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Comparative Analysis of effect of Turning Parameters on Surface Roughness and Hardness of Austenitic Stainless Steel under dry and conventional cooling conditions

Rajendrakumar V. Kadi[1], Suresh T. Dundur[2]

[1](Mechanical Engineering Department, Tontadarya College of Engineering, Gadag582101, India)

[2](Industrial and Production Engineering Department, Basaveshwara Engineering College, Bagalkot587101 India)

Email: rajendravk@yahoo.co.in

Abstract : *Due to excellent corrosion and fatigue strength, the austenitic stainless steel gained its wide application in various industries. The rising use of stainless steel attracted the many researchers to study the effect of process parameters during its different fabrication processes. In the present experimental investigation an attempt has been made to estimate and optimize the three different speeds (120, 150 and 180 m/min), with three feed rates (0.2, 0.25 and 0.3mm/rev) and three depths of cut (0.5, 1.0 and 1.5mm) during CNC turning to minimize surface roughness and maximize surface hardness. Turning is carried out separately under dry and conventional cooling condition using TiN coated carbide insert to make comparative analysis to arrive at better method of cooling. Taguchi's L9 orthogonal array is used to design the experiments. The analysis of means (ANOM) and analysis of variance (ANOVA) were used to determine the optimal parameter levels and obtain the level of importance of the cutting parameters, respectively. Validation tests with optimal levels of parameters were performed at 95% confidence interval to illustrate the effectiveness of Taguchi optimization. It has been found that, during dry turning feed rate plays significant role in minimizing surface roughness where as combined effect of speed and feed rate in maximizing surface hardness. On the other hand, under conventional cooling condition again feed rate is the dominating parameter in reducing surface roughness and depth of cut in increasing surface hardness. Finally it has been concluded that dry turning gives better surface hardness where as wet turning produces better surface finish.*

Keywords: *Austenitic stainless steel, CNC Turning, Conventional cooling, Dry cutting, Taguchi Method, Surface Roughness, Surface hardness, ANOVA.*

I. INTRODUCTION

Austenitic stainless steel, because of its excellent resistance to oxidation and corrosion, is found in variety of industries such as marine, chemical, dairy, power and biomedical etc. [1, 4, 5, 9, and 10]. Therefore, Austenitic grade of stainless steel is among largest consumed steel which makes up to 70% of total stainless steel consumed worldwide [1, 8, 10, and 11]. However, machining of this hard to cut material is not that easy due to its high strength, poor surface finish, lower thermal conductivity, higher work hardening, high ductility, more micro structural and mechanical sensitivity to strain and strain rate, etc. [1-9]. As a result of it, this material induces rapid wear in cutting tools and tool wear related problems while machining. It is also found that addition of free cutting additives like lead, sulfur, selenium and tellurium increase the machinability of austenitic stainless steels, [2, 3]. Producing machined surfaces with good finish and resistance to wear are the prime requirements especially when Austenitic steel is used in medical equipment and food processing containers. Fine surface is also entailed for the improvement of tribological properties, corrosion resistance, fatigue strength, creep life and aesthetic appeal in the manufactured parts etc.[4, 8, and 12].Surface finish in particular is found to be affected by parameters like nose radius along with cutting speed, cutting depth and feed rate [13]. Machining at lower speeds has a tendency to form built up edge causing increased surface roughness. But the formation of built up edge can be avoided by choosing higher cutting speeds [4].Ibrahim Ciftci [7] while machining austenitic stainless steel with cemented carbide inserts having multiple coatings of TiN observed that, increase in cutting velocity initially reduces the surface roughness till it reaches a lower value and then it increases. A general consensus prevails amongst the investigators regarding predominance of cutting speed and feed rate amongst all those factors influencing roughness of machined surface [10, 15, 16, 24, 25 and 26]. However, in contrast to it few investigators such as Kaladhar et al. [8] and Dilbag Singh and Venkateswara Rao [13] identified that, after the feed rate next most predominant factors are nose radius, rake angle and cutting velocity. From the literature it can be revealed that substantial work has been carried out in analyzing the cause of machining parameters on roughness of the turned surface but, little focus on wear resistance and the micro-hardness of machined subsurface. Therefore, the main intention of this investigation is to find the optimal turning parameters(speed, feed and cut depth) for the combined effect of surface roughness and micro hardness of the turned surfaces while machining austenitic stainless steel 316 with TiN-coated carbide insert under dry and wet condition. A comparative study is carried out to find the optimal method of cooling for better surface properties.

Taguchi's L9 orthogonal array has been used to achieve the above objective. And also, a numerical analysis (ANOVA) has been performed to know which process variables and their interactions are statistically important. Finally, ANOM is done to find the optimum level of each variable for both surface roughness (Ra) and micro hardness (mHV), and results are compared with the experimental values. Statistical package MINITAB-16 was used to perform the statistical analysis.

II. METHODOLOGY

The present study is carried out using Taguchi's fractional factorial design by taking L9 orthogonal array to optimize the responses. The orthogonal arrays consider simultaneously the effect of many controlling factors on the response quantity. The orthogonal experiments were conducted to obtain the optimum level for every controlling factor. Further these experiments provide information about effect of individual as well as interactive effect of the parameters on response[18, 19].

In this optimization technique objective function is formed on the basis of "signal to noise (S/N) ratio" which is subjected to the constraints formed by the noise factors using orthogonal matrix.[18, 19]. Thus Taguchi method gives the expected optimal performance under the noise factors. Based on the nature of variable i.e. S/N values ratios, the objective function can be selected as to "smaller the better", "larger the better" and "nominal the best" type. ANOM of S/N ratio helps in determining the admirable combination of controlling parameters and their levels. The ANOVA helps in understanding the individual and interactive effect of control factors on the responses [18, 19].

III. EXPERIMENTATION

In the present investigation, cylindrical turning trails were carried out as per the L_9 orthogonal array design matrix. Three control factors namely cutting speed, depth of cut and feed rate are chosen as control factors for the present study. The different levels of cutting parameters are decided in accordance with the tool manufacturer's recommendation for the given material used in the experiments. Each controlling factors is considered at three levels and are illustrated in Table 1. According to Taguchi's fractional factorial design method, L_9 orthogonal array was used in the design of experiment. Table 2 gives the detailed outline of experimentation. The CNC lathe machine with Fanuc control (11 kW with spindle speed up to 4000 rpm) was used to conduct the turning trails in both dry and conventional cooling conditions separately. The work material used in both experiments are round bars of 32 mm diameter Austenitic Stainless Steel AISI316 and Table 3 gives detail composition of it.

The carbide inserts with CVD coating of TiN (*CNMG 120416)* having integrated chip breaker were used during the experiment. The tool having combination of tungsten carbide as base matrix and TiN as a coating material, exhibit the properties of high thermal resistance and low frictional coefficient. This makes the tool to become ideal for turning of hard to cut materials. A square shank tool holder with ISO specification of GCLNR2020 K12 was used during machining. Straight turning trails were done on specimen for the length of 30 mm each for every combination of three parameters with three levels which is depicted in Fig.1 and Fig.2.

The measured surface roughness and microhardness were considered to assess the surface quality and wear resistance of turned surface respectively. The Mitutoyo Surf Test model 'SJ-201' was employed to determine the values of surface roughness at five various locations around the turned surface to reduce the error. A cut-off length of 0.8 mm for the 5 samples was chosen during the measurement. The mean values of R_a was used for the analysis of surface roughness. The microhardness of every specimen was determined by using low load Vickers hardness tester (Technosys, 0.2-5Kg with 40X magnification) and is illustrated in fig.3.

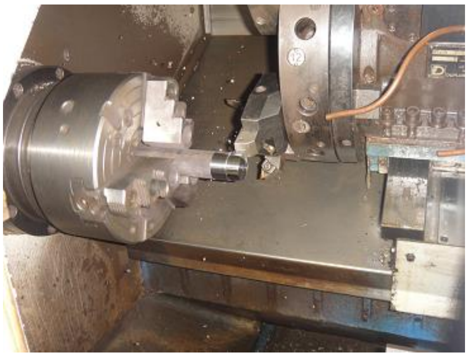


Fig1. Experimental setup for CNC Dry turning

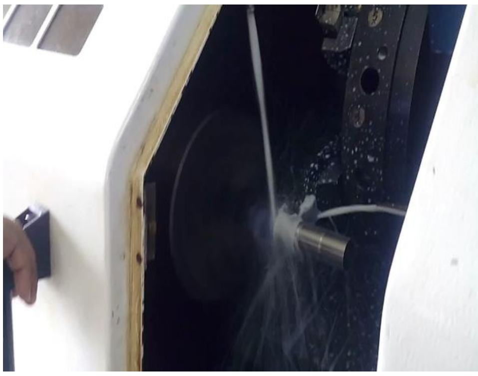


Fig2. Experimental setup for CNC Wet turning.

Fig.3 Vickershardness tester.

Table1. Control factors with chosen levels.

Code	Control Factor	Level		
		1	2	3
A	Speed, M/min	120	150	180
B	Feed, mm/rev	0.20	0.25	0.30
C	Cut depth, mm	0.5	1.0	1.5

Table-2: Orthogonal array (L_9), measured response and corresponding S/N ratios.

Trail no.	Speed	Feed	DOC	Surface Roughness (Ra)				Surface Hardness (mHV)			
				Dry	S/N ratio	Wet	S/N ratio	Dry	S/N ratio	Wet	S/N ratio
1	120	0.2	0.5	2.332	-7.3546	1.37	-2.73441	248	47.8890	208	46.3613
2	120	0.25	1.0	3.736	-11.4481	2.03	-6.14992	315	49.9662	224	47.0050
3	120	0.30	1.5	3.832	-11.6685	1.89	-5.52924	331	50.3966	266	48.4976
4	150	0.2	1.0	2.632	-8.4057	1.466	-3.32268	315	49.9662	239	47.5680
5	150	0.25	1.5	2.610	-8.3328	1.48	-3.40523	375	51.4806	248	47.8890
6	150	0.30	0.5	4.418	-12.9045	2.152	-6.65685	305	49.6860	206	46.2773
7	180	0.2	1.5	1.664	-4.4231	1.446	-3.20337	378	51.5498	267	48.5302
8	180	0.25	0.5	3.460	-10.7815	1.79	-5.05706	273	48.7233	212	46.5267
9	180	0.30	1.0	4.886	-13.7791	2.296	-7.21944	339	50.6040	221	46.8878

Table-3. Chemical composition of Austenitic Stainless Steel (AISI 316)

Elements	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Co	Ti	V	Nb	Fe
Wt.(%)	0.058	0.349	1.080	0.019	0.013	16.536	10.769	2.086	.559	0.079	0.009	0.014	0.020	68.319

IV. RESULTS AND OBSERVATIONS

Under dry turning.

ANOM and ANOVA

The present investigation on dry turning, roughness of the machined surface is to be smaller and the hardness is to be larger. To attain this S/N ratio for all runs of the orthogonal array is given by:

$$\eta_1 = -10\log_{10}\left({R_a}^2\right) \quad (1)$$
$$\eta_2 = -10\log_{10}\left(H^{-2}\right) \quad (2)$$

The successive S/N ratios for all the runs of L_9 are depicted in Table 2. To arrive at control factors with the optimum levels, ANOM based on S/N ratio was used and summery of which is illustrated in Table 4 and 5. The level of control factor having greatest S/N ratio is the optimum level. For minimum surface roughness the set of optimum control factors for R_a value is A3, B1 and C3 and for maximum hardness of turned surface, control factors with best levels are found to beA2, B3 and C3.

To know the relative contribution of every control factors, ANOVA based on S/N ratio has been used [18, 19] and Tables 6 and7 represent these results. It can be observed from ANOVA Table that, for R_a value of surface roughness feed rate (45.69%) plays an important role where as depth of cut (18.74%) and combined effect of speed and depth of cut(17.14%) have slight effect.On the other hand, for maximizing the hardness of the turned surface, interaction of speed and feed (36.42%) and depth of cut(25.23%) play significant effect, whereas cutting speed and feed rate do not affect significantly in increasing microhardness.

Table 4. Optimum level of R_a Values using ANOM

Parameter Code	Levels			Optimum Level
	1	2	3	
A	-10.752	-9.601	-9.456	3
B	-7.814	-9.878	-12.117	1
C	-10.771	-10.693	-8.346	3

Table 5.S/N ratio based ANOM for Micro hardness

Parameter code	Levels			Optimum Level
	1	2	3	
A	49.56	50.20	49.63	2
B	49.58	49.65	50.16	3

C	49.35	49.60	50.43	3

Table 6.S/N ratio based ANOVA for R_a value.

Parameter Code	Degree of Freedom	Sum of squares	Mean square	% Contribution
A	2	9.077	4.5387	4.97
B	2	83.362	41.6810	45.69
C	2	34.186	17.0928	18.74
A*B	4	8.128	2.0321	4.45
A*C	4	31.265	7.8162	17.14
B*C	4	3.143	0.7858	1.72
Error	8	13.294	1.6617	7.29
Total	26	182.455	75.6083	100

Table 7.S/N ratio based ANOVA for Micro Hardness.

Parameter Code	Degree of Freedom	Sum of squares	Mean square	% Contribution
A	2	2.2406	1.12029	9.88
B	2	1.7960	0.89798	7.92
C	2	5.7209	2.86045	25.23
A*B	4	8.2533	2.06332	36.42
A*C	4	0.2533	0.06334	1.12
B*C	4	0.1868	0.04670	0.82
Error	8	4.2201	0.52752	18.61
Total	26	22.6710	7.57960	100

For predicting and confirming the projected output based on the greatest combined effect of control factors, the predicted Taguchi's signal to noise ratio (η_{opt}) is obtained from [18, 19]:

$$\eta_{opt} = m + \sum_{j=1}^{p}\left[(m_{i,j})_{max} - m\right] \quad (4)$$

Where, $(m_{i,j})_{max}$ is the S/N ratio of the best combination i^{th}level with j^{th} factor for p^{th} main design factor. The quality characteristic of the experiments conducted for the conformation of methodology is expressed by the confidence interval (CI). It is determined by using the following relation[19]:

$$CI=\sqrt{F_{(1,\gamma_e)}V_e\left(\frac{1}{\eta_{eff}}+\frac{1}{\eta_{ver}}\right)} \quad (5)$$

where $F_{(1,\gamma_e)}$ is the F value for 95% CI, $\gamma_e$is the degree of freedom for error, V_e is the variance for error,$\eta_{eff} = \frac{N}{1+\gamma}$; N=Total number of trials in orthogonal array and γ= degree of freedom of main control factor and η_{ver} is number of validation test trials taken. This confidence interval is determined to witness the proximity of the observed value (η_{obs}) to that of predicted value (η_{opt}).

Table 8 shows the results of validation tests and it reveals that the predicted error i.e., (η_{opt}-η_{obs}) is within confidence interval value. Thus, Taguchi technique was used to optimize the surface roughness and micro hardness with a 0.05 significance level. The optimum level of control factors that reduce the surface roughness and increase the surface hardness are presented in Table 9.

Table 8. Test report of confirmation experiments.

Performance measures	**R_a**	**Hardness**
Levels (A, B, C)	3, 1, 3	2, 3, 3
S/N predicted (η_{opt}),dB	-5.74311	51.19889
Observed value	1.664 µm	335 Hv
S/N observed(η_{obs}),dB	-4.4231	50.5009
Prediction error, dB	-1.32001	0.69799
Confidence interval value (CI),	$\pm$1.876208	$\pm$1.289606

Table 9. Optimal combination of control factors with optimal values of out puts.

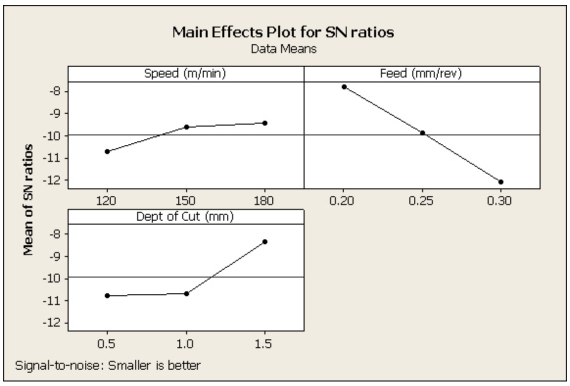
Response	Optimal combination of input variable			
	Speed (m/min)	Feed (mm/rev)	Depth of cut(mm)	Optimal value
Surface roughness	180	0.20	1.5	1.664 µm
Hardness	150	0.30	1.5	335

Effects of cutting parameters

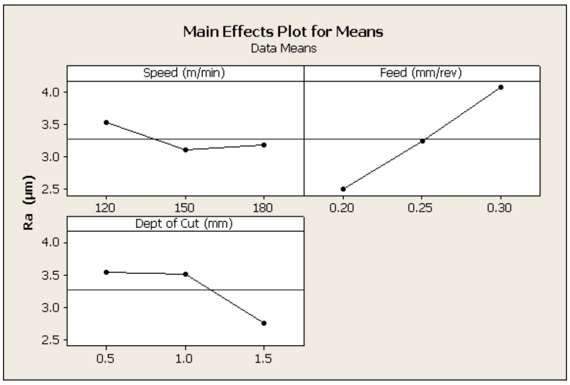
To determine the effect of cutting parameters on surface roughness (R_a) and surface hardness during dry turning direct main effect plots are drawn using MINITAB 16 software [20].

Analysis of surface profile

The main effect of cutting parameters on surface profile when they change from the minimum to maximum levels can be observed in fig.4 for R_a. From the S/N ratio analysis in fig.4 (a), the optimum cutting variables for minimum R_a value are found to be 180 m/min of speed, 0.20 mm/rev of feed rate and 1.5 mm or cut depth.



(a)



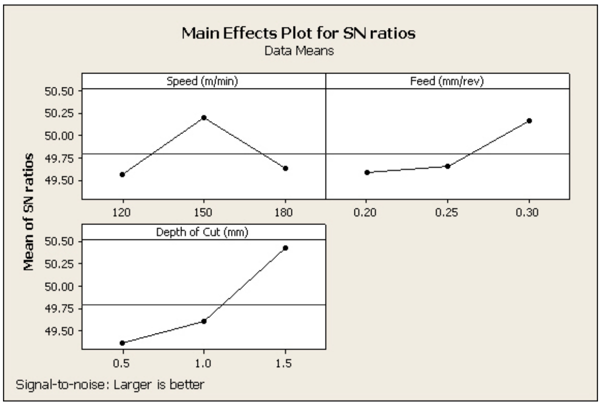
(b)

Fig.4. Main effect plots (a) Means of S/N ratio for R_a (b) Effect of control factors on R_a.

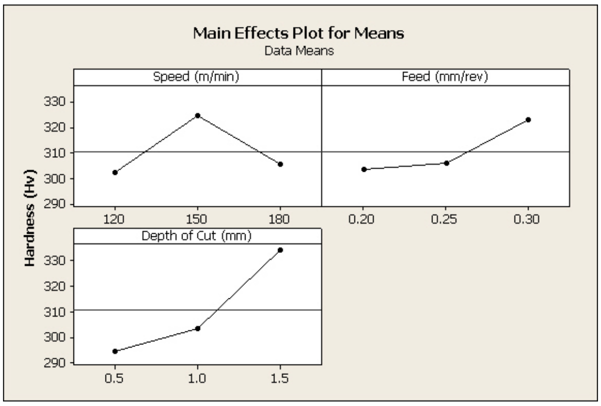
From the effect of control factor plots of surface roughness for R_a value in Fig.4(b), it can be seen that, as the cutting speed increaese from 120 m/min to 150 m/min there is decrease in Ra value, but further increase to 180 m/min increaes the R_a valuewhich may be, due to the presence of chatter at higher speed,formation of builtup edges during low cutting speeds and fluctuation in cutting force [5,7]. The surface roughness increases with increase in feed rate due to heat generation thereby tool wear hence, the higher surface rougness. Formation of chatter at higher feed rate may also be the cause for higher surface roughness. And also, as the depth of cutincreases the $R_a$value decreases and same was also observed by Kaladhar et al.,[8] and this may be attributed by interactive effect of speed and cut depth.

Analysis of surface Hardness.

Fig. 6 (a) shows the optimum values of cutting parameters for maximum surface hardness in consideration with S/N ratio. According to this, 150m/min of speed, 0.3mm/rev of feed rate and 1.5mm of depth of cutare observed as optimum parameters. It can be observed from the fig.5 (b) that, increase in cutting speed from 120 m/min to 150 m/min increases the surface hardness. It is attributed by more time of penetration of cutting tool in to the work material during low speed which leads to more plastic deformation hence more work hardening. But further increase from 150 m/min to 180 m/min of speed reduced the surface hardness, may be due to increased surface deformation because of increased work hardening recovery due to rise in temperature



(a)



(b)

Fig.5. Main effect plots (a) Means of S/N ratio Hardness (b) Effect of control factors on hardness.

. It can be seen from the fg.5(b) that, Increase in feed rate increases the surface hardness which is, because of increased heat generation and hence more work hardening. With increase in depth of cut there is an increase in micro hardness of the turned surface. This is due to more strain hardening because of thermal softening of the material at high depth of cut [21].

Under Wet turning.

The similar procedure as during dry turning has been followed in wet turning to find the optimum level of cutting parameters and their contribution.

The results of ANOM for surface roughness (R_a) and hardness (H) are represented in Tables 10 and 11 respectively. The level of a parameter with the highest value of S/N ratio is the best combination level. The optimal parameter setting is found to be A1, B3, C1 for minimum surface roughness (R_a); and A3, B1, C3for maximum hardness.

TABLE 10.ANOM for Surface Roughness (R_a) Based on S/N Ratio

Parameter code	Levels			Optimum Level
	1	2	3	
A	-3.848	-4.114	-4.035	1
B	-5.502	-4.133	-2.361	3
C	-3.783	-4.111	-4.103	1

TABLE 11.ANOM for Micro Hardness Based on S/N Ratio

Parameter code	Levels			Optimum Level
	1	2	3	
A	47.30	47.25	47.33	3
B	47.50	47.16	47.23	1
C	46.40	47.18	48.31	3

To investigate the effects of turning process parameters quantitatively, the analysis of variance (ANOVA) based on S/N ratio has been employed [22]. Tables 12 and 13 give the summary of ANOVA results of surface roughness (R_a) and hardness, respectively. It can be seen from the ANOVA tables that feed (93.53%) in case of $R_a$make major contributions to minimizing the surface roughness; whereas speed and depth of cut have least effects in minimizing the surface roughness. The depth of cut (90.63%) play major role in maximizing the hardness, whereas speed and feed do not show noticeable effects in controlling the hardness.

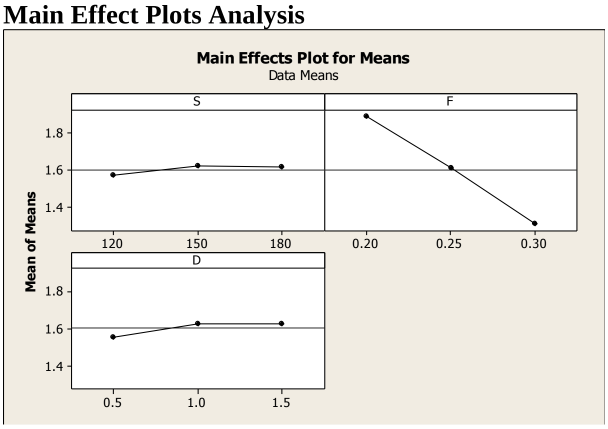
TABLE 12.ANOVA for Surface Roughness (Ra) Based on S/N Ratio

Parameter Code	**Degree of Freedom**	**Sum of squares**	**Mean square**	**% Contribution**
A	2	0.1117	0.05583	0.70
B	2	14.8836	7.44181	93.53
C	2	0.2103	0.10515	1.32
Error	8	0.7084	0.35421	4.45
Total	26	15.9140	7.957	100.00

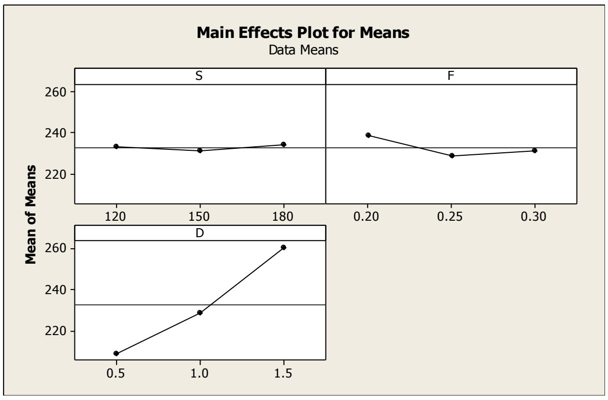
TABLE 13.ANOVA for Micro Hardness Based on S/N Ratio

Parameter Code	**Degree of Freedom**	**Sum of squares**	**Mean square**	**% Contribution**
A	2	0.00964	0.00482	0.16
B	2	0.20118	0.10059	3.28
C	2	5.55358	2.77679	90.63
Error	2	0.36317	0.18158	5.93
Total	8	6.12756	3.06378	100

Main Effect Plots Analysis



(a)



(b)

Fig.7 Main effect plots (a) Means of S/N ratio on R_a (b) Means of S/N ratio on hardness.

The analysis is made with the help of software package MINITAB-16. The main effect plots are shown in Fig. 7 (a) and (b). It shows the variation of individual response with three parameters i.e. speed, feed and depth of cut separately. In the plot, x-axis represents the value of each process parameter and y-axis is response value. Horizontal line indicates the mean of the response. The main effect plots are used to determine the optimal design conditions to obtain the optimal surface finish. According to this main effect plot, the optimal conditions for minimum surface roughness (R_a) are speed at level 1 (120 RPM), feed rate at level 3 (0.30 mm/rev) and depth of cut at level 1 (0.5mm); the optimal conditions for maximum hardness are speed at level 3 (180 RPM), feed rate at level 1 (0.20 mm/rev) and depth of cut at level 3 (1.5mm).

Table 14 shows the results of validation tests and it reveals that the predicted error i.e., (η_{opt}-η_{obs}) is within confidence interval value. Thus, Taguchi technique was used to optimize the surface roughness and micro hardness with a 0.05 significance level. The optimum level of control factors that reduce the surface roughness and increase the surface hardness are presented in Table 15.

TABLE 14.Results of Confirmatory Tests

Performance measures	**Ra**	**Hardness**
Levels (A, B, C)	1, 3, 1	3, 1, 3
S/N predicted (η_{opt}),dB	-1.994	48.56
Experimental value	1.2 µm	267.5 Hv
S/N experimental (η_{expt}),dB	-1.58362	48.5465
Prediction error, dB($\eta_{expt} - \eta_{opt}$)	0.41038	-0.0135
Confidence interval value (CI), dB	+0.5653	+56.97

TABLE 15. Combination of control factors with optimal values of out puts.

Response	Optimal combination of input variable			
	Speed (m/min)	Feed (mm/rev)	Depth of cut(mm)	Optimal value
Surface roughness	120	0.30	0.5	1.2 µm
Hardness	180	0.30	1.5	267.5 Hv

V. CONCLUSIONS

The following conclusions are inferred based on the experimental results.

- During dry turning it is evident that, feed rate is the principal parameter that contributes more on minimizing the surface roughness value of Ra with 45.69%. Depth of cut and its interaction with speed have become next dominating factors with contribution of 18.74% and 17.14% respectively. Where as in wet turning Analysis of variance (ANOVA) demonstrates that the feed rate has the highest influence on surface roughness. Ra is influenced by feed rate with 93.53% contribution. Nevertheless, the depth of cut and cutting speed has negligible influence on the surface roughness at the reliability level of 95%.
- The optimal levels for maximizing the surface hardness of the work specimen after dry turning were measured and it revealed that, joint effect of feed and speed has become the significant factor with 36.42% of contribution and is followed by depth of cut with 25.23%. In wet turning, it is found that feed rate has the highest influence on hardness. Hardness is influenced by feed rate with 83.76% of contribution. Depth of cut and cutting speed has negligible influence on the hardness.
- The optimal combination of process parameters for minimum surface roughness (Ra) under wet cutting are obtained at 120 m/min, 0.3 mm/rev and 0.5mm of speed, feed and depth of cut respectively. In dry turning the optimum levels are 180 m/min of speed, 0.2 mm/rev of feed and 1.5mm depth of cut.
- Under wet turning, the optimal combination of process parameters for maximum hardness is obtained at 180 m/min cutting speed, 0.3 mm/rev feed, 1.5 mm depth of cut. And in dry turning
- It is observed from the experimental results under both cooling conditions that, the surface finish is better under wet condition where as surface hardness under dry cutting.

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