THE EFFECT OF WOOD POWDER COMPOSITION AND PARTICLE SIZE ON THE ROUGHNESS OF CO_2 LASER BIOCOMPOSITES

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Abstract

This study aims to analyze the effects of pine wood powder composition and particle size on the surface roughness of biocomposites produced by CNC CO_2 laser cutting. An experimental method was employed using wood powder:PVA composition ratios of 70:30, 60:40, and 50:50, with particle sizes of mesh 60, 140, and 200. The specimens were fabricated through manual mixing without pressure during molding and were evaluated using a surface roughness tester with five measurements for each specimen variation. The data were analyzed using two-way ANOVA to determine the effects of composition, particle size, and their interaction on surface roughness. The results indicated that composition, particle size, and their interaction significantly affected surface roughness ($p < 0.05$). The lowest Ra value was obtained for specimen B3 (60:40, mesh 200), reaching 8.0566 µm, while the highest Ra value was observed for specimen C3 (50:50, mesh 200) at 16.780 µm. The high roughness value of specimen C3 was attributed to possible microstructural irregularities caused by shrinkage during the drying process, resulting in non-uniform laser–material interaction. In addition, defects including burning, voids, and incomplete cuts were identified and contributed to the overall cutting quality. These findings demonstrate that the surface quality of CNC CO_2 laser-cut biocomposites is significantly influenced by the combined effects of material composition and particle size.

Keyword: *Biocomposite, Pine Wood Powder, Polyvinyl Alcohol (PVA), Surface Roughness, CNC CO_2 Laser Cutting.*

I. INTRODUCTION

Biocomposites are environmentally friendly composite materials consisting of natural reinforcements and polymer matrices, and they have increasingly been developed as sustainable material alternatives in engineering and manufacturing applications (Jawaid, Salit and Alothman, 2017; Sultan *et al.*, 2021). One promising type of biocomposite is based on pine wood powder as a filler and Polyvinyl Alcohol (PVA) as a binding matrix. Pine wood powder contains cellulose, hemicellulose, and lignin, which support its utilization as a reinforcing filler in composite materials, while PVA exhibits good adhesive properties and is capable of forming a homogeneous bond with reinforcing particles (Budiyantoro and Yudhanto, 2024; Filimon *et al.*, 2025).

In manufacturing processes, the surface quality of cut materials is an important parameter that determines the quality of the final product. Surface roughness is one of the primary indicators used to evaluate machining quality because it influences both the functional and aesthetic characteristics of a material (Vorburger and Raja, 1990; Obilanade, Dordlofva and Törlind, 2021). Among various cutting methods, CNC CO_2 laser cutting is widely applied due to its high precision, non-contact operation, and ability to produce complex cutting geometries (Steen and Mazumder, 2010; Mushtaq *et al.*, 2020).

However, the quality of laser cutting on biocomposite materials is strongly influenced by material characteristics, particularly matrix–filler composition and wood powder particle size. Studies conducted by Madić et al. (2013) serta Ahmad Sobri et al. (2025) reported that both material properties and laser processing parameters affect cut-edge quality and surface roughness. In addition, defects such as burning, voids, and incomplete cuts may occur during the cutting process and potentially reduce the overall quality of the final product.

Although numerous studies have investigated the influence of laser processing parameters on the cutting quality of wood and composite materials, most have focused on variations in laser power, cutting speed, and other processing parameters affecting cutting performance (Steen and Mazumder, 2010; Mushtaq *et al.*, 2020; Ahmad Sobri *et al.*, 2025). n contrast, studies examining the influence of material characteristics, particularly the combination of wood powder–PVA composition and wood powder particle size, on the cutting quality of CNC CO_2 laser-processed biocomposites remain limited. Furthermore, the interaction between these factors in relation to surface roughness and the occurrence of cutting defects such as burning, voids, and incomplete cuts has not been extensively reported. Therefore, this study contributes by simultaneously evaluating the effects of wood powder–PVA composition and particle size on the surface roughness of CNC CO_2 laser-cut biocomposites, while also investigating the occurrence of burning, void, and incomplete-cut defects as indicators of cutting quality.

Based on these considerations, this study is limited to the analysis of the effects of pine wood powder–PVA composition and particle size on the surface roughness of biocomposites processed using CNC CO_2 laser cutting. The composition ratios investigated were 70:30, 60:40, and 50:50 (wood powder), while particle sizes of mesh 60, 140, and 200 were employed. The objective of this study is to determine the effects of these variables on surface roughness and to identify the optimal combination for achieving improved surface quality in laser-cut biocomposites.

II. THEORY

Biocomposites

Biocomposites are materials composed of two or more different constituents, namely a filler or reinforcement and a matrix, which are combined to obtain improved properties compared with those of the individual components (Jawaid, Salit and Alothman, 2017; Sultan *et al.*, 2021). In this study, pine wood powder was used as the filler due to its cellulose, hemicellulose, and lignin content, which contribute to the strength and structural stability of the material (Budiyantoro and Yudhanto, 2024).

Polyvinyl Alcohol (PVA) was selected as the matrix because of its good adhesive properties, water solubility, and ability to form relatively homogeneous bonds with lignocellulosic particles (Park, Friest and Liu, 2023; Filimon *et al.*, 2025). The interaction between the filler and matrix is a key factor influencing the internal structure and surface quality of biocomposites.

Surface Roughness

Surface roughness is a parameter commonly used to evaluate the quality of surfaces produced by manufacturing processes. One of the most widely used roughness parameters is Ra (Arithmetic Average Roughness), which represents the average absolute deviation of the surface profile from the mean line over a specified evaluation length (Vorburger and Raja, 1990).

Lower Ra values indicate smoother surfaces, whereas higher Ra values represent rougher surfaces. In this study, surface roughness was used as an indicator of the cutting quality of biocomposites processed using CNC CO_2 laser cutting.

CNC CO_2 Laser Cutting

CNC CO_2 laser cutting is a non-contact manufacturing process that utilizes thermal energy from a laser beam to melt, burn, or vaporize material along a cutting path (Steen and Mazumder, 2010; Mushtaq *et al.*, 2020). The main advantages of this method include high precision, the ability to produce complex geometries, and minimal mechanical deformation of the workpiece.

However, when applied to wood-based composite materials, the process may generate defects such as burning, voids, and incomplete cuts, which are influenced by both material characteristics and cutting parameters (Ahmad Sobri *et al.*, 2025).

Defects and Defect Scoring

During CNC CO_2 laser cutting of biocomposites, several common defects may occur, including burning, voids, and incomplete cuts. Burning is characterized by darkening of the cut edge caused by thermal effects from laser energy. Voids appear as cavities or gaps within the material structure and may result from non-uniform particle distribution, inter-particle spaces, or localized shrinkage during drying. Incomplete cuts occur when the laser energy is insufficient to completely penetrate the material, leaving uncut regions along the cutting path (Steen and Mazumder, 2010; Ahmad Sobri *et al.*, 2025).

he severity of defects in this study was evaluated using an ordinal scoring method ranging from 0 to 3, where 0 indicates no defect, 1 indicates a minor defect, 2 indicates a moderate defect, and 3 indicates a severe defect. The classification was based on the dominance of the defect area along the cut edge and adapted from visual defect quality standards (Solutions, 2011). This approach facilitates the interpretation and comparison of defect severity among specimen variations.

Visual defect scoring was employed to provide a semi-quantitative assessment of defects observed after laser cutting. This method is commonly used in manufacturing quality evaluations when defect characteristics are more readily identified through visual inspection than direct measurement. To minimize subjectivity, each score category was defined using clear and consistent visual criteria. Therefore, all specimens were evaluated using the same predefined scoring guidelines to ensure consistency throughout the assessment process.

III. METHOD

The research object was a biocomposite consisting of pine wood powder as the filler and Polyvinyl Alcohol (PVA) as the matrix. The composition ratios investigated were 70:30 (A), 60:40 (B), and 50:50 (C) (wood powder), while the particle sizes were varied at mesh 60 (1), mesh 140 (2), and mesh 200 (3).

Prior to mixing, the pine wood powder was oven-dried at 55°C for 12 h to reduce moisture content and improve material consistency. The mixture was then manually homogenized and molded without the application of pressure. After molding, the specimens were subjected to a staged drying process. The initial drying stage was conducted at 50–55°C for approximately 5 h until free surface moisture disappeared and the specimen surface appeared dry. Subsequently, further drying was performed at 60–65°C for 24–34 h to obtain stable specimens suitable for cutting and testing.

For each material variation, a fabricated biocomposite panel was cut into five test specimens with dimensions of 30 mm × 20 mm. The actual specimen thickness after drying ranged from 1.94 to 2.64 mm due to shrinkage occurring during the drying process. All specimens were prepared using the same fabrication procedure and drying conditions to maintain consistency among treatment variations.

The cutting process was carried out using a 40 W CNC CO_2 laser machine (M2 Controller). The laser parameters were maintained constant for all specimens, with a power setting of 40% and a cutting speed of 5 mm/s. After cutting, surface roughness measurements were performed using a surface roughness tester. Five measurements were taken at different locations on each specimen, and the average value was calculated to represent the surface roughness (Ra). In addition, visual observations were conducted to identify cutting defects, including burning, voids, and incomplete cuts.

Defect severity was evaluated using an ordinal visual scoring method with scores ranging from 0 to 3, where 0 indicates no defect, 1 indicates a minor defect, 2 indicates a moderate defect, and 3 indicates a severe defect. The scoring criteria were based on the dominance of the defect area along the cut edge, where a score of 1 was assigned when the defect occupied less than 50% of the cut length, a score of 2 when the defect occupied approximately 50–75%, and a score of 3 when the defect exceeded 75%. This approach was adapted from visual defect quality standards to ensure consistent evaluation among specimens (Solutions, 2011).

All defect evaluations were conducted by the same evaluator using predefined scoring guidelines. The observations were performed under uniform lighting conditions, and all specimens were assessed using identical visual criteria to maintain evaluation consistency. Since defect analysis served as a supporting descriptive evaluation rather than a primary research variable, the scoring method was employed to provide a comparative description of the severity of burning, void, and incomplete cut defects among material variations.

The experimental data were analyzed using two-way analysis of variance (two-way ANOVA) because the study involved two independent factors, namely wood powder–PVA composition and wood particle size, and aimed to evaluate both their individual effects and interaction effects on surface roughness (Ra). Prior to ANOVA, the data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test at a significance level of 5%. After the assumptions were satisfied, two-way ANOVA was performed to determine the significance of composition, particle size, and their interaction on the surface roughness values.

TABLE I
Surface Roughness Test Results

Variation	(µm)					Average
	T1	T2	T3	T4	T5	
A1	15,26	10,98	13,91	13,72	11,38	13,05
A2	13	16,71	12,65	14,85	11,66	13,774
A3	10,54	8,72	11,75	12,67	14,71	11,678
B1	16,87	17,17	15,67	15,07	12,99	15,554
B2	12,55	14,45	10,94	14,22	11,28	12,688
B3	9,724	9,668	7,557	6,889	6,445	8,0566
C1	15,44	16,68	14,89	16,69	12,02	15,144
C2	17,89	9,245	15,67	12,67	10,83	13,261
C3	16,55	15,9	18,68	17,27	15,5	16,78

IV. RESULTS AND DISCUSSION,

This study evaluated the surface roughness (Ra) of biocomposites fabricated with different pine wood powder–PVA compositions and particle sizes, followed by statistical analysis using two-way ANOVA. In addition, cutting defects were observed as indicators of surface quality.

The surface roughness (Ra) measurements for each composition and particle size variation are presented in Table I.

Based on Table I, the surface roughness values varied across the different combinations of composition and particle size. In general, increasing the PVA content tended to improve material homogeneity and, in several variations, resulted in lower Ra values. However, this effect did not exhibit a completely linear trend across all treatment combinations. As a matrix material, PVA promotes more uniform bonding among wood powder particles, thereby reducing surface irregularities generated during the cutting process. Conversely, higher wood powder content may increase the likelihood of void formation and non-uniform particle distribution, which contribute to higher surface roughness.

The role of PVA extends beyond its function as an adhesive matrix. It also affects the homogeneity of filler distribution within the biocomposite structure. When the matrix content is sufficient, wood particles can be bonded more uniformly, reducing local stress concentrations and structural irregularities in regions interacting with the laser beam. A more homogeneous structure tends to produce a more stable material ablation process and smoother cut surfaces. In contrast, non-uniform matrix distribution may create voids or regions with different local densities, leading to variations in material removal rates during laser cutting and consequently increasing surface roughness.

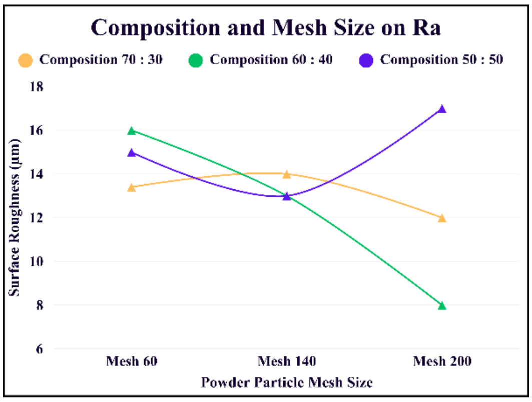

Fig 1. *Effect of Composition and Particle Size on Surface Roughness*

Particle size also exhibited a noticeable influence on surface roughness. Finer particles (higher mesh numbers) generally produced lower Ra values than coarser particles. This behavior can be attributed to the ability of smaller particles to fill inter-particle spaces more effectively, resulting in a denser material structure and smoother cut surfaces.

To illustrate the relationship between composition, particle size, and surface roughness, the experimental results are presented graphically in Fig. 1.

As shown in Fig. 1, the influence of composition and particle size on surface roughness did not follow a completely linear pattern. In general, the use of finer particles reduced surface roughness because smaller particles filled inter-particle spaces more efficiently, producing a denser and more uniform structure. This trend was particularly evident in variations A and B, where Ra values decreased as the mesh number increased.

However, a different trend was observed in variation C (50:50), particularly for specimen C3 (mesh 200), which exhibited the highest roughness value of 16.78 µm. This result indicates that increasing the PVA content does not necessarily guarantee a smoother surface. At higher matrix contents, the drying process may induce greater shrinkage, potentially generating localized microstructural irregularities or voids within the material. Such conditions can lead to non-uniform interactions between the laser energy and the material, resulting in a rougher cut surface.

In addition to material characteristics, the quality of the cut surface is strongly influenced by heat transfer mechanisms during laser cutting. The absorbed laser energy is converted into heat, causing melting, thermal degradation, and partial vaporization of the material along the cutting path. When heat distribution occurs uniformly, smoother cut surfaces can be produced. However, internal structural heterogeneity may result in uneven energy distribution, creating regions with different levels of thermal degradation. These variations may contribute to increased surface roughness and defect formation along the cut edge.

These findings are consistent with the results of the two-way ANOVA, which revealed a significant interaction between composition and particle size. Therefore, the surface quality of CNC CO_2 laser-cut biocomposites is influenced not only by the individual effects of composition and particle size but also by the interaction between these factors, which governs the internal characteristics of the material during fabrication.

Prior to conducting the two-way ANOVA, the assumptions of normality and homogeneity of variance were evaluated. The Shapiro–Wilk test produced a significance value of 0.955 ($p > 0.05$), indicating that the residuals were normally distributed. Furthermore, Levene's test yielded a significance value of 0.232 ($p > 0.05$), confirming the homogeneity of variances among groups. Since both assumptions were satisfied, the dataset was considered suitable for two-way ANOVA.

The results of the statistical analysis are presented in Table II.

The two-way ANOVA results indicate that biocomposite composition significantly affected surface roughness ($F = 8.494$, $p = 0.001$), as did wood particle size ($F = 5.208$, $p = 0.010$). In addition, the interaction between composition and particle size was found to be significant ($F = 8.426$, $p < 0.001$). These results demonstrate that changes in surface roughness are not governed solely by the independent effects of composition and particle size, but also by the interaction between both factors.

TABLE II
Two-Way ANOVA Results

Factor	df	F	p
Composition	2	8.494	0.001
Particle Size (Mesh)	2	5.208	0.010
Composition × Particle Size	4	8.426	$p < 0.001$
Error	36	-	-

In other words, the effect of particle size on surface roughness depends on the composition used, and vice versa.

In addition to surface roughness measurements, visual observations identified three primary cutting defects, namely burning, voids, and incomplete cuts, as shown in Fig. 2. Defect severity was evaluated qualitatively using a scoring scale ranging from 0 (no defect) to 3 (severe defect).

Based on the defect observation results, the severity levels of burning, voids, and incomplete cuts varied among the composition and particle size combinations. Burning resulted from thermal energy accumulation in the cutting zone, causing carbonization or discoloration of the material surface. The severity of burning was influenced by the ability of the material to absorb and dissipate heat during laser processing. Meanwhile, void formation was associated with the internal structure of the biocomposite, particularly the presence of inter-particle spaces and matrix shrinkage during drying. These voids may lead to non-uniform laser energy distribution and increased irregularity of the cut surface.

Incomplete cuts occurred when the laser energy delivered to the material was insufficient to achieve complete penetration along the cutting path. This defect may be influenced by local material density, filler–matrix distribution, and internal structural variations that affect laser energy penetration. These findings indicate that cutting quality is determined not only by laser processing parameters but also by the microstructural characteristics of the biocomposite formed during fabrication.

Overall, the results demonstrate that the combination of composition and particle size plays a significant role in determining the surface quality of CNC CO_2 laser-cut biocomposites.

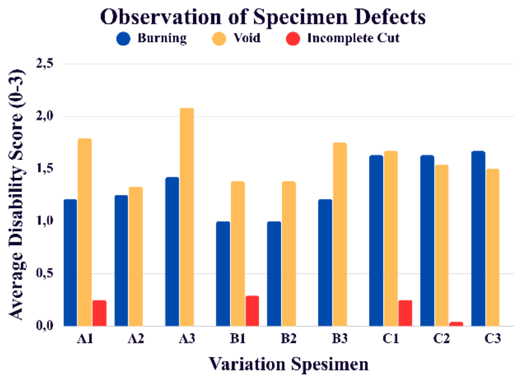

Fig 2. *Observation of Specimen Defects*

The ANOVA results confirmed that both factors and their interaction significantly affected surface roughness. These findings suggest that cutting quality is governed not only by composition or particle size individually, but also by the combined influence of both factors on material homogeneity, heat distribution during laser cutting, and the resulting biocomposite microstructure.

V. CONCLUSIONS

Based on the experimental results, the pine wood powder–PVA composition and particle size significantly affected the surface roughness (Ra) of biocomposites processed using CNC CO_2 laser cutting. The two-way ANOVA results confirmed that composition, particle size, and their interaction had significant effects on surface roughness. The lowest Ra value was obtained for specimen B3 (60:40 composition, mesh 200), with an average surface roughness of 8.0566 µm, whereas the highest Ra value was observed for specimen C3 (50:50 composition, mesh 200), reaching 16.780 µm.

The anomalous behavior observed in specimen C3 indicates that a higher PVA content combined with finer particle size does not necessarily produce a smoother surface. This phenomenon is likely associated with microstructural irregularities caused by shrinkage during the drying process, which may lead to non-uniform laser energy distribution and consequently increase surface roughness. In addition, defect observations revealed the presence of burning, voids, and incomplete cuts with varying severity levels among the specimen variations.

Overall, the results demonstrate that the surface quality of CNC CO_2 laser-cut biocomposites is governed by the combined effects of material composition and particle size, which influence the microstructural characteristics of the material and its interaction with laser energy during the cutting process.

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