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Effects of depth of cut and feed rate on dimensional accuracy and surface roughness in CNC nesting of HMR panels

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Abstract

The rapid adoption of digital manufacturing and smart CNC machining in furniture production has made the optimization of machining parameters for engineered wood panels increasingly important. High Moisture Resistance (HMR) panels are widely used because of their superior moisture resistance compared with Medium Density Fiber board (MDF). However, studies on CNC machining performance of HMR panels remain limited, particularly regarding dimensional accuracy and surface roughness. This study evaluates the effects of depth of cut and feed rate in CNC nesting on dimensional accuracy and surface quality of HMR panels. Four machining combinations were tested using depths of cut of 2 and 4 mm and feed rates of 33 and 66 mm/s, with three replications for each treatment. Specimen dimensions and average surface roughness (Ra) were measured after machining. The results show that depth of cut significantly affected dimensional accuracy, while feed rate significantly influenced surface roughness. The interaction between depth of cut and feed rate was not significant for specimen length, but was significant for specimen width and roughness. Optimal dimensional accuracy and surface quality were achieved using the lowest depth of cut (2 mm) in conjunction with the lowest feed rate (33 mm/s).

Keywords:
Depth of cut, feed rate, HMR, dimension, surface roughness.

1 Introduction

The evolution of manufacturing technology has undergone substantial progress in response to industrial demands for products characterized by high dimensional accuracy, excellent surface finish, and consistent quality. In earlier stages, mechanical machining processes were predominantly performed using manually operated conventional equipment such as lathes, milling machines, grinders, and planers. However, these systems have gradually been replaced by computer-based numerical control technology, commonly referred to as Computer Numerical Control (CNC). The implementation of CNC systems allows machining operations to be conducted automatically with a high degree of precision and repeatability, leading to improved product quality and increased production efficiency. This technological transition is in line with the principles of the Fourth Industrial Revolution, which focuses on the integration of automation, digital technologies, and data-driven process management [1], [2].

Within the context of contemporary manufacturing, CNC machines are utilized not only for the processing of metallic materials but also widely utilized for non-metallic materials, including plastics, composites, and wood-based products. Various studies have indicated that the performance and quality of CNC machining results are highly dependent on operating parameters such as cutting speed, feed rate, and depth of cut, which have a direct impact on surface roughness, dimensional precision, and tool wear [3], [4], [5], [6], [7]. Therefore, the optimization of CNC machining parameters has emerged as a crucial factor in improving product quality and supporting the long-term sustainability of manufacturing operations [8] .

Wood-based materials exhibit characteristics that differ significantly from metallic materials, such as anisotropy, structural heterogeneity, and variations in density and moisture content. These factors result in more complex material responses during machining processes and necessitate precise parameter settings to effectively control surface quality and dimensional accuracy. In the furniture and interior industries, the use of engineered wood panels has become increasingly dominant due to material efficiency, ease of shaping, and improved dimensional stability compared to solid wood [9].

One widely used type of engineered wood panel is High Moisture Resistant (HMR) board. HMR panels are composed of wood particles combined with specific resins to enhance moisture resistance and achieve higher material density. Materials classified under HMR include chipboard, engineered wood, and multiplex, with chipboard being the most extensively utilized in the furniture industry. The advantages of HMR panels include resistance to humid environments, relatively good dimensional stability, ease of machining, and availability in various sizes on the market. Compared to Medium Density Fiberboard (MDF), HMR panels generally exhibit longer service life and mechanical characteristics that more closely resemble those of solid wood [10], [11] .

In CNC machining processes involving engineered wood materials, the quality of the final product is typically assessed based on surface roughness, dimensional accuracy and precision, and process time efficiency. Surface roughness is a critical indicator as it directly influences product aesthetics, finishing quality, and mechanical performance in certain applications. Furthermore, dimensional accuracy plays a crucial role in ensuring component conformity with design specifications, particularly in modular and knock-down furniture systems [12] .

A considerable number of studies have examined how CNC machining parameters influence surface roughness and overall machining performance. Surface roughness prediction models based on cutting conditions and machining vibration signals have been formulated using regression approaches and artificial neural networks, indicating that specific combinations of process variables play a significant role in determining surface quality [3]. Furthermore, differences in cutting parameters and tool coating materials have been shown to affect surface roughness and burr generation in micro-milling operations [4]. Collectively, these results highlight that optimizing machine parameters is essential for effective surface quality control.

Comprehensive reviews of factors affecting surface roughness in machining processes emphasize the importance of controlling cutting parameters to support sustainable manufacturing practices [8]. Other findings indicate that feed rate and depth of cut are dominant parameters in determining surface quality, as demonstrated through various machine learning models applied to the machining of aluminum alloys [9]. Further studies confirm that machining parameter optimization can reduce surface roughness while enhancing process stability and extending tool life [13], [14].

In the field of wood-based and engineered wood materials, a number of studies have reported consistent results concerning the influence of CNC machining parameters on surface characteristics. Feed rate is often reported as the most dominant factor affecting surface roughness, followed by depth of cut and spindle speed. In addition, engineered wood materials such as MDF and HMR exhibit more stable machining behavior compared to solid wood due to their homogeneous structure. Optimization of these parameters is essential to achieve a balance between surface quality and machining efficiency [15], [16], [17], [18], [19].

Additional research indicates that cutting forces and tool characteristics have a direct impact on surface roughness in the machining of complex surfaces [20]. Studies on wood-based composite materials further demonstrate that process parameter optimization can enhance surface quality while improving machining efficiency [21]. Moreover, the thermal and mechanical properties of materials have been reported to contribute to surface integrity and material removal rates in CNC processes [22].

CNC nesting machines are specifically designed for efficient and precise cutting of flat panels in mass production environments. These machines are widely utilized in the furniture industry due to their ability to perform cutting, drilling, and shaping processes in an integrated manner. The quality of cutting results produced by CNC nesting machines is strongly influenced by process parameter settings, particularly depth of cut and feed rate, which are directly associated with cutting forces, machining stability, surface roughness, and dimensional accuracy of the machined components [12].

Based on the reviewed literature, it can be inferred that while the influence of CNC machining parameters on surface quality and dimensional precision has been widely explored for metallic materials, composites, and engineered wood products such as MDF, research that specifically focuses on the effects of depth of cut and feed rate variations on the dimensional accuracy and surface roughness of HMR panels is still limited. Accordingly, this study seeks to analyze the impact of variations in depth of cut and feed rate in CNC nesting operations on the dimensional accuracy and surface roughness characteristics of HMR panels. The outcomes of this research are expected to provide scientific contributions to the development of CNC machining knowledge for engineered wood materials and to function as a practical guideline for the furniture industry in selecting optimal processing parameters.

2 Research methodology

2.1 Material preparation

The test specimens were prepared from HMR panels with a uniform thickness of 18 mm. Each specimen measured 50 mm in length and 35 mm in width. All fabrication procedures were executed utilizing CNC nesting machine (Felder Format 4 Profit H008). During the cutting process, the bottom surface of the HMR panel was supported by an HMR-based spoil-board serving as a backing layer, ensuring complete material separation. The cutting tool used in this study was a three-flute carbide end mill with a diameter of 6 mm. Fig. 1 illustrates the CNC nesting machine used for the fabrication of all research specimens.

Fig. 1. CNC nesting machine.

Subsequent to material preparation, the cutting operation was performed by introducing variations in the depth of cut and feed rate parameters. The first configuration applied a depth of cut of 2 mm combined with a feed rate of 33 mm/s, whereas the second configuration maintained the same depth of cut of 2 mm while increasing the feed rate to 66 mm/s. In the third configuration, the depth of cut was increased to 4 mm with a feed rate of 33 mm/s, and the fourth configuration employed a depth of cut of 4 mm in conjunction with a feed rate of 66 mm/s, spindle speed is kept constant at 15,000 rpm. For each parameter configuration, three specimens were fabricated. A comprehensive description of the experimental configurations adopted in this study is provided in Table 1.

Table 1. Test scheme

Scheme	Depth of cut	Feed rate
1	2 mm	33 mm/s
2	2 mm	66 mm/s
3	4 mm	33 mm/s
4	4 mm	66 mm/s

2.2 Material testing

The material testing phase commenced with the measurement of the specimen length and width following the completion of the cutting process. This measurement was intended to determine the magnitude of dimensional deviations resulting from variations in the applied machining parameters. The measuring instrument used was a digital vernier caliper manufactured by Mitutoyo, with a measurement resolution of 0.01 mm. The digital vernier caliper was selected due to its high accuracy and capability to provide precise measurement results. Fig. 2 illustrates the digital vernier caliper utilized to determine the dimensions of the specimens subsequent to the cutting process.

Fig. 2. Digital vernier caliper.

The subsequent test involved surface roughness evaluation of the specimens. This test was performed to evaluate the effect of variations in the cutting method and depth of cut on the surface quality of the workpiece. Surface roughness is a critical parameter, as in addition to ensuring dimensional accuracy, lower roughness values can reduce the need for subsequent finishing processes during later production stages. Surface roughness measurements were carried out using a Surfcorder Flower SE 1700 with parameter settings including a cut-off length (λc) of 2.5 mm, a stylus tip radius of 2 mm, a drive unit speed of 0.75 mm/s, and an x-axis range of 10 mm. Fig. 3 illustrates the Surfcorder Flower SE 1700 used in the testing process, as well as the stylus tip traversal path during surface roughness data acquisition.

Fig. 3. Surfcorder Flower SE 1700.

2.3 Experimental design

The research phase begins with a literature review and field study to identify the problem and determine the appropriate research approach. Based on these results, specimen preparation and experimentation were conducted. In this study, the independent variables used were the depth of cut (depth of cut) and feed rate (feed rate), while the dependent variables included length deviation, width deviation, and surface roughness (Ra). Furthermore, specimens were made according to the predetermined parameter variations and tested to obtain data dimensions and surface roughness for further explanation.

In this study, the cutting method used is the outside profile cutting process to obtain the dimensions of the length and width of the material and using four machining parameter variation schemes is determined. The fabricated specimens were then subjected to length and width dimension evaluation, in addition to surface roughness assessment. Each parameter scheme consists of three specimens that serve as replications. Each specimen was tested individually to determine its length dimension, width dimension, and surface roughness value. It is important to note that surface roughness measuring instruments have inherent measurement limitations. Therefore, if the specimen cannot be read by the instrument, the specimen must be remade to ensure that accurate surface roughness data resulting from the cutting process can be obtained.

2.4 Data analysis

The data derived from measurements of length, width, and surface roughness were analyzed using an experimental framework based on a completely randomized design with three replications for each variation in machining parameters. The compiled dataset was subsequently subjected to Analysis of Variance (ANOVA) to evaluate the effects of the applied treatments. When the ANOVA results revealed statistically significant differences, the analysis was extended using Duncan's multiple range test to more precisely distinguish the differences among the treatments.

3 Results and discussion

3.1 Result of specimen length dimension testing

Measurements of specimen length were conducted on all specimens after the cutting process using the predetermined machining parameters. The expected specimen length was 50 mm, corresponding to the CAD design dimensions as shown in Fig. 4. The measurement results indicate that the average specimen length ranged from 49.99 to 50.04 mm. The measured length (t = 0.05 mm) is well within the EN 14322 tolerance (±0.3–0.5 mm), indicating high dimensional precision [23]. The graphical depiction of the specimen length measurement results is presented in Fig. 5. According to the statistical analysis presented in Table 2, the p-value associated with the effect of depth of cut was 0.0091. As this value is below the 0.05 threshold, it indicates that the depth of cut parameter exerts a statistically significant influence on the specimen length dimension. In contrast, the p-value corresponding to the effect of feed rate was 0.1263, which exceeds 0.05, suggesting that the feed rate parameter does not significantly affect the specimen length dimension. Furthermore, the p-value for the interaction between depth of cut and feed rate was 0.0677, also greater than 0.05, indicating that the interaction between these two parameters does not have a statistically significant impact on the specimen length dimension.

Table 2. Statistical test result of specimen length dimension (ANOVA)

Source of variation	SS	df	MS	F	P-value	F crit
Sample	0.0032	1	0.0032	9.6333	0.0091	4.7472
Columns	0.0009	1	0.0009	2.7000	0.1263	4.7472
Interaction	0.0013	1	0.0013	4.0333	0.0677	4.7472
Within	0.0040	12	0.0003			
Total	0.0095	15				

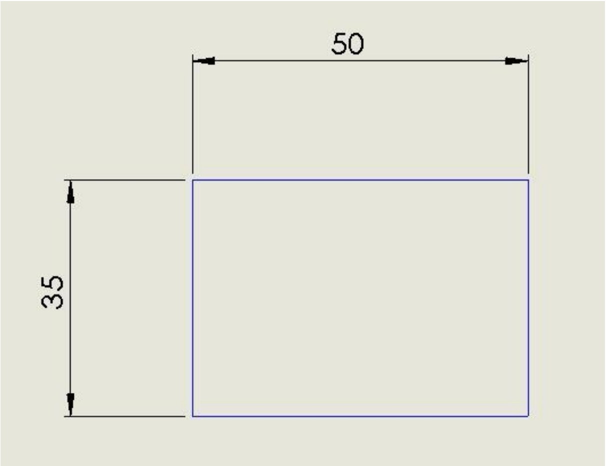

Fig. 4. Target specimen dimension.

The pronounced effect of depth of cut on the specimen length dimension generated through CNC machining can be attributed to the elevated Material Removal Rate (MRR) associated with greater depth of cut values. An increased MRR leads to greater cutting forces acting on the HMR specimens, causing the material removal mechanism to be influenced not only by the shearing action of the cutting tool flutes but also by the axial thrust force generated during the depth of cut motion. This phenomenon results in dimensional deviations in the machined specimens [24], [25].

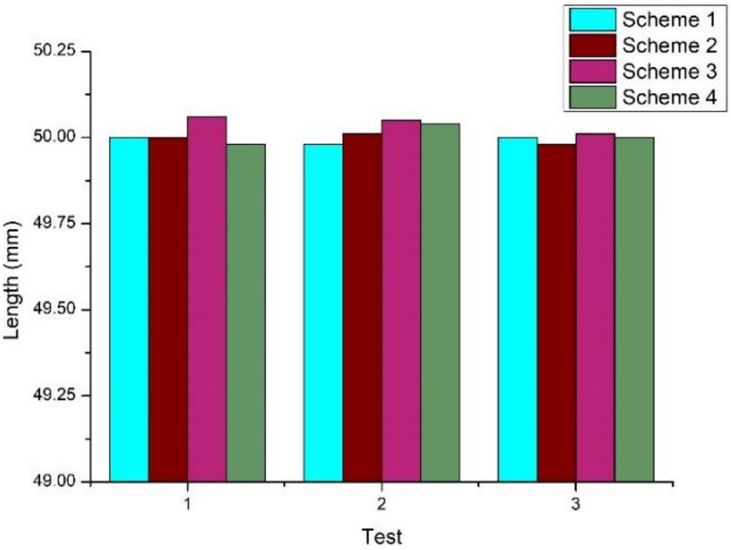

Fig. 5. Specimen length measurement result.

3.2 Result of specimen width dimension testing

Measurements of specimen width were performed on all specimens following the cutting process under the specified machining parameters. The target specimen width was 35 mm, in accordance with the dimensional specifications defined in the CAD design as illustrated in Fig. 4. The measurement results show that the average specimen width ranged from 34.95 to 35.01 mm. The measured width deviation (t = 0.06 mm) falls well within the tolerance limits specified by EN 14322 (±0.3–0.5 mm), indicating a high level of dimensional precision in the CNC machining process [23]. The graphical results of the specimen width measurements are presented in Fig. 6.

Based on the statistical analysis in Table 3, the p-value for the effect of depth of cut is 0.0494, which is below the 0.05 threshold. This indicates that the depth of cut significantly impacts the specimen width dimension. In contrast, the p-value for the effect of feed rate is 0.8998, exceeding 0.05, indicating that feed rate does not significantly affect the specimen width dimension. The p-value associated with the interaction between depth of cut and feed rate was 0.0120, which is below the 0.05 threshold, indicating that the interaction between these two parameters exerts a statistically significant effect on the specimen width dimension.

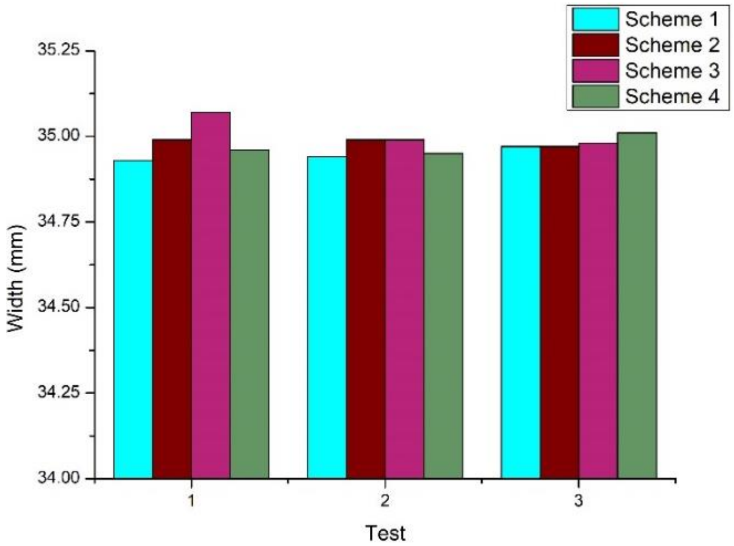

Fig. 6. Specimen width measurement result.

Table 3. Statistical test result of specimen width dimension (ANOVA)

Source of variation	SS	df	MS	F	P-value	F crit
Sample	0.0032	1	0.0032	4.7769	0.0494	4.7472
Columns	0.0000	1	0.0000	0.0165	0.8998	4.7472
Interaction	0.0059	1	0.0059	8.7438	0.0120	4.7472
Within	0.0081	12	0.0007			
Total	0.0172	15				

The effect of depth of cut on specimen width can be attributed to the fact that an increased depth of cut generates higher cutting forces, which may induce tool deflection or deformation, thereby affecting the dimensional accuracy of the final product width. A similar phenomenon is observed for both width and length dimensions, where the material removal mechanism is not purely governed by the shearing action of the cutting tool flutes but is also influenced by the magnitude of the cutting forces generated during machining [24] [18] .

The statistically significant interaction between depth of cut and feed rate on specimen width arises from the inherent interdependence of these two parameters within CNC machining processes. Depth of cut governs the volume of material removed in each pass, whereas feed rate regulates the quantity of material removed per tool revolution. When both parameters increase simultaneously, the cutting force magnitude and tool vibration also increase, resulting in a significant interaction effect on the dimensional accuracy of the machined specimens [7], [25].

A strong interaction between depth of cut and feed rate results in elevated reactive forces acting in the horizontal direction, which also act on the specimen material. These elevated cutting forces can induce microscopic elastic deformation in the specimen, ultimately affecting the final width dimension of the machined specimens [26].

3.3 Result of specimen surface roughness testing

Surface roughness measurements were conducted on all specimens after the cutting process using the specified machining parameters. In general, optimal machining parameter settings are expected to produce lower surface roughness values. The measurement results indicate that the average surface roughness values ranged from 26.65 to 38.34 μm. The obtained surface roughness values (26.65–38.34 μm) fall within the typical range reported for CNC-machined HMR surfaces, indicating a moderate surface quality that generally requires additional finishing processes [15]. The graphical representation of the surface roughness measurement results is shown in Fig. 7.

According to the statistical analysis summarized in Table 4, the p-value associated with the effect of depth of cut was 0.1288. As this value exceeds 0.05, it indicates that depth of cut does not exert a statistically significant influence on the surface roughness of the specimens. In contrast, the p-value for the effect of feed rate was 0.0130, which is below 0.05, demonstrating that feed rate has a statistically significant effect on specimen surface roughness. Furthermore, the p-value corresponding to the interaction between depth of cut and feed rate was 0.0499, also below 0.05, indicating that the interaction between these two parameters significantly affects the surface roughness of the specimens.

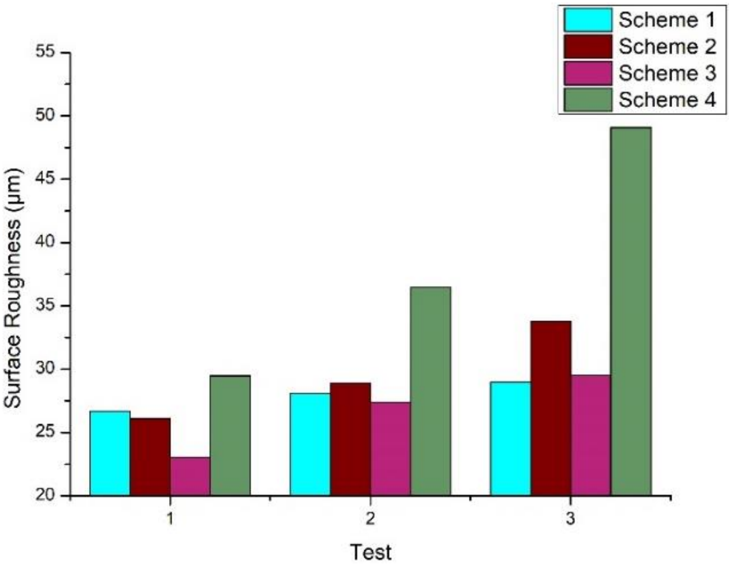

Fig. 7. Surface roughness measurement result.

Table 4. Statistical test result of surface roughness (ANOVA)

Source of variation	SS	df	MS	F	P-value	F crit
Sample	55.9504	1	55.9504	2.6601	0.1288	4.7472
Columns	178.6678	1	178.6678	8.4944	0.0130	4.7472
Interaction	100.0000	1	100.0000	4.7543	0.0499	4.7472
Within	252.4031	12	21.0336			
Total	587.0212	15				

The statistically significant effect of feed rate on surface roughness can be attributed to the fact that an increase in feed rate enlarges the spacing between successive tool paths formed on the workpiece surface and geometrically increases the height of the surface waviness profile. Furthermore, higher feed rates increase cutting forces and machining vibrations, causing the cutting mechanism to shift from a shearing-dominated process toward a tearing mechanism, which results in higher surface roughness values [27].

The statistically significant interaction effect between depth of cut and feed rate on surface roughness indicates the combined influence of these parameters on the resulting surface characteristics can be explained by the combined influence of both parameters on cutting mechanics. An elevated feed rate increases the contact area between the cutting tool and the material, while a greater depth of cut increases the tool penetration depth. The interaction between these parameters becomes more pronounced lateral cutting forces, thereby exacerbating surface irregularities and leading to increased surface roughness in the machined material [28], [29].

4 Conclusions

This research demonstrates that CNC nesting parameters significantly affect the dimensional accuracy and surface quality of HMR panels. The machined specimens showed lengths of 49.99-50.04 mm and widths of 34.95-35.01 mm, indicating only small deviations from the target dimensions. Surface roughness values ranged from 26.65 to 38.34 μm. Statistical analysis showed that depth of cut significantly influenced both length and width deviations, while feed rate significantly affected surface roughness. The interaction of depth of cut and feed rate was not significant for specimen length, but was significant for specimen width and roughness. Therefore, the depth of cut was the main factor governing dimensional accuracy, whereas feed rate was more critical for surface finish. The optimal machining condition was obtained at a depth of cut of 2 mm and a feed rate of 33 mm/s, which produced the best dimensional accuracy and the lowest surface roughness. These findings provide practical guidance for improving CNC nesting quality and productivity in HMR panel furniture manufacturing.

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