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Investigation on the Effect of Turning of AISI 304 Stainless Steel Using MQL Technique with Corn Oil as Cutting Fluid and Comparison with Dry Condition †

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Abstract: This study's objective is to turn AISI 304 stainless steel (304 SS) utilizing the Minimum Quantity Lubrication (MQL) technique while comparing the outcomes to dry turning. Based on the responses, cutting force, surface roughness, and temperature, three process parameters, speed, feed, and depth of cut (doc), were optimized and regressed for both dry and wet conditions. Dry turning and wet turning are carried out, and the responses are noted. Later, the surface roughness (R_a) of the machined component under both conditions is tested with the help of a surface roughness measuring instrument. The surface roughness of the component under wet turning is reduced to 0.5958 µm from 0.7425 µm with dry turning. The cutting temperature was controlled very well in wet turning with a value of 61.21 °C than with a value of 84.16 °C in the case of dry turning. The cutting force developed during dry turning is reduced by applying a mist of oil, which lubricates the surface, thereby reducing the cutting force to a value of 4.987 Kgf from 5.254 kgf. Corn oil produces better results and can be used as an alternate cutting fluid.

Keywords: AISI 304; minimum quantity lubrication; corn oil; dry turning; wet turning

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1. Introduction

Increasing productivity, quality, customer satisfaction, and other contemporary production developments present producers with technical hurdles such as tool life, surface integrity, and high machining temperatures. As the cutting process is evolving, cutting fluids are being introduced to improve the tribological processes at work on the surface of contact between the job and tool. Cutting fluid usage lengthens the life of the tools, promotes more cost-effective cutting speeds, and enhances overall production system effectiveness. A film of anti-friction adsorption forms on metallic surfaces when vegetable oils are used in place of mineral oils. Using carbide tools, Anthony et al. [1] checked the turning of the AISI 304 austenitic stainless steel effect using cutting fluids to examine the roughness of the surface and wear of the tool. Additionally, coconut oil was compared to two additional cutting fluids and an emulsion to discover that cutting fluid has a significant impact on both surface roughness and tool wear. Carbide cutting tools were used by Agrawal et al. [2] for machining M2 steel under different machining parameters, and they found that R_a and the wear of the tool were reduced by using aloe vera rather than conventional cutting fluid. With carbide drill bits, Balaji et al. [3] studied drilling on 304 SS to conclude that the evolution of tool wear causes the drill bit vibration to rise. Benedicto et al. [4], by focusing on the financial, environmental, and technical issues, recommended the use of cutting fluids as the primary alternatives in machining, such as MQL, dry machining, solid lubrication, cryogenic cooling, gaseous cooling, sustainable cutting fluids, and nanofluids. Handawi et al. [5] studied the MQL technique using castor oil as a cutting fluid when hardened stainless steel is being machined with coated carbide cutting tools at speeds up to 170 m/min and feed rates of 0.24 mm/rev. Ekinovic et al. [6] revealed that the cutting force is decreased which leads to less power consumption in the case of the MQL turning of carbon steel with vegetable oil. Emel et al. [7] reviewed and listed the advantages and disadvantages of cutting fluids. Jyothi et al. [8] used non-edible vegetable oils like Neem and Honge to evaluate and investigate the performance of the drilling operation of mild steel on cutting temperature, hardness, and surface roughness and compared the results under dry cutting conditions. Potdar et al. [9] concluded that as cutting force decreases with an increase in cutting speed and increases with an increase in feed and depth of cut during the dry turning of AISI 904L stainless steel. Hui-Bo He et al. [10] studied the influencing factor cutting temperature using the single factor experiment method during dry turning of AISI 304 stainless steel and showed that cutting temperature generally increases with the increase of cutting speed and feed rate. Thus, many of the researchers performed the turning of different materials using the MQL technique with edible and non-edible vegetable oil to study the effect of cutting parameters to study the process performance. The aim of this research is to use corn oil as a cutting fluid, which is applied in the form of mist, and the responses like cutting force, temperature, and surface roughness are measured for different combinations of factors like speed, feed, and depth of cut, and they are compared under dry conditions. Then, optimization and regression are performed, and values are obtained.

2. Experimental Setup

The material 304 SS is turned in a lathe (MTT636) with a workpiece 150 mm in length and 32 mm in diameter. A PVD-coated insert (CCMT 09T308 HMP PC9030) was used for the turning process, and they are held with a suitable tool holder (SCLCR 1212 H09T3). Initially, the turning operation was carried out under dry conditions, and later, the process was carried out under wet conditions. Here, corn oil was used as a cutting fluid with the help of a mist cooling system. The selected vegetable oil must be applied in the form of a mist. Hence, a required mist cooling system was made by assembling the required components, and they were installed in the lathe machine while performing wet turning operations, which are shown in Figure 1a,b. An air compressor is used as a source for pressurized air. It can hold a maximum pressure of 12 bar. A valve is opened to release the air stored in it, which mixes with oil to produce the mist. An airtight glass container is used as a storage for vegetable oil. It has two holes. One is the air inlet, and the other is the oil outlet. The outlet pipe carries a filter at the end to avoid dust particles entering it. This chamber contains two inlets and one outlet. The air and oil were mixed, and the resultant mixture was forced through the outlet. It also contains two flow controllers for controlling the amount of oil and air in the chamber. A fine mist is produced with the help of a nozzle, and it helps in directing the flow of mist. The diameter at the end of the nozzle must be small enough to produce the mist, and it increases its velocity, thereby producing a better cooling rate. The components are assembled with the help of scissors, Teflon tapes, cutting pliers, and spanners. The assembled component is checked for leaks, and then the flow is controlled to obtain the required proportion of mist. The cutting force, temperature, and surface roughness obtained under dry and wet conditions are noted down and tabulated.

(**a**) (**b**)

Figure 1. (**a**) Lathe installed with mist cooling system; (**b**) Mist cooling system.

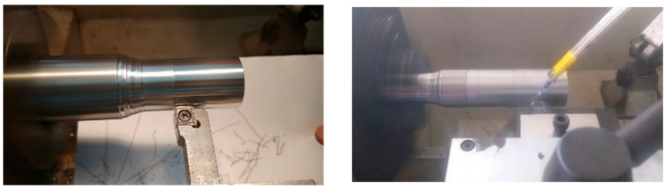
The most popular austenitic stainless steel is AISI 304, which has a stronger corrosion resistance than normal steel and is used frequently because it is simple to mold into a variety of shapes. Various home and commercial uses for it include screws, mechanical parts, automobile headers, and food-handling gear. Additionally, it is employed in the realm of architecture for outside accents like water and fire features. It is also a typical coil material for vaporizers that can be rebuilt. The workpiece sample is checked to conform to 304 grade, Table 1.

Table 1. Chemical composition for AISI 304.

Element	C	Mn	Si	S	P	Cr	Ni	Mo
Weight (%)	0.053	1.09	0.40	0.010	0.037	18.44	8.46	0.12

Dry and Wet Turning

The workpiece is firmly held in three jaw self-centering chuck, and the tool holder with the insert is placed inside the dynamometer sensor and held tightly with the help of Allen screws, as shown in Figure 2a,b. The gears are shifted in the lathe machine to obtain the required speed and feed. The depth of cut is given with the help of a transverse slide. Then, the lever is engaged for automatic turning. Here, the experiment is conducted without the application of cutting oil, i.e., dry turning, and the cutting force and temperature developed during the turning process are observed from the instruments and noted down. The turning parameters and levels of process parameters are shown in Tables 2 and 3, respectively. The same process is carried out again, but now corn oil is applied as mist at the tool and workpiece interface with the help of a mist cooling system, and again, the temperature and the corresponding cutting forces are observed and noted down. The levels of process parameters are considered at three levels that are tabulated in Table 4.



(**a**) (**b**)

Figure 2. (**a**) Dry turning; (**b**) wet turning.

Table 2. Turning parameters.

Turning Parameter	Values
Spindle Speed (rpm)	300, 755, 1255
Feed (mm/rev)	0.111, 0.122, 0.134
Depth of cut (mm)	0.1, 0.15, 0.2

Table 3. Machining parameters and their levels.

Process Parameters	Levels		
	Level I	Level II	Level III
Cutting speed v (rpm)	300	755	1255
Feed ḟ (mm/rev)	0.111	0.122	0.134
Depth of cut d (mm)	0.1	0.15	0.2

Table 4. L27 orthogonal array.

S. No.	Speed (rpm)	Feed (mm/rev)	Depth of Cut (mm)	S. No.	Speed (rpm)	Feed (mm/rev)	Depth of Cut (mm)
1	300	0.111	0.10	15	755	0.122	0.20
2	300	0.111	0.15	16	755	0.134	0.10
3	300	0.111	0.20	17	755	0.134	0.15
4	300	0.122	0.10	18	755	0.134	0.20
5	300	0.122	0.15	19	1255	0.111	0.10
6	300	0.122	0.20	20	1255	0.111	0.15
7	300	0.134	0.10	21	1255	0.111	0.20
8	300	0.134	0.15	22	1255	0.122	0.10
9	300	0.134	0.20	23	1255	0.122	0.15
10	755	0.111	0.10	24	1255	0.122	0.20
11	755	0.111	0.15	25	1255	0.134	0.10
12	755	0.111	0.20	26	1255	0.134	0.15
13	755	0.122	0.10	27	1255	0.134	0.20
14	755	0.122	0.15				

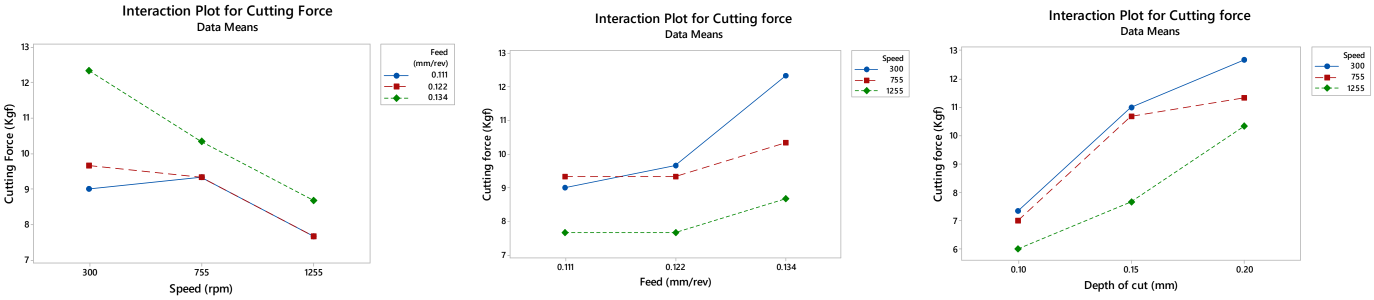
When using a good cutting fluid, the tool should be under very little heat, and the workpiece and tool will also be affected. This will result in a longer tool life and better machining accuracy. Here, an edible vegetable oil, corn oil, is used as a cutting fluid, which is applied in the form of mist while performing the turning operation under wet conditions.

3. Observation, Analysis, and Discussion

3.1. Cutting Force (F_c)

Based on the regression equation as developed through experimental observation, studies are carried out to analyze the effects of the various process parameters on the cutting force under dry conditions. In Figure 3, the cutting force decreases with an increase in speed, and also, the value of the cutting force decreases with a decrease in feed rate. Thus, the cutting force is maximal when the speed is minimal, and the feed is maximal and the cutting force is minimal when the speed is maximal and the feed is minimal. Also, the cutting force value increases with an increase in the depth of the cut. Thus, the maximal cutting force occurs when the depth of the cut is maximal, and the cutting force is minimal when the depth of the cut is minimal.

$$\text{Fc (dry)} = 61.6 + 0.01500\ \text{V} - 1117\ \text{F} + 45.2\ \text{D} - 0.000002\ \text{V} \times \text{V} + 4758\ \text{F} \times \text{F} - 267\ \text{D} \times \text{D} - 0.1051\ \text{V} \times \text{F} - 0.0103\ \text{V} \times \text{D} + 730\ \text{F} \times \text{D}$$



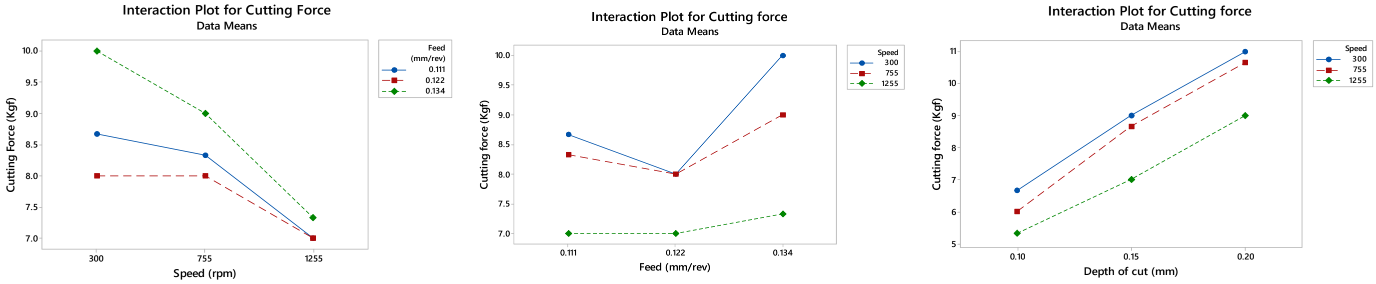
(**a**) (**b**) (**c**)

Figure 3. Interaction plot—(**a**) speed vs. cutting force (dry); (**b**) feed vs. cutting force (dry); (**c**) depth of cut vs. cutting force (dry).

From ANOVA, we obtain the responses of cutting force under wet conditions for various process parameters along with their interactions, and subsequently, dof, SS, MS, square root, F_{dist}, and p are also calculated. The value R^2 = 87.90% indicates that the model can predict the response with high accuracy. The model indicates significant terms with the help of the value of "Prob>F" if it is less than 0.0500. The regression equation for cutting force under wet conditions is as follows:

$$\text{Fc (wet)} = 77.3 + 0.00769\ \text{V} - 1283\ \text{F} + 25.1\ \text{D} - 0.000002\ \text{V} \times \text{V} + 5343\ \text{F} \times \text{F} - 44.4\ \text{D} \times \text{D} - 0.0468\ \text{V} \times \text{F} - 0.00719\ \text{V} \times \text{D} + 294\ \text{F} \times \text{D}$$

Based on the regression equation as developed through experimental observation, studies are carried out to analyze the effects of the various process parameters on the cutting force under wet conditions. In Figure 4, the cutting force decreases with an increase in speed, and the value of the cutting force decreases with a decrease in feed rate. Thus, the cutting force is maximal when the speed is minimal, and the feed is maximal and the cutting force is minimal when the speed is maximal and the feed is minimal. The cutting force value increases with an increase in the depth of the cut. Thus, the maximal cutting force occurs when the depth of cut is maximal, and cutting force is minimal when the depth of cut is minimal.



(**a**) (**b**) (**c**)

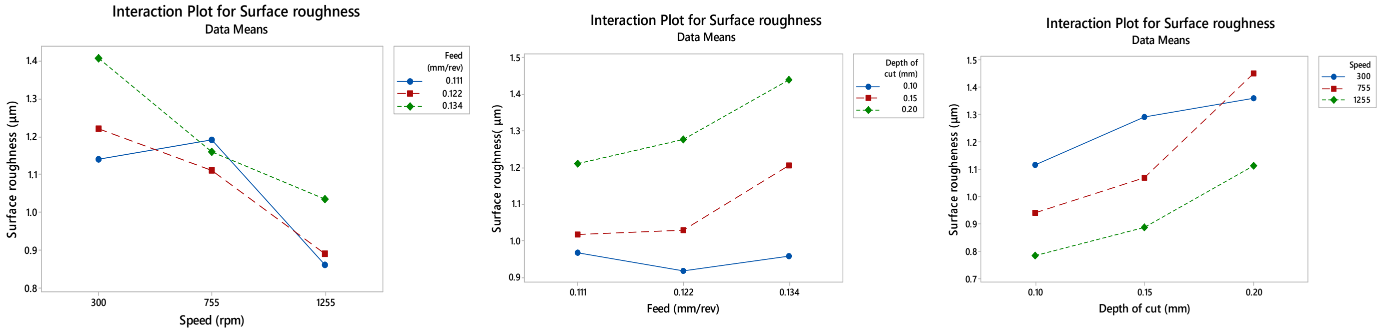
Figure 4. Interaction plot—(**a**) speed vs. cutting force (wet); (**b**) feed vs. cutting force (wet); (**c**) depth of cut vs. cutting force (wet).

3.2. Surface Roughness (R_a)

From ANOVA, we obtain the responses of surface roughness under dry conditions for various process parameters along with their interactions, and subsequently, dof, SS, MS, square root, F_{dist}, and p are also calculated. The value R^2 = 95.32% indicates that the model can predict the response with high accuracy. The model indicates significant terms with the help of the value of "Prob>F" if it is less than 0.0500. The regression equation for surface roughness under dry conditions is as follows:

$$\text{Ra (dry)} = 8.29 + 0.000385\ V - 109.8\ F - 15.17\ D + 421\ F \times F + 17.8\ D \times D - 0.00392\ V \times F + 0.00082\ V \times D + 104.8\ F \times D$$

Based on the regression equation as developed through experimental observation, studies are carried out to analyze the effects of the various process parameters on the surface roughness under dry conditions. In Figure 5, the surface roughness value decreases with an increase in speed, and the value of surface roughness decreases with a decrease in the feed rate. Thus, surface roughness is maximal when the speed is minimal, and the feed is maximal and the surface roughness is minimal when the speed is maximal and the feed is minimum. The surface roughness value increases with an increase in the depth of the cut. Thus, the maximal surface roughness occurs when the depth of cut is maximal, and the surface roughness is minimum when the depth of cut is minimum.



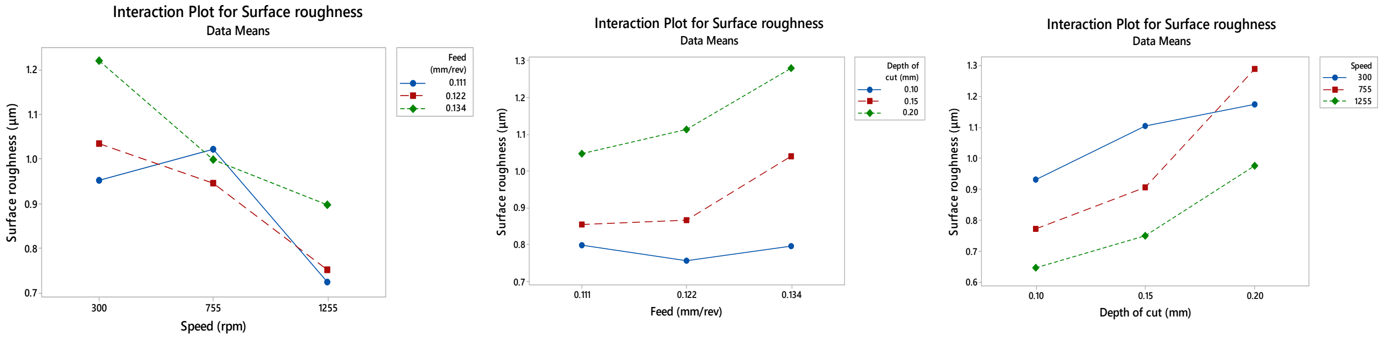
(**a**) (**b**) (**c**)

Figure 5. Interaction plot—(**a**) speed vs. surface roughness (dry); (**b**) feed vs. surface roughness (dry); (**c**) depth of cut vs. surface roughness (dry).

From ANOVA, we obtain the responses of surface roughness under wet conditions for various process parameters along with their interactions, and subsequently, dof, SS, MS, square root, F_{dist}, and p are also calculated. The value $R^2 = 94.49\%$ indicates that the model can predict the response with high accuracy. The model indicates significant terms with the help of the value of "Prob>F" if it is less than 0.0500. the regression equation for surface roughness under wet conditions is as follows:

$$\text{Ra (wet)} = 7.92 + 0.000432\ V - 107.7\ F - 14.75\ D + 415\ F \times F + 17.8\ D \times D - 0.00400\ V \times F + 0.00083\ V \times D + 101.5\ F \times D$$

Based on the regression equation as developed through experimental observation, studies are carried out to analyze the effects of the various process parameters on the surface roughness under wet conditions. In Figure 6, the surface roughness value decreases with an increase in speed, and the value of surface roughness decreases with a decrease in feed rate. Thus, surface roughness is maximal when the speed is minimal, and the feed is maximal and the surface roughness is minimal when the speed is maximal and the feed is minimal. The surface roughness value increases with an increase in the depth of the cut. Thus, the maximal surface roughness occurs when the depth of the cut is maximal, and surface roughness is minimal when the depth of the cut is minimal.



(**a**) (**b**) (**c**)

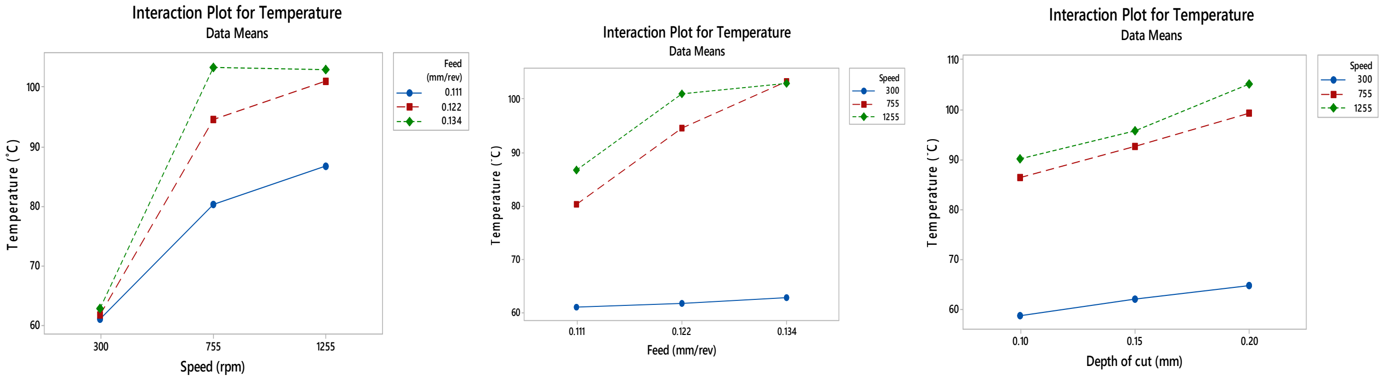
Figure 6. Interaction plot—(**a**) speed vs. surface roughness (wet); (**b**) feed vs. surface roughness (wet); (**c**) depth of cut vs. surface roughness (wet).

3.3. Temperature

From ANOVA, we obtain the responses of temperature under dry conditions for various process parameters along with their interactions, and subsequently, dof, SS, MS, square root, F_{dist}, and p are also calculated. The value $R^2 = 95.72\%$ indicates that the model can predict the response with high accuracy. The model indicates significant terms with the help of the value of "Prob>F" if it is less than 0.0500. The regression equation for temperature under dry conditions is as follows:

$$\text{Temperature (dry)} = -395 + 0.0422\ V + 6461\ F + 254\ D - 0.000063\ V \times V - 24557\ F \times F + 222\ D \times D + 0.638\ V \times F + 0.0933\ V \times D - 2280\ F \times D$$

Based on the regression equation as developed through experimental observation, studies are carried out to analyze the effects of the various process variables like speed, feed, and depth of cut on the temperature under dry conditions. In Figure 7, the temperature decreases with a decrease in speed, and the value of temperature decreases with a decrease in feed rate. Thus, the temperature is maximal when the speed is maximal, and the feed is maximal and the temperature is minimal when the speed is minimal and the feed is minimal. The temperature value increases with an increase in the depth of the cut. Thus, the maximal temperature occurs when the depth of cut is maximal, and the temperature value is minimal when the depth of cut is minimal.



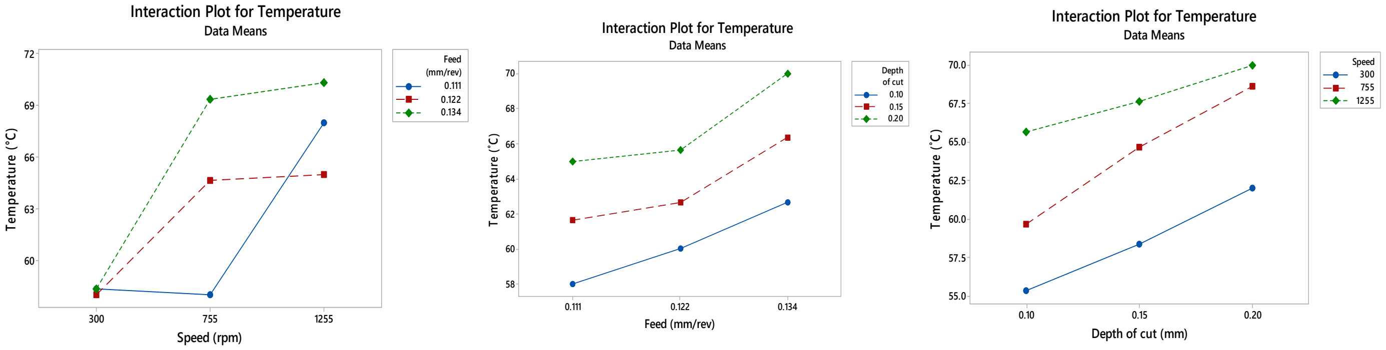
(**a**) (**b**) (**c**)

Figure 7. Interaction plot—(**a**) speed vs. temperature (dry); (**b**) feed vs. temperature (dry); (**c**) depth of cut vs. temperature (dry).

From ANOVA, we obtain what represents the responses of temperature under wet conditions for various process parameters along with their interactions, and subsequently, dof, SS, MS, square root, F_{dist}, and p are also calculated. The value $R^2 = 96.68\%$ indicates that the model can predict the response with high accuracy. The model indicates significant terms with the help of the value of “Prob>F” if it is less than 0.0500.

$$\text{Temperature (wet)} = 140 + 0.0200\ V - 1808\ F + 66\ D - 0.000006\ V \times V + 8052\ F \times F - 0\ D \times D + 0.024\ V \times F - 0.0256\ V \times D + 164\ F \times D$$

Based on the regression equation as developed through experimental observation, studies are carried out to analyze the effects of the various process parameters on the temperature under wet conditions. In Figure 8, the temperature decreases with a decrease in speed, and the value of temperature decreases with a decrease in feed rate. Thus, the temperature is maximal when the speed is maximal, and the feed is maximal and the temperature is minimal when the speed is minimal and the feed is minimal. The temperature value increases with an increase in the depth of the cut. Thus, the maximal temperature occurs when the depth of the cut is maximal, and the temperature value is minimal when the depth of the cut is minimal.



(**a**) (**b**) (**c**)

Figure 8. Interaction plot—(**a**) speed vs. temperature (wet); (**b**) feed vs. temperature (wet); (**c**) depth of cut vs. temperature (wet).

4. Process Optimization of AISI 304

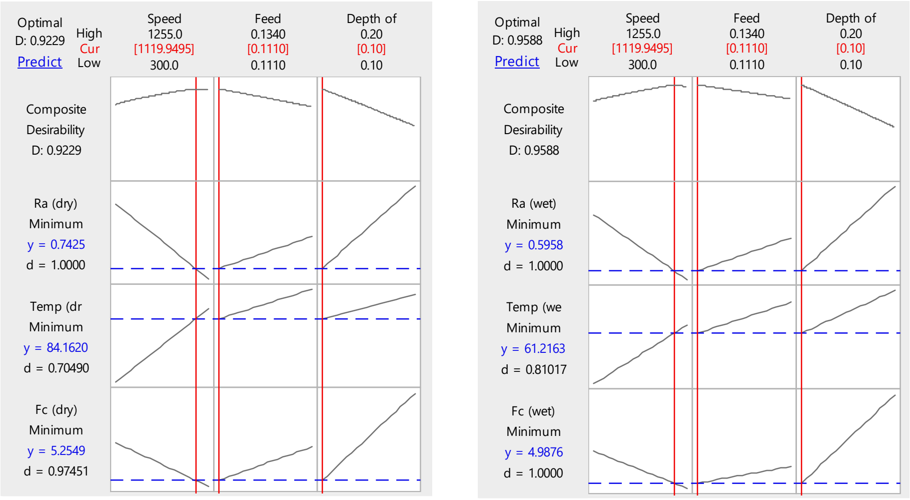
The optimization is performed, and the conditions for optimization are minimum cutting force, minimum cutting temperature, and minimum surface roughness. The following are the input parameters (Table 5) obtained from the software model, which is shown in Figure 9. The obtained optimal combination of factors produces low cutting force, good surface finish, and low cutting temperature. Also, from Table 6, it is observed that the use of corn oil in wet turning produces good results in comparison with dry turning, and it can be substituted for cutting fluids in the case of traditional manufacturing.

Table 5. Optimized input parameters.

Material	Speed (rpm)	Feed (mm/rev)	Depth of Cut (mm)
AISI 304	1120	0.111	0.1

Table 6. Comparison of dry and wet (mist) turning.

Condition	Cutting Force (Kgf)	Temperature (°C)	Surface Roughness (µm)
Dry	5.254	84.16	0.7425
Wet	4.987	61.21	0.5958



(**a**) (**b**)

Figure 9. Optimized parameters for (**a**) dry and (**b**) wet conditions.

5. Conclusions

In this study, the experiment is conducted by considering the three process parameters, namely speed, feed, and depth of cut. The objective is to compare and optimize the cutting force, temperature, and surface roughness obtained under dry and wet turning. The following conclusions are drawn:

- The surface roughness of the component under wet turning is slightly less in comparison with dry turning.
- The cutting temperature was controlled very well in wet turning than dry turning.
- The cutting force developed during dry turning is reduced by applying a mist of oil, which lubricates the surface, thereby reducing the cutting force.
- Corn oil yields superior effects as it forms a very thin protective layer between the workpiece and tool when it is supplied in the form of an aerosol, thus reducing the friction between them to yield good process responses. Consequently, it can be utilized as a substitute cutting fluid for traditional manufacturing.
- The optimized input parameters are speed: 1120 rpm, feed: 0.111 mm/rev, and depth of cut: 0.1 mm.

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Institutional Review Board Statement: Not applicable.

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Conflicts of Interest: The author declares no conflict of interest.

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