with its performance evaluation, were successfully conducted. The developed machine has overall dimensions of 160 × 100 × 85 cm, equipped with a 60 W laser source, and provides a working area of 110 × 72 × 2 cm. The axis movement speed can be adjusted within the range of 1–230 mm/s through parameter settings in the Ruida control system. Performance evaluation showed that the surface roughness test results exhibited a notable difference between MDF and acrylic materials. MDF produced an average Ra value of 6.25 µm, categorized as smooth, which indicates sufficient evenness with minimal finishing requirements. In contrast, acrylic achieved an average Ra value of 0.85 µm, classified as very smooth, reflecting superior cutting quality with a cleaner and more uniform surface. These findings highlight that acrylic is more suitable for applications requiring high precision and aesthetic quality, while MDF remains appropriate for applications that allow moderate surface tolerance. To further improve the performance and versatility of the machine, it is recommended to employ jigs or fixtures during the construction process to enhance structural accuracy. Additionally, the integration of a rotary axis (U-axis) is suggested to broaden the machine's capabilities, particularly for more diverse cutting and engraving applications.

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