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Optimization of CNC Milling Parameters for Surface Roughness and Hardness of SS 316

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ABSTRACT

CNC milling of stainless steel (SS) 316 faces considerable difficulties in obtaining the desired hardness and surface quality as a result of machining variability. This investigation focuses on the optimization of spindle speed, feed rate, and depth of cut using the Taguchi method, where soluble oil served as the cutting fluid. The Taguchi method was used with an L9 orthogonal array was implemented to design the experimental trials and the responses of surface roughness (Ra) and hardness (HRB) were quantified according to ISO standards. The findings reveal that the minimum surface roughness is obtained at a spindle speed of 2100 rpm, feed rate of 50 mm/min, and depth of cut of 0.2 mm and the maximum hardness is achieved at 1500 rpm, 50 mm/min, and 0.2 mm. Generally, higher feed rates and depths of cut contribute to poorer surface finish, whereas elevated spindle speeds are associated with improved surface quality. The observed reduction in hardness is primarily linked to thermal accumulation in the cutting zone, which is partly alleviated by the use of soluble oil. These findings emphasize the need to consider distinct optimal conditions for surface roughness and hardness must be considered to ensure superior CNC milling outcomes for SS 316 stainless steel.

1. INTRODUCTION

Stainless steel (SS) 316 is an austenitic alloy composed of chromium, nickel, and molybdenum [1][2]. This material is extensively utilized in the manufacturing of industrial equipment components, particularly in the energy [3], biomedical [4], and food industries, among others [5]. Its corrosion resistance makes SS 316 a preferred choice across various industrial sectors. In addition to its corrosion resistance, austenitic stainless steel possesses high ductility, low thermal conductivity, and high compressive strength [6][7]. Therefore, cutting tools with high wear resistance, high hardness, and resistance to changes in feed motion are required [8].

The selection of cutting tool geometry is crucial for achieving optimal results in machining, particularly when working with difficult-to-machine materials. Proper tool geometry helps prevent excessive wear that may otherwise compromise machining outcomes [9]-[11]. Surface quality and dimensional accuracy in machining are influenced by various factors, including machining conditions, tool geometry, tool vibrations, and cutting parameters [12][13]. Vibrations generated during the milling process accelerate tool wear, thereby directly affecting the surface quality of the machined workpiece [14][15]. Furthermore, the use of cutting tools with larger grain sizes tends to shorten tool life. A 41.9% difference in grain size between 0.18 µm and 0.31 µm has been shown to increase tool life by 26.2%. Hence, employing carbide tools with smaller grain sizes has been proven to extend tool life in the milling of SS 316L [16].

To enhance cutting tool performance, the application of coated tools in machining processes has been shown to influence surface roughness significantly [17]. Among the various coating types, tools with Physical Vapor Deposition (PVD) coatings achieve lower surface roughness than those with Chemical Vapor Deposition (CVD) coatings, with a difference of approximately 25% in the minimum surface roughness [18]. In addition

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to improving surface quality, coated tools also exhibit greater wear resistance. Studies on machining AISI 316 with coated inserts revealed improved tool wear resistance compared to uncoated tools, highlighting the role of coatings in reducing friction forces during the machining process [19][20].

Nevertheless, surface quality in machining is not solely determined by cutting tool characteristics. The effectiveness of machining operations is strongly influenced by cutting parameters, namely feed rate, depth of cut, and spindle speed, which directly affect chip formation, cutting forces, and the resulting surface [21][22]. In their investigation of CNC milling of AISI 316L using carbide inserts, Equbal et al. [23] reported that the feed rate had the greatest effect on surface roughness. At the same time, the depth of cut was the dominant factor influencing material removal rate (MRR). Consistent with this, Farooq [24] found that in dry machining of additively manufactured SS 316L, increasing both feed rate and depth of cut elevated surface roughness by as much as 62.5%. Similarly, Truong et al. [25] demonstrated that surface roughness is highly affected by the combined effects of feed rate and spindle speed. While higher spindle speeds generally improve surface finish, excessively low or high feed rates can induce plastic deformation, degrading surface quality.

Beyond conventional dry machining, prior research has highlighted the importance of cooling strategies in enhancing surface quality. The implementation of natural-based cutting fluids under MQL conditions during SS 316 turning has proven effective in achieving considerable reductions in surface roughness [26][27]. Moreover, the integration of nanoparticles into MQL systems has proven effective in mitigating tool wear and enhancing surface finish, attributed to the dual mechanisms of improved cooling and lubrication [28][29]. However, nanoparticle-enhanced coolants have also been reported to accelerate corrosion rates in SS 316 compared to conventional coolants [30]. In addition to surface roughness, machining process and cooling conditions have also been shown to influence other mechanical properties, such as material hardness.

The friction between the cutting edge and the workpiece surface generates frictional forces, which in turn produce heat in the cutting zone [31]. Kadi et al. [32] in a turning study on 316L using coconut-oil-based Minimum Quantity Lubrication (MQL), an increase in hardness up to 230 µHv. This effect was primarily attributed to the depth of cut parameter, as the heat generated during machining was concentrated in the cutting zone and partially dissipated through the chips. Similarly, Avci et al. [33] investigated CNC milling of AISI 1050 under wet-cooling conditions. They found that the use of cutting fluids enhanced surface hardness, with the effect strongly influenced by spindle speed. Such hardness improvement through heat treatment improves the material’s resistance to frictional wear [34][35]. In industrial machine components, mating-part interaction typically occurs at the asperity peaks of machined surfaces. These interactions determine whether the contact response is elastic or plastic under applied loading [36][37]. The hardness of a material is directly related to its resistance in these contact areas, particularly under deformation caused by contact stresses. Hence, hardness plays a vital role in the ability of surface asperities to resist deformation and wear [38].

Extensive research has addressed the role of cutting parameters—including feed rate, depth of cut, and spindle speed—in the surface roughness of SS 316, primarily in dry machining and Minimum Quantity Lubrication (MQL) environments. Nevertheless, comprehensive investigations into how these parameters simultaneously affect surface roughness and hardness when soluble oil is applied as the cutting fluid remain scarce. In practice, however, soluble oil is still widely employed in industry due to its cost efficiency and ease of application. Therefore, this study is essential to investigate how the combination of machining parameters and soluble oil affects surface roughness and hardness, thereby supporting improvements in the service life and performance of machined components.

2. Materials and Methods

2.1. Material

2.1.1. Material specification

The material used in this study was stainless steel AISI 316, selected for its molybdenum content, which enhances corrosion resistance [39]. The specimens were prepared with dimensions of 50 mm × 30 mm × 10 mm. The chemical composition in Table 1 and the mechanical properties of SS 316 are presented in Table 2.

Table 1. Chemical Composition SS 316

Unsur	C	Si	Mn	P	S	Ni	Cr	Mo
Weight%	0.019	0.54	0.96	0.031	0.003	10.17	16.80	2.1

Table 2. Mechanical Properties of SS 316

Mechanical Properties	Value
Yield Strength	303 Mpa
Tensile Strength	581 Mpa
Elongation (%)	56
Hardness	88 HRB

2.1.2. Tool Material

Figure 1 illustrates a cylindrical carbide cutting tool with a 10 mm diameter, four flutes, and a total length of 71.4 mm. Due to its high wear resistance and hardness, carbide is well-suited as a cutting tool material for machining AISI 316 stainless steel [8].

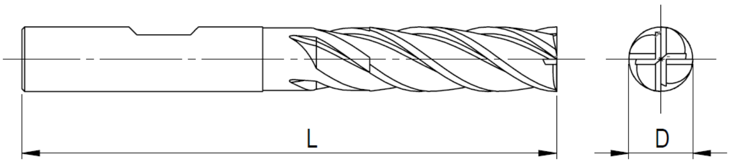

Figure 1. Design and geometry of the sample endmill tool

2.2. CNC Milling Process

In this study, the CNC milling machine employed was a DAHLIH MCV 1020, with the parameters summarized in Table 3. Soluble oil was used as both the coolant and lubricant during SS 316 machining. The selection of machining parameters was based on recommendations from industrial practice [26].

Table 3. Parameter CNC milling

Factor (Parameter)	Level		
	1	2	3
Spindle Speed (rpm)	1500	1800	2100
Feed Rate (mm/min)	50	100	150
Depth of Cut (mm)	0.2	0.5	0.8

2.3. Taguchi Experimental Design

The Taguchi method was employed in the experimental design due to its ability to minimize the number of experimental trials by systematically narrowing the input parameters and their levels, thereby ensuring the collection of relevant, statistically valid data [40]-[42]. Orthogonal array, considering three machining parameters at three levels. Optimization was performed by applying the "smaller-the-better" approach for surface roughness and the "larger-the-better" approach for hardness, thereby identifying the optimal machining conditions for SS 316. The signal-to-noise (S/N) ratio for surface roughness was subsequently derived using Equation (1) and for hardness using Equation (2):

$$S/N = -10\log_{10}\left[\frac{1}{K}\sum_{k=1}^{K}(y_k)^2\right] \tag{1}$$

$$S/N = -10\log_{10}\left[\frac{1}{K}\sum_{k=1}^{K}\frac{1}{{y_k}^2}\right] \tag{2}$$

2.4. Surface Roughness and Hardness Testing

Figure 2 illustrates the measurement points, taken at three locations on the specimen surface, with a spacing of 12.5 mm between them. Surface roughness was evaluated using a portable surface roughness tester (LANDTEK SRT-6210) in compliance with ISO 21920-3:2021. A cut-off length of 0.8 mm was applied, and the arithmetic mean roughness (Ra) was determined as the average deviation of the surface profile from the mean line over the specified cut-off region.

Hardness testing was conducted using a CARSON MOPAO3 Hardness Tester with the Rockwell B (HRB) method. The procedure was performed in accordance with ISO E18-22, applying a load of 100 kgf with a steel ball indenter of 1.588 mm in diameter. Both the surface roughness tester and the hardness tester were calibrated every six months to ensure consistent, accurate results.

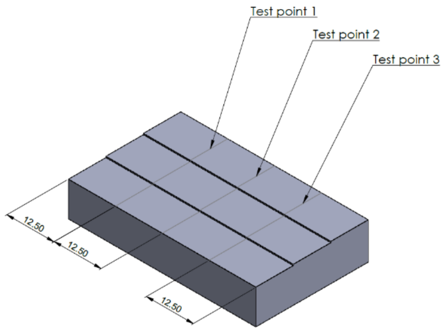

Figure 2. Specimen testing points

Figure 3 presents the research flow for obtaining surface roughness and hardness data of CNC-milled specimens. The process began with a literature review and field study to formulate the research problem, followed by the preparation of G-code, tools, and materials. The selection of cutting tools and machining parameters was carried out to achieve optimal results. After machining, the specimens were inspected; those that did not meet the required criteria were reprocessed. Eligible specimens were then tested for surface roughness and hardness according to standard procedures. Finally, the test results were analyzed to draw conclusions and provide research recommendations.

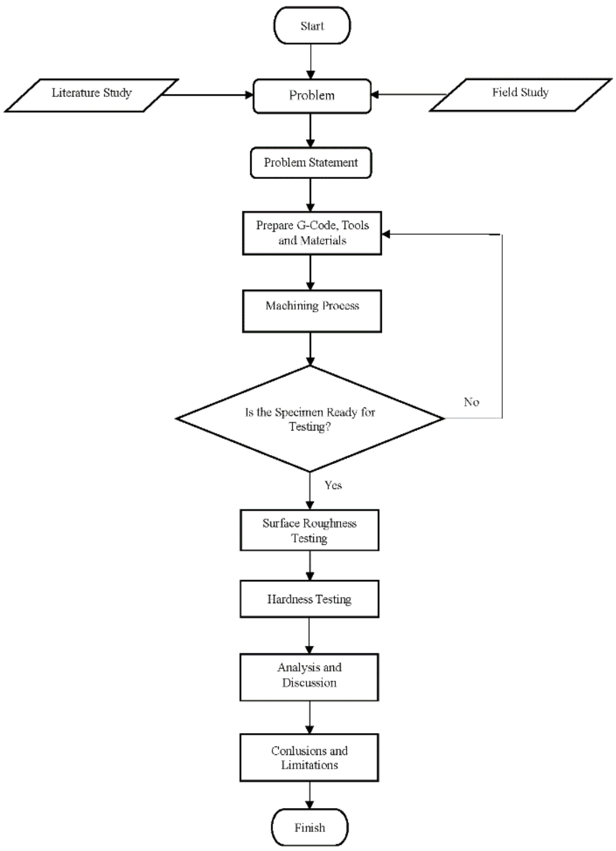

Figure 3. Research Flow Chart

3. RESULTS AND DISCUSSION

The measurement results of surface roughness and hardness are presented in Table 4. The primary objective of this experimental design was to identify the most influential factors and their interactions in achieving the lowest possible surface roughness and the highest possible hardness. Here, Ra represents the surface roughness, while HRB denotes the hardness obtained from the machining process.

Table 4. Experimental results of surface roughness and hardness

Spindle Speed	Feed Rate	DoC	Ra	HRB
1500	50	0.2	0.252	77.2
1500	100	0.5	1.235	74.7
1500	150	0.8	1.163	69.8
1800	50	0.5	0.457	68.2
1800	100	0.8	0.677	65.2
1800	150	0.2	0.478	68.7
2100	50	0.8	0.302	69.2
2100	100	0.2	0.405	70.0
2100	150	0.5	0.500	66.7

3.1 Surface Roughness

The optimal machining parameters in CNC milling were identified using Signal-to-Noise (S/N) ratio analysis based on the “smaller-the-better” criterion. The parameter combination with the highest S/N ratio was recognized as the optimal condition, since it corresponds to the lowest mean surface roughness. A summary of these results is provided in Table 5.

Table 5. Response table for S/N ratios of surface roughness

Factor	Surface Roughness (R_a)			
	Level 1	Level 2	Level 3	Delta
	S/N Ratio			
Spindle Speed	2.938	5.536	8.089	5.151
Feed Rate	9.717	3.136	3.710	6.581
Depth of Cut	8.743	3.666	4.155	5.077

The data analysis shown in Figure 4 illustrates the effect of variations in the input parameters on surface roughness. The spindle speed parameter exhibited a decreasing trend in surface roughness, with the optimal value obtained at 2100 rpm, corresponding to the lowest average roughness of 0.402 µm. The relationship between feed rate and surface roughness showed a nonlinear trend, with the optimal feed rate at 50 mm/min, yielding the lowest average roughness of 0.337 µm. Similarly, the depth of cut showed a nonlinear relationship, with the optimal depth of cut at 0.2 mm, resulting in the lowest average surface roughness of 0.378 µm.

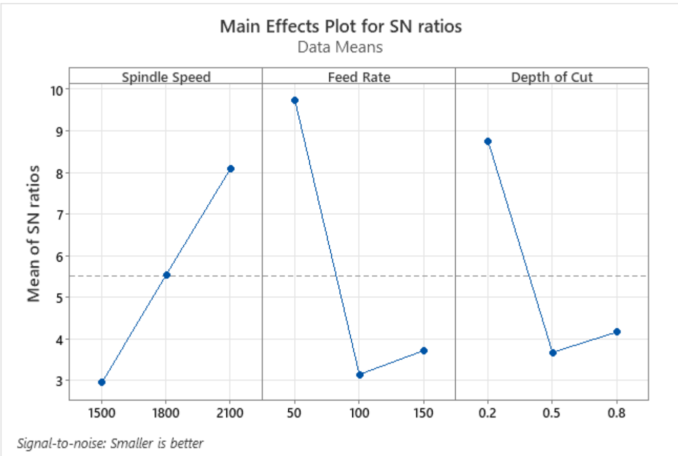

Figure 4. Surface Roughness main effects plot

Following the Taguchi S/N ratio analysis, the surface roughness results were further validated using Analysis of Variance (ANOVA). ANOVA was employed to identify the dominant factors and their percentage contributions to the response. The ANOVA results for surface roughness are presented in Table 6 at a 95% confidence level. Based on the results, the parameter with the most significant contribution to surface roughness was spindle speed, accounting for 36.28%, followed by feed rate at 32.82% and depth of cut at 23.28%. The 7.62% error may be attributed to coolant pressure and tool wear during the cutting process.

Table 6. Results of ANOVA surface roughness

Parameter	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Spindle Speed	2	0.369	0.184	4.76	0.174	36.28%
Feed Rate	2	0.334	0.167	4.31	0.188	32.82%
Depth of Cut	2	0.237	0.118	3.05	0.247	23.28%
Error	2	0.077	0.038			7.62%
Total	8	1.018				100%

The interaction plot in Figure 5 shows that surface roughness (Ra) is affected by the combined influence of spindle speed, feed rate, and depth of cut. The presence of non-parallel or intersecting lines indicates that the effect of one parameter depends on the levels of the others. Increasing the feed rate at low spindle speeds tends to significantly increase Ra, whereas higher spindle speeds result in lower surface roughness. Similarly, variations in depth of cut exhibit different effects depending on the combination of the other two parameters. This confirms that surface quality results from the combined effects of all three cutting variables.

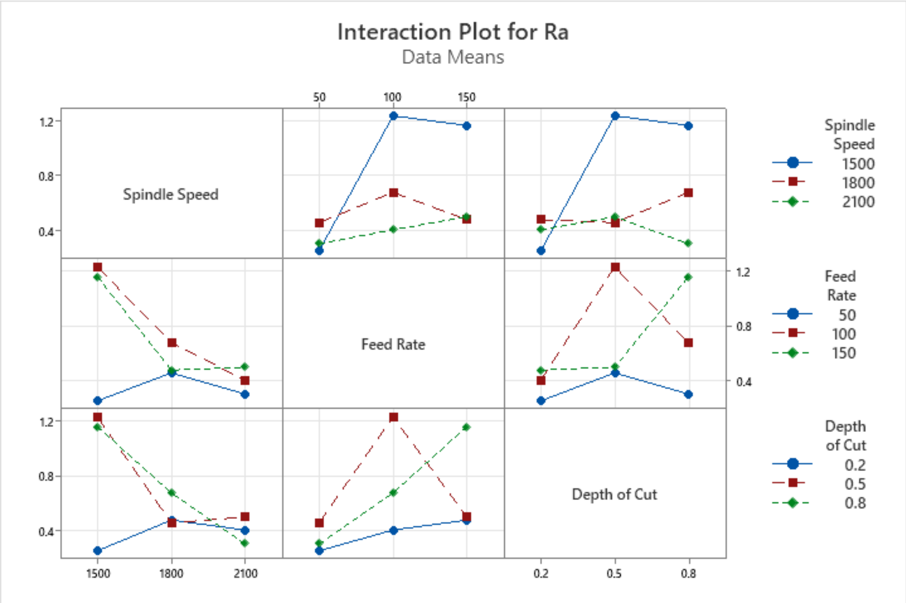

Figure 5. Interaction plot for surface roughness

An increase in spindle speed leads to the formation of thinner chips, as the cutting tool engages with the workpiece more rapidly, thereby producing a smoother surface finish [25][40][32]. At higher spindle speeds, the formation of built-up edge (BUE) decreases, thereby reducing scratches on the machined surface that typically result from material adhesion at the tool tip [43].

However, increasing the feed rate results in higher thrust forces and vibrations, thereby elevating surface roughness [44][45]. Moreover, depth of cut is recognized as another critical parameter governing machining performance [23]. Larger depths of cut generally increase surface roughness due to higher resistance, vibration, and tool wear [44]. At 0.5 mm, the highest roughness is observed, attributed to machining instability and chatter [46]. Interestingly, further increasing the depth of cut to 0.8 mm, a reduction in surface roughness occurs as the cutting process becomes more stable [46][26].

To minimize surface roughness, higher spindle speeds and controlled feed rates can be applied. However, the concurrent increase in both parameters can raise the cutting temperature, which in turn accelerates tool wear and deteriorates the workpiece's surface finish [25][9].

3.2 Material Hardness

To determine the optimal machining parameters in CNC milling, the Signal-to-Noise (S/N) ratio was analyzed using the 'larger-the-better' criterion, along with average hardness. The results of the S/N ratio analysis and the mean hardness are presented in Table 7.

Table 7. Response table for S/N ratios of hardness

Factor	Hardness			
	Level 1	Level 2	Level 3	Delta
S/N Ratio				
Spindle Speed	37.36	36.56	36.73	0.80
Feed Rate	37.07	36.88	36.70	0.37
Depth of Cut	37.13	36.87	36.65	0.48

Figure 6 illustrates the effect of input parameter variations on hardness. The spindle speed parameter exhibits a nonlinear relationship with hardness, with an optimal value of 1500 rpm, corresponding to the highest average hardness of 73.83 HRB. A similar trend is observed for the feed rate, which shows a decreasing hardness trend, with the highest average hardness of 71.51 HRB. Likewise, the depth of cut also demonstrates a decreasing hardness trend, with the highest average hardness of 71.94 HRB.

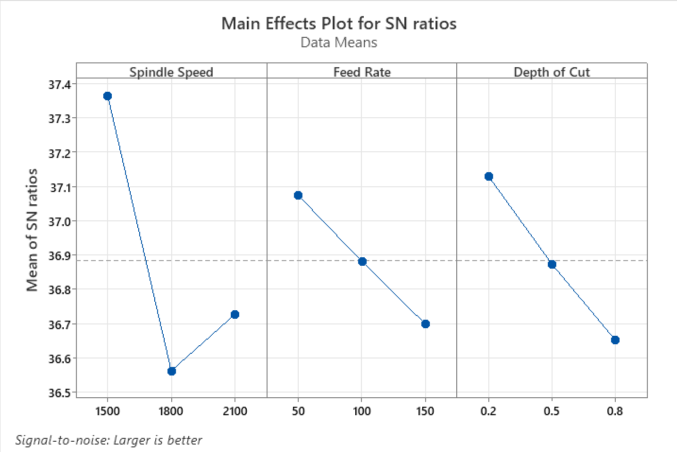

Figure 6. Hardness main effects plot

After obtaining the S/N ratios from the Taguchi analysis, the hardness test results were further analyzed using ANOVA (Analysis of Variance). ANOVA was employed to identify the dominant factors and their percentage contributions to the test results. The ANOVA results for hardness are presented in Table 8 at the 95% confidence level. According to the ANOVA results presented in Table 8, spindle speed exerts the dominant influence on hardness, accounting for 69.17% of the total variation. Depth of cut and feed rate contribute comparatively less, at 15.40% and 4.20%, respectively. However, the 3.24% error rate in the ANOVA results may be attributed to uninvestigated variables.

Tabel 8. Results of ANOVA Hardness

Parameter	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Spindle Speed	2	72.200	36.100	19.71	0.048	63.38%
Feed Rate	2	14.519	7.259	3.96	0.201	12.84%
Depth of Cut	2	22.727	11.363	6.20	0.139	20.09%
Error	2	3.663	1.832			3.24%
Total	8	113.109				100%

To clarify the relationships among the variables, an interaction plot analysis was conducted. Figure 7 shows that the interaction between spindle speed, feed rate, and depth of cut influences material hardness (HRB). The intersecting lines indicate that the effect of one parameter depends on the values of the other parameters. At low spindle speeds, an increase in feed rate tends to significantly reduce hardness, whereas at high spindle speeds, the effect is more negligible. The variation in depth of cut also shows a non-constant effect: a greater cutting depth can decrease hardness, depending on its combination with the other two parameters.

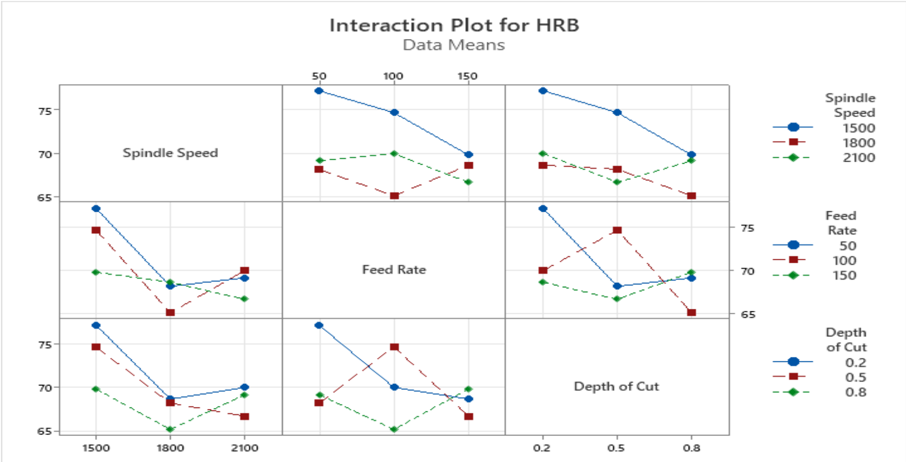

Figure 7. Interaction plot for hardness

From the interaction plot and the S/N ratio, the highest spindle speed corresponds to the lowest hardness. Frictional interaction between the cutting edge and the workpiece surface during spindle rotation produces considerable heat in the machining zone [31]. Owing to the limited thermal conductivity of 316 stainless steel, the dissipation of this heat is restricted, thereby causing thermal concentration in the vicinity of the cutting interface [48]. The introduction of soluble oil as a coolant partially alleviates heat concentration, ultimately reducing material hardness [49].

Beyond the effect of spindle speed, feed rate significantly influences the thermal characteristics of the machining process, fostering localized heat accumulation at the cutting edge and the workpiece interface [50]. As the feed rate increases, the material removal rate (MRR) rises proportionally, thereby intensifying the cutting energy demand [23]. Consequently, heat accumulation in the contact area tends to increase with higher feed rates. However, when machining is performed with a cooling medium, the generated heat can be reduced, leading to a decrease in hardness [51]. The thermal state of the cutting zone is greatly affected by the depth of cut. Thus, most of the heat generated during machining is removed by the chips, whereas only a small portion is transferred to the tool and workpiece. In the case of austenitic stainless steels, which exhibit low thermal conductivity, a reduced depth of cut diminishes the chip's capacity to transport heat away from the cutting zone. This results in higher thermal retention within the workpiece, thereby increasing the local surface temperature of the machined material [26].

4. CONCLUSION AND LIMITATION

The study demonstrates that the optimal conditions for minimizing surface roughness are obtained at 2100 rpm spindle speed, 50 mm/min feed rate, and 0.2 mm depth of cut. The percentage contributions of machining parameters to surface roughness are 36.28% for spindle speed, 32.82% for feed rate, and 23.28% for depth of cut, confirming spindle speed as the most critical factor. This is attributed to its ability to suppress the formation of built-up edges, thereby improving the surface finish. Conversely, increases in feed rate exacerbate roughness due to higher thrust forces and increased vibration, while a depth of cut of 0.5 mm leads to machining instability. At 0.8 mm, however, the process becomes more stable, resulting in reduced surface roughness.

For hardness, the optimal results are achieved at a spindle speed of 1500 rpm, a feed rate of 50 mm/min, and a depth of cut of 0.2 mm. Parameter contribution analysis reveals that spindle speed has the most significant influence (63.38%), followed by depth of cut (20.09%) and feed rate (12.84%). The observed decline in hardness is predominantly attributed to thermal accumulation within the cutting zone, induced by intense tribological interactions at the tool–workpiece interface. Such localized heating alters the microstructural stability of the machined layer, thereby reducing its hardness. Due to SS 316's low thermal conductivity, more heat is absorbed by the workpiece. The use of soluble oil helps reduce the cutting temperature but generally lowers the surface layer's hardness.

This study was conducted only on the parameters and soluble oil. Future research should focus on exploring a wider range of cutting parameters, including higher spindle speeds and depths of cut. Additionally, investigating alternative environmentally friendly cooling fluids, such as minimum quantity lubrication (MQL) or vegetable oil-based cutting fluids, is essential to support the sustainability of the machining process.

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