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The Influence of Cutting Methods and Feed Rate on Dimensional Accuracy and Surface Roughness of HMR Panel

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Abstract: This study investigates the influence of cutting methods and feed rates on the dimensional accuracy and surface roughness of HMR (High Moisture Resistance) panels. The aim is to determine the optimal cutting parameters that yield precise dimensions and smooth surfaces in CNC machining. Two cutting methods—single and double passes—were applied using feed rates of 2, 4, and 6 m/min. Dimensional accuracy was measured using a digital caliper, while surface roughness was evaluated with a surface tester. The results indicate that the double-pass cutting method significantly improves both dimensional accuracy and surface finish. Statistical analysis using ANOVA revealed that feed rate has a significant effect on surface roughness ($p < 0.05$), whereas dimensional accuracy is primarily influenced by the cutting method. These findings provide practical insights for optimizing CNC machining processes in furniture manufacturing using HMR panels.

Keywords: ANOVA; CNC machining; cutting method; dimensional accuracy; feed rate; HMR panel

1. Introduction

Mechanical machining processes have evolved significantly over time, transitioning from traditional manual operations to advanced computer-numerical-controlled (CNC) systems [1]. In the current era of Industry 4.0, precision and efficiency have become critical objectives in manufacturing, driving the widespread adoption of CNC technology across various sectors [2]. Numerical control systems are increasingly utilized to operate machining tools, aligning with the overarching goal of producing high-quality and dimensionally accurate products [3].

CNC technology is extensively applied not only in the processing of metals, glass, and plastics but also in the machining of wood and engineered wood products such as Medium-Density Fiberboard (MDF), plywood, and High Moisture Resistance (HMR) panels [4]. In the furniture industry, the use of engineered wood panels—particularly MDF and HMR—has grown substantially due to their favorable mechanical properties and cost-effectiveness [5].

HMR panels are engineered wood materials enhanced with specific resin compositions to improve durability and increase material density. Common types of HMR include chipboard, engineered wood, and plywood, with chipboard being the most widely used. Compared to MDF,

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which is prone to damage under certain conditions, HMR panels offer superior resistance to moisture and mechanical stress, making them suitable for long-term applications [6].

Key indicators of machining quality include surface roughness, dimensional accuracy, and processing time. These parameters can be optimized through appropriate adjustments to CNC machining settings [7]. Several studies have explored the influence of machining parameters on wood-based materials. Jiang et al. reported that cutting force significantly affects the surface quality of walnut wood [8]. Other research has examined the effects of cutting depth, number of cutting edges, and abrasive grit on surface roughness, revealing that these factors play a crucial role in determining finish quality [9]. Additionally, cutting speed, feed rate, moisture content, and material density have been shown to impact the surface characteristics of engineered wood during CNC machining [10].

Surface roughness tends to decrease with higher spindle speeds and lower feed rates [11]. Koc et al. found that increasing spindle speed and reducing cutting depth improved the surface finish of MDF boards [12]. Similarly, Deus et al. demonstrated that surface roughness decreased as cutting speed increased and cutting depth decreased [13].

While extensive research has been conducted on machining parameters for solid wood and MDF, studies focusing on HMR panels remain limited. Given the growing application of HMR in furniture manufacturing, further investigation is needed to understand how variations in cutting methods and feed rates affect dimensional accuracy and surface roughness in CNC milling of HMR panels. This study aims to address that gap by evaluating the influence of these parameters, thereby contributing to the optimization of CNC machining processes for engineered wood materials.

2. Methods

2.1. Material Preparation

Specimens measuring 50 mm in length and 35 mm in width were fabricated from a single Medium-Density Fiberboard High Moisture Resistance (MDF-HMR) panel with a uniform thickness of 18 mm. The original panel had dimensions of 1220 mm × 2440 mm × 18 mm. To generate the cutting layout, a CAD design of rectangular specimens (50 mm × 35 mm) was created and saved in the .DWG format. This file was then converted into a CAM file with the .TCN extension, which was subsequently transferred to the CNC machine for execution.

All specimens were machined using a CNC Nesting Felder Format 4 Profit H008 system. During the cutting process, an HMR spoilboard was placed beneath the workpiece to provide support and ensure complete penetration of the cutting tool through the material.

A 3-flute end mill with a diameter of 6 mm was employed for all machining operations. The number of flutes and the material properties influence the chip load, which for HMR ranges between 0.047 mm and 0.082 mm. This corresponds to a feed rate of approximately 33 mm/s to 66 mm/s.

The cutting parameters were set as follows: a constant cutting depth of 2 mm, a plunge rate of 15 mm/s, and a spindle speed of 15,000 RPM. Four machining schemes were implemented:

Scheme 1: Conventional cutting method with a feed rate of 33 mm/s
Scheme 2: Climb cutting method with a feed rate of 33 mm/s
Scheme 3: Conventional cutting method with a feed rate of 66 mm/s
Scheme 4: Climb cutting method with a feed rate of 66 mm/s

To ensure repeatability and reliability of results, each scheme was performed in triplicate. The CNC machine used in this study is illustrated in Figure 1.

Figure 1. CNC Nesting Machine (Felder Format4 Profit H08) for specimen cutting
(Source: Personal Documentation)

2.2. Material Testing

Material testing was performed by measuring the post-machining dimensions of each specimen, specifically the length and width, to evaluate the degree of dimensional deviation resulting from variations in machining parameters. A Mitutoyo digital Vernier caliper with a resolution of 0.01 mm was used to ensure precise measurements.

The digital caliper utilized in this study is depicted in Figure 2.

Figure 2. Digital Vernier Caliper
(Source: Personal Documentation)

The next test is surface roughness testing. This test was conducted to observe the effect of variations in cutting method and feed rate on the surface roughness of the workpiece. Surface roughness is an important parameter because, in addition to achieving accurate product dimensions, a low surface roughness can also reduce post-processing work on the surface when the product moves to the next stage [14]. The surface roughness of the specimens was tested using the Surfcorder Flower SE 1700, with the following settings: cut-off λc: 2.5mm, stylus tip: 2nm, drive unit speed: 0.75mm/s, and x measurement range: 10mm. The data obtained from this instrument included the Arithmetic Mean Value (Ra), Root Mean Square (Rq), 10-point height of the profile (Rz), and maximum height (Ry). Equation (1) shows the calculation for the average surface roughness (Ra).

$$Ra = \frac{a + b + c + d + e + \cdots}{n} \quad (1)$$

Equation (2) shows the calculation for the Root Mean Square (Rq) of the surface roughness.

$$Rq = \frac{\sqrt{a^2 + b^2 + c^2 + d^2 + e^2 + \cdots.}}{n} \quad (2)$$

Where: (Rq) is the root mean square roughness. (a, b, c, etc.) represents the height deviation of the profile at point. (n) is the number of measurement points along the surface.

2.3. Data Analysis

The results of the length, width, and surface roughness measurements were analyzed using an experimental design in the form of a simple completely randomized design (CRD) with a single factor, with three repetitions for each machining parameter setting. The data obtained were then analyzed using Analysis of Variance (ANOVA), and Duncan's test was performed if significant differences were found. Figure 3 shown the surface roughness testing machine used for this study.

Figure 3. Surface roughness machine
(Source: Personal Documentation)

3. Results and Discussion

3.1. Result of Specimen Length Dimension

The length dimensions were measured after all specimens were cut according to the specified parameters. The target specimen length was 50 mm, as defined in the design created using CAD software (see Figure 4). The initial hypothesis assumed no variation in length dimensions among the specimens. Post-measurement results indicated that the average specimen length ranged from 49.92 mm to 50.01 mm.

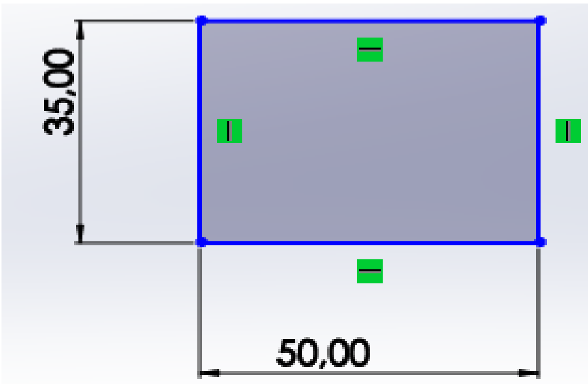

Figure 4. Expected dimension of specimen length and width
(Source: Personal Documentation)

The most accurate length dimensions were achieved using the conventional cutting method at feed rates of 33 mm/s and 66 mm/s. In contrast, the greatest deviation in length—measuring 49.92 mm—was recorded with the climb cutting method at a feed rate of 66 mm/s.

This substantial deviation was attributed to the combination of a high feed rate and the climb cutting technique. The cutting phenomenon was influenced not only by the flute engagement of the tool but also by the shear forces generated during the process, resulting in excessive material removal.

Consequently, the final length was reduced compared to the intended design dimension [15]. In climb cutting, the tool engages the workpiece with the maximum chip thickness at the beginning of the cut, which gradually decreases to zero at the end. This cutting mechanism induces higher forces at the initial stage, potentially leading to vibrations or tool deflection [16]. Table 1 presents the specimen length measurement data in tabular format.

Table 1. Result for the length dimension (mm) test of HMR panel

	Specimen 1	Specimen 2	Specimen 3	Mean	S.Dev	Max.	Min.
Scheme 1	50	49.98	50	49.99	0.012	50	49.98
Scheme 2	50	50.01	49.98	50.00	0.015	50.01	49.98
Scheme 3	49.96	49.98	49.94	49.96	0.020	49.98	49.94
Scheme 4	49.96	49.92	49.92	49.93	0.023	49.96	49.92

Statistical analysis revealed that the specimen length dimensions differed significantly across cutting methods, with a p-value of 0.0309. This result indicates that the cutting method has a statistically significant effect on the final length of the specimens.

In contrast, the effect of feed rate yielded a p-value of 0.4600, suggesting no statistically significant influence. Similarly, the interaction between cutting method and feed rate produced a p-value of 0.1778, indicating that the combined effect of these two factors was not statistically significant.

The statistical test results for specimen length dimensions are summarized in Table 2, while Figure 5 presents the measurement data in graphical form.

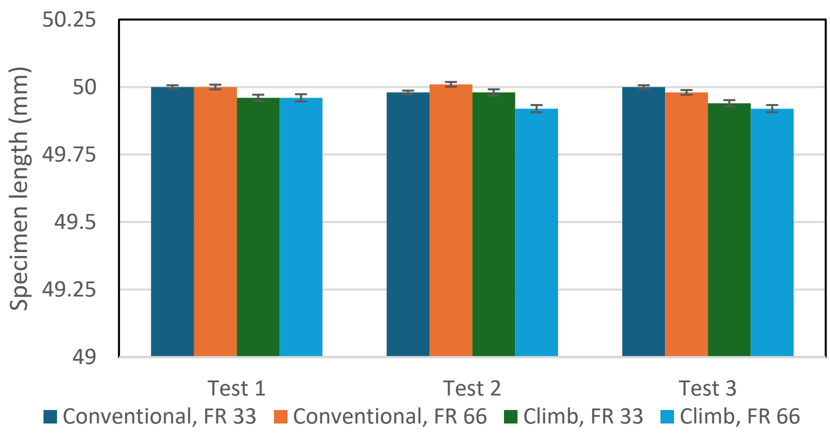

Figure 5. Length measurement results of specimens with varying cutting methods and feed rates (Source: Personal Documentation)

The large p-values (>0.05) indicate that the feed rate and the interaction between cutting method and feed rate does not significantly affect the specimen length dimensions. This is due to the use of CNC machines that are fully integrated from design creation, CAM code conversion, to material processing with CNC machines, resulting in accurate and precise products [2].

Table 2. Statistical test result for the length dimension of HMR panel

ANOVA						
Source of variation	*Sum of Square (SS)*	*df*	*MS*	*F*	*P-value*	*F crit*
Cutting Method	0.0032	1	0.0032	10.66667	0.030906	7.708647
Feed Rate	0.0002	1	0.0002	0.666667	0.460051	7.708647
Interaction	0.0008	1	0.0008	2.666667	0.177808	7.708647
Within	0.0012	4	0.0003			
Total	0.0054	7				

3.2. Result of Specimen Width Dimension

The width of all specimens was measured following the cutting process using the specified parameters. The target width was 35 mm, corresponding to the design specifications defined in the CAD model, as illustrated in Figure 6. The initial hypothesis assumed that no significant differences would be observed in the width dimensions across all specimens. However, post-experimental measurements revealed that the average specimen width ranged from 34.86 mm to 34.99 mm. Table 3 presents the specimen width measurements in tabular format.

Table 3. Result for the width dimension (mm) test of HMR panel

	Specimen 1	Specimen 2	Specimen 3	Mean	S.Dev	Max.	Min.
Scheme 1	34.93	34.94	34.97	34.95	0.021	34.97	34.93
Scheme 2	34.99	34.99	34.97	34.98	0.012	34.99	34.97
Scheme 3	34.93	34.87	34.94	34.91	0.038	34.94	34.87
Scheme 4	34.92	34.92	34.86	34.90	0.035	34.92	34.86

The most accurate width dimension was obtained using the conventional cutting method at a feed rate of 66 mm/s, resulting in a specimen width of 34.99 mm. In contrast, the greatest deviation—measuring 34.86 mm—was recorded using the climb cutting method at the same feed rate.

This deviation was primarily attributed to the combination of a high feed rate and the climb cutting technique. The cutting phenomenon was influenced not only by flute engagement but also by the shear forces exerted by the tool, which led to excessive material removal. Consequently, the final width was reduced from the intended design dimension [15].

Additionally, the combination of a high feed rate and climb cutting method contributed to increased temperatures during the cutting process. This thermal elevation can adversely affect dimensional accuracy, particularly in engineered wood, which is sensitive to heat. Therefore, in machining operations involving engineered wood, dimensional precision must be considered alongside productivity when selecting cutting parameters [17].

As illustrated in Figure 6, the specimen widths resulting from various machining parameters did not reach the expected value of 35 mm, as defined in the CAD model shown in Figure 5. A dimensional deviation of 0.14 mm, equivalent to approximately 0.4%, was observed. Despite this deviation, the result remains within acceptable tolerance limits, as the error is below 2% [18].

Statistical analysis revealed that the specimen width dimensions differed significantly with respect to the cutting method, as indicated by a p-value of 0.0303. This result demonstrates that the cutting method has a statistically significant influence on the final width of the specimens.

In contrast, the effect of feed rate yielded a p-value of 0.2679, and the interaction between cutting method and feed rate produced a p-value of 0.8933. These high p-values (> 0.05) suggest that neither the feed rate nor the interaction between cutting method and feed rate had a statistically significant effect on the specimen width dimensions.

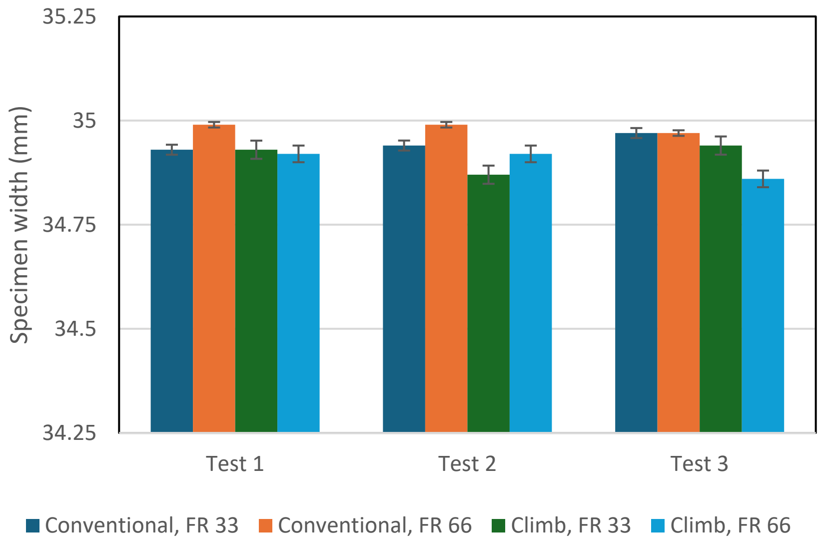

Figure 6. Width measurement results of specimens with varying cutting methods and feed rates
(Source: Personal Documentation)

Table 4 presents the statistical test results for specimen width dimensions after cutting. Based on these data, it can be concluded that the cutting method significantly influenced the width dimension, while the feed rate and its interaction with the cutting method did not.

To enhance dimensional accuracy during machining, factors such as automated workpiece clamping, proper installation of supporting equipment, and the use of appropriate cutting tools are essential. These measures not only improve process efficiency but also contribute to achieving precise product dimensions [19].

Furthermore, these findings align with the results reported by Bal et al., which demonstrated that feed rate significantly affects the surface roughness of MDF material [14].

Table 4. Statistical test result for the width dimension of HMR panel

ANOVA						
Source of variation	*Sum of Square (SS)*	*df*	*MS*	*F*	*P-value*	*F crit*
Cutting Method	0.007	1	0.007	10.796	0.0303	7.709
Feed Rate	0.001	1	0.001	1.653	0.2679	7.709
Interaction	0.000	1	0.000	0.020	0.8933	7.709
Within	0.002	4	0.001			
Total	0.010	7				

3.3. Result of Specimen Surface Roughness

Surface roughness is a critical parameter influenced by machining process settings. While in certain applications a moderately rough surface may be desirable, optimal machining parameters generally lead to reduced surface roughness levels [20].

In this experiment, the surface roughness data of the specimens following the cutting process are presented in Table 5.

Table 5. Result for the surface roughness (μm) test of HMR panel

	Specimen 1	Specimen 2	Specimen 3	Mean	S.Dev	Max.	Min.
Scheme 1	22.81	24.14	24.83	23.93	1.027	24.83	22.81
Scheme 2	26.47	29.03	34.08	29.86	3.872	34.08	26.47
Scheme 3	34.81	35.87	37.14	35.94	1.167	37.14	34.81
Scheme 4	34.05	34.58	39.94	36.19	3.258	39.94	34.05

As illustrated in Figure 7, the fourth machining scheme—climb cutting method with a feed rate of 66 mm/s—resulted in the highest surface roughness. The peak average surface roughness (Ra) reached 39.94 µm. In contrast, the lowest surface roughness of 22.81 µm was achieved using the conventional cutting method at a lower feed rate of 33 mm/s.

A lower feed rate corresponds to a reduced material removal rate (MRR), which consequently leads to a product with minimal surface roughness [16].

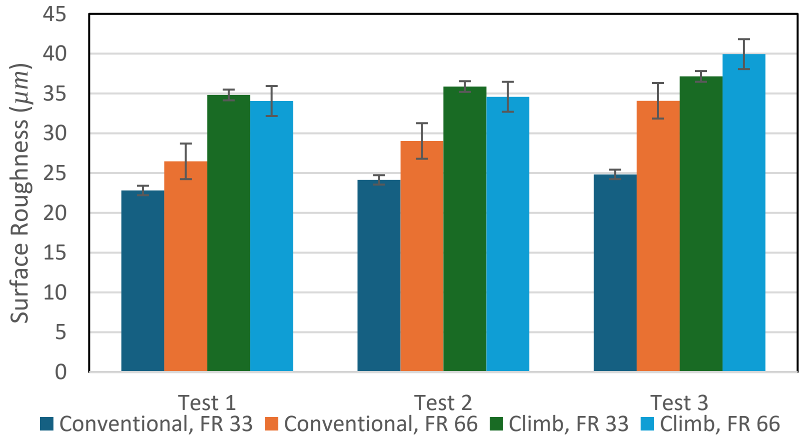

Figure 7. Surface roughness measurement results of specimens with varying cutting methods and feed rates (Source: Personal Documentation)

The machining parameter settings in Scheme 2 (conventional cutting method, feed rate of 66 mm/s) and Scheme 3 (climb cutting method, feed rate of 33 mm/s) yielded average surface roughness (Ra) values of 29.86 µm and 35.94 µm, respectively. Although these values are lower than the maximum surface roughness observed, they remain relatively higher compared to the Ra value obtained under Scheme 1.

This outcome is attributed to the cutting direction and the increased feed rate, which contribute to a higher material removal rate (MRR) and, consequently, a greater final surface roughness [12].

Table 6. Statistical test result for the surface roughness of HMR panel

ANOVA						
Source of variation	*Sum of Square (SS)*	*df*	*MS*	*F*	*P-value*	*F crit*
Cutting Method	254.026	1	254.026	52.559	0.0019	7.709
Feed Rate	12.650	1	12.650	2.617	0.1810	7.709
Interaction	6.195	1	6.195	1.282	0.3208	7.709
Within	19.333	4	4.833			
Total	292.204	7				

Based on the data presented in Table 6, statistical analysis of the surface roughness (Ra) values indicates that the cutting method significantly influences the average surface roughness. This is evidenced by a p-value of 0.0019, confirming that the cutting method induces a statistically significant difference in Ra across all specimens.

In contrast, the feed rate and the interaction between cutting method and feed rate did not exhibit a statistically significant effect on surface roughness, as indicated by p-values of 0.1810 and 0.3208, respectively ($p > 0.05$). Improper selection of machining parameters not only prolongs production time and reduces dimensional accuracy but also adversely affects the surface quality of the manufactured components [21].

Notably, greater surface roughness was observed in specimens processed using the climb cutting method. This phenomenon is attributed to the cutting direction, which coincides with the spindle movement. As a result, in addition to the primary cutting action, material removal may also occur due to the pressing force and centrifugal force exerted by the rotating tool. This combined effect contributes to increased surface roughness [22].

These findings provide practical insights for the furniture manufacturing industry, particularly in CNC machining of materials such as HMR, MDF, and plywood. By optimizing cutting parameters, manufacturers can achieve precise dimensions and reduced surface roughness, thereby minimizing the need for post-processing.

4. Conclusions

A series of cutting tests were conducted on CNC-milled specimens using four machining schemes that varied in cutting method and feed rate. The findings demonstrate that the cutting method significantly influences the dimensional accuracy of the specimens, particularly in terms of length and width. In contrast, the feed rate and its interaction with the cutting method did not show a statistically significant effect on these dimensions. Although the climb cutting method resulted in higher surface roughness, it remains suitable for roughing operations where a high material removal rate (MRR) is desired. Conversely, the conventional cutting method is more appropriate for finishing processes that require precise dimensions and smoother surfaces. The most accurate specimen dimensions were achieved using the conventional cutting method at a low feed rate of 33 mm/s. Furthermore, the cutting method was found to significantly affect the average surface roughness (Ra), with climb cutting producing higher Ra values than conventional cutting. The lowest surface roughness (22.81 µm) was obtained using conventional cutting at a low feed rate, while the highest surface roughness (39.94 µm) was observed with climb cutting at a high feed rate of 66 mm/s. These results highlight the importance of selecting appropriate machining parameters to balance dimensional accuracy and surface quality. Future studies are recommended to explore the effects of cutting depth, plunge rate, and material characteristics to further optimize CNC milling performance across various applications.

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Conflict of Interest

The authors declare no conflicts of interest.

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