Applying multi-response optimization for sustainable machining of 316 stainless steel with coconut oil assisted minimum quantity lubrication

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Abstract

Environmental machining was investigated using coconut oil and minimal quantity lubrication (MQL) in the turning of AISI 316 stainless steel. The turning parameters and MQL flow rate were optimized using ANOM and ANOVA in multi-response analysis to produce the best hardness and minimum surface roughness in the machined surface of AISI 316 stainless steel. The feed, speed, depth of cut, and MQL flow rate during turning were used as the input parameters and surface roughness and hardness as the output parameters. The experimental plan was developed using Taguchi's L9 orthogonal array. It was found that minimum surface roughness (Ra: 1.12 μm and Rz: 6.37 μm) was achieved at a cutting speed of 120 m/min, feed rate between 0.25 to 0.3 mm/rev, the depth of cut between 1.0 to 1.5 mm and a MQL flow rate of 90 ml/hr. Micro hardness was measured from the machined surface to a depth of 1.075 mm to determine the machining affected zone (MAZ). It has been noted that the hardness reduced with an increase in machined surface depth. The MQL with coconut oil was shown to be an ecofriendly lubrication method for machining difficult-to-cut materials like stainless steel and keeping good surface integrity.

Keywords

Austenitic stainless steel, Machining, Surface roughness, Surface hardness, MQL, Multi-response optimization, Coconut oil

1. Introduction

The main goal of the machining industry is to increase production and enhance surface quality while lowering production cost. Owing to high tensile strength, limited heat conductivity, and significant strain hardening, austenitic stainless steel is regarded as one of the hardest alloy to work with and machine [1]. However, the austenitic stainless steel, despite its challenges in machining, offers a wide range of applications in several industries including marine, dairy, chemical processing and power plants to name a few due to its excellent corrosion and oxidation resistance and superior mechanical properties [2]. As a result, the austenitic stainless steel is one of the most extensively used grades, accounting for up to 70% of global stainless steel consumption [3]. Surface characteristics of the work piece, such as surface finish, hardness, corrosion resistance, fatigue strength, aesthetic appeal, and so on, are the important indicators of quality of machined components. Feed, cutting speed, effective rake angle, and nose radius, as well as the kind and manner of coolant supply, are also considered significant contributing parameters in machining that impact the surface finish [4, 5]. With appropriate selection of the machining parameters, optimum surface characteristics can be achieved. The formation of built-up edges through bonding of chips at the cutting edge at low speeds during turning of stainless steel can result in rougher surfaces, whereas higher cutting speed enhances the surface finish by eliminating bonding of chips because the chip and the tool have shorter contact time [6]. As a result, cutting speed has a significant impact on machined surface roughness [7]. Although tool nose radius and feed rate appear to be the most important parameters for surface finish during turning of austenitic stainless steel, two-factor interactions between feed rate and cutting speed, or depth of cut and cutting speed, seem to have major implications [5, 8]. It is also worth mentioning that as the feed increases, so does the radial force, causing a greater friction between the freshly created surface and the flank face, resulting in an increased surface roughness [9]. The friction between the tool rake face and the chip raises the cutting zone temperature, causing the cutting tool to deform, wear, and fail. Cooling while machining is critical for achieving efficient and effective machining [10]. The choice of appropriate coolants and cooling conditions help in increasing tool life as well as improving surface properties of the machined components. Traditional flood cooling with cutting fluids such as mineral, synthetic, and semi-synthetic has a number of negative consequences, including contamination of surface and ground water, air, soil, and agricultural products/food. Furthermore, persons who are exposed to cutting fluid on a regular basis for an extended length of time may develop major health concerns such as lung cancer, respiratory disease, dermatological, and genetic diseases. [11, 12]. As a result, the machining community is under huge pressure to develop alternative ways to reduce or eliminate the detrimental effects of cutting fluids. Metal working fluids (MWFs) are widely utilized and serve vital roles in cutting operations such as improving productivity, tool life, and surface quality while lowering temperature at the tool-workpiece interface. In machining operation, the primary tasks of MWFs are to provide lubrication and facilitate removing chips from the cutting zone. They may also have supplementary roles, such as limiting resistance to oxidation and corrosion [13]

Green manufacturing is becoming more popular in the manufacturing industry as environmental and worker health concerns are continuously growing. Green production improves operator working conditions by making the best use of the cutting fluid. Many researchers [14, 15] investigated the dry cutting, machining with a coated tool, MQL, and cryogenic cooling techniques. MQL offers cost-effective and environmentally favorable approach that improves machining efficiency and surface quality while also in some situations MQL has been shown to outperform better than dry and coolant-assisted turning processes. In MQL, cutting fluid droplets are mixed with compressed air to form a mist or aerosol, which is then sprayed directly in the contact zone using an air atomizing nozzle [16]. More recently, using vegetable-based cutting fluids (VBCFs) in combination with minimal quantity lubrication (MQL) and near-dry cutting have shown the potential towards sustainable machining as CFs are used infrequently and in small quantity in MQL [17]. Furthermore, the detrimental effects of the mineral oil based synthetic coolants on the environment should be avoided in order to keep a machining process as clean as possible, which necessitates the development of more and more bio-based and biodegradable cutting fluids [18]. Researchers are developing highly efficient new cutting fluids for MQL applications, such as biodegradable oils or chlorine-free mineral oils. Environmental hazards of the traditional lubricants can be reduced by the new generation of cutting fluids along with other benefits such as improving machining efficiency [19]. Adding nano-sized metallic, non-metallic, or nano-fiber particles to MQL base oil enhances thermal conductivity and decreases cutting temperature [20, 21]. According to Amrita Pal et al. [22], the nano fluid MQL technology improves machining efficiency by resolving heat exchange ability in the cutting zone. Muhammad and Mehmood [23] tested Inconel 718 turning in MQL mode with castor and sunflower oils as cutting fluids and compared the results with dry turning. They revealed that mixing MQL with sunflower oil improved the surface finish due to its viscosity, wetting capabilities and increased strain hardened layer. Therefore, the best way to improve MQL operation is to use a good combination of oil base and nano-additives. Recently, interest has been shifted towards using biodegradable vegetable oils in machining due to its higher viscosity index, higher flash point, fewer health risks, lower toxicity, lower disposal cost. Revuru et al. [24] reported that as compared to dry and flood circumstances, vegetable-based soybean oil in MQL performs better in terms of machining characteristics. Pereira et al. [25] evaluated the tool life of an end mill cutter while milling 718 under MQL conditions using various vegetable oils. The results show that using high oleic sunflower oil is not only a feasible alternative for progressing toward a more ecofriendly machining process, but also it significantly improves the machining processes when compared to commonly used industrial canola oils.

Using coconut oil to turn Inconel 718 and AISI 304 in MQL mode, Wickramasinghe et al. [26] investigated the temperature at the work piece tool interface and cutting forces. Cutting forces and temperatures at the work-piece tool interface were found to be lower. The size of vegetable oil molecules is more consistent than that of mineral oil molecules, thus properties like viscosity and boiling temperature are more stable in vegetable oil[27]. Vegetable oils stay more fluid when the temperature drops, allowing for faster chip drainage from the machining zone. When turning AISI D2 steel under MQL cooling conditions, Sharma et al. [28] employed vegetable oil as a coolant. Considerable improvements in turning process performance characteristics were found in MQL conditions due to a significant drop in machining zone temperature when compared to dry machining conditions. Sivaiah and Chakradhar [29] carried out turning studies on 17-4 PH SS in MQL, wet, as well as dry machining conditions and found that under MQL environment, a significant reduction in surface roughness, tool flank wear at a high material removal rate. Fernando et al. [30] investigated the effectiveness of coconut oil as a metal working fluid in turning of mild steel and austenitic stainless steel (AISI 304). It was observed that coconut oil improved the surface quality of mild steel. Vegetable oil outperforms traditional fluids in MQL with various cutting circumstances. Nilesh and Dattaraya [31] studied the hazardous effects of vegetable oil cutting fluids by comparing dry, flood, and MQL cutting. It was concluded that MQL is a far superior method of applying cutting fluid and poses less health risks. Sivaiah [32] evaluated turning performance under MQL cooling by varying process parameters. They observed that the mathematical models constructed using the RSM approach accurately predicted performance results. Surface roughness and tool wear were also reduced dramatically as the MQL flow rate was increased.

Khan et al. [33] investigated the effects of MQL on turning AISI 9310 alloy steel with a vegetable oil-based cutting fluid and concluded that the significant decrease in chip–tool interface temperature, the elimination of traces of built-up edge formation, and an enhancement in surface finish owing to the less wear and damage at the cutting tool tip.

The preceding discussion clearly demonstrates that there is limited information available on using coconut oil as the cutting fluid in MQL turning of stainless steel. Therefore, further investigation into the performance of pure coconut oil under the MQL system are needed in order to determine its impact on the machined surface. As a result, in this study, coconut oil was employed as a green cutting fluid in MQL turning of AISI 316 austenitic stainless steel without the inclusion of any additives. The main aim of this study is to use RSM as a design of experiment approach to investigate the influence of varied cutting parameters (speed, feed, and depth of cut) and different MQL discharge rates on surface roughness and surface hardness of the turned workpiece. To discover the optimum levels of parameters and their importance on the observed responses, Taguchi's L_9 orthogonal array was used to arrange the experiments; Taguchi methods, Factorial design, and Response Surface Methodology (RSM) are common design of experiments approaches used for valid objective conclusions and process parameter optimization [34]. Analysis of Means (ANOM), Analysis of Variance (ANOVA), Main effect plots, Signal to Noise ratio (S/N), and 3D surface plots will be utilized. Finally, the linear regression equation will be used to describe correlation equations.

2. Methodology

2.1. Materials

A round bar of Austenitic Stainless Steel AISI 316 with dimensions of 360 mm in length and 30 mm in diameter was selected as the work piece material. The chemical composition, physical and mechanical properties of the AISI 316 steel material are shown Table 1 and Table 2 respectively.

Table 1. Elemental concentrations (wt.%) in austenitic stainless steel (AISI 316)

Elements	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Co	V	Fe
Wt. (%)	0.056	0.35	1.02	0.02	0.012	17.01	10.8	2.02	0.6	0.10	0.015	67.97

Table 2. Physical and Mechanical properties of austenitic stainless steel (AISI 316)

Property	**Value**
Density(g/cm³)	8.0
Hardness (HB)	156±8
Poisson’s Ratio	0.26
Yield strength (MPa)	295
Modulus of Elasticity (GPa)	196
Tensile strength (MPa)	586
Elongation at break	50.34%

2.2. Experimental plan

In the present experimental study, four machining parameters (cutting speed, feed, depth of cut, and MQL discharge rates) with three levels were considered. The values at different levels were selected from the cutting tool manufacturer's handbook. The details of MQL parameters, machining parameters and their levels are listed in Table 3 and Table 4 respectively.

Table 3. MQL Parameters used during the cutting tests

MQL fluid	Pure Coconut Oil
Air pressure (MPa)	0.6
MQL oil flow rate (ml/h)	30, 60, 90
Discharge rate from the pump (cc/stroke)	40
Nozzle standoff distance (mm)	50

Table 4. Control factor values at different levels.

Code	**Control Factor**	**Level**		
		1	2	3
Vc	Cutting speed (m/min)	120	150	180
f	Feed rate (mm/rev)	0.20	0.25	0.30
ap	Depth of Cut (mm)	0.5	1.0	1.5
Q	MQL flow rate (ml/h)	30	60	90

Using Taguchi L_9 (4^3) standard orthogonal array, the nine experimental trails of turning process were performed and details of process data are shown in Table 5. The objective function in this optimization technique was based on the "signal to noise (S/N) ratio," which was subjected to noise factor constraints utilizing orthogonal matrices [35,36]. Under the noise considerations, the Taguchi approach provides the expected best performance. The objective function could be "smaller the better," "bigger the better," or "nominal the best" depending on the nature of the variable.

Table 5. Taguchi L_9 standard orthogonal array and experimental data.

Trail No.	**Cutting Speed Vc**	**Feed rate f**	**Depth of Cut ap**	**MQL Q**
01	1	1	1	1
02	1	2	2	2
03	1	3	3	3
04	2	1	2	3
05	2	2	3	1
06	2	3	1	2
07	3	1	3	2
08	3	2	1	3
09	3	3	2	1

In this study, the smaller the better ratio (in dB) was used for obtaining the optimal conditions to achieve a minimum surface roughness (R_a and R_z values) as defined by Equation 1 and Equation 2.

$$\eta_1 = -10\log10\,({R_a}^2) \quad (1)$$

$$\eta_2 = -10\log10\,({R_z}^2) \quad (2)$$

Whereas, larger, the better criterion was used for the surface hardness to achieve maximum hardness in the turned components as defined by Equation 3.

$$\eta_3 = -10\log10\,(H^{-2}) \quad (3)$$

2.3. Experimental set-up and characterization

Orthogonal turning studies were carried out on a CNC lathe (Ace Turn Mill Fanuc-LT-2XLMMC) with maximum spindle speed limit of 4000 rpm and a 'GCLNR 2020MK12' tool holder. Coated carbide inserts with chip breaker (ISO geometry-CNMG 120416) were employed throughout the studies. For heat resistance and low coefficient of friction during machining, TiN coating was applied on the inserts using a moderate-temperature chemical vapour deposition (MT CVD) process. The entire series of tests was carried out in an MQL setting with coconut oil [37, 38]. Straight turning trials were carried out on the specimens with a length of 30 mm for each of the four characteristics with three levels according to the Taguchi orthogonal array.

Surface roughness was measured using a (Mitutoyo Surf test type SJ-201P) portable surface roughness device. Each measurement was taken with a cutoff length of 0.8 mm with an average of five values. The maximum distance between peak and valley of the roughness profile (Rz) within the cut off length was considered as the maximum surface roughness and average surface roughness (Ra) was calculated by taking an arithmetic mean of all absolute distances from the centre line to the roughness profile within the cut off length. To determine the surface microhardness (μHV), each specimen was first sliced crosswise using a wire cutting machine at a radial distance of 5 mm from the turned surface, and then mounted with acrylic resin. The surface hardness of the wire cut specimens was assessed by taking an average of three measurements using Vickers hardness tester (Technosys, 0.2-5.0 kg) by applying a weight of 0.3 kg from the surface to different depths into the specimens across the length and around the perimeter. The effect of surface alterations generated by the turning process was presented using the hardness value. The experimental work procedure followed in this study is depicted in Figure 1.

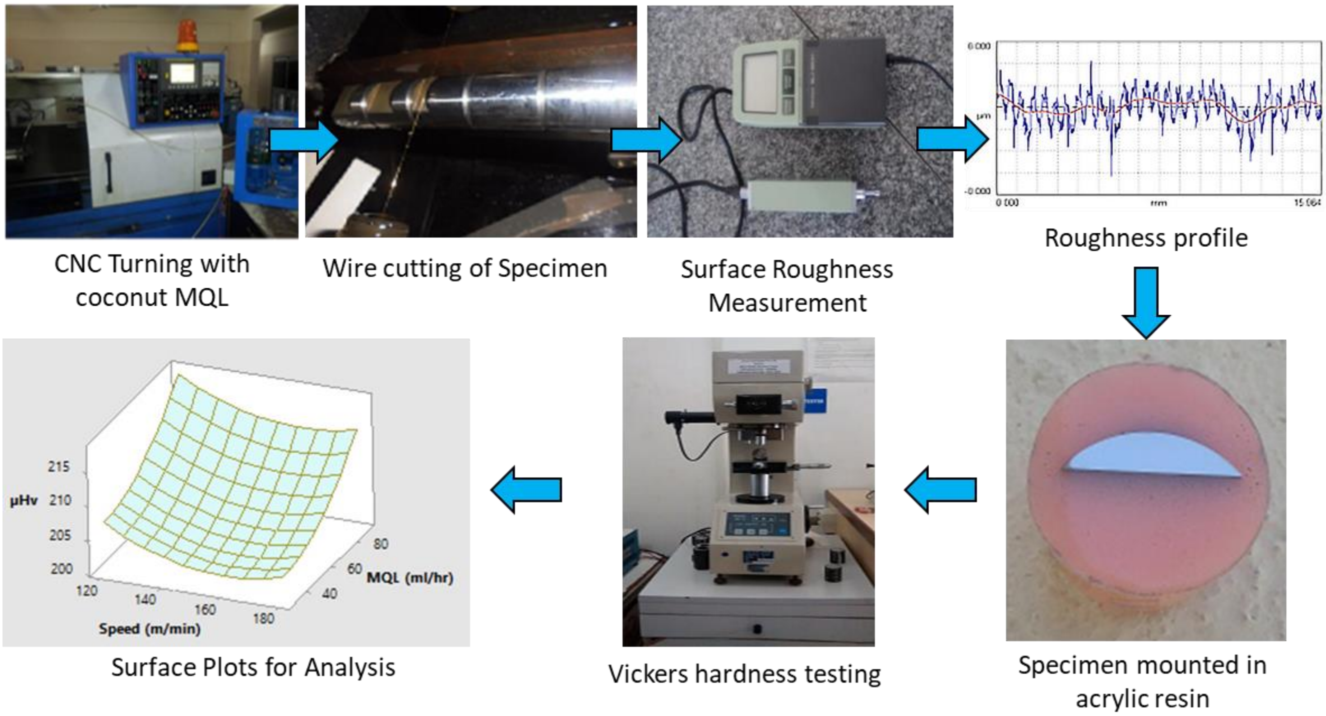


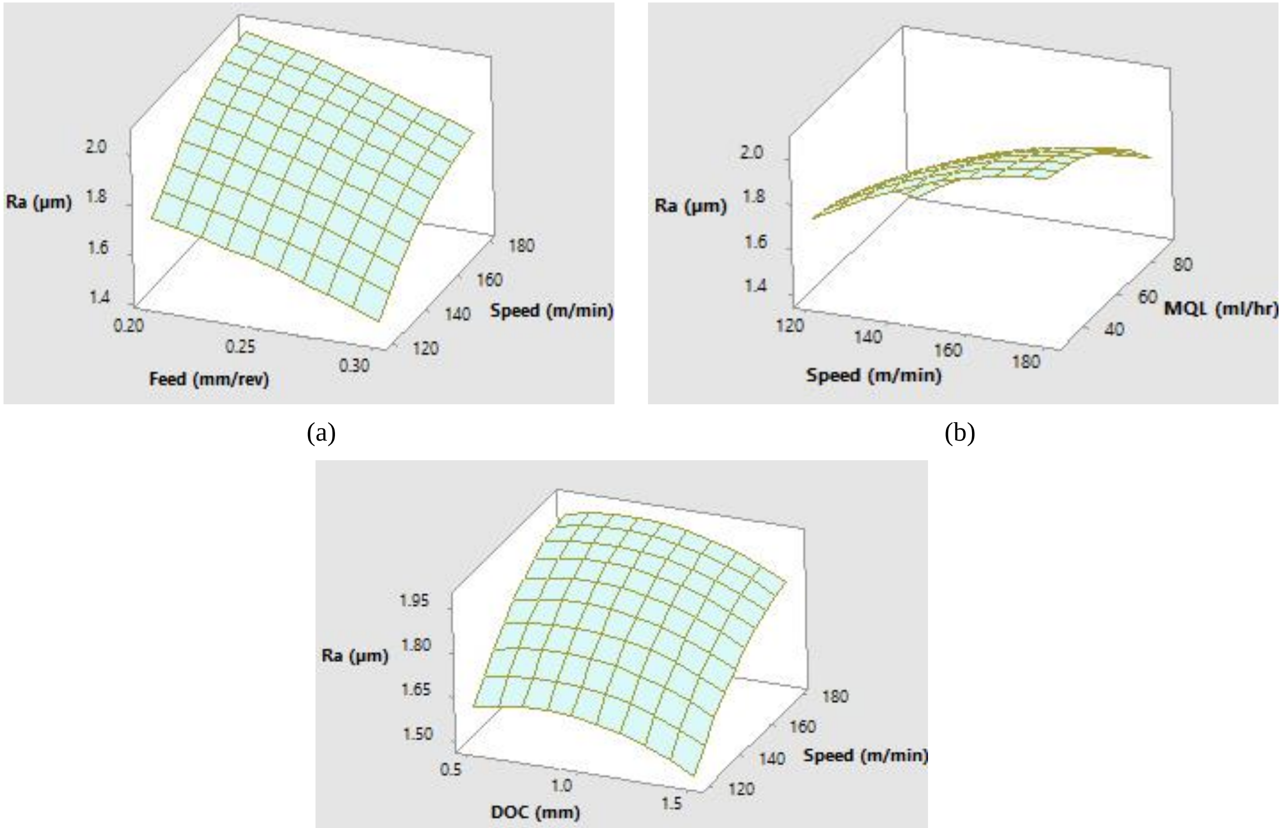
Figure 1. Basic workflow of experimentation work.

3. Results and Discussion

Surface roughness is one of the key characteristics of part quality in the turning process and a reliable indicator of the potential performance of a mechanical component. Good surface roughness improves tribological properties, fatigue strength, corrosion resistance and aesthetics. In tribology, rough surfaces often wear out faster and can have higher coefficients of friction than smooth surfaces. It is essential that these qualities are conveyed primarily through the metalworking processes to which the components have been subjected. As a result, most cutting operations damage surface integrity by imparting roughness and microcracks to the surface and creating residual tensile stresses.

3.1. Surface roughness and hardness analysis.

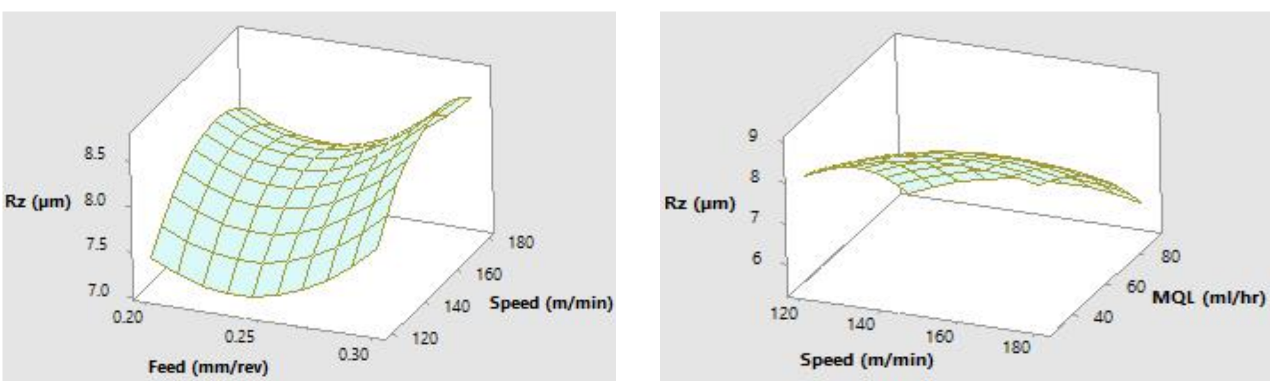
Surface roughness of components after machining is one of the most important parameters to consider throughout their engineering applications. In the turning process, the cutting parameter settings and cooling conditions have a great impact on the surface roughness and microhardness. The 3D surface plots obtained by RSM using Minitab 16 software are shown in Figure 2, Figure 3, and Figure 4.



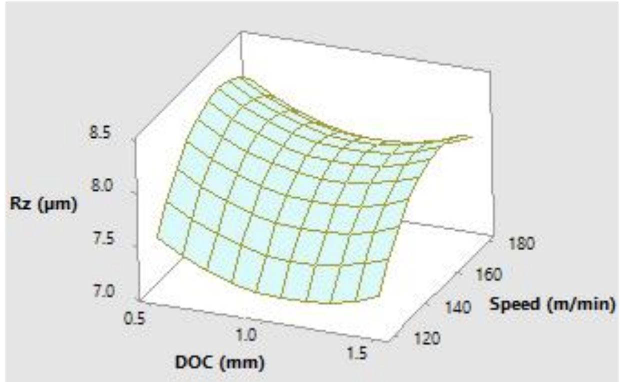
(a) (b)

(c)

Figure 2. 3D Response surface plots for R_a with varying (a) cutting speed and feed (b) cutting speed and MQL and (c) cutting speed and depth of cut.

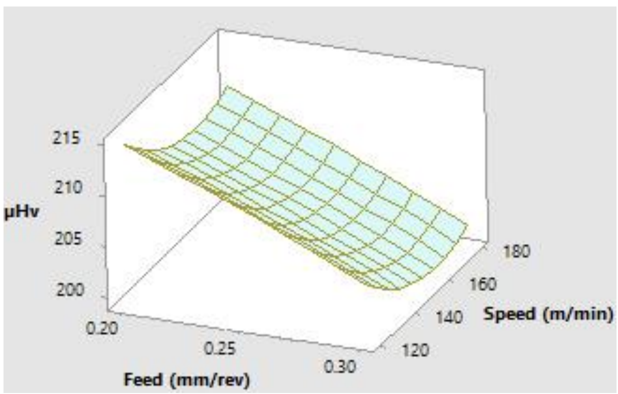


(a) (b)

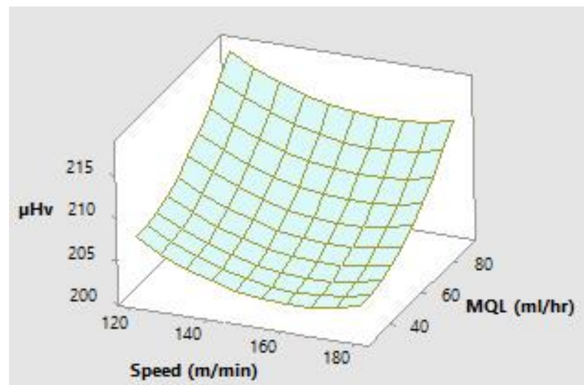


(c)

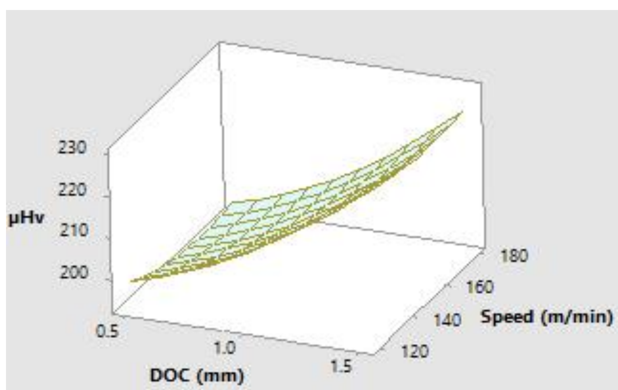
Figure 3. 3D Response surface plots for R_z with varying (a) cutting speed and feed, (b) cutting speed and MQL and (c) cutting speed and depth of cut.



(a)



(b)



(c)

Figure 4. 3D Response surface plots for microhardness (µHV) with varying (a) cutting speed and feed, (b) cutting speed and MQL and (c) cutting speed and depth of cut.

The influence of each level of cutting parameters and MQL discharge rate on the surface roughness and hardness was determined using the signal to noise (S/N) ratio. The measured values of surface roughness and hardness, as well as the associated S/N ratios, are reported in Table 5.

Table 5. Orthogonal Array (L9) measured responses and corresponding S/N ratios.

Trail No	Speed	Feed	DOC	MQL	R_a	R_z	μHv	S/N Ratio for R_a	S/N Ratio for R_z	S/N Ratio for μHv
01	120	0.2	0.5	30	1.813	8.688	201	-5.16796	-18.7784	46.0639
02	120	0.25	1.0	60	1.622	7.165	210	-4.20102	-17.1043	46.4444
03	120	0.3	1.5	90	1.101	6.299	232	-0.83575	-15.9854	47.3098
04	150	0.2	1.0	90	1.731	6.399	218	-4.76594	-16.1222	46.7691
05	150	0.25	1.5	30	1.832	9.021	222	-5.25851	-19.1051	46.9271
06	150	0.3	0.5	60	1.701	9.041	189	-4.61409	-19.1243	45.8893
07	180	0.2	1.5	60	1.941	8.155	230	-5.76051	-18.2285	47.6763
08	180	0.25	0.5	90	1.709	6.391	203	-4.65484	-16.1114	46.0639
09	180	0.3	1.0	30	1.912	9.425	198	-5.62976	-19.4856	45.9333

Table 6 presents highest and minimum S/N ratio values (Delta), and main effect plots for S/N ratios at different levels. A1B3C3D3, which had a 120 m/min cutting speed, 0.3 mm/rev. feed, 1.5 mm depth of cut, and 90 ml/hr MQL discharge rate, were found to be the best cutting parameters for minimum surface roughness value of R_a. Similarly, the best cutting parameters for R_z were identified to be A1B2C2D3, which had 120m/min cutting speed, 0.25mm/rev. feed, 1.0 mm depth of cut, and 90 ml/hr MQL discharge. The ideal cutting and MQL discharge parameters for maximum surface hardness were identified as A1B1C3D3, which are 120 m/min cutting speed, 0.2 mm/rev. feed, 1.5mm depth of cut, and 90 ml/hr MQL discharge rate.

Table 6. Responses table for S/N ratios and means.

Factors	Surface Roughness (Ra)				Surface Roughness (Rz)				Surface hardness (HV)			
	Level1	Level2	Level3	Delta	Level1	Level2	Level3	Delta	Level1	Level2	Level3	Delta
	S/N ratio (dB)											
Vc	-3.402	-4.880	-5.348	1.947	-17.29	-18.12	-17.94	0.83	46.61	46.41	46.44	0.20
f	-5.231	-4.705	-3.693	1.538	-17.71	-17.44	-18.20	0.76	46.69	46.51	46.26	0.43
ap	-4.812	-4.866	-3.952	0.914	-18.00	-17.57	-17.77	0.43	45.91	46.38	47.16	1.24
Q	-5.352	-4.859	-3.419	1.933	-19.12	-18.15	-16.07	3.05	46.31	46.40	46.74	0.43
	Means											
Vc	**1.512**	1.755	1.854	0.342	**7.384**	8.154	7.990	0.770	**214.3**	209.7	210.3	4.7
f	1.828	1.721	**1.571**	0.257	7.747	**7.526**	8.255	0.729	**216.3**	211.7	206.3	10.0
ap	1.741	1.755	**1.625**	0.130	8.040	**7.663**	7.825	0.377	197.7	208.7	**228.0**	30.3
Q	1.852	1.755	**1.514**	0.339	9.045	8.120	**6.363**	2.682	207.0	209.7	**217.7**	10.7

The influence of speed and feed on the R_a value is shown in the 3D surface plot (Figure 2a) and the major effect plot in Figure 5. The surface roughness reduced as the feed was increased. The highest surface roughness was obtained at a cutting speed of 150 m/min, which could be related to the existence of chatter at higher speeds and the variability in cutting force [7, 39]. However, as greater lubrication reduced friction at the chip tool interface and increased the cooling effect at the work tool interface, the Ra value dropped rapidly at maximum MQL discharge rate with minimal cutting speed (Figure 2b). The reduced surface roughness value of R_a with the interaction of lower cutting speed and larger depth of cut is shown in Figure 2(c) and Figure 5(b). This could be due to the fact that an increasing depth of cut increased the heat at the cutting zone, which softened the work material and reduced the surface roughness.

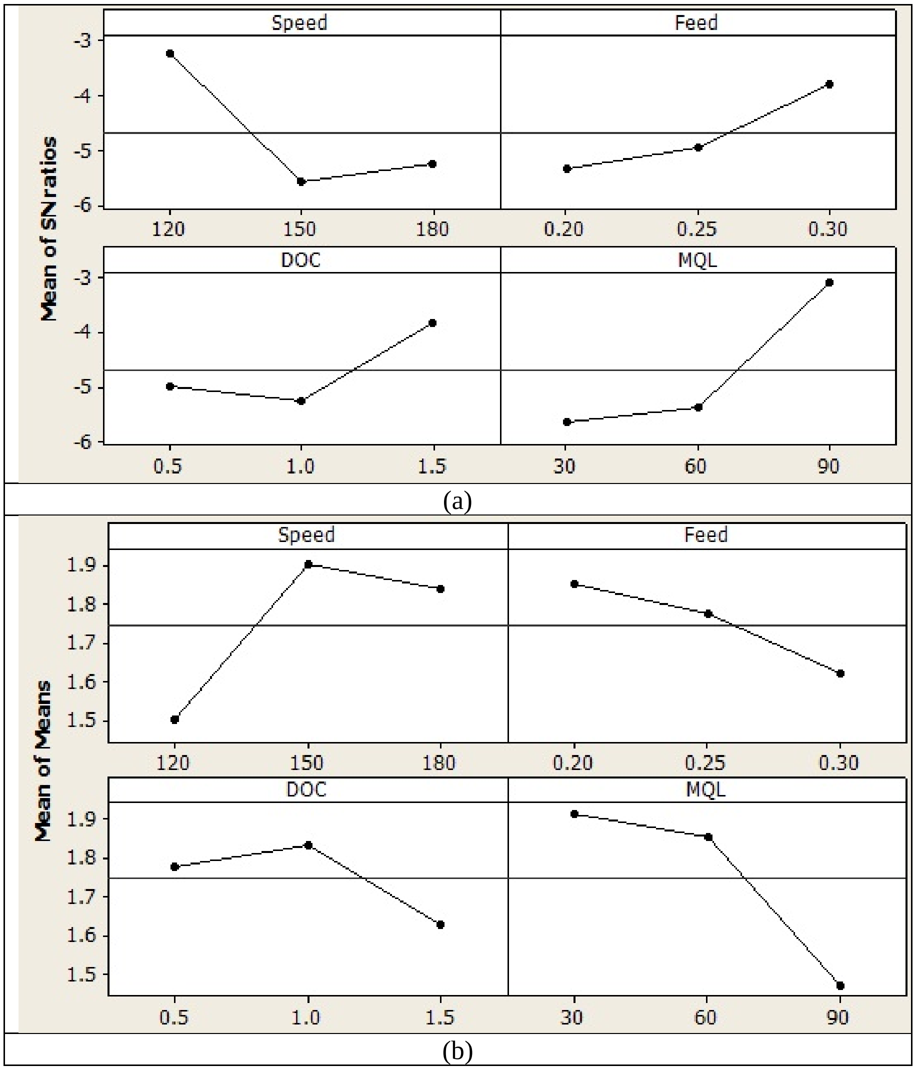


Figure 5. Plots of main effect: (a) Mean of S/N ratio for Ra and (b) Influence of control factors on Ra

The influence of factors on the R_z value of surface roughness is shown in Figure 6. It was noticed that that as speed increased, the R_z value increased, but with further increase in the speed, the R_z value decreased. It could be attributed to a reduction in cutting forces at high speeds, especially in hard turning, which aids in machining system stability. Furthermore, when the feed rate increased, R_z value decreased, and with further increase in the feed rate, R_z value increased, possibly due to an increased vibration at the cutting zone. Due to a reduced friction and a significant cooling effect at the cutting zone, the MQL's highest discharge rate produced the least surface roughness. Changes in depth of cut had a minor impact on R_z. Using the 3D surface plots given in Figure 3, the interactive influence of the parameters on R_z may be investigated. When the lowest speed and highest feed were combined, the R_z value was the smallest (Figure 3a). In contrast, the finest surface roughness value of R_z was observed in Figure 3(b) at the lowest speed and highest MQL discharge rate.

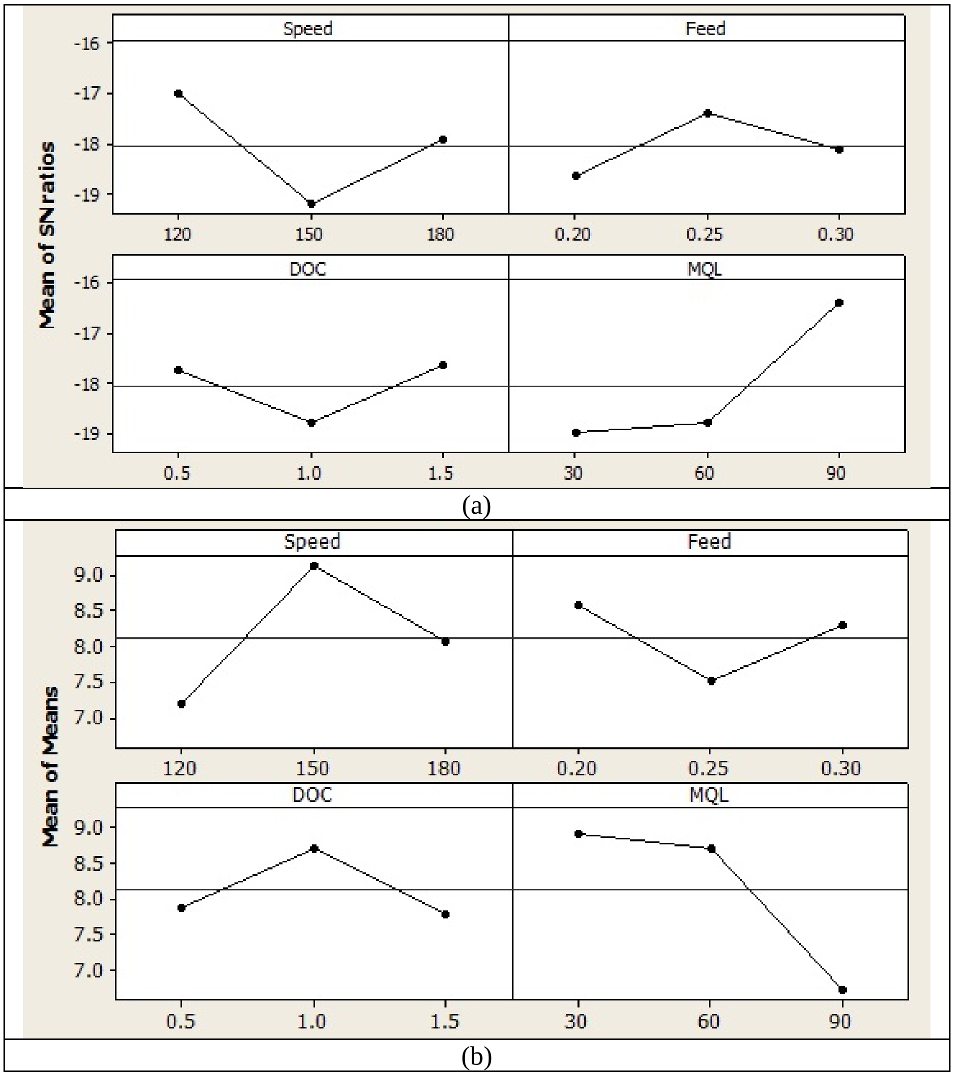


Figure 6. Plots of main effect: (a) Mean of S/N ratio for R_z (b) Influence of control factors on R_z

The influence of factors on the hardness value is seen in Figure 7. The change in surface hardness with speed was found to be insignificant. However, depth of cut had a considerable impact on the surface hardness as it caused severe shear deformation in the machined surface [40]. At the highest depth of cut, the highest value of hardness was reached. A higher feed rate lowered the hardness value due to increasing work hardening recovery caused by an increased temperature [41]. A slight increase in hardness was observed with the coolant flow but with further increase no change in hardness was observed. Figure 4 shows the interactive influence of various parameters on the hardness value using 3D surface plots for the surface hardness parameter. Maximum surface hardness was attained at the minimum feed rate with maximum cutting speed (Figure 4a) or by combining a low cutting speed with a high MQL discharge rate (Figure 4b). On the other hand, the surface hardness improved as the depth of cut increased, while cutting speed showed no effect (Figure 4c).

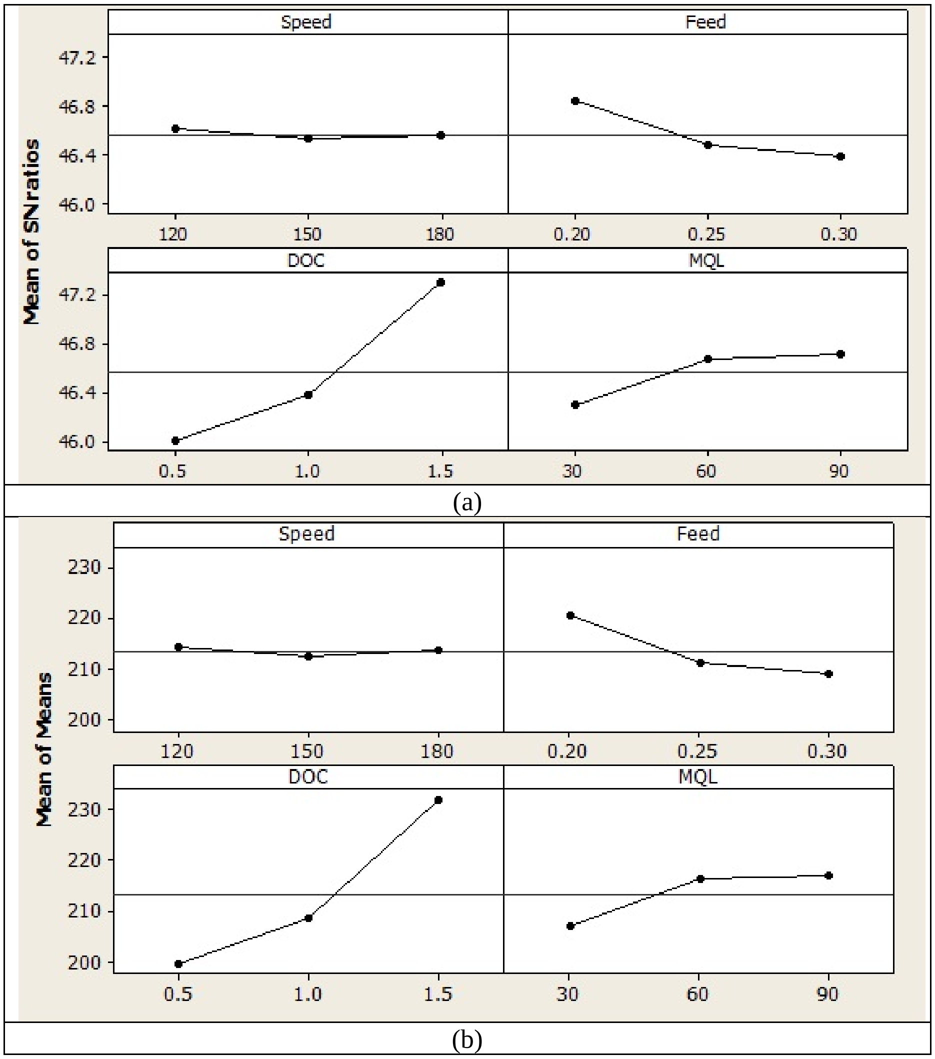


Figure 7. Plots of main effect: (a) Mean of S/N ratio for µHv (b) Influence of control factors on µHv.

3.2. Variance Analysis (ANOVA).

Analysis of variance (ANOVA) can be performed to investigate the impact of various cutting and cooling settings on the desired responses. The chosen experiment design was evaluated at a 95% confidence level. Table 7 shows the ANOVA findings for all surface quality variables investigated in this study, namely R_a, R_z, and µHv. Significance of each parameter is shown by its P-value, and the table also shows the percentage contribution of each parameter. The parameters with a significance level of less than 0.05 (5% significance) have a substantial impact on the desired responses of the quality attributes.

Cutting speed, feed, and MQL discharge rate are important determinants for the R_a value according to the ANOVA results. With percentage contributions of 35.18 % and 34.50 %, respectively, the cutting speed and MQL discharge rates contributed almost the same. The feed rate, on the other hand, contributed by 19.86%. MQL discharge rate was found to be the most significantly impacting parameter for the R_z value accounting for 81.8%, while the other parameters were found to be not important. When it came to surface hardness, the depth of cut appeared to be the most important factor, accounting for 77.18%. The contributions from the MQL discharge rate and feed rate by 8.39% and 9.55% respectively, were identified as the additional variables that influence the hardness. According to the ANOVA results, cutting speed, feed, and MQL discharge rate were found to be the major variables that influenced the R_a. Cutting speed and MQL discharge rates contributed nearly the same percentages of 35.18 % and 34.50 %, respectively in contrast to the feed rate contribution of 19.86%. The MQL discharge rate showed the greatest impact on the R_z value, accounting for 81.8%, while the other factors were found to be insignificant. The highly significant factor affecting the surface hardness was the depth of cut, which accounted for 77.18 %. The additional variables that determine the hardness included the MQL discharge rate and feed rate, which influenced by 8.39 % and 9.55 %, respectively.

Table 7. Analysis of Variance (ANOVA) for Responses.

Source	DF	SS	MS	F	P	Significance level	Contribution (%)
Surface Roughness Ra							
Vc	1	0.175446	0.175446	22.03	0.009	Significant	35.18
F	1	0.099074	0.099074	12.44	0.024	Significant	19.86
Ap	1	0.020300	0.020300	2.55	0.186	Insignificant	4.07
Q	1	0.172043	0.172043	21.60	0.010	Significant	34.50
Error	4	0.031857	0.007964				6.39
Total	8	0.498719					100
Surface Roughness Rz							
Vc	1	0.5515	0.5515	1.60	0.275	Insignificant	4.19
F	1	0.3866	0.3866	1.12	0.349	Insignificant	2.93
Ap	1	0.0693	0.0693	0.20	0.677	Insignificant	0.53
Q	1	10.7870	10.7870	31.27	0.005	Significant	81.88
Error	4	1.3797	0.3449				10.47
Total	8	13.1740					100
Surface Hardness μHv							
Vc	1	24.00	24.00	1.51	0.286	Insignificant	1.34
F	1	150.00	150.00	9.47	0.037	Significant	8.39
Ap	1	1380.17	1380.17	87.09	0.001	Significant	77.18
Q	1	170.67	170.67	10.77	0.030	Significant	9.55
Error	4	63.39	15.85				3.54

Total	8	1788.22	100

3.3. RSM -based models

Using the experimental results in Table 8, linear regression analysis was used to build RSM-based linear mathematical models of surface roughness values (R_a and R_z) and surface hardness (µHv).

Table 8. Summary of ANOVA for RSM based surface roughness and hardness.

Surface Roughness value	Sum of squares		Degree of freedom		Mean square		F-ratio
	Regression	Residual	Regression	Residual	Regression	Residual	
R_a	0.466862	0.031857	4	4	0.116716	0.007964	14.66
R_z	11.7944	1.3797	4	4	2.9486	0.3449	8.55
µHv	1724.83	63.39	4	4	431.21	15.85	27.21

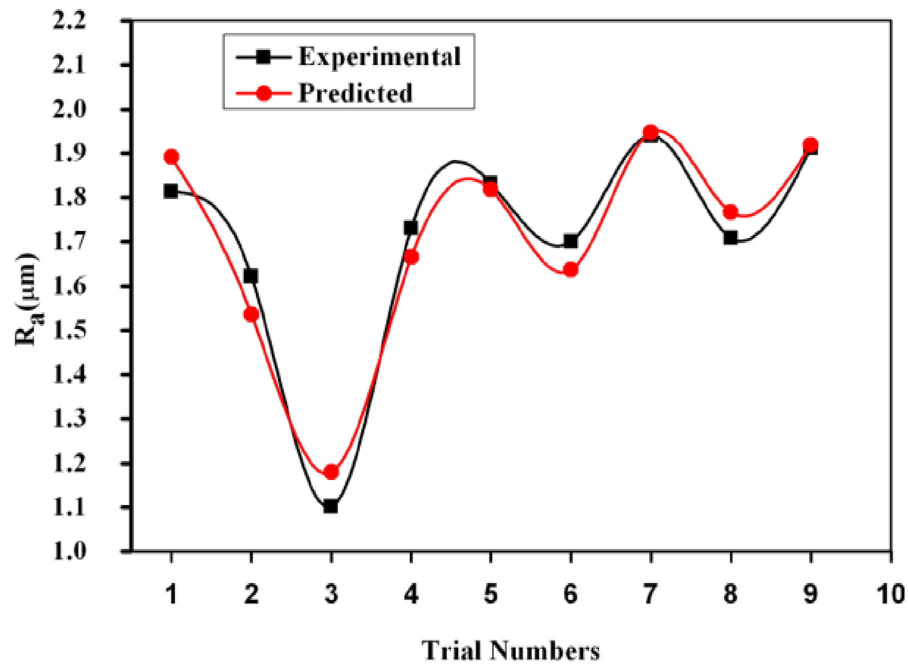
Equation 4, Equation 5, and Equation 6 provide mathematical models for predicting R_a, R_z and µHV values of surface integrity during turning of austenitic stainless steel AISI 316.

$$R_a = 1.94939 + 0.0057Vc - 2.57f - 0.1164ap - 0.005644Q \quad (4)$$

$$R_z = 7.95433 + 0.0101056Vc + 5.07667f - 0.215ap - 0.0446944Q \quad (5)$$

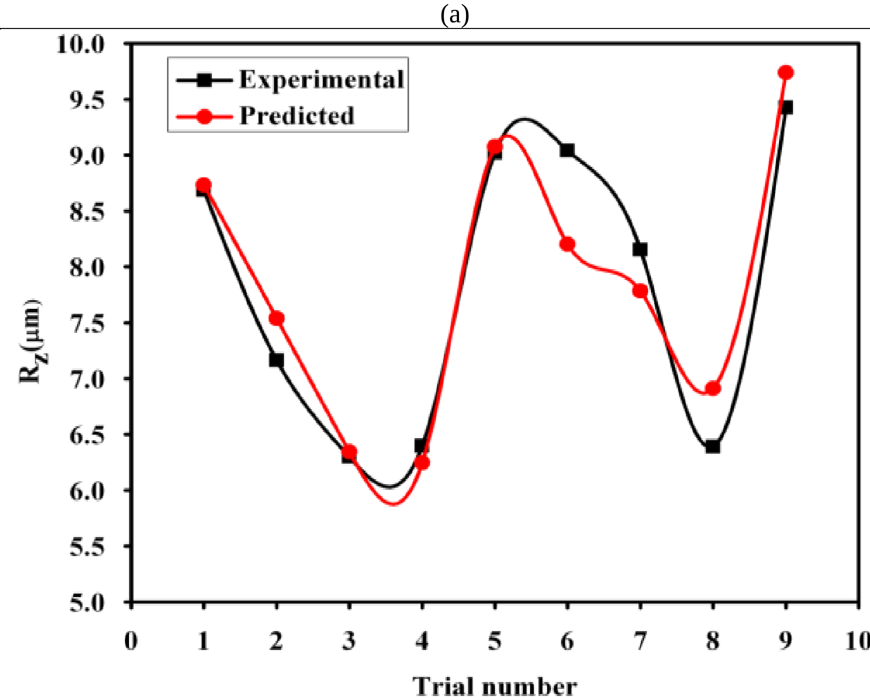
$$\mu Hv = 205.444 - 0.0666667Vc - 100f + 30ap + 0.177778Q \quad (6)$$

The coefficient of determination (R^2) and modified coefficient of determination were also used to assess the models' goodness of fit (R^2adj). The process parameters and their interactions can be used to explain R^2, which is a measure of variability in the observed response. R^2 adj, on the other hand, is the coefficient of determination in a regression model that has been corrected for the number of independent variables. R_a has R^2 and R^2adj values of 0.93 and 0.87, R_z has R^2 and R^2adj values of 0.895 and 0.79, and microhardness has R^2 and R^2adj values of 0.96 and 0.93, demonstrating the importance of the non-linear regression model. The accuracy of the generated model was tested, and the percentage prediction error was calculated. The created models had an average prediction error of 5.99 % for R_a, 3.77 % for R_z, and 1.13 % for microhardness when tested with experimental data from an orthogonal array. Figure 8 shows a comparison between RSM predicted and experimental values for the R_a, R_z, and µHv.



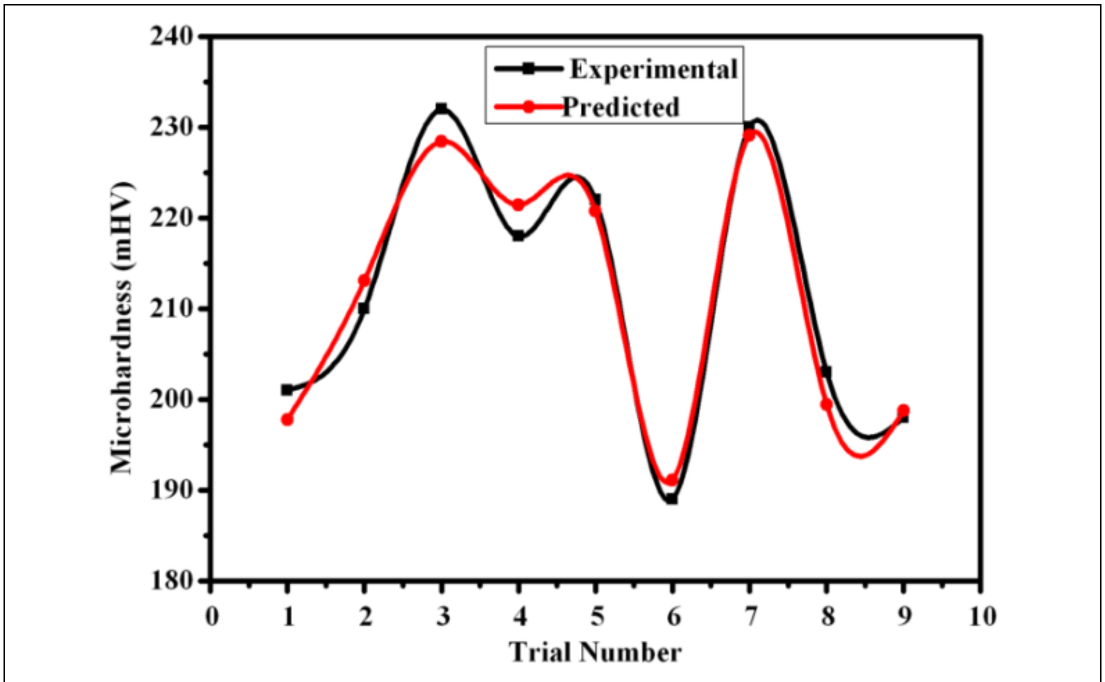
Experimental
Predicted
R_a (μm)
Trial Numbers

(a)



Experimental
Predicted
R_Z (μm)
Trial number

(b)



(c)

Figure 8. Comparison of experimental and RSM predicted values (a) R_a, (b) R_z and (c) µHv.

3.4. Model confirmation test

The validation test results (Table 9) showed that the expected error, (η_{opt}-η_{obs}) was within the confidence interval. With a 0.05 significance level, the Taguchi approach was employed to optimize the surface hardness values under the MQL conditions. Table 10 shows the ideal level of control parameters for maximizing surface roughness. It should be noted that for obtaining the best surface roughness and hardness, highest MQL flow rate (90 ml/hr) was suggested to use.

Table 9. Results of Confirmatory Tests

Performance measures	**R_a**	**R_z**	**µHv**
Levels (Vc, f, ap, Q)	1,3,3,3	1,2,2,3	1, 1, 3, 3
S/N predicted (η_{opt}),dB	-0.83625	-15.025	47.745
Observed value	1.12 µm	6.37µm	227
S/N observed(η_{obs}),dB	-0.98436	-16.0828	47.12
Prediction error, dB	0.14811	1.0578	0.6245
Confidence interval value (CI), dB	±0.233624	±1.537438	±10.42

Table 10. Optimal output response values with input process parameter

Response	Optimal combination of input variables				
	Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	MQL Flow rate (ml/hr)	Optimal value
Surface roughness (R_a, µm)	120	0.3	1.5	90	1.12
Surface roughness (R_z, µm)	120	0.25	1.0	90	6.37
Microhardness (µHv)	120	0.20	1.5	90	227

3.5. Analysis of machining affected zone (MAZ)

In addition to surface quality, machined components should have outstanding subsurface properties for a longer and more dependable service life. As a result, the micro hardness of the machined surface and the depth of the machining affected zone (MAZ) were measured in this study. Using a 0.3 kg indentation force, the surface hardness of the specimens was assessed from the surface along the depth. To avoid edge effect, the sequential indentations in a rotated specimen were differentiated in the circumferential direction. For each specimen, the average of six measurements was considered. The effect of surface change due to machining was determined using the hardness measured along the cross section. A specimen machine with extreme cutting parameters, such as 180 m/min cutting speed, 0.2 mm/rev. feed rate, and 1.5 mm depth of cut, was chosen for selective analysis of the MAZ. The degree of work hardening (DWH) was calculated using Liu and Barash's equation [42] to determine the specimen's work hardening behavior.

$$DWH(\%) = \frac{MH_s - MH_b}{MH_b} \quad (7)$$

Where, MH_s is the microhardness of a machined surface and MH_b is the microhardness of the bulk material. The microhardness profile of the sample collected by the image analyzer utilized in the experiment is shown in Figure 9. Point P1 is considered exactly on the machined surface not on the cross section surface, which was considered as the reference surface at depth 0.0 µm. Figure 10 depicts the microhardness profile of the subsurface.

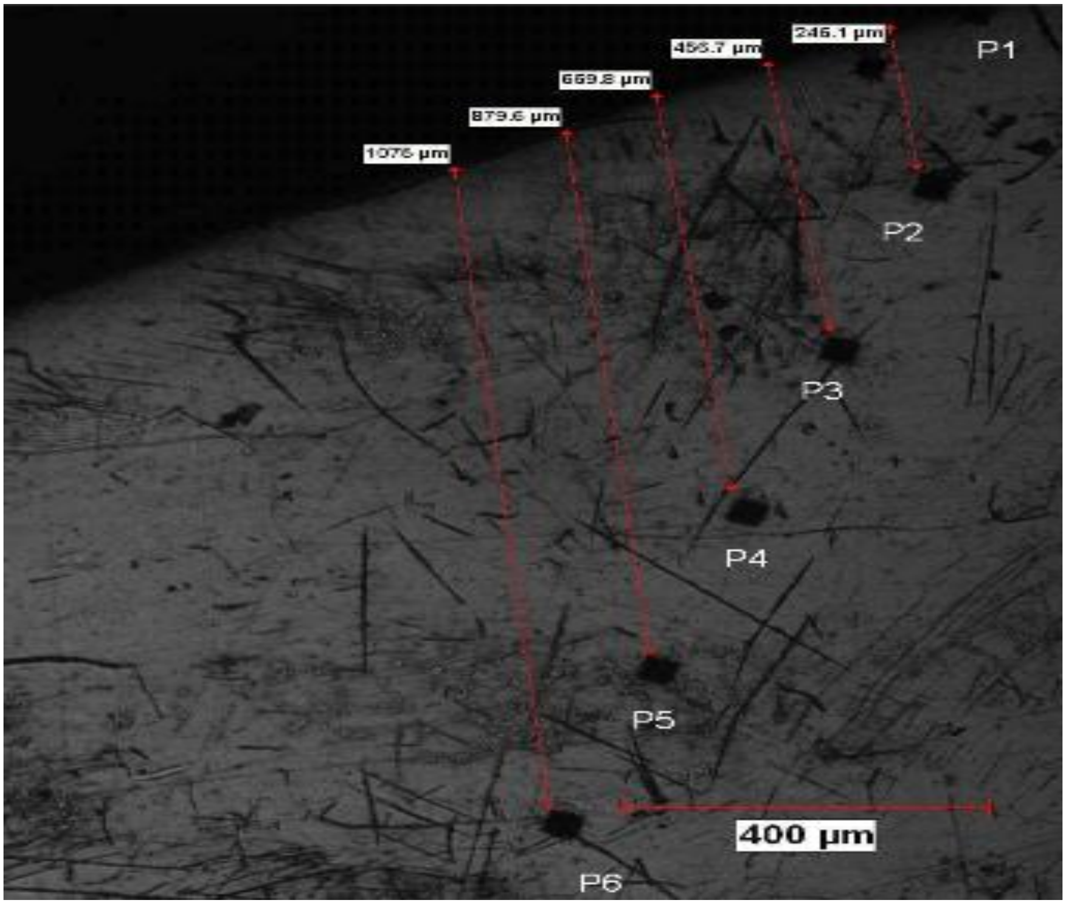


Figure 9. Micro-indentations on the machined surface of AISI 316 steel under MQL cutting condition.

The vertical depth of each micro-indentation from the machined surface is shown in Table 11. The microhardness of the specimens ranged from 230 to 158, with MAZ depths varying from 40 to 1,075 µm. The hardness depth profile is presented in Figure 10.

Table 11. Hardness profile at different depths from the machined surface

Radial depth from machined surface (µm)	Hardness (µHv)
0.0	230
41.23	213
246.1	169
456.7	162
669.8	159
879.6	161
1075.0	158

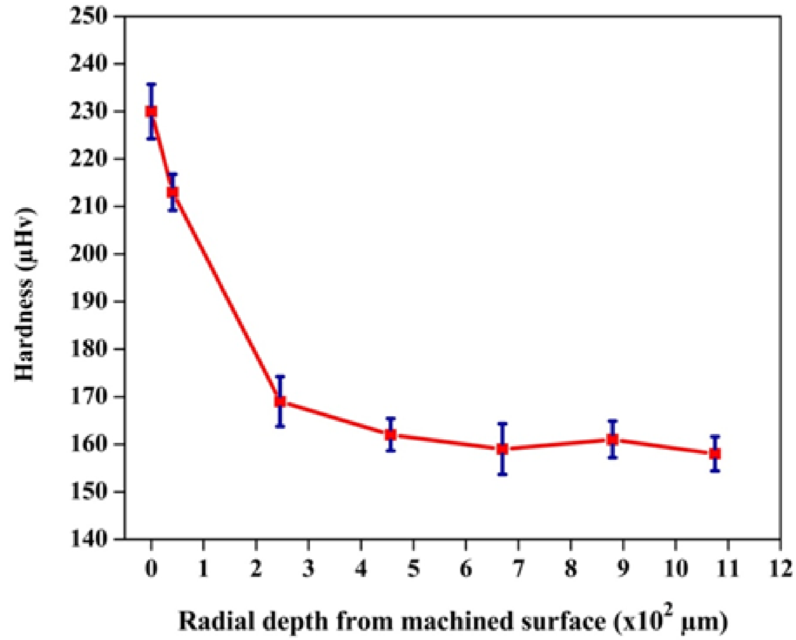


Figure 10. Microhardness profile of the machined subsurface

The DWH of MAZ was determined as 43.75%.

$$\text{DWH}_{\text{(MQL)}} = \frac{230-160}{160} \times 100 = 43.75\% \qquad (8)$$

Higher work hardening in the machined surface is expected when machining is carried out at severe levels of cutting speed, feed rate, and depth of cut, according to Pawade et al. [43]. A large majority of the heat generated during metal machining is transported away by the chips, while a small portion is dissipated in the work [44]. As the austenitic stainless steel was a poor thermal conductor of heat, the quantity of heat carried away by the chips created would be relatively low, resulting in a higher proportion of heat dissipated in the machined item. Machining in the MQL environment revealed a moderate depth of MAZ. Under the MQL cutting, the effective MAZ depth of around 0.45 mm was recorded. This could be due to a high stream of compressed air striking flushes the chips formed during the cutting process away immediately, leaving the chip with little time to absorb the heat. As a result, the amount of heat dissipated in the work will be greater. MQL cutting produced the lowest DWH value (43.75 %), which could be related to the MQL system's usage of coconut oil as a cutting fluid. Coconut oil is a good heat conductor and transfers the remaining heat away from the machined surface, resulting in less work hardening.

4. Conclusions

The influence of cutting parameters and MQL discharge rate on surface roughness values and surface hardness while CNC turning austenitic stainless steel AISI 316 was investigated in this work using a multi response optimization with Taguchi and Response Surface Methodologies. Three levels of cutting speed, feed, and depth of cut were used as cutting parameters during turning experiments, while three levels of MQL discharge rates were used as cooling parameters. To promote environmental friendliness, occupational safety [45], and cleaner machining, coconut oil was utilized as a lubricant instead of standard mineral oils. Based on the findings of this inquiry, the following conclusions can be derived.

In order to obtain a minimal value of R_a, the following cutting and MQL discharge rate parameters were found to be optimal: 120 m/min cutting speed, 0.25mm/rev. feed, 1.0mm depth of cut, and 90 ml/hr MQL discharge. Cutting speed and MQL discharge rates showed approximately identical relevance on minimizing the Ra value with percentage contributions of 35.18% and 34.50%, respectively.

MQL's maximum discharge rate (90 ml/hr) was the most important factor in lowering the R_z value of surface roughness, accounting for 81.88 % contribution. The optimum cooling condition for minimizing surface roughness during heavy turning could be obtained in MQL machining with coconut oil as the coolant.

The most important parameter in producing turned surfaces with maximum hardness was found to be the depth of cut, which contributed by 77.18%, followed by MQL discharge rate and feed rate, which contributed by 9.55 % and 8.39%, respectively.

Under MQL conditions, a moderate level of MAZ depth (0.45 mm) and 43.75% degree of work hardening (DWH) were recorded for the machining conditions considered in this study.

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