



## The Influence of Machining Parameters on Surface Roughness of MDF in Milling Operation

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This paper examined the effect of machining parameters on surface roughness of medium density fiberboard (MDF) machined using a computer numerical control (CNC) router. The machining parameters such as spindle speed, feed rate, depth of cut, and tool diameter were examined for milling. The experiments were conducted at two levels of spindle speeds, four levels of feed rates, two levels of tool diameters, and two levels of axial depths of cut. The surface roughness values of MDF grooved by CNC were measured with stylus-type equipment. Statistical methods were used to determine the effectiveness of the machining parameters on surface roughness. The influence of each milling parameter affecting surface roughness was analyzed using analysis of variance (ANOVA). The significant machining parameters affecting the surface roughness were the feed rate, spindle speed, and tool diameter ( $p < 0.05$ ). There was no significant influence of axial depth of cut on the surface roughness. The surface roughness decreased with increasing spindle speed and decreasing feed rate. The value of surface roughness increased with the increase of tool diameter.

*Keywords:* Surface roughness; Spindle speed; Feed rate; Milling operation

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## INTRODUCTION

The surface quality of wood materials is an important criterion, especially for finishing and surface lamination applications and machining method (*i.e.*, milling, drilling, sanding) in the furniture industry. Moreover, it is necessary to know the machining parameters of optimum surface quality in order to use efficient and cost-effective use of advanced technology machines and to save on the process time. The quality characteristics of the machined surfaces are determined by the surface roughness parameters (Davis 1962). Several approaches have been proposed to determine surface roughness, and the first surface roughness measurements were conducted using sensory methods. Because sensory methods are very subjective, the contact (stylus type of profilometer) and non-contact (laser or ultrasonic systems) measurement methods have been proposed for measurement of surface roughness (Funck *et al.* 1992; Hızıroğlu 1996). In recent years, atomic force microscopy (AFM) and scanning electron microscopy (SEM) methods have been used to evaluate the surface properties of machined materials (Haq and Srivastava 2016). In addition, the optimization approaches such as genetic algorithm (GA), response surface method (RSM), and desirability function (DF) have been used to estimate optimum machining parameters, which make it possible to achieve a minimum surface roughness value (Hazir *et al.* 2018).

The surface quality of wood and wood-based materials depends on the parameters associated with material properties (*i.e.*, wood species, anatomical properties, moisture content, density), machining parameters (*i.e.*, spindle speed, cutting force, feed rate, axial depth of cut), and cutting tool properties (*i.e.*, tool wear, diameter, tool geometry) (Coelho *et al.* 2008; Magos 2008). In the milling of gypsum fiber composite, the effect of the processing parameters such as spindle speed, feed rate, and depth of cut on the cutting force has been optimized by RSM based on a mathematical model (Li *et al.* 2017). General standards and recommendations have been used due to the lack of a standardized method for determining the surface roughness of wood, medium density fiberboard (MDF), or particleboards. This has led to the use of a wide range of measuring instruments and parameters such as filters, filtering cut-off length, measuring length, and measuring resolution (Gurau and Irle 2017).

Previous studies on the surface roughness of wood material have focused on evaluating the effect of material properties such as wood species (Malkoçoğlu and Özdemir 2006), radial and tangential machining direction (Kılıç 2015, 2017), wood density, early wood and latewood ratio (Sadoh and Nakata 1987; Malkoçoğlu 2007; Zhong *et al.* 2013), and fiber direction (Mitchell and Lemaster 2002; Iskra and Tanaka 2005; Sütçü 2013). Moreover, the effects of computer numerical control (CNC) machining parameters such as spindle speed, feed rate, and cutting depth on the surface quality of wood have been monitored (Sütçü and Karagöz 2013; Koc *et al.* 2017; Sofuoglu 2017). CNC machines are widely used in the furniture industry for wood and MDF panels, especially for surface milling. MDF panels must have smooth surfaces for painting and finishing. The effects of machining parameters such as spindle speed, cutting speed, and feed rate on the surface quality of MDF machined with CNC have been investigated in many studies. Aguilera *et al.* (2000) reported that surface roughness of CNC machined MDF decreased with increasing material density. Davim *et al.* (2009) investigated the effect of processing parameters on surface roughness of MDF, which was grooved 5 mm depth of cut with CNC router, and stated that the surface roughness values decreased at high spindle speed and low feed rate. In another study, Gisip *et al.* (2009) indicted that the surface quality of MDF machined with the tool wear was decreased. Deus *et al.* (2015) also revealed that the surface roughness decreased with low depth of cut, high spindle speed, and low feed rate. Sütçü and Karagöz (2012) investigated the effect of machining parameters such as spindle speed, feed rate, stepover, and depth of cut on surface roughness of MDF pocket milling with CNC. They found that surface roughness value increased with increasing feed rate, stepover, and depth of cut and that material removal rate increased with high spindle speed at optimum surface roughness. In another study, the surface roughness of MDF panels has been shown to play an important role in the thin overlay applications such as thin melamine paper or polyvinyl chloride and other decorative overlays on the MDF surface (Aguilera 2000; Hizirolu and Kosonkorn 2006; Kılıç *et al.* 2009). At the same time, Li *et al.* (2018) investigated the surface color change of wood materials machined with a laser machine and found that the color change on the wood surfaces decreased with the increasing of feed speed and sweep width and decreasing of laser power.

As can be seen from the literature studies, the surface quality changes of different materials such as wood and wood based materials, MDF panels under different processing conditions (*i.e.*, milling, drilling, sanding, laser modification) were investigated by different experimental design methods. The differences of this study from other studies are different processing parameters with CNC router.

The efficiency and accuracy of machining in materials seem to be a very significant

criterion for the furniture industry. It is important to define the optimum surface machining parameters for the removal of additional sanding costs and labor in surfaces milled with CNC. Therefore, in this study, the effects of machining parameters on surface roughness of MDF panels machined with CNC milling have been examined. The grooving processing was performed on the MDF surfaces using varying processing parameters such as spindle speed, feed rate, depth of cut and tool diameter. The average roughness ( $R_a$ ) and mean peak to valley height ( $R_z$ ) of surface parameters were evaluated with a stylus type measurement device. The main and interaction effect of machining parameters on surface quality were analyzed by a statistical analysis program.

## EXPERIMENTAL

### Materials

MDF panels of 18 mm thickness (Kronospan, Kastamonu, Turkey) were used for surface milling. The density values ( $752 \text{ kg/m}^3$ ) and moisture content (7%) of the MDF panels were evaluated according to EN 323 (1993). MDF profile density value is an important factor affecting surface roughness. The density profiles of the MDF panels were obtained from the manufacturer to determine the effect of the depth of cut and density on the surface roughness. The density profile of MDF is shown in Fig. 1. The surface of the MDF was grooved with a CNC router that was used to process the aesthetic pattern, especially on the door surfaces. Two different CNC tools of 4 and 6 mm diameter were used for grooving. The rake angles of tools are  $7^\circ$ . The tool geometry is presented in Fig. 2a. A total of 36 experimental samples were grooved on MDF panels with a CNC router, as shown in Fig. 2b.

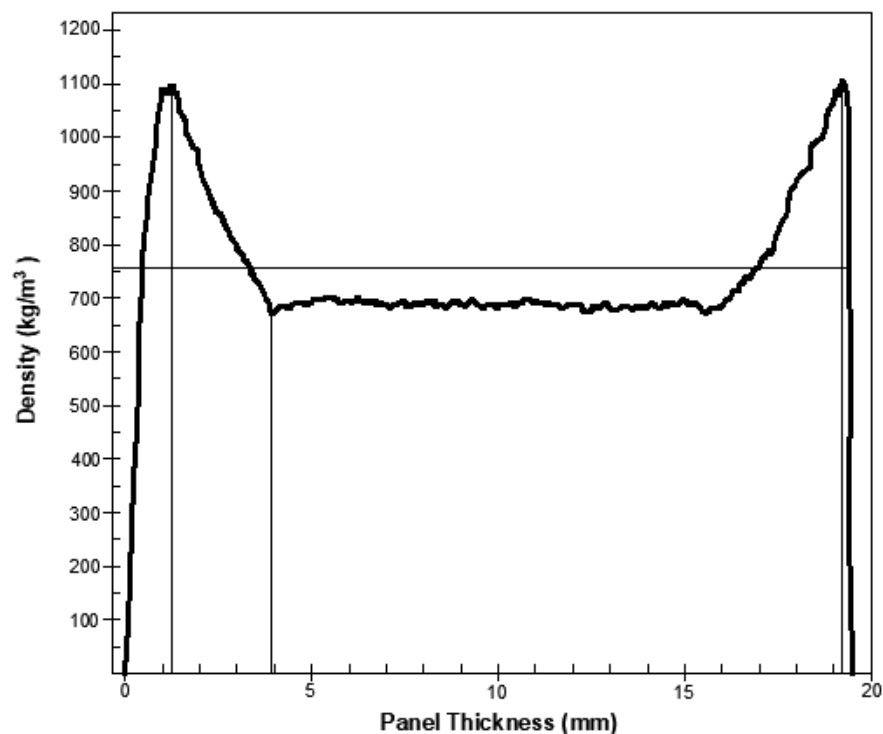


Fig. 1. Density profile of MDF panels

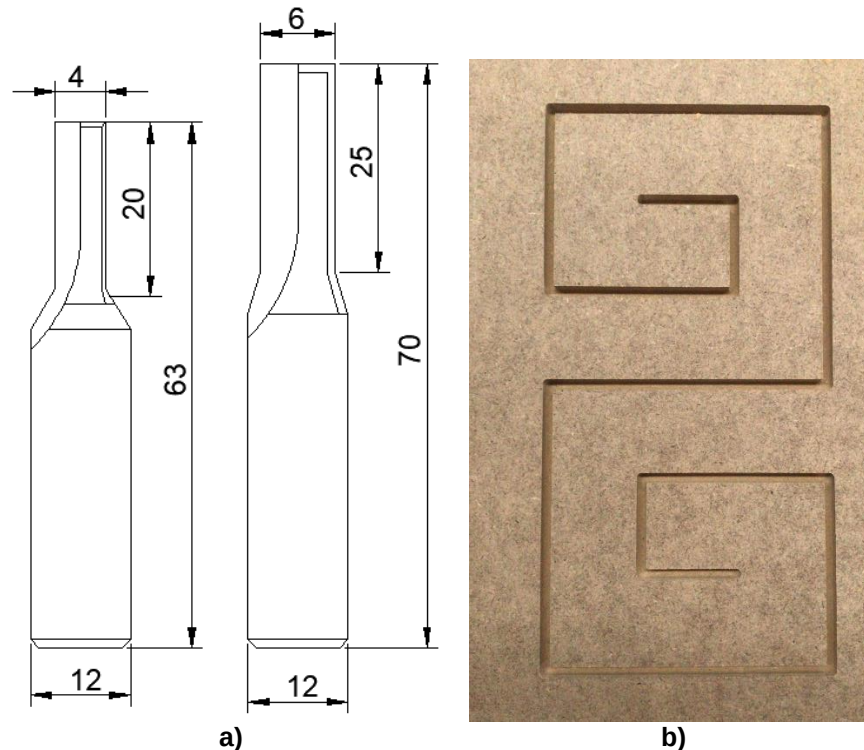


Fig. 2. a) The tool geometry and b) grooved MDF samples

## Methods

Milling parameters such as spindle speed, feed rate, tool diameter, and depth of cut were determined for MDF grooving milling tests, as shown in Table 1.

Table 1. Machining Parameters for MDF Grooving

| Parameters    | Unit   | Level_1 | Level_2 | Level_3 | Level_4 |
|---------------|--------|---------|---------|---------|---------|
| Spindle speed | rpm    | 18000   | 24000   | -       | -       |
| Feed rate     | mm/min | 2500    | 5000    | 7500    | 10000   |
| Depth of cut  | mm     | 4       | 6       | -       | -       |
| Tool Diameter | mm     | 4       | 6       | -       | -       |

Surface roughness was measured with a Handysurf E-35 measurement equipment (Tokyo, Japan) based on stylus technique (Fig. 3). Roughness measurement was performed from 10 different points on each samples. The average roughness ( $R_a$ ) and mean peak to valley height ( $R_z$ ) are considered roughness parameters and characterized by ISO 4287 (1997). The tip diameter was 5  $\mu\text{m}$ , and the measuring force was 4 mN. The surface roughness parameter was measured over a length of 1.25 mm and cut-off length of 0.25 mm. Experimental data of surface roughness was analyzed statistically using analysis of variance (ANOVA), which was performed at the confidence level of 95%. The parameters having a p-value less than 0.05 ( $p < 0.05$ ) were considered significant. The difference between the levels of the parameters with significant value ( $p < 0.05$ ) was determined by the t-test and Duncan test.



**Fig. 3.** The surface roughness measurement system

## RESULTS AND DISCUSSION

In this study, experiments were performed to determine the effects of milling parameters on surface roughness. Four different machining parameters (such as spindle speed, feed rate, tool diameter, dept. of cut) were selected for grooving on MDF with CNC router. A total of 32 experimental elements were produced and surface roughness was measured. Before the statistical analysis, a One-Sample Kolmogorov-Smirnov Test indicated that the surface roughness measurement data showed a normal distribution. The main and interaction effects of machining parameters on surface roughness values were analyzed with variance analysis (ANOVA) at a 95% confidence level. Table 2 and Table 3 present main and interaction effects of machining parameters on surface parameters  $R_a$  and  $R_z$ , respectively.

**Table 2.** Result of the ANOVA for  $R_a$

| Source          | DF  | SS        | MS    | F-value | Sig.   |
|-----------------|-----|-----------|-------|---------|--------|
| Spindle Speed_A | 1   | 5.118     | 5.118 | 7.815   | 0.006* |
| Feed Rate_B     | 3   | 15.674    | 5.225 | 7.978   | 0.000* |
| Depth of cut_C  | 1   | 0.228     | 0.228 | 0.349   | 0.555  |
| Tool diameter_D | 1   | 3.380     | 3.380 | 5.162   | 0.024* |
| A*B             | 3   | 0.432     | 0.144 | 0.220   | 0.883  |
| A*C             | 1   | 0.018     | 0.018 | 0.027   | 0.869  |
| A*D             | 1   | 0.660     | 0.660 | 1.007   | 0.316  |
| B*C             | 3   | 4.705     | 1.568 | 2.395   | 0.069  |
| B*D             | 3   | 2.138     | 0.713 | 1.088   | 0.354  |
| C*D             | 1   | 0.284     | 0.284 | 0.433   | 0.511  |
| A*B*C           | 3   | 1.462     | 0.487 | 0.744   | 0.527  |
| A*B*D           | 3   | 1.907     | 0.636 | 0.971   | 0.407  |
| A*C*D           | 1   | 1.492     | 1.492 | 2.278   | 0.132  |
| B*C*D           | 3   | 3.466     | 1.155 | 1.764   | 0.154  |
| A*B*C*D         | 3   | 1.548     | 0.516 | 0.788   | 0.501  |
| Error           | 288 | 188.607   | 0.655 |         |        |
| Total           | 320 | 10600.009 |       |         |        |
| Corrected Total | 319 | 231.121   |       |         |        |

DF: Degrees of freedom, SS: Sum of squares, MS: Mean square, \*:p<0.05

There were significant effects of the spindle speed, feed rate, and tool diameter parameters on the  $R_a$  value and  $R_z$  at a confidence level of 95% (Tables 2 and 3). The depth of cut had no significant influence on surface roughness (*i.e.*,  $R_a$  and  $R_z$ ). There was no significant interaction between the model parameters (Tables 2 and 3).

**Table 3.** Result of the ANOVA for  $R_z$

| Source          | DF  | SS         | MS      | F-value | Sig.   |
|-----------------|-----|------------|---------|---------|--------|
| Spindle Speed_A | 1   | 189.682    | 189.682 | 10.114  | 0.002* |
| Feed Rate_B     | 3   | 351.119    | 117.040 | 6.241   | 0.000* |
| Depth of cut_C  | 1   | 3.438      | 3.438   | 0.183   | 0.669  |
| Tool diameter_D | 1   | 120.651    | 120.651 | 6.433   | 0.012* |
| A*B             | 3   | 16.875     | 5.625   | 0.300   | 0.825  |
| A*C             | 1   | 31.356     | 31.356  | 1.672   | 0.197  |
| A*D             | 1   | 40.677     | 40.677  | 2.169   | 0.142  |
| B*C             | 3   | 126.655    | 42.218  | 2.251   | 0.083  |
| B*D             | 3   | 44.833     | 14.944  | 0.797   | 0.496  |
| C*D             | 1   | 23.866     | 23.866  | 1.273   | 0.260  |
| A*B*C           | 3   | 34.675     | 11.558  | 0.616   | 0.605  |
| A*B*D           | 3   | 41.559     | 13.853  | 0.739   | 0.530  |
| A*C*D           | 1   | 0.911      | 0.911   | 0.049   | 0.826  |
| B*C*D           | 3   | 35.587     | 11.862  | 0.633   | 0.595  |
| A*B*C*D         | 3   | 13.563     | 4.521   | 0.241   | 0.868  |
| Error           | 288 | 5401.280   | 18.754  |         |        |
| Total           | 320 | 253768.290 |         |         |        |
| Corrected Total | 319 | 6476.725   |         |         |        |

DF: Degrees of freedom, SS: Sum of squares, MS: Mean square, \*:p<0.05

To examine the effects of levels of these machining parameters, t-tests were utilized to determine whether the differences associated with the two spindle speed factors (18000 and 24000 rpm) and two tool diameter factors (4 and 6 mm) were significant. The t-test results for the effect of spindle speed and tool diameter on the surface roughness are presented in Table 4. The effects of spindle speed and tool diameter levels on surface roughness were different. The surface roughness value ( $R_a = 5.82 \mu\text{m}$ ) at a spindle speed of 18000 rpm was higher than the surface roughness value ( $R_a = 5.565 \mu\text{m}$ ) at a spindle speed of 24000 rpm (Table 4). This result suggested that the surface roughness decreased with increasing spindle speed. The surface roughness values increased as the tool diameter increased. The surface roughness value ( $R_a = 5.795 \mu\text{m}$ ) at a tool diameter of 6 mm was higher than the surface roughness ( $R_a = 5.589 \mu\text{m}$ ) at a tool diameter of 4 mm (Table 4).

**Table 4.** Results of the t-test for Spindle Speed and Tool Diameter Level

| Parameters    | Level | N   | Mean  | SS      | t test | P     |
|---------------|-------|-----|-------|---------|--------|-------|
| Spindle Speed | 18000 | 160 | 5.818 | 0.838   | 0.627  | 0.008 |
|               | 24000 | 160 | 5.565 | 0.848   |        |       |
| Tool Diameter | 4     | 160 | 5.589 | 0.73401 | 11.689 | 0.031 |
|               | 6     | 160 | 5.795 | 0.94528 |        |       |

The effects of four different feed rate levels (2500, 5000, 7500, and 10000 mm/min) on surface roughness values were determined by the Duncan test, and the results are summarized in Table 5. There was no statistically significant difference between the effects of feed rate level 1 (2500 mm/min), level 2 (5000 mm/min), and level 3 (7500 mm/min)

on the surface roughness, while level 4 (10000mm/min) of feed rate was significantly different than the remaining levels (Table 5). The highest surface roughness value was obtained with feed rate of 10000 mm/min ( $R_a = 6,057 \mu\text{m}$ ), while the lowest surface roughness value was obtained with feed rate of 2500 mm/min ( $R_a = 5,486 \mu\text{m}$ ). The effects of the machining parameters on the mean surface roughness values are shown in Fig. 4. The surface roughness value increased with increasing feed rate and tool diameter and with decreasing spindle speed. The effect of the depth of cut parameter on the surface roughness value was negligible because of the same density in the profile area. Although the surface roughness decreased with increasing feed rate, the illustration shows that the average  $R_a$  value decreased slightly at 7500 mm/min of feed rate. This can be explained by the interaction effect of the tool diameter-feed rate. The interaction effects of machining parameters on the surface roughness are presented in Fig. 5. The interaction effect of spindle speed-feed rate, tool diameter-feed rate, and spindle speed-tool diameter feed influenced the surface roughness. However, the interaction effect of machining parameters was not significant. From the effect of dual interactions graph of spindle speed- feed rate, the surface roughness is found to be minimal at high spindle speed (24000 rpm) with low feed rate (2500 mm/min). In addition, the friction, machining force, and contact area between the cutting tool and the workpiece increases with the increased feed rate. Further, higher spindle speed means higher tooth passing frequencies and provides shorter plane area/reduction in chip thickness and hence the machining force and surface roughness decreases (Sarıkaya and Güllü 2014). The surface roughness is found to be minimal at high cutting speed with low feed rate. According to tool diameter- feed rate interaction, the high surface roughness occurred with an increase in tool diameter and feed rate. The reason for the high roughness can be explained with the increasing feed rate and tool diameter, causing vibration and a temperature rise between the work piece and the cutting tool (Suresh *et al.* 2012). The surface roughness values of the machined samples with 4 mm of tool diameter and 7500 mm/min of feed rate were observed, according to the processing conditions of 4 mm tool diameter and 5000 mm/min feed rate. However, with the increase in tool diameter (6 mm), the 5000 mm/min of feed rate provided a smoother surface quality than 7500 mm/min of feed rate. The effect of dual interaction graph of spindle speed-tool diameter shows that the surface roughness decreased with increasing spindle speed and decreasing tool diameter. Also, the best surface roughness was observed at a small tool diameter (4 mm) and a high spindle speed (24000 rpm). Compared to the surface roughness values with different spindle speeds (18000 rpm and 24000 rpm) at 4 and 6 mm of depth of cut, the lowest roughness value was provided at 2400 rpm of spindle speed and 4 mm of depth of cut.

**Table 5.** Results of the Duncan Test for Feed Rate Levels

| Feed_rate (mm/min) | N  | Mean  | HG |
|--------------------|----|-------|----|
| 2500               | 80 | 5.486 | a  |
| 7500               | 80 | 5.550 | a  |
| 5000               | 80 | 5.676 | a  |
| 10000              | 80 | 6.057 | b* |

HG: Homogenous group \*: The highest surface roughness value



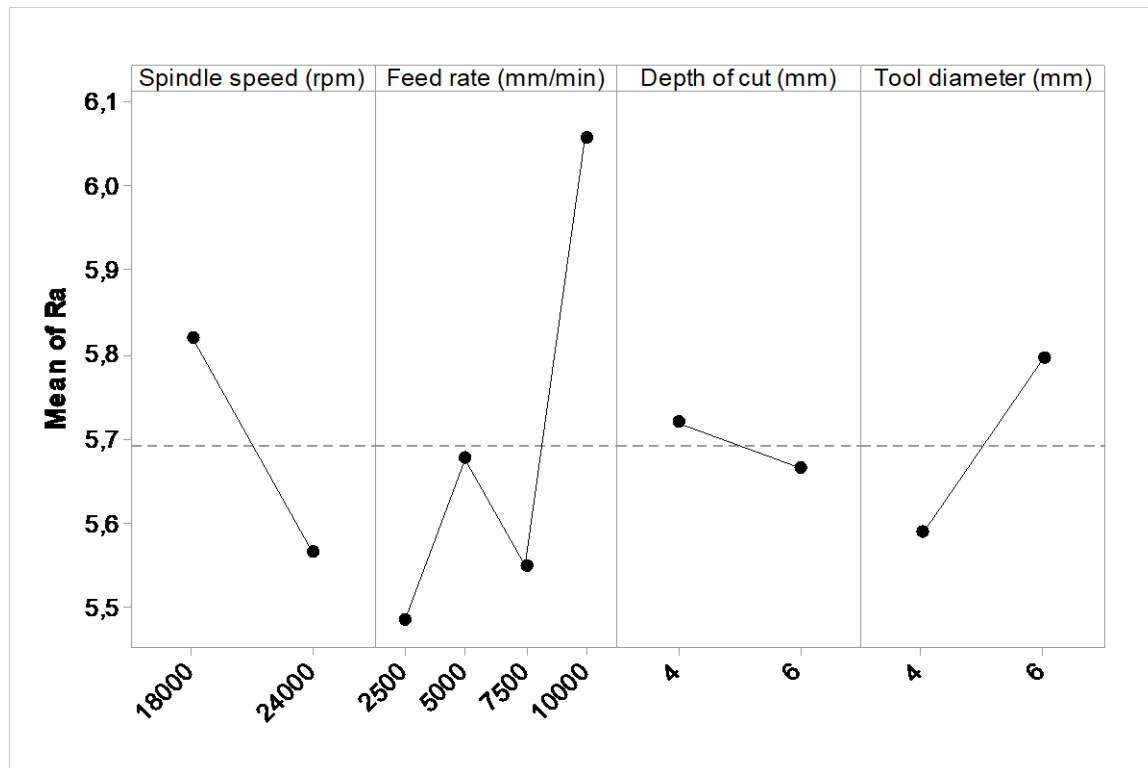


Fig. 4. Mean surface roughness values in machining parameters for  $R_a$

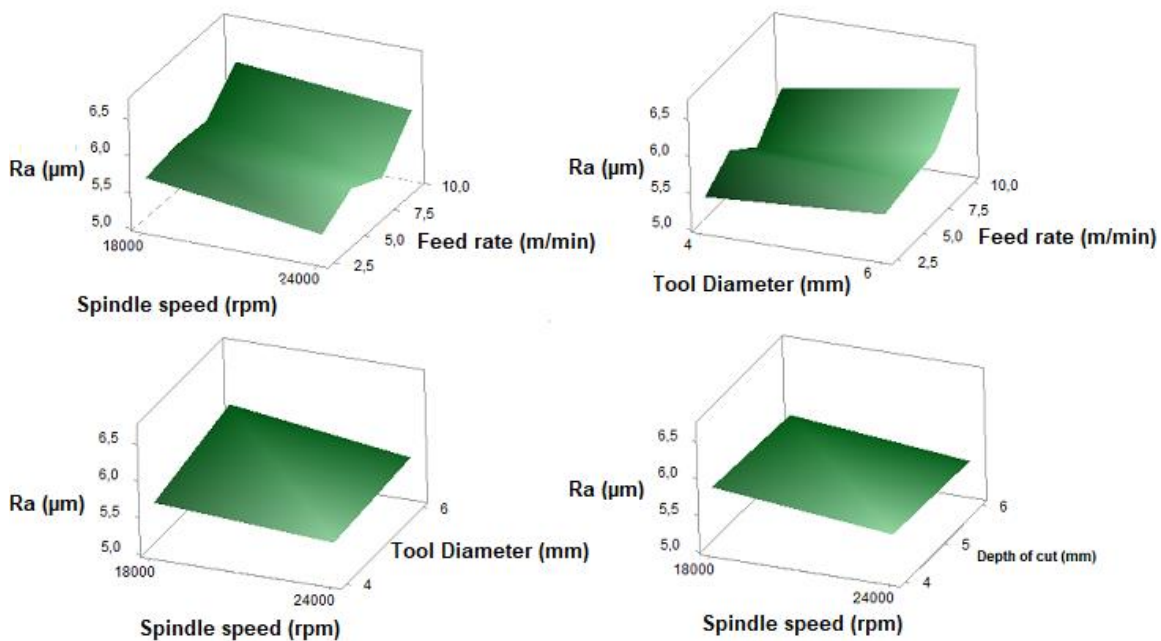


Fig. 5. The surface plots of  $R_a$  according to interactions effect of machining parameters

The main effects of factors (tool diameter, feed rate, spindle speed) on roughness were statistically significant, although interaction of factors had no effect on surface roughness. Spindle speed was a significant factor affecting surface roughness. The surface roughness decreased with increasing spindle speed. The spindle speed at 24000 rpm

provided the smallest surface roughness value. The feed rate at 10000 mm/min provided the highest surface roughness value, while feed rates of 2500 mm/min, 5000 mm/min, and 7500 mm/min provided similar results. The 4 mm tool diameter provided a lower surface roughness value than the 6 mm tool diameter. Depending on other machining factors, the roughness increased as the friction area between the material and tool increased with the increasing tool diameter. Previous studies indicated that the surface roughness decreases with increasing spindle and decreasing feed rate (Davim *et al.* 2009; Sütçü 2013; Sütçü and Karagöz 2013; Sofuoğlu 2015). The results of this study were consistent with the previous research.

Vertical density profile is one of the most important features that characterize the surface roughness properties of MDF in milling. The vertical density value decreases from the surface layer towards the core layer of MDF (Gupta *et al.* 2006). Therefore, the increasing the axial depth of the cut increases the roughness because the density of MDF layer decreases. Surface roughness increases with increasing axial depth of cut in MDF milling (Aguilera *et al.* 2000; Sütçü and Karagöz 2012; Sofuoğlu 2017). Deus *et al.* (2015) reported that surface roughness of MDF exhibits lower values with 1 mm depth of cut, higher spindle speeds, and lower feed rates. In this study, the statistical analysis indicated that there was no significant difference between axial depth cuts of 4 and 6 mm. Because the 4 and 6 mm depth of cut results in the same MDF profile density value, it had no effect on surface roughness (Fig. 1).

## CONCLUSIONS

1. Because depth of cut is same density zone in the MDF vertical density profile, the depth of cut is not an important factor affecting the surface roughness.
2. The increasing the tool diameter increases the cutting temperature, cutting force, and vibration intensity. In addition, tool wear occurs due to friction between the tool and the material. The value of surface roughness increased with the increase of tool diameter. The tool diameter of 6 mm achieved surface roughness higher than 4 mm tool diameter.
3. The value of surface roughness decreased with increasing spindle speed. Spindle speed at 24000 rpm were able to produce the best surface roughness in milling operation.
4. The value of surface roughness increased with the increase of feed rate. Feed rate at 10000 mm/min provided roughest surface from other feed rate levels (2500, 5000, 7500 rpm).

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