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Research Article

INFLUENCE OF THERMAL MODIFICATION OF ASH WOOD *(Fraxinus excelsior* L.*)* AND MACHINING PARAMETERS IN CNC FACE MILLING ON SURFACE ROUGHNESS USING RESPONSE SURFACE METHODOLOGY (RSM)

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ABSTRACT

The objective of this research was to analyse the effect of thermal modification of ash wood *(Fraxinus excelsior* L.*)* at moderate temperature of 160°C and three processing parameters: spindle speed, feed rate and depth of cut in CNC face milling operation on surface quality, expressed by arithmetic surface roughness parameter (Ra).

In order to determine material properties, moisture content (MC), density, swelling, anti-swelling efficiency (ASE) and contact angle for both untreated and thermo-treated ash wood have been measured.

Highly effective, incomplete 3^3 Box-Behnken factorial design was made, with three levels of cutting speed: 8.000, 12.000, and 16.000 rpm; three levels of feed rate: 1.000, 1.500 and 2.000 mm/min; and three levels of depth of cut: 2, 4, and 6 mm. According to the above design matrix, all groups of 50x50x30mm samples have been machined with two machining strategies: *raster* and *offset*. Surface roughness parameter Ra was measured per each run. Response - surface analysis (RSM) was applied to the parameter Ra for all sets of samples. The 3-D response surface plots, polynomial equations and ANOVA tables have been obtained per each observed input variable, for both machining strategies (*raster* and *offset*).

The results indicated that the thermal modification of ash wood at 160 °C improved it`s physical properties: decreased MC, improved wood density, improved ASE and increased wood hydrophobicity.

Polynomial equations and ANOVA tables showed different behaviour of untreated and treated ash wood regarding changing of machining parameters in experimental space. O*ffset* processing strategy, gave better results in the quality of wood surface, than *raster* processing strategy for all types of samples. Thermal modification of ash wood at 160°C improved surface quality after machining for both processing strategies.

Keywords: Ash wood, thermo-wood, surface roughness, response surface methodology (RSM), design of experiment (DOE), CNC face milling.

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1. INTRODUCTION

The effects of thermal modification on wood are well known since sixties. Some effects of thermal treatments, on equilibrium moisture content (EMC), and on change of thickness swelling (TS) of different wood species were stated [1, 4, 12, 14, 22, 24].

Temperature greater than 180ºC causes significant changes in chemical properties in wood [13, 22]. High temperatures reduce hemicelluloses [19].

Another much more significant change in physical properties due to high temperatures is greater dimensional stability, i.e. lower hygroscopicity of the wood [13, 19, 22, 24].

Boonstra et al. [2] indicate that during thermal modification at temperatures up to 200^{o}C in hard wood species such as ash wood *(Fraxinus excelsior* L.) there is a collapse of the trachea and deformation of wood fibers (libriform) located in their immediate vicinity. Damage to cell walls administratively on the direction of wood fibers occurs in the form of transverse cracks and this leads to a decrease in bending.

Thermal modification causes a significant decrease in the hemicelluloses content in the cell walls of ash wood and increases the content of lignin and extractives, which is expressed at temperatures higher than 200ºC [8]. The quality of the treated surface is most often determined by the surface roughness parameter Ra, which is widely recognized and the most widespread in international frameworks [6, 7, 11, 17, 18, 20, 21]. But thermal modification of wood on lower temperatures also can improve it`s machinability regarding power consumption and surface quality. The surface roughness depends on many parameters of processing such as feed rate, grit number of sanding belt during sanding [16], spindle speed, the depth of cut, feed rate, the angle of processing and the type and material from which the tool was made during milling [11].

Karagoz et al. [11] examined the influence of thermal modification of wood on surface roughness, during processing on the CNC machine. The samples are 50x50x150 mm in size, of four wood species: white pine wood (*Pinus sylvestris* L.), Oriental beech *(Fagus orientalis* Lipsky.), Turkish dishes (*Abies bornmülleriana Mattf.*) and Canadian poplar (*Populus canadensis)*. Thermal modification was performed at temperatures of 120, 160 and 200°C.

Hazır and Koç [6, 7] investigated optimization process by combined approach of central composite face-centered (CCFC) experimental design and response surface methodology (RSM). The second order mathematical models in terms of machining parameters were developed for surface roughness using response surface methodology. Hazır and Koç [7] in the second research used three steps Taguchi technique to find "best" combination of inputs in CNC milling of Beech pine (*Fagus orientalis* Lisky) regarding surface roughness parameter Ra.

Sufuoglu [20] used an artificial neural network (ANN) modelling approach to predict and control of surface roughness (Ra and Rz).

The main objective of this research was to analyze the effect of thermal modification of ash wood *(Fraxinus excelsior* L.*)* at moderate temperature of 160^{o}C and three processing parameters: spindle speed, feed rate and depth of cut in CNC face milling operation (with two machining strategies: *raster* and *offset*) on surface quality, expressed by arithmetic surface roughness parameter (Ra).

The second objective was to determine material properties, analyzing moisture content (MC), density, swelling, anti-swelling-efficiency (ASE) and contact angle for both untreated and thermo-treated ash wood.

2. MATERIALS AND METHODS

The research material in the form of 32mm thick tangential planks of dried ash wood (*Fraxinus Excelsior* L.), and 32mm thick tangential planks, thermally modified at temperatures of 160°C has been taken from industrial production. From these planks 30 control samples of the untreated ash wood and 30 samples of thermally modified ash wood has been made. (Figure 1).

2.1. Material properties

Material physical properties such as MC, density and swelling has been determined by standard methods as described earlier [9, 26, 27].

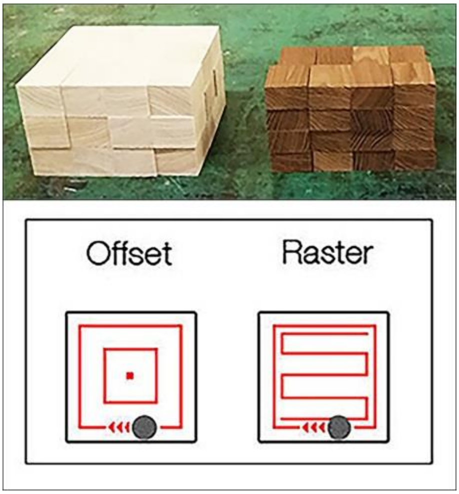

Figure 1. Untreated and thermo-treated ash wood samples for machining in two strategies: *offset* and *raster*

Contact angle (θ) has been measured and expressed by usual method [9, 26] from digital photos (Figure 2). The measurement was performed three times, for each droplet position, on three samples, on two types of samples, and was presented as a mean.

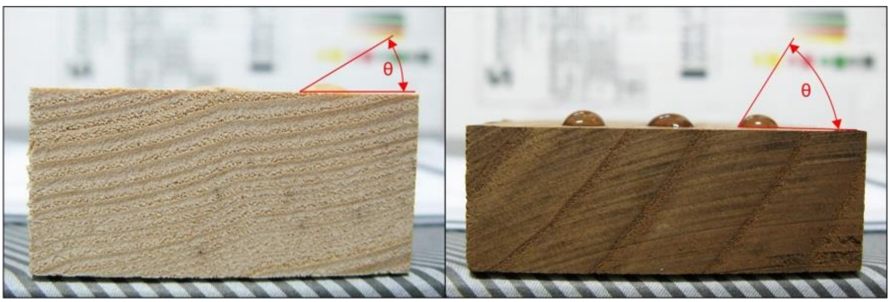

Figure 2. Contact angle measurement (θ) on untreated and thermo-treated ash wood samples

Anti-swelling-efficiency (ASE) is measure of effectiveness of wood treatment. The samples were oven-dried and after stabilization in the conditioning chamber, the specimens were soaked in a water bath at temperature of 20±1°C for each type of sample for 7 days.

Anti-swelling-efficiency (ASE) has been calculated as follows:

$$ASE(\%) = \frac{S_r - S_t}{S_t} \cdot 100[\%] \tag{1}$$

where

$$S(\%) = \frac{V_2 - V_1}{V_1} \cdot 100[\%] \tag{2}$$

S_r – volumetric swelling coefficient of untreated samples
S_t - volumetric swelling coefficient of treated samples
V_1 – volume of wood before soaking (cm^3)
V_2 - volume of wood after soaking (cm^3)

2.2. Experimental design (ED)

Incomplete 3^3 Box-Behnken factorial design was made, which requires 15 runs for the analysis, unlike 27 runs for full factorial design. Box-Behnken factorial design is widely accepted in industrial experimentation [3, 5, 6, 15, 25].

The values of three experimental variables were chosen carefully to cover the feasible range of each variable, as follows:

- 1.000, 1.500 and 2.000 mm/min for feed rate
- 8.000, 12.000, and 16.000 rpm for spindle speed
- 2, 4, and 6 mm for depth of cut.

After computer analysis by software *Statgraphics Centurion XVI* (*StatPoint Technologies, Inc.*), ANOVA tables, second order polynomial equations and 3-D response surface plots have been obtained.

The general form of the second order polynomial equation is:

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \beta_3 x_{3i} + \beta_{11} x_{1i}^2 + \beta_{22} x_{2i}^2 + \beta_{33}^2 x_{3i} + \beta_{12} x_{1i} x_{2i} + \beta_{13} x_{1i} x_{3i} + \beta_{23} x_{2i} x_{3i} + r_i \tag{3}$$

Yi -response for the ith run
β_0 -constant
β_1 -linear influence of the first factor
β_2 -linear influence of the second factor
β_3 -linear influence of the third factor
β_{11} - second order parameter to estimate curvature for the first factor
β_{22} - second order parameter to estimate curvature for the second factor
β_{33} - second order parameter to estimate curvature for the third factor
β_{12},β_{13},β_{23} - parameters of interaction
x_1 – feed rate (m/min)
x_2 – spindle speed (rpm)
x_3 – depth of cut (mm)
r_i - residual error

The ANOVA table partitions the variability in observed sets of data into separate pieces for each of the effects. It then tests the statistical significance of each effect by comparing the mean square against an estimate of the experimental error. Polynomial equations which have been fitted to the data are displayed at the bottom of ANOVA tables below. Values of the variables are specified in their original units.

2.3. CNC face milling operation

According to the computer-generated experimental design matrix, all groups of 50x50x30mm samples have been machined on CNC machine *(BDARK 2120 PRO, Turkey)* in face milling operation, with two machining strategies - *offset* and *raster* (Figure 3). The CNC machine was programmed by software Autodesk ArtCAM 2018 (Autodesk, Inc. USA).

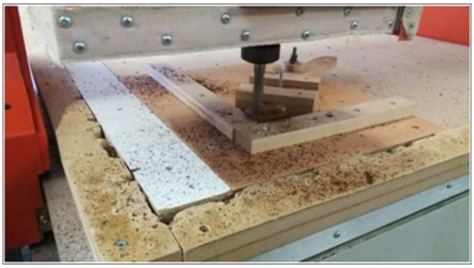

Figure 3. CNC machine *(BDARK 2120 PRO, Turkey)* in face milling operation

Figure 4. Stylus contact tester *(TR200 TIME, China)* for measurement of parameter Ra

2.4. Measurements of arithmetic surface roughness parameter (Ra)

The average arithmetic surface roughness parameter (Ra) was measured on 4 reference lengths of (2.5mm), per each sample, in the latewood zone. The measurement was carried out by stylus contact tester (model TimeSurf TR200, manufacturer Beijing TIME High Technology Ltd.), in accordance with ISO 4287:1997 protocol (Figure 4). The diameter of the diamond stylus tip was 2 μm, and the stylus was pressed on the surface by the force of 4 mN.

3. RESULTS

3.1. Physical properties: MC, ratio βt/βr, ASE, contact angle (θ)

Control (untreated) samples of ash wood had an average MC of 7.58%, while thermally modified samples at a temperature of 160^0C had an average MC of 4.42%. Thermally modified samples at a temperature of 160^0C had an average tangential swelling of 3.54%, while the average tangential swelling in the control samples was 6.90%. Thermally modified samples at a temperature of 160^0C had an average radial swelling of 4.51%, while average radial swelling in the control samples was 5.68%.

Wood anisotropy, expressed through the ratio of tangential and radial swelling βt/βr, is a very important indicator of the impact of physical properties on the quality of the surface processed wood. This βt/βr swelling ratio of wood over water and βt/βr swelling ratio of wood in the water is shown in table 1.

It can be noted that the ratio in tangential and radial direction in control (untreated) samples of ash wood is highest and it is 1.61%, while in thermally modified samples at temperature of 160 ^{0} C, this ratio is 1.44% what idicates that thermal modification make wood more stabile.

Anti Swelling Efficinecy parameter (ASE) was as expected (28.19%), considering relatively low temperature of thermal treatment of 160^oC.

Table 1. Tangential - radial swelling ratio βt/βr

Type of samples	Tangential - radial swelling ratio βt/βr	
	Swelling over water (7 days)	**Swelling in water (7 days)**
Untreated	1.61	1.84
Thermo-treated at 160^0C	1.44	1.51
Anti-Swelling Efficiency parameter (ASE)		28.19%

Table 2 shows the value of the contact angle of the water droplet, whose change was tracked from the starting zero position, (0s) to a total of 20 seconds. The contact angle value was measured every 10 seconds. The decline of the contact angle over time (and the increase in its cosines) is faster in the control (untreated) samples of the ash wood.

Table 2. Wettability of ash wood-contact angle θ

Type of samples	**Contact angle θ (^{o})**		
	0 s	**10 s**	**20 s**
No treated	33.98	13.43	5.78
Treated at 160 °C	61.79	53.93	46.31

3.2. Arithmetic surface roughness parameter (Ra)

ANOVA tables and second order polynomial equations showed different behaviour of untreated and treated ash wood regarding changing of machining parameters in experimental space. The main indicator of machined surface quality was arithmetic surface roughness parameter (Ra) expressed by polynomial equations and response surface graphs. Response surface graphs has been shown in the function of feed rate and spindle speed, with depth of cut fixed at 4mm in every observed case.

The ANOVA table partitions the variability in sets of data into separate pieces for each of the effects. The accuracy of the fitted model was tested by R-Squared statistic who indicates in which percent the fitted model explains the variability in the process.

The Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on the order in which they occur in the data file. Since in all observed cases the P-value was greater than 0.05, there were no indication of serial autocorrelation in the residuals.

Table 3. ANOVA table for surface roughness parameter Ra and polynomial equation (untreated. *raster*)

Variable	**Sum of Squares**	**Degrees of freedom**	**Variance ratio**	**F value**	**P – value**
A: feed rate	0.071442	1	0.071442	0.34	0.5859
B: spindle speed	0.011781	1	0.011781	0.06	0.8226
C: depth of cut	1.88277	1	1.88277	8.93	0.0305
AA	0.520039	1	0.520039	2.47	0.1772
AB	0.400689	1	0.400689	1.90	0.2266
AC	0.0484	1	0.0484	0.23	0.6522
BB	0.034413	1	0.034413	0.16	0.7030
BC	0.099540	1	0.099540	0.47	0.5227
CC	0.462596	1	0.462596	2.19	0.1987
Residual error	1.05475	5	0.21095		
Total (corrected)	4.66747	14			
Ra (untreated. *raster*) $= 9.05771 - 0.0070315\times A - 0.000312906\times B + 1.0221\times C + 0.00000150117\times A^2 + 1.5825E\text{-}7\times A\times B + 0.00011\times A\times C + 6.03386E\text{-}9\times B^2 - 0.0000197188\times B\times C - 0.0884896\times C^2$					

$R^2=0.774$

The R-Squared statistic indicates that the model as fitted explains 77.402% of the variability in (untreated. *raster*).

Analysis showed the highest influence of factor C (depth of cut) on arithmetic surface roughness parameter Ra, followed by A^2 (feed rate-squared) and C^2 (depth of cut-squared) and interactions AB (feed rate x spindle speed).

Table 4. ANOVA table for surface roughness parameter Ra and polynomial equation (T160 ^{0}C. *raster*)

Variable	Sum of Squares	Degrees of freedom	Variance ratio	F value	P – value
A: feed rate	0.00418612	1	0.00418612	0.02	0.8945
B: spindle speed	0.0489845	1	0.0489845	0.23	0.6534
C: depth of cut	0.15429	1	0.15429	0.72	0.4358
AA	0.34498	1	0.34498	1.60	0.2613
AB	0.00416025	1	0.00416025	0.02	0.8948
AC	0.116281	1	0.116281	0.54	0.4953
BB	0.159616	1	0.159616	0.74	0.4285
BC	0.00038025	1	0.00038025	0.00	0.9681
CC	0.000310256	1	0.000310256	0.00	0.9712
Residual error	1.07602	5	0.215205		
Total (corrected)	1.87842	14			
Ra (T160 ^{0}C. *raster*) $= 7.81071 - 0.00411075 \times A - 0.00026325 \times B - 0.190021 \times C + 0.00000122267 \times A^2 - 1.6125E\text{-}8 \times A \times B + 0.0001705 \times A \times C + 1.29948E\text{-}8 \times B^2 - 0.00000121875 \times B \times C + 0.00229167 \times C^2$					

R^2=0.4272

The R-Squared statistic indicates that the model as fitted explains 42.716% of the variability in (T160 ^{0}C. *raster*).

The factor A^2 (feed-rate squared) showed the highest influence on arithmetic surface roughness parameter Ra, while other factors were unsignificant.

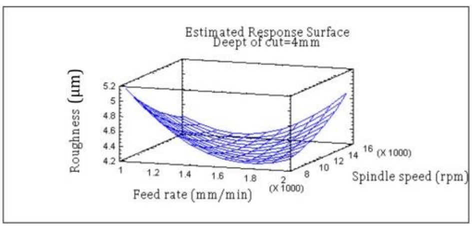

Figure 5. Surface roughness Ra response surface graph for untreated wood and raster processing strategy

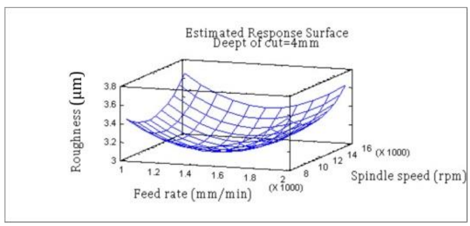

Figure 6. Surface roughness Ra response surface graph for treated wood at 160^{o}C and raster processing strategy

Table 5. ANOVA table for surface roughness parameter Ra and polynomial equation (untreated. *offset*)

Variable	Sum of Squares	Degrees of freedom	Variance ratio	F value	P – value
A: feed rate	0.166176	1	0.166176	0.59	0.4765
B: spindle speed	0.5	1	0.5	1.78	0.2396
C: depth of cut	0.0294031	1	0.0294031	0.10	0.7594
AA	0.0711254	1	0.0711254	0.25	0.6362
AB	0.000064	1	0.000064	0.00	0.9885
AC	0.0135722	1	0.0135722	0.05	0.8347
BB	0.144084	1	0.144084	0.51	0.5059
BC	0.042436	1	0.042436	0.15	0.7135
CC	0.549308	1	0.549308	1.96	0.2208
Residual error	1.40422	5	0.280844		
Total (corrected)	2.98345	14			
Ra (untreated. *offset*) = 4.20571 – 0.00163425×A– 0.000288312×B +0.559854×C + 5.55167E-7×A^2 + 2.E-9×A×B +0.00005825×A×C + 1.23463E-8×B^2 +0.000012875×B×C– 0.0964271×C^2					

R^2=0.529

The R-Squared statistic indicates that the model as fitted explains 52.933% of the variability in (untreated. *offset*).

Factors C^2 (depth of cut-squared) and B (spindle speed) showed the highest influence on arithmetic surface roughness parameter Ra, while other factors were unsignificant.

Table 6. ANOVA table for surface roughness parameter Ra and polynomial equation (T160^{0}C. *offset*)

Variable	Sum of Squares	Degrees of freedom	Variance ratio	F value	P – value
A: feed rate	0.111628	1	0.111628	2.05	0.2112
B: spindle speed	0.905185	1	0.905185	16.66	0.0095
C: depth of cut	0.326432	1	0.326432	6.01	0.0578
AA	1.02564	1	1.02564	0.00	0.9990
AB	0.047961	1	0.047961	0.88	0.3906
AC	0.00801025	1	0.00801025	0.15	0.7168
BB	0.0195866	1	0.0195866	0.36	0.5744
BC	0.00042025	1	0.00042025	0.01	0.9333
CC	0.000400641	1	0.000400641	0.01	0.9349
Residual error	0.271625	5	0.0543251		
Total (corrected)	1.69188	14			
Ra (T160^{0}C. *offset*) = 1.81558 + 0.00071225× A + 0.000112406×B +0.0284167×C + 6.66667E-10× A^2– 5.475E-8× A ×B +0.00004475× A ×C– 4.55208E-9×B^2– 0.00000128125×B×C + 0.00260417×C^2					

R^2=0.83945

The R-Squared statistic indicates that the model as fitted explains 83.945% of the variability in (T160^{0}C. *offset*).

The highest influence on arithmetic surface roughness parameter Ra, indicated factor B (spindle speed), followed by C (depth of cut) and factor A (feed rate), while other factors were unsignificant.

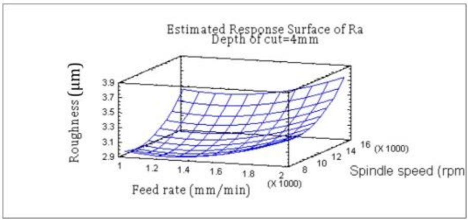

Figure 7. Surface roughness Ra response surface graph for untreated wood and offset processing strategy

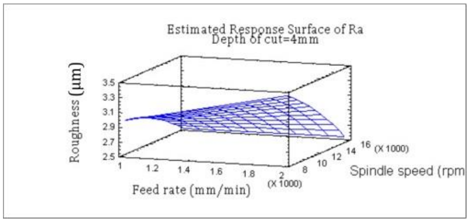

Figure 6. Surface roughness Ra response surface graph for treated wood at 160^oC and offset processing strategy

4. DISCUSSION

Analysis of tangential - radial swelling ratio βt/βr proved that thermal modification of ash wood at 160^oC improved it`s physical properties: decreased MC, improved ASE and increased wood hydrophobicity. Anti-Swelling-Efficiency parameter (ASE) was as expected (28.19%), considering relatively low temperature of thermal treatment of 160^oC. Other authors have found much more significant change in physical properties due to higher temperatures. Dimensional stability was greater, i.e. lower hygroscopicity of the wood [13, 19, 22, 24]. But thermal modification of ash wood at 160^oC is good balance between its physical properties improvement and surface quality after CNC face milling.

Karagoz et al. [11] examined the influence of thermal modification of wood on surface roughness, during processing on the CNC machine. They found that the values for the parameter Ra were higher in the radial than in the tangential direction, while the overall results suggest that the Ra was lower with the thermal modification temperature rising.

Analyses showed that o*ffset* processing strategy, gave better results in the quality of wood surface, than *raster* processing strategy for all types of samples. Uddin et al. [23] found the same results by exploring the 2D trajectory of the work tool movement during CNC milling operation. They found that the spiral (*offset*) processing strategy obtained better quality of the treated surface compared to raster processing strategy.

Sofuoglu [21] found the similar results: smallest values for the surface roughness parameters Ra and Rz were obtained at spindle speed of 16000 rpm. The parameter Rz was smaller in *offset* processing strategy, while Ra parameter values were approximate. The most optimal processing was *offset strategy,* with spindle speed of 16000 rpm and feed rate of 1000 mm/min.

5. CONCLUSION

- Average MC of no-treated ash wood was 7.58% while average MC of thermally treated ash wood at 160 ^0C was 4.42%.
- Anisotropy of thermally treated ash wood at 160^0C was stabilized what was indicated by βt/βr ratio: on samples over water, it was lowered from 1.61 to 1.44 and on samples submerged into water it was lowered from 1.84 to 1.51. It means that swelling in tangential and radial direction was more uniform, and wood has become more stable.
- The decrease of contact angle was faster over time (spilling), with control (untreated) samples.

- Anti-Swelling-Efficiency parameter (ASE) was as expected (28.19%), considering relatively low temperature of thermal treatment of 160°C.
- Polynomial equations and ANOVA tables showed different behavior of untreated and treated ash wood regarding changing of machining parameters in experimental space.
- O*ffset* processing strategy, gave better results in the quality of wood surface, than *raster* processing strategy for all types of samples. Thermal modification of ash wood at 160°C improved surface quality after machining for both processing strategies.

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