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Article

MECHANISMS OF SURFACE IRREGULARITY FORMATION IN CNC MILLING OF SOLID WOOD

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ABSTRACT

Achieving high surface quality in CNC milling of solid wood remains a critical challenge due to the complex interaction between machining parameters and the heterogeneous structure of wood. This study investigates the causes of surface irregularities formed during CNC milling of three representative wood species – spruce (Picea abies L.), beech (Fagus sylvatica L.), and oak (Quercus robur L.). The primary objective was to analyse the influence of technological parameters, particularly feed speed and rotational speed, on surface roughness and waviness, and to relate these findings to the microscopic analysis. Samples were milled under controlled conditions using a 5-axis CNC machining centre, with feed speeds ranging from 10 $m \cdot min^{-1}$ to 18 $m \cdot min^{-1}$ and rotational speeds from 16,000 rpm to 20,000 rpm. Surface quality and microscopic analysis were evaluated using a Keyence VHX-7000 digital microscope. Roughness parameters (Ra, Rz, Rp, Rv, and Rk) and waviness parameters (Wa and Wz) were analysed alongside microscopic observations of defects such as torn fibres, fuzziness, and tool marks. The results demonstrated that feed speed had a dominant effect on surface quality, with increasing feed speed leading to higher roughness values. Conversely, higher rotational speeds contributed to a reduction in surface irregularities. The optimal combination of parameters was identified at 20,000 rpm and 10 $m \cdot min^{-1}$, where the lowest roughness and minimal defects were observed. The results showed that the effects of the technological parameters are mediated by feed per tooth. Additionally, the study confirmed that wood species and anatomical structure significantly influence surface formation, with denser wood species generally producing smoother surfaces. The findings provide a comprehensive understanding of the mechanisms behind surface irregularities and contribute to the optimization of CNC milling parameters for improved surface quality in wood machining.

Keywords: *surface roughness; surface waviness; CNC milling; solid wood; VHX-7000*

1 INTRODUCTION

CNC milling of solid wood and wood-based composites is widely used in industry, where achieving the required surface quality remains a major challenge [1,2]. Surface defects generated during milling can be evaluated at both macroscopic and microscopic levels. Macroscopic defects include fibre tear-out and delamination [3,4], which negatively affect product appearance and functionality. Their occurrence is influenced by tool geometry, cutting strategy,

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feed speed, rotational speed, feed per tooth, and material properties such as density, hardness, and wood anisotropy [5]. At the microscopic level, surface quality is commonly assessed through roughness and waviness parameters [6]. Surface irregularities arise from the kinematics of tool motion, local fibre failures, wood anatomical structure, and machining conditions. Feed speed, through its effect on feed per tooth, is considered one of the most influential factors affecting surface roughness. In contrast, rotational speed generally contributes to roughness reduction by increasing cutting speed. Roughness and waviness parameters are therefore essential indicators for milling process optimisation. Numerous studies have developed regression, statistical, and predictive models to describe the relationship between machining parameters and resulting surface quality [7–9]. Although numerous studies have modelled the effects of machining parameters on surface roughness, relatively few have combined quantitative roughness and waviness measurements with microscopic analysis to explain the underlying mechanisms of surface defect formation. The novelty of this study is the integration of these approaches for three wood species with different anatomical structures, enabling direct interpretation of the relationship between machining conditions, wood anatomy, and the resulting surface irregularities.

This research aimed to analyse the mechanisms governing surface irregularity formation during CNC milling of solid wood. The effects of feed speed and rotational speed on surface roughness, waviness, and defect generation were evaluated for spruce, beech, and oak wood. Particular emphasis was placed on identifying the physical mechanisms responsible for surface deterioration through microscopic observation of machined surfaces. The study focused on the occurrence of fibre pull-out, surface fuzziness, cutter-induced kinematic ripples, and anatomical effects related to wood structure. By combining quantitative surface measurements with microscopic analysis, the research sought to explain how machining conditions and wood properties interact to determine the final surface quality.

2 MATERIALS AND METHODS

2.1 Materials and Sample Preparation

Three wood species representing major anatomical groups were selected: Norway spruce (*Picea abies* L.), European beech (*Fagus sylvatica* L.), and common oak (*Quercus robur* L.). Spruce represented a conifer, beech a diffuse-porous hardwood, and oak a ring-porous hardwood.

2.2 CNC Milling

Samples were machined on a 5-axis SCM Tech Z5 CNC machining centre (SCM group, Rimini, Italy) using a 20 mm-diameter Klein T143 finishing spiral milling cutter (Sistemi S.r.l., Pesaro, Italy) with positive cutting edges and monolithic tungsten carbide. Edge milling was performed in two passes, with the second pass generating the final surface for evaluation. Climb milling was applied with a radial depth of cut of 1 mm. The selected feed speeds were 10 $m \cdot min^{-1}$, 14 $m \cdot min^{-1}$, and 18 $m \cdot min^{-1}$. The selected rotational speeds were 16 000 rpm, 18 000 rpm, and 20 000 rpm. These values result in feed per tooth values ranging from 0.17 mm to 0.38 mm. Six samples were prepared for each of the technological parameter combinations. Sixteen replicate measurements were considered for each sample ($3 \times 3 \times 6 \times 16 = 2592$ data).

2.3 Surface roughness, waviness, and microscopic analysis

Surface irregularities were measured using a Keyence VHX-7000 digital microscope (Keyence Corporation, Osaka, Japan) equipped with a VH-Z100R (Keyence Corporation, Osaka, Japan) lens at ×200 magnification. Four scans (3 mm × 18 mm) were recorded along each milled edge, and four profiles were evaluated from each scan. Roughness and waviness profiles were separated using a double Gaussian filter according to ISO 21920 [10] standards. The applied filtering parameters were $\lambda c = 2.5$ mm and $\lambda s = 8$ µm. To evaluate processing-related roughness independently of wood anatomy, the parameters *R*k, *R*pk, and *R*vk were additionally measured using an INSIZE ISR-300 stylus profilometer (INSIZE Czech s.r.o., Brno, Czech Republic). Microscopic observations of machined surfaces were performed at ×300 magnification. The reason for using such magnification was the need to capture changes in the surface in detail.

2.4 Statistical Analysis

Data were analysed using STATISTICA 14 (TIBCO Software Inc., Palo Alto, California). Outliers (measurement errors) exceeding ± 2 standard deviations were removed and remeasured according to the standard score or 68% - 95% - 99.7% rule. Remeasured data were included in the final ANOVA. Descriptive statistics were followed by two-way ANOVA with a significance level of $\alpha = 0.05$ and Duncan's post hoc test. Data normality and homogeneity of variance were assessed using the Shapiro-Wilk and Levene tests, respectively.

3 RESULTS AND DISCUSSION

3.1 Waviness of CNC-milled surface

To evaluate the effects of the independent variables (wood species, feed speed, and rotational speed) and their interactions on the surface roughness and waviness parameters, an analysis of variance was performed at a significance level of $\alpha = 0.05$. The analysis revealed that all main effects, together with all two-way and three-way interactions, significantly influenced the evaluated surface roughness and waviness parameters (p-level < 0.001).

Waviness generally increased with increasing feed speed (Figures 1 and 2), particularly in spruce and oak wood, consistent with previous studies [11–13]. In contrast, rotational speed showed little influence on waviness, confirming the findings of [14]. Beech wood exhibited only minor changes in waviness across the tested feed speeds, similarly to observations reported for maple wood by [15]. Higher rotational speeds may contribute to waviness through tool vibration and run-out; however, this effect was not clearly demonstrated in the present study.

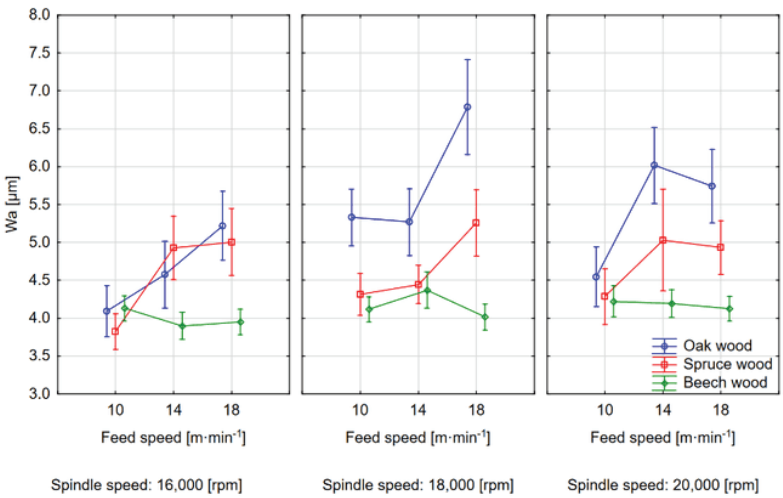

Figure 1. Parameter of waviness *W*a for all investigated types of wood at varying rotational speed and feed speed (vertical bars denote 0.95 confidence intervals)

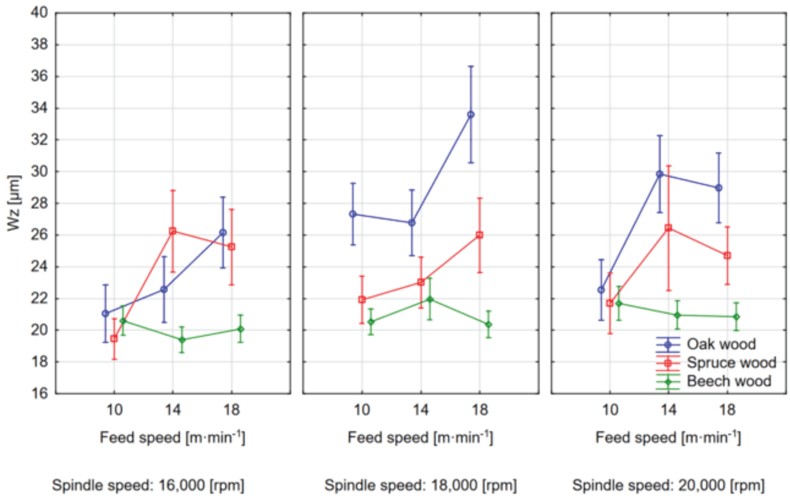

Figure 2. Parameter of waviness Wz for all examined types of wood at varying rotational speed and feed speed (vertical bars denote 0.95 confidence intervals)

3.2 Roughness of CNC-milled surface

The results presented in Figures 3 and 4 showed that the highest surface roughness was measured for spruce wood at a rotational speed of 16,000 rpm and a feed speed of 18 $m \cdot min^{-1}$. This can be attributed to the lower density of spruce wood and the associated formation of protruding fibres and surface fuzziness during CNC milling. Surface fuzziness consists of incompletely severed fibres remaining attached to the surface, which significantly increases roughness values. Previous studies have shown that low-density wood species are more susceptible to this defect mechanism [16, 17]. The effect became particularly pronounced as feed speed increased, leading to a sharp rise in roughness values, confirming observations reported in [18, 19].

In contrast, the lowest surface roughness was observed for oak wood at a feed speed of 10 $m \cdot min^{-1}$ and a rotational speed of 20,000 rpm. Oak wood also exhibited the highest density among the investigated species. The results, therefore, indicate a possible relationship between wood density and surface quality, where denser wood species tend to produce smoother surfaces. Similar conclusions were reported by [20, 21]. The overall roughness ranking corresponded to the measured densities of the investigated species, with oak exhibiting the lowest roughness, followed by beech and spruce.

For all investigated wood species, surface roughness increased with increasing feed speed and generally slightly decreased with increasing rotational speed. Statistical analysis showed that the influence of feed speed was significant in most cases, whereas the effect of rotational speed was less pronounced. The relatively small differences between the tested rotational-speed range (16,000–20,000 rpm) may explain the limited influence of this factor. Increasing rotational speed generally improved surface quality because it reduced feed per tooth and increased cutting speed. However, within the investigated range (16,000 – 20,000 rpm), its effect was considerably weaker than that of feed speed. Furthermore, some studies have reported that increasing rotational speed may not always improve surface quality due to the occurrence of tool vibrations and dynamic instability during machining [22].

The observed increase in roughness with feed speed is consistent with machining theory. Consequently, the cutting edge experiences higher loading and vibration amplitudes, which contribute to the formation of more pronounced surface irregularities. This effect was reflected not only in the *R*a parameter but also in the *R*z parameter, indicating an increase in the height of surface irregularities. Microscopic observations confirmed that higher feed speeds intensified both tool marks and surface fuzziness, identifying these mechanisms as the primary contributors to roughness formation during CNC milling. The present results indicate that the influence of feed speed and rotational speed on surface quality is primarily mediated through feed per tooth. Increasing feed speed directly increases feed per tooth, resulting in a thicker uncut chip and greater material removal by each cutting edge. This leads to higher cutting forces, stronger fibre deformation before fracture, and more pronounced kinematic tool marks. Conversely, increasing rotational speed at a constant feed speed decreases feed per tooth, thereby reducing chip thickness and improving cutting conditions. The findings therefore suggest that feed per tooth represents the principal technological parameter governing the formation of surface irregularities, while feed speed and rotational speed act mainly through their combined effect on this variable. This can be observed in Figure 3.

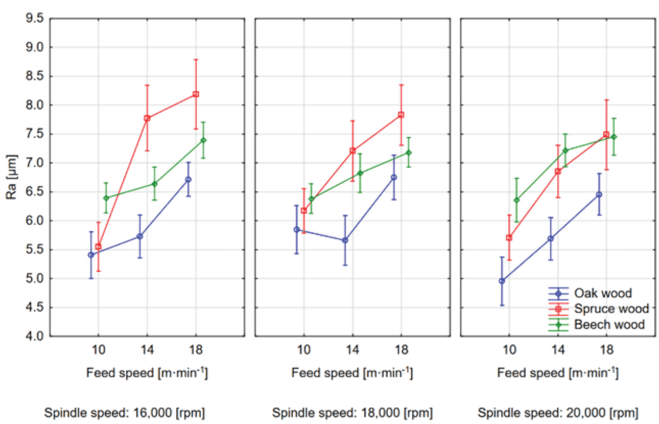

Figure 3. Development of the *R*a parameter with varying feed speed and rotational speed in the three investigated types of wood (vertical bars denote 0.95 confidence intervals)

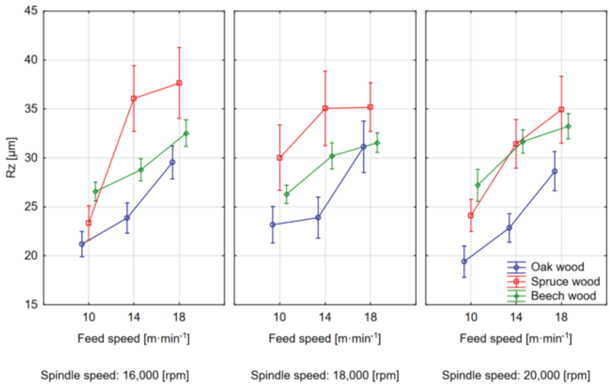

Figure 4. Development of the *Rz* parameter with varying feed speed and rotational speed in the three investigated types of wood (vertical bars denote 0.95 confidence intervals)

3.3 Microscopic analysis of the milled surface

Microscopic analysis revealed the mechanisms responsible for surface irregularity formation during CNC milling. Under the least optimal machining conditions (16,000 rpm and 18 $m \cdot min^{-1}$), the surface of beech wood was characterised by pronounced fuzziness and regularly recurring ripples produced by the cycloidal motion of the cutting edge (Figure 5). The presence of protruded fibres explained the increase in the roughness parameter *Rz*, while the ripples represented the kinematic movement of the tool. These observations confirmed the strong influence of feed speed on surface quality, as higher feed speed intensified both defect mechanisms. Spruce wood exhibited the highest roughness among all investigated species. Microscopic observations showed extensive surface fuzziness concentrated mainly within the earlywood zones (Figure 6). Due to the substantially lower density of earlywood compared with latewood, the cutting edge interacted differently with these regions, resulting in greater fibre pull-out and more pronounced surface irregularities. Lower density and lower mechanical resistance promoted the formation of protruded fibres, which significantly increased the overall roughness of spruce surfaces. In oak wood, the dominant irregularities were tool marks and kinematic ripples rather than extensive fibre pull-out. Although protruding fibres were present under non-optimal machining conditions, they were less pronounced than in beech and spruce wood. This behaviour can be attributed to the higher density of oak wood and the greater mechanical strength. Microscopic examination further showed that reducing feed speed and increasing rotational speed significantly decreased the visibility of cutter marks (Figure 6b). Under optimal machining conditions, the characteristic ripples could only be identified microscopicly, whereas under the non-optimal conditions, they were visible even to the naked eye.

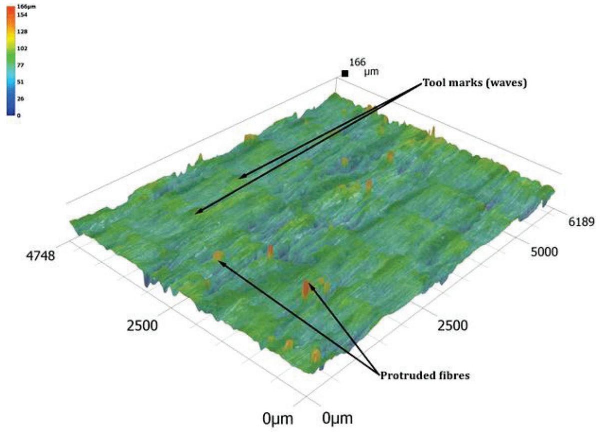

Figure 5. Tool marks and protruded fibres on the surface of beech wood at a feed speed of 18 m·min^{-1} and 16,000 rpm; (lens magnification: ×300)

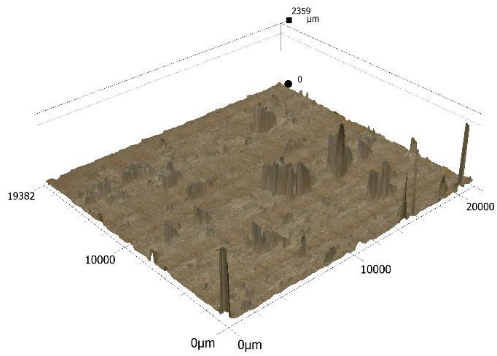

Figure 6. Distribution of unevenness of the surface of spruce wood at a feed speed of 18 m·min^{-1} and 16,000 rpm (lens magnification: ×300)

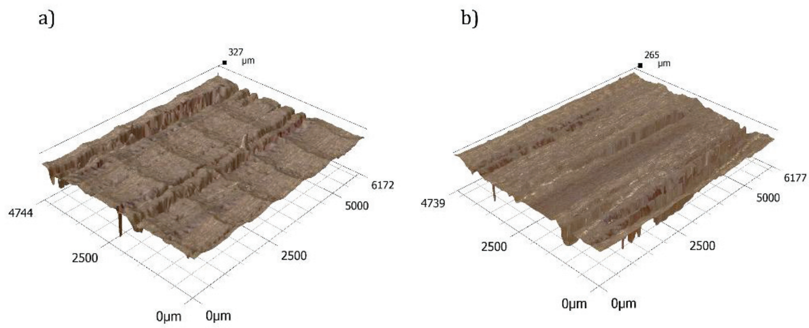

Figure 7. Roughness of the surface of oak wood – (a): Distribution of unevenness of the surface of oak wood at a feed speed of 18 m·min^{-1} and 16,000 rpm; (b): Distribution of unevenness of the oak wood surface at a feed speed of 10 m·min^{-1} and 20,000 rpm (lens magnification: ×300)

Overall, microscopic observations demonstrated that surface roughness in CNC milling was governed by three principal mechanisms: formation of surface fuzziness through fibre pull-out, generation of kinematic ripples by cutter motion, and anatomical differences between earlywood and latewood zones. The relative contribution of each mechanism depends on the machining parameters and the physical properties of the wood species. Wood density probably influenced the mechanical resistance of the material to fibre deformation and pull-out. The denser oak wood produced smoother surfaces because the fibres were better supported during cutting, whereas the low-density spruce was more susceptible to fibre lifting and surface fuzziness. The anatomical structure of the wood also affected the surface irregularities. In spruce, the pronounced contrast between earlywood and latewood promoted localized fibre pull-out and surface fuzziness within the less dense earlywood zones. In contrast, the more homogeneous structure of beech and the greater mechanical resistance of oak resulted in less extensive fibre pull-out, with surface irregularities being dominated by kinematic tool marks. These findings indicate that while wood density primarily determines the overall resistance of the material to machining, anatomical structure can govern the mechanisms and spatial distribution of surface defect formation.

CONCLUSIONS

This study investigated the mechanisms responsible for the formation of surface irregularities during CNC milling of spruce (Picea abies), beech (Fagus sylvatica), and oak (Quercus robur) wood at varying feed and rotational speeds. Based on the obtained results, the following conclusions can be drawn:

Feed speed was identified as the dominant technological parameter influencing both surface roughness and waviness. Increasing feed speed led to a significant deterioration in surface quality due to increased feed per tooth, cutting forces, and the intensity of surface defect formation.

Surface waviness was primarily associated with the feed speed of the milling cutter. The height of waviness profiles increased with feed speed, whereas rotational speed had only a minor effect on waviness formation within the investigated range of cutting conditions.

Three principal mechanisms of surface irregularity formation were identified: 1. – surface fuzziness caused by fibre pull-out and incompletely severed fibres, 2. – kinematic ripples generated by the cycloidal motion of the cutting edge, and 3. – anatomical irregularities resulting from differences between earlywood and latewood zones.

Microscopic analysis confirmed that surface fuzziness was the dominant defect mechanism responsible for roughness deterioration, particularly at high feed speeds. The formation of protruding fibres significantly increased the height parameters of roughness and contributed to the overall degradation of surface quality.

Spruce wood, characterized by the lowest density, exhibited the highest roughness values and the greatest degree of fibre pull-out. Conversely, oak wood produced the smoothest surfaces due to its higher density and greater mechanical resistance.

The anatomical structure and properties of wood played an important role in surface formation. In spruce wood, irregularities were concentrated mainly within earlywood zones, where lower density promoted fibre deformation and pull-out. This finding demonstrates that surface quality is determined not only by machining parameters but also by the heterogeneous nature of wood.

Increasing rotational speed generally improved surface quality because it decreased feed per tooth at a constant feed speed. However, the improvement was less pronounced than that achieved by reducing feed speed, indicating that feed per tooth is the principal technological parameter governing surface irregularity formation.

The best surface quality was achieved at a rotational speed of 20,000 rpm and a feed speed of 10 $m \cdot min^{-1}$, where the occurrence of fuzziness, fibre pull-out, and kinematic ripples was minimized.

The results demonstrate that the combination of surface roughness measurements and microscopic analysis provides a deeper understanding of surface irregularity formation mechanisms and can support the optimization of CNC milling processes for improved surface quality in solid wood machining.

AUTHOR CONTRIBUTIONS

Conceptualization, L.A. and R.K.; methodology, L.A. and R.K.; software, L.A.; validation, L.A., R.K., and A.B.; formal analysis, L.A.; investigation, L.A.; resources, R.K.; data curation, L.A.; writing – original draft preparation, L.A.; writing – review and editing, A.B.; visualization, L.A.; supervision, R.K.; project administration, R.K.; funding acquisition, R.K. All authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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