Assessment of Surface Roughness in Milling of Wood with Different Material Temperature and Cutting Parameters

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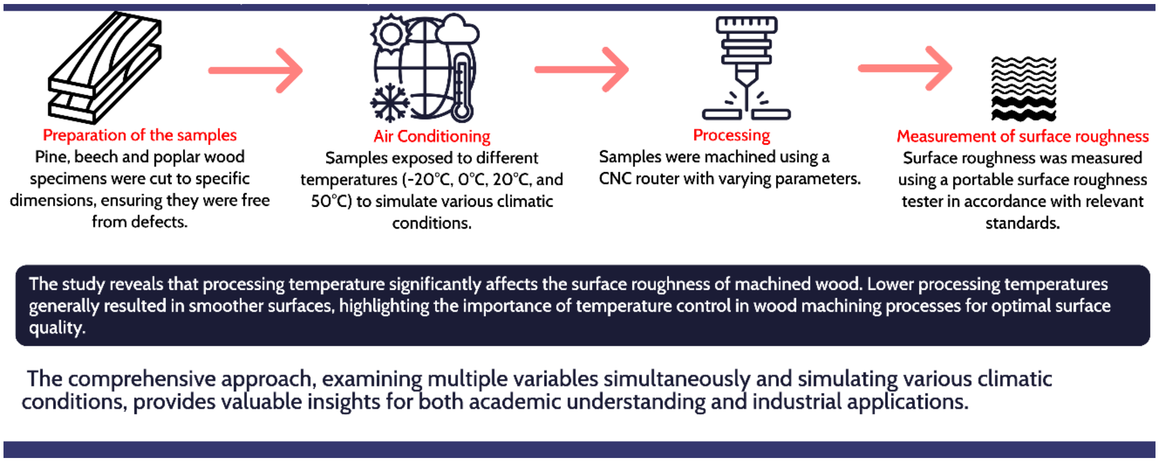
GRAPHICAL ABSTRACT



Preparation of the samples
Pine, beech and poplar wood specimens were cut to specific dimensions, ensuring they were free from defects.

Air Conditioning
Samples exposed to different temperatures (-20°C, 0°C, 20°C, and 50°C) to simulate various climatic conditions.

Processing
Samples were machined using a CNC router with varying parameters.

Measurement of surface roughness
Surface roughness was measured using a portable surface roughness tester in accordance with relevant standards.

The study reveals that processing temperature significantly affects the surface roughness of machined wood. Lower processing temperatures generally resulted in smoother surfaces, highlighting the importance of temperature control in wood machining processes for optimal surface quality.

The comprehensive approach, examining multiple variables simultaneously and simulating various climatic conditions, provides valuable insights for both academic understanding and industrial applications.

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Effects of wood temperature were studied during CNC router processing relative to the resulting surface roughness, addressing a considerable gap in wood machining research. Three wood species (Scots pine, beech, and poplar) were machined at four temperatures (-20 °C, 0 °C, 20 °C, and 50 °C) to simulate diverse climatic conditions. The experiments were conducted at varied spindle speeds (6000, 12000, and 18000 rpm) and feed rates (3000 and 6000 mm/min). Surface roughness was measured using a portable tester in accordance with relevant ISO standards. A full factorial design was used to evaluate the effects of wood species, temperature, spindle speed, and feed rate on surface roughness. Results revealed a strong correlation between processing temperature and surface roughness, with a 25.9% increase in roughness observed as temperature rose from -20 °C to 50 °C. This temperature effect was consistent across all wood species, though its magnitude varied. The study also found that wood type, spindle speed, and feed rate significantly influenced surface quality, interacting with temperature effects. These findings suggest that controlling wood temperature during processing could be crucial for maintaining consistent surface quality in industrial applications, especially in facilities operating under variable environmental conditions.

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Keywords: CNC; Surface roughness; Machining; Climatic temperature

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INTRODUCTION

Wood is a versatile material with a wide range of applications due to its unique properties. It is a natural biopolymer composite primarily composed of cellulose and lignin, which constitute a significant portion of its dry weight (Wang *et al*. 2019a). This composition allows wood to be used as a feedstock for preparing polymeric materials, thereby broadening its potential applications in various industries. Its strength properties and natural durability make wood suitable for a wide range of applications, such as building materials, tools, furniture, and industrial purposes (Cabral and Blanchet 2021). Since wood itself is a porous natural composite comprised of cellulose, hemicellulose, and lignin, it can be regarded as a good candidate for use in composite applications due to its good mechanical properties at low density (Kyzioł and Murawski 2014; Siegel *et al*. 2023).

Compared to materials such as concrete and steel, wood offers a favorable balance between mechanical strength, mass, beauty, low energy consumption during processing, good thermal insulation properties, and easy machinability (Rodrigues 2019). Even in the Paleolithic age, mankind was able to process wood by using high-density materials such as flint, obsidian, animal teeth, and nails. The oldest known wooden structure made by human hands consists of two wooden logs that were carved with stone and interlocked with each other. They have been well preserved due to being in a waterlogged environment and are dated to approximately 475,000 years ago (Barham *et al*. 2023). Today, wood has an almost unlimited potential for use in various fields, ranging from lightweight wooden structures to mass-produced furniture, from spacecrafts to solar panels. This potential is fully realized using different machines and techniques in wood processing.

Various machining operations, such as cutting, planning, sanding, milling, and turning, can be performed on wood (Bila *et al*. 2020). Until the late 90s, these operations were carried out by manually controlled electric machines, which were considered technological at the time, and often each of them was dedicated to a single task. Although woodworking has historically been considered a low-tech industry, it has witnessed significant technological advances in recent years, especially with Computer Numerical Control (CNC) machines (Camcı *et al*. 2018).

Using CNC in woodworking offers several advantages that enhance efficiency and quality in wood processing. The CNC technology allows for precise and automated control of woodworking machinery, leading to increased accuracy and consistency in cutting, shaping, and carving wood materials (Demir *et al*. 2022). This precision results in improved surface quality and finishing of wood-based products, making them more visually appealing and suitable for various applications (Cakiroglu *et al*. 2019). Additionally, CNC machines can handle complex geometries and intricate designs with ease, enabling the production of highly personalized and customized wood products (Sun *et al*. 2022). Additionally, the use of CNC in woodworking contributes to optimizing production processes by reducing waste, enhancing material utilization, and minimizing errors (Pelit *et al*. 2021; Çakıroğlu *et al*. 2022; Yaghoubi and Rabiei 2023). The CNC machining centers can be integrated into digital wood production systems, connecting with other equipment to streamline operations and achieve cost efficiency in a shorter timeframe (Sun *et al*. 2022). Furthermore, CNC technology enables the implementation of optimal cutting conditions, leading to energy savings and reduced processing time, which are crucial factors in enhancing productivity and sustainability in the woodworking industry (Yao *et al*. 2024).

Wood machinability refers to the ability of wood to be processed efficiently while maintaining quality and minimizing tool wear and cutting force (Hodžić *et al*. 2023). Factors influencing wood machinability include cutting speed, feed direction, depth of cut, tool sharpness, and wood modifications such as thermal treatments (Kotlarewski *et al*. 2019; Pelit *et al*. 2021). Optimal processing parameters play a crucial role in improving the surface quality and surface roughness of wood and wood-based panels (Çakıroğlu *et al*. 2022; Yaghoubi and Rabiei 2023). The surface roughness significantly impacts the adhesion, durability, and aesthetic quality of the coatings. It is preferable to minimize surfaces roughness prior to applying surface treatments such as paint and varnish. Surfaces with high roughness values can be smoothed with applications, such as sanding, scraping, and polishing, which require labor, time, and resources (Zhong 2021). This situation, which causes serious losses for companies, can be solved "at the source of the problem" with the right processing methods and parameters.

Parameters, such as cutting tools capable of operating at high rotation speeds, adjustable feed, and plunge rates, and interchangeable cutters, are critical determinants of the product quality in CNC milling machines. The CNC router processing is influenced by various factors including spindle speed, feed rate, cutting depth, and the type of wood material used. Studies have shown that adjusting these parameters can affect the surface quality of the processed wood (Petrović *et al*. 2016; Ibrisevic 2023). The correct adjustment of these parameters is a fundamental determining factor in obtaining suitable surfaces with minimal resources and time. However, the determination of these parameters is often achieved through trial-and-error experience by operators.

The process of parameter determination for wood processing presents significant challenges due to its heterogeneous and anisotropic structure, which manifests itself in varying properties even among samples derived from trees of the same species (Hodžić *et al.* 2023; Korkmaz *et al.* 2023; Rošić *et al.* 2023; Yu *et al.* 2023). Studies on the machining of different wood species on different machines also point to this difficulty. Beyond these intrinsic characteristics, the material's interaction with environmental factors further contributes to the variability of outcomes in wood processing. Notably, the temperature of wood during processing, a factor often overlooked in laboratory studies, potentially plays a crucial role in determining surface properties. However, there is a dearth of research specifically investigating the impact of temperature on surface characteristics during wood processing. In real-world applications, both ambient and material temperatures are significant variables. Seasonal fluctuations, diverse climatic conditions across geographical locations, and variations in production environments collectively contribute to temperature differentials during material processing. These thermal variations can substantially influence wood properties and significantly impact the processing outcomes.

This study aims to address this research gap by examining the effects of wood temperature during CNC router processing, in conjunction with specific processing parameters, on resultant surface roughness. The primary objective is to simulate and evaluate the impact of temperature variations, characteristic of different geographical locations, on post-processing surface roughness. This will be achieved through the manipulation of various processing parameters, providing insights into the complex interplay between environmental conditions and wood processing outcomes. Through investigating these factors, this study seeks to enhance the understanding of temperature-dependent variables in wood processing, potentially leading to more precise and geographically adaptable CNC routing strategies for optimal surface quality.

EXPERIMENTAL

Materials

Wood Materials

Scots pine (*Pinus sylvestris* L.), beech (*Fagus orientalis* Lipsky), and poplar (*Populus nigra* L.) wood species were chosen for this study. The samples were prepared from parts of the kiln-dried lumber free from defects such as cracks, knots, fiber distortions, *etc*. Specimens measuring 25 × 50 × 500 mm^3 (tangential × radial × longitudinal) were used.

Acclimatization Process

The prepared specimens were initially conditioned in a climate-controlled chamber at 65% relative humidity and 20 °C until they reached equilibrium moisture content (approximately 12%), corresponding to air-dry conditions. This process was continued until the samples achieved constant mass. Subsequently, all specimens were hermetically sealed to maintain their moisture content.

To simulate different climatic conditions, the sealed samples were then exposed to environments with varying temperatures. The specimens were kept in these conditions until their core temperature matched the surrounding temperature. The following temperature ranges were used: -20 ± 1 °C (specimens were stored in a deep freezer), 0 ± 1 °C (specimens were kept in a refrigerator), +20 ± 1 °C (specimens remained in the climate-controlled chamber), and + 50 ± 1 °C (specimens were placed in a laboratory oven). This conditioning process ensured that the wood samples accurately represented material properties across a range of temperatures typically encountered in various geographical and seasonal contexts.

Machining Process

Upon achieving thermal equilibrium, the specimens were transported to the CNC machine area in thermally insulated polystyrene foam containers to maintain their conditioned temperatures. Subsequently, the samples were swiftly transferred from the insulated containers onto a custom-designed fixture for immediate processing. The machining operation utilized new, unused 2-flute solid carbide end mills with a diameter of 10 mm, a flute angle of 38 degrees and a rake angle of 18 degrees (Fig. 1).

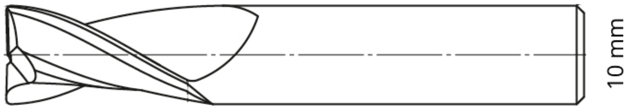

Fig. 1. Technical drawing of the end-mill

A 3-axis CNC machining center was used for the milling operations, equipped with a 7.5 kW spindle motor and a maximum spindle speed of 24,000 rpm. The machine’s rigidity and precision ensured accurate and repeatable cutting conditions throughout the experiments. Conventional (up) milling was employed during the cutting process to ensure optimal surface quality and minimize material deformation.

The spindle speeds and feed parameters were determined considering literature studies on the mechanical structures of CNC machines and cutting tools, as well as based on preliminary experimental observations. The factors and levels used in the experiments are presented in Table 1.

Table 1. Factors and Levels

Factor	Symbol	Levels	Values
Wood Type	A	3	Pine; Beech; Poplar
Wood Temperature (°C)	B	4	-20; 0; 20; 50
Spindle Speed (rpm)	C	3	6000; 12000; 18000
Feed Rate (mm/min)	D	2	3000; 6000

The cutting edge of the 2-flute solid carbide end mill was inspected using a digital microscope at 100× magnification before starting the experiment and after every 72 cuts (representing 1/8 of the total cuts). Flank wear (FW) was measured along each cutting edge and recorded at each inspection interval. A predefined wear criterion of $FW_{\max}$ = 0.3 mm was established as the threshold for tool replacement. If this threshold was reached, the tool was replaced with an identical new one to ensure consistency in cutting conditions.

Measurement of Surface Roughness

The surface roughness properties of the test specimens were determined in accordance with TS 6212 EN ISO 21920-3 (2022) and TS 2495 EN ISO 3274 (2005) standards. Measurements were conducted using a TIME TR-200 portable surface roughness tester, employing a contact method with a diamond stylus (tip radius: 2 µm) capable of measuring consecutive profile variations. The device reports the average roughness value (R_a) as the center line between profile valleys and peaks. Prior to measurements, the roughness tester was calibrated using a reference specimen with known roughness values. The device was then set to the following parameters: measurement speed of 15 mm/min, sampling length of 5 mm, and a cut-off value of 5. These parameters were selected to ensure accurate representation of the wood surface characteristics while adhering to the relative standards. To mitigate errors arising from surface irregularities, all specimens were processed in both tangential and radial directions using the selected parameters. The range of processing temperatures (-20 °C, 0 °C, 20 °C, and 50 °C) was chosen to simulate various climatic conditions that wood products might encounter during manufacturing or use. Spindle speeds (12,000 rpm, 15,000 rpm, and 18,000 rpm) and feed rates (3,000 mm/min and 6,000 mm/min) were selected based on common industry practices and preliminary tests to cover a representative range of machining conditions.

For each set of processing parameters, measurements were taken at two different points on the four cut channels, and 8 measurements were taken for each parameter. Measurements were performed in the radial direction. The experimental design encompassed 3 wood species, 4 processing temperatures, 3 spindle speeds, and 2 feed rates. This factorial design resulted in a total of 576 measurements ($3 \times 4 \times 3 \times 2 \times 8$). All measurements were conducted in a climate-controlled laboratory environment maintained at 20 ± 2 °C and 65 ± 5% relative humidity to ensure consistency across all trials.

Statistical Analysis

In this study, four main factors were examined during CNC operations: wood types (Scots pine, beech, poplar), wood temperatures (-20 °C, 0 °C, 20 °C, and 50 °C), spindle speeds (6000 rpm, 12000 rpm, and 18000 rpm), and feed rates (3000 mm/min, 6000 mm/min). Each factor was investigated at multiple levels using a full factorial experimental design using a statistical analysis software. The analysis aimed to elucidate the effects of these factors on machining parameters and statistically validate the experimental results. The effects of wood species, processing temperatures, spindle speeds, and feed rates on surface roughness were investigated using a full factorial experimental design and evaluated using analysis of variance (ANOVA).

RESULTS AND DISCUSSION

Friction is inevitable in wood machining processes due to the contact between the cutting tool and the workpiece. This friction is influenced by factors such as the cutting tool geometry, cutting speed, feed rate, characteristics of the workpiece, and materials of the cutting tool. Incorrect selection of these parameters can increase forces on the cutting tool, adversely affecting the quality of the machined surface. In the context of wood materials, various processing parameters' effects on surface roughness have been investigated. Experimental results were modeled using a full factorial experimental design, and average main effect plots for surface roughness were generated as shown in Fig. 2. To fully understand the relationships between the factors and surface roughness, interaction plots were also generated and are displayed in Fig. 3.

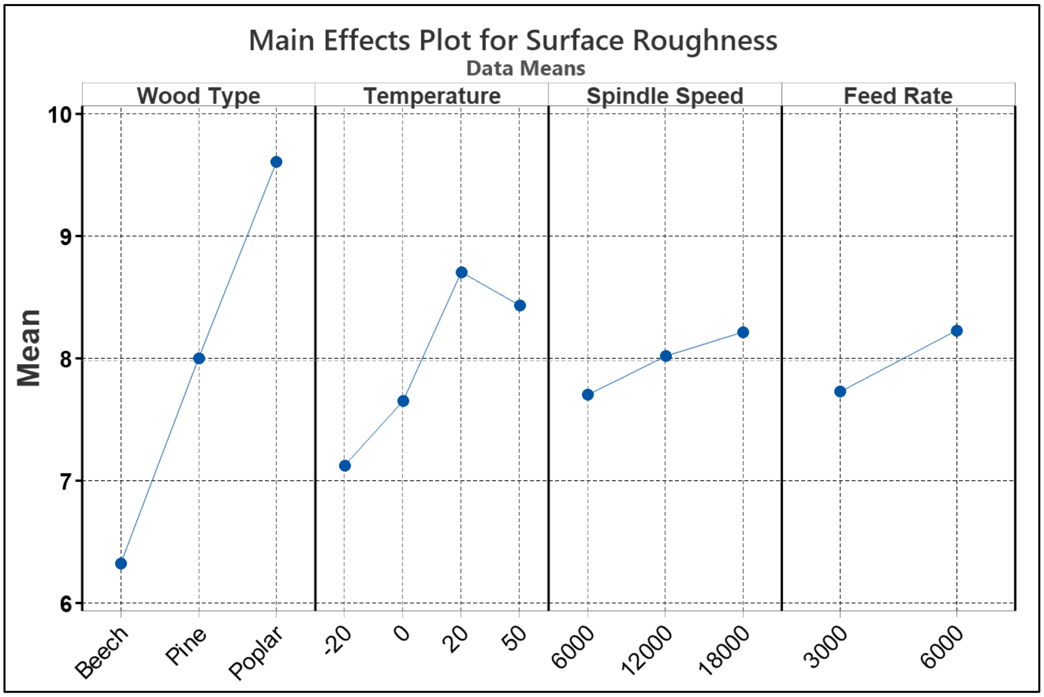

Fig. 2. The effects of processing parameters on surface roughness

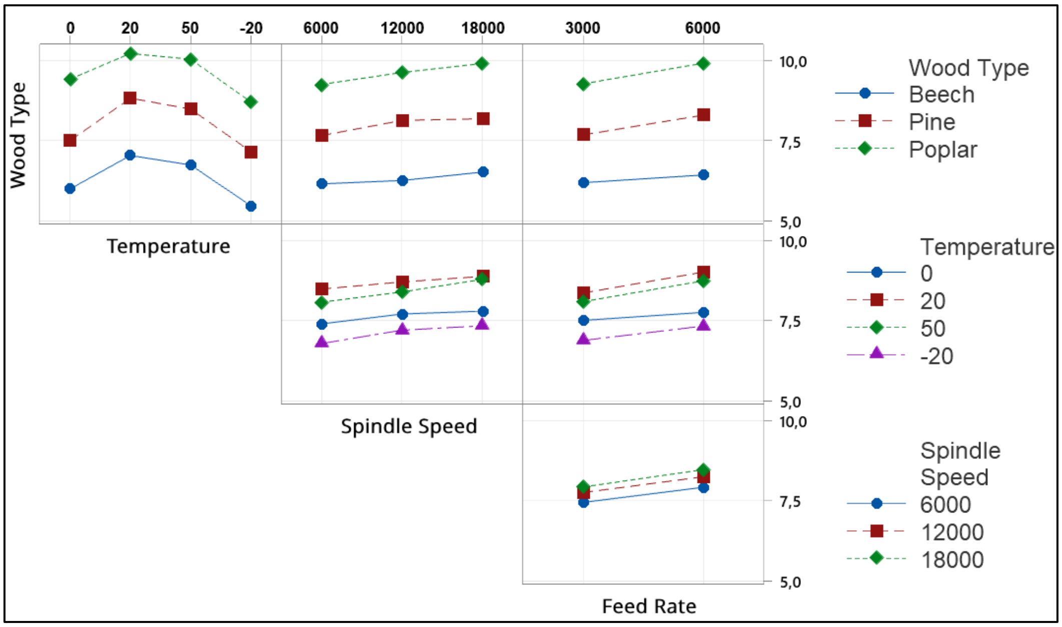

Fig. 3. Interaction plots for surface roughness

The plots in Figs. 2 and 3 illustrates the impact of various machining parameters on average value of surface roughness (R_a). Among the wood types, the lowest surface roughness was observed in pine, while the highest was in poplar, indicating that poplar yielded a lower surface quality. This difference can be attributed to the structural properties of the wood species. Pine, with its generally finer and more uniform grain structure, tends to result in a smoother surface when machined. In contrast, poplar has a more variable grain structure with a higher density of softer and harder zones, which can lead to greater variation in surface roughness and a rougher finish. This variability in grain density and hardness affects how the wood interacts with the cutting tools, leading to increased surface roughness in poplar.

In terms of processing temperatures, surface roughness increased with temperature, with the lowest values at -20 °C and the highest at 50 °C, suggesting that higher temperatures adversely affect surface quality.

Regarding spindle speed, the lowest surface roughness was achieved at 6000 rpm, while higher speeds of 12000 rpm and 18000 rpm resulted in increased roughness, indicating that higher spindle speeds can reduce surface quality. For feed rate, a lower rate of 3000 mm/min produced lower surface roughness compared to a higher rate of 6000 mm/min, which increased roughness, suggesting that higher feed rates negatively impact surface quality. At higher feed rates, the cutting tools engage with the wood more aggressively, which can lead to increased tool wear and a rougher surface finish. These findings indicate that for optimal surface quality, lower temperatures, spindle speeds, and feed rates should be preferred.

The standardized effects of wood type, wood temperature (°C), spindle speed (rpm), feed rate (mm/min), and their interactions on surface roughness (R_a) are presented in the Pareto chart in Fig. 4.

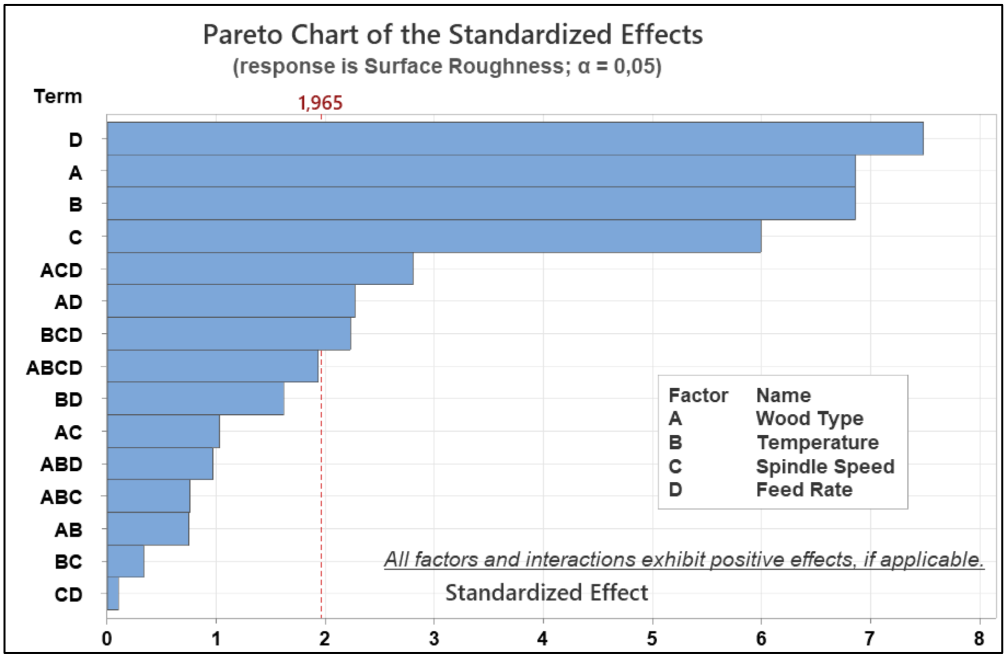

Fig. 4. Standardized Pareto charts of processing parameters on the results (α = 0.05)

The Pareto chart in Fig. 4 reveals that feed rate (Factor D) had the largest impact on surface roughness. This was followed by wood type (Factor A), temperature (Factor B), and spindle speed (Factor C). Additionally, interaction effects between factors (such as AB, ACD, AD) were considered, although their impacts were not as significant as the main factors. The critical threshold value is set at 1.965, indicating that factors above this value have a significant effect on surface roughness. Therefore, to optimize surface roughness, it is essential to focus on the most influential factors: feed rate, wood type, temperature, and spindle speed. Although the interaction effects between factors exceed the Pareto line, their percentage contributions are quite low. These values are provided as percentages in Table 2.

Based on the ANOVA results presented in Table 2, several significant factors and interactions were identified. The main effects of wood type (A), processing temperature (B), spindle speed (C), and feed rate (D) all showed highly significant influences on the response variable, with P-values less than 0.005. The wood type exhibited the most substantial influence, as indicated by its high F-value. The two-way interaction between A*B was highly significant, while the interaction between A*D was also significant. Notably, higher-order interactions were observed to be significant, including the three-way interaction ACD, the three-way interaction BCD, and the four-way interaction ABCD. These findings suggest complex relationships among the factors affecting the response variable. However, several two-way interactions (AC, BC, BD, CD) and the three-way interaction ABC were not statistically significant. The low MS value for the error term compared to the significant factors and interactions indicates that the model accounts for a considerable portion of the variance. The presence of significant higher-order interactions underscores the complexity of the system, highlighting the critical importance of comprehensive studies to fully understand the intricate relationships between these factors and their combined effects.

Table 2. ANOVA Results of Surface Roughness (µm) Values

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
Model	71	1379.85	80.92%	19.434	30.11	0.000
Linear	8	1304.86	76.53%	163.107	252.74	0.000
Wood Type (A)	2	911.46	53.45%	455.728	706.17	0.000
Temperature (B)	3	331.12	19.42%	110.375	171.03	0.000
Spindle Speed (C)	2	26.05	1.53%	13.026	20.18	0.000
Feed Rate (D)	1	36.22	2.12%	36.225	56.13	0.000
2-Way Interactions	23	30.35	1.78%	1.319	2.04	0.003
A*B	6	16.06	0.94%	2.677	4.15	0.000
A*C	4	3.11	0.18%	0.778	1.21	0.308
A*D	2	4.89	0.29%	2.446	3.79	0.023
B*C	6	2.26	0.13%	0.376	0.58	0.744
B*D	3	3.91	0.23%	1.302	2.02	0.110
C*D	2	0.12	0.01%	0.058	.,09	0.914
3-Way Interactions	28	31,11	1.82%	1.111	1.72	0.013
A*B*C	12	7,77	0.46%	0.648	1.00	0.444
A*B*D	6	4,42	0.26%	0.737	1.14	0.336
A*C*D	4	9,54	0.56%	2.386	3.70	0.006
B*C*D	6	9,37	0.55%	1.561	2.42	0.026
4-Way Interactions	12	13.53	0.79%	1.128	1.75	0.054
A*B*C*D	12	13.53	0.79%	1.128	1.75	0.054
Error	504	325.26	19.08%	0.645		
Total	575	1705.11	100.00%			

Table 3. Duncan Multiple Range Test Results for Different Wood Types, Processing Temperatures, Spindle Speeds, and Feed Rates

Factor	Group	Mean R_a (StDv) (µm)	LSD*	HG**
Wood Type	Beech	8.255 (1.18)	0.161	B
	Pine	6.651 (1.37)		A
	Poplar	9.732 (0.92)		C
Processing Temperature (°C)	-20	7.258 (1.46)	0.186	A
	0	7.685 (1.62)		B
	20	8.872 (1.66)		C
	50	9.135 (1.44)		D
Spindle Speed (rpm)	6000	7.935 (1.64)	0.161	A
	12000	8.252 (1.70)		B
	18000	8.451 (1.78)		C
Feed Rate (m/min)	3000	7.961 (1.60)	0.131	A
	6000	8.463 (1.79)		B

(*Least significant difference value; **Homogeneity group)

To discern which specific groups within each factor differed significantly from one another, a *post hoc* analysis was conducted using Duncan's Multiple Range Test at a significance level of α = 0.05. Table 3 provides a comprehensive overview of the mean values for each parameter and their interactions and highlights the statistically significant differences between groups.

At the wood species level, beech samples exhibited 24.1% higher R_a values compared to pine samples. The poplar samples with the highest R_a values had 17.9% higher R_a values compared to beech samples and 46.3% higher R_a values compared to pine samples. This disparity can be attributed to the more homogeneous structure of pine and the diffuse-porous nature of beech wood (Wang *et al*. 2019b). Furthermore, the anatomical characteristics of pine wood, such as the prevalence of resin and the sharp transition from earlywood to latewood (Uggla *et al*. 2001), may contribute to its lower surface roughness. Previous studies in literature also report lower R_a values for pine wood compared to beech (Ozdemir and Hiziroglu 2009; Sogutlu 2010; Pelit *et al*. 2021). In contrast, poplar wood is characterized by structural features, such as thin cell walls, large cell cavities, and short fibers, which contribute to its low density and high porosity (Bao *et al*. 2017). This feature is explanatory for the significantly high R_a value for this tree species. These characteristics explain the significantly high R_a value observed for this tree species. The findings of the present study are consistent with existing literature in this regard.

For processing temperature, a gradual increase in surface roughness was observed as temperature was raised. The transition from -20 °C to 0 °C resulted in a 5.9% increase in roughness. The most substantial increment occurred between 0 °C and 20 °C, with a 15.4% increase. From 20 to 50 °C, a smaller 2.96% increase was noted. Overall, from the lowest to highest temperature (-20 to 50 °C), surface roughness increased 25.9%. This finding suggests that lower processing temperatures may contribute to smoother surface finishes. There is no direct previous study suggesting that the processing temperature of wood has a significant impact on its surface roughness. Previous studies primarily have focused on the effects of heat treatment before machining, rather than the processing temperature during machining. The heat treatment process, which involves exposing wood to high temperatures (ranging from 140 to 210 °C) for a certain period, has been shown to affect the surface roughness of wood. Some studies have reported an increase in surface roughness with heat treatment (Budakçı *et al*. 2011; Karagoz *et al*. 2011; Palermo *et al*.

2014; Gurau *et al*. 2019), while others have found a decrease (Pinkowski *et al*. 2016). There are also studies suggesting that there is no linear relationship between heat treatment temperature and surface roughness (Kvietková *et al*. 2015; Nabil *et al*. 2018). The inconsistencies in these findings may be attributed to differences in wood species, heat treatment temperatures, and machining parameters. However, research specifically investigating the effect of processing temperature on surface roughness appears to be lacking. This gap in the literature underscores the novelty and importance of the present study.

In the present study, it was observed that the surface roughness of wood samples decreased as the processing temperature decreased. This phenomenon can be explained by considering the temperature-dependent behaviors of primary components of wood, cellulose, and lignin. As demonstrated by in a previous study on rayon, a regenerated cellulose fiber, cellulose exhibits glass-like behavior at low temperatures, with restricted chain mobility. This reduced mobility of cellulose chains at lower temperatures may contribute to a smoother surface during the cutting process. Concurrently, lignin, another major component of wood, exhibits more brittle and friable properties as the temperature moves further below its glass transition point. The glass transition temperature of lignin varies depending on moisture content and species but typically ranges from 60 °C to 180 °C (Goring 1965; Nakajima *et al*. 2009; Gasparik and Barcik 2014). As the processing temperature decreases, moving further away from lignin's glass transition temperature, the increased brittleness of lignin may facilitate cleaner cuts during machining, resulting in reduced surface roughness. These combined effects of temperature on cellulose mobility and lignin brittleness provide a plausible explanation for the observed inverse relationship between processing temperature and surface roughness in the current study. The more rigid, glass-like state of both cellulose and lignin at lower temperatures appears to promote the formation of smoother surfaces during the cutting process. Conversely, as temperature increases, the enhanced mobility of cellulose chains and the more plastic behavior of lignin may lead to increased deformation during cutting, resulting in higher surface roughness.

Studies examining the effect of temperature on the mechanical properties of cellulose-based materials can provide important insights into understanding the impact of processing temperature on wood surface roughness. A previous study on rayon, a regenerated cellulose fiber, demonstrates the significant effect of temperature on cellulose structure (Roseveare and Poore 1954). According to study, completely dry rayon exhibits glass-like behavior at low temperatures, with no chain slippage observed and only deformation in valence bonds and angles under reversible strain. In contrast, while wet rayon fibers exhibit rubber-like behavior above 50 °C, chain movement is restricted below this temperature, leading to a yield point in wet stress-strain curves and poor work recovery. These findings are important for understanding the temperature-dependent behavior of cellulose, the main component of wood. The observation in this study that wood samples processed at lower temperatures have lower surface roughness may be related to the reduced mobility of cellulose chains at low temperatures. This condition may contribute to the formation of a smoother surface during the cutting process. In contrast, increased chain mobility at high temperatures may lead to more deformation during cutting and consequently a rougher surface.

Regarding spindle speed, an increase from 6000 rpm to 12000 rpm led to a 4.0% rise in surface roughness. This suggests a moderate impact of spindle speed on the final surface quality. Analysis of spindle speed's impact on surface roughness reveals a trend consistent with existing literature: an inverse relationship is observed, where higher spindle speeds correspond to reduced surface roughness. This finding aligns with previous studies that have demonstrated the efficacy of high spindle speeds in reducing surface roughness during machining processes (İşleyen and Karamanoğlu 2019; Pelit *et al*. 2021; Putra 2023). The phenomenon can be attributed to several factors. Primarily, higher spindle speeds increase the work done by the cutter per unit time, resulting in a greater impact on the unit surface area (Zhu *et al*. 2022). Additionally, elevated spindle speeds facilitate more efficient cutting, reducing the duration of each cutting pass. This shortened of cutting time may lead to diminished heat generation, potentially contributing to a smoother surface finish. Furthermore, the increased centrifugal force at higher speeds may improve chip evacuation, reducing the likelihood of chip interference with the newly cut surface. The combination of reduced material temperature and increased centrifugal force can result in a more accurate cut as the cooler, stiffer wood fibers can be more cleanly separated by the cutting tool.

This indicates that feed rate has a pronounced effect on surface roughness, within the ranges tested in this study. This relationship can be attributed to several factors. Higher feed rates lead to larger chips being removed from the wood surface, which tend to leave more pronounced marks, contributing to increased roughness (Pakzad *et al*. 2022). As feed rate increases, the cutting tool spends less time engaged with each point on the wood surface, potentially resulting in a less smooth finish (Pelit *et al*. 2021). Increased feed rates generally lead to higher cutting forces, which can cause more significant deformation of the wood fibers.

While this study provides valuable insights into the effects of temperature on wood machining, it is crucial to consider its practical implications for industrial settings. In real-world applications, wood processing facilities often operate under varying environmental conditions, which can significantly impact product quality and process efficiency. The results from this study suggest that temperature control in wood storage and processing areas could be a critical factor in maintaining consistent surface quality. For example, facilities in colder climates might benefit from machining at lower room temperatures, while those in warmer regions may need to implement cooling strategies. Furthermore, the observed relationship between processing temperature and surface roughness could inform the development of adaptive CNC systems that adjust machining parameters based on material temperature. Future research could focus on validating these findings in industrial-scale operations and exploring cost-effective methods for temperature management in wood processing facilities. Additionally, investigating the potential energy savings and quality improvements that could result from optimized temperature control would provide valuable information for the wood machining industry.

CONCLUSIONS

1. As the processing temperature increased from -20 °C to 50 °C, surface roughness increased by 25.9%, highlighting the importance of temperature control for achieving smooth surfaces.
2. Poplar exhibited the highest surface roughness, followed by beech and pine. These differences underscore the need for tailored machining parameters based on wood type to optimize surface quality in industrial applications.

3. Higher spindle speeds and feed rates generally increased surface roughness, with variations depending on wood species and processing temperature. This interplay emphasizes the complexity of wood processing and the need for comprehensive optimization strategies.
4. The inverse relationship between processing temperature and surface smoothness can be attributed to the temperature-dependent behaviors of cellulose and lignin. At lower temperatures, increased rigidity of these components likely facilitates cleaner cuts, resulting in smoother surfaces.
5. These results have significant implications for the wood processing industry, especially for facilities in varying climatic conditions. The strong influence of processing temperature on surface quality suggests that implementing temperature control measures in wood storage and processing areas could be crucial for maintaining consistent product quality. Additionally, these results point towards developing adaptive CNC systems that adjust machining parameters based on material temperature, leading to improved efficiency and product quality in wood processing operations.

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