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Effect of Cutting Parameters in Precision Turning of Nickel Alloy by RSM

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Abstract: Nickel based alloys are widely used for manufacturing aerospace components. During machining of nickel-based alloys, cutting tool materials always undergo severe mechanical and thermal loads leading to rapid tool wear and subsequently short tool life. Surface integrity plays an important role in performing actual service applications of Nickel based products. Present paper discusses the investigation on machined surface roughness in dry precision turning by using RSM. It is investigated that cutting speed significantly influences the surface roughness of machined components. Also, surface alterations on machined surfaces has been analysed by SEM micrographs.

***Index Terms* – Nickel alloy, Precision Turning, RSM, ANOVA, SEM.**

I. INTRODUCTION

In the aerospace industry, nickel-based alloys are widely used for critical structural components, particularly due to their maximum strength at low and high temperatures, and higher wear and chemical degradation resistance. However, because of their critical thermal properties, deformation and friction-induced microstructural changes prevent the end products from having good surface integrity properties. In addition to surface roughness, microhardness changes, and microstructural alterations, the machining-induced residual stress profiles of titanium and nickel-based alloys contribute in the surface integrity of these products. Machining processes often utilized as the finishing process in the process chain of producing nickel-based super alloyed end products [1]. During machining of nickel-based alloys, cutting tool materials always undergo severe mechanical and thermal loads leading to rapid tool wear and subsequently short tool life. Many machining tests were conducted to investigate the wear behaviors of coated carbide tools and a number of theories on wear mechanisms were proposed [2-5]. Therefore, due to high content of nickel it is very difficult-to-cut material. Lot of difficulties has been experienced by previous researchers for turning of Nickel alloys. Following researchers have been studied machining of Nickel and other difficult-to-cut materials by using turning process.

Ulutan et al. conducted turning experiments on Nickel IN100 alloy by using multi objective particle swarm optimization by measuring output parameter as residual stresses [2]. Author found that objectives are solved for minimizing tensile residual stresses on the surface, maximizing peak compressive residual stresses, and minimizing the variance of these variables in order to increase certainty in the predictions. Xue et al. carried out to investigate the performance and the wear mechanisms of PVD-TiAlN coated carbide tool in machining of nickel-based alloy GH4169 [3]. Author concluded that the adhering layer protected tool surfaces from the scrubbing action of hard carbide particles contained in the GH4169 alloy, by covering the surface rather than exposing it to the underside of chip or the transient face of work during machining. Luo et al. conducted turning experiments on Nickel G-3 alloy and studied wear behaviour accordingly. Author found crater and groove wear on tool nose and also seen water-solubility enriched coolant has much better behaviors in turning [4]. Jagtap et al. carried out dry turning experiments on pure Nickel alloy by Taguchi DOE [5]. It was found that spindle speed is having statistical significant effect on machined surface flatness.

Jagtap et al. carried out turning experiments on Co-Cr-Mo alloy (difficult-to-cut material) by using dry cutting environment [6-10]. Author found that feed rate is having significant effect on machined surface roughness by using Taguchi DOE also carried out electrochemical tests on machined specimens for finding out corrosion rate [6]. Also author machined specimens by using Response Surface Methodology (RSM) in dry turning and found that feed rate and cutting speed both have significant effect on machined surface roughness [7]. Author analysed chip dimensions and correlated it to machined surface integrity and concluded that feed rate is having dominating effect on chip thickness ratio [9]. Author analysed cutting force during machining of Co-Cr-Mo alloy and reported that feed rate and cutting speed are having dominating effect on cutting force and correlated it with surface integrity [10].

Therefore, the main objective of the paper is that to optimize the process parameter by using RSM to get the better surface roughness can be useful to manufacture aero parts. Present research focuses the application of RSM in face turning of pure Nickel alloy with CBN inserts by CNC machine and developing mathematical model of surface roughness (*Ra*).

II. RESPONSE SURFACE METHODOLOGY (RSM)

RSM is a collection of mathematical and statistical methods that are helpful for the modelling and analysis of problems in which a response of attention is prejudiced by a number of variables and the purpose is to optimize this response. RSM also computes relationships among one or more measured responses and the crucial input parameters. Statistical software has been used to extend the experimental preparation for RSM. After analyzing each response, multiple response optimization have been carried out, either by assessment of the interpretation plots, or with the graphical and statistical tools offered for this purpose. It was revealed previously that RSM designs also helps in computing the bond between single or multiple considered responses and the fundamental input parameters. In order to resolve if there exist a relationship between the aspects and the response variables considered, the data composed must be analysed in a statistically sound approach using regression. A regression is carried out in order to illustrate the data gathered whereby an observed, experimental variable (response) is approximated based on a practical relationship among the predictable variable, y_{est} and single or multiple regressor or key variable x_1, $x_2, \ldots\ldots x_i$. In the case, if there exist a non-linear relationship between a meticulous response and three input variables, it is expressed by a quadratic equation as given in equation 1.

$$y_{est} = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_1x_2 + b_5x_1x_3 + b_6x_2x_3 + b_7x_1^2 + b_8x_2^2 + b_9\,x_3^2 + error \qquad (1)$$

It may be used to illustrate the practical relationship between the predictable variable, y_{est} and the key variables x_1, x_2 and x_3. The least square technique is being used to fit a model equation including the supposed regressors or input variables by minimizing the residual error considered by the addition of square variations between the definite and the estimated responses. The calculated coefficients or the model equation necessitate to however be tested for algebraic significance. In this respect, the test for significance of the regression model, test for significance on individual model coefficients and test for lack-of-fit are carried out accordingly.

The Design Expert® software (Stat-Ease Inc; USA) version 9.0.6.2 is used to develop the experimental plan for RSM. The software is also used to analyze data gathered from experimentation. The RSM was employed for modeling and analyzing machining parameters in dry face turning process as well as polishing process in order to obtain the machinability performances in terms of surface roughness.

III. EXPERIMENTAL DETAILS

Initially face turning process was employed to determine the machinability of Nickel alloy in dry cutting environment. A production type CNC turning precision lathe (Model Jobber XL Make Micromatic, India) having maximum spindle speed 5000 rpm and 13 KW capacity was used for machining the samples. Fig. 1 shows the schematic of the experiment for machining of Nickel alloy.

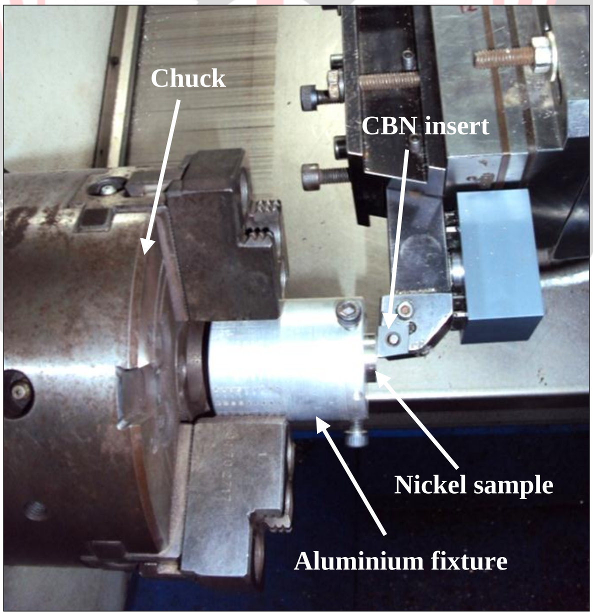


Fig. 1. Closed view set up of precision turning of Nickel Alloy

CBN is used to machine difficult-to-cut materials. The inserts used for machining were manufactured by Kyocera® Korea with ISO designation of CNGA120404 S01225 ME (80 degree rhombic insert/negative). The objective of experimental design is to reduce the test activity and utilize the result quality. In the present work, the experimental data have been collected by the face centered, CCD method. The factorial fraction of the CCD is a full factorial design with all mixtures of factors at two levels (low -1 and high +1). The star points at face of the cubic fraction on the design corresponding to a value of 1. This type of design is generally called as face centered. Table 1 shows the cutting parameters with the design layout with experimental results. Dimensions of samples exactly made to size Ø20 X 10 mm thickness. An aluminium turning fixture was fabricated having size of Ø60 X 110 mm length to make easy holding of substrates during turning operation (See Fig. 1). For considering the environment care, all the samples were machined in dry cutting environment as per the experimental design given in Table 1 in a single block of RSM. After CNC machining experiment, the machined surfaces have been measured to analyse profile on surface tester having model: SRT-1 made by MGW precision, India. Each machined surface was measured at three different locations. The 2D profiles were traced for the 10 mm assessment length with 0.25 mm sampling length at three point locations.

Table 1 Design layout for machining of Nickel alloy with experimental results

Std. sample number	**Run sequence**	**Block**	**Depth of cut, a_p** (mm)	**Cutting speed, V_c** (m/min)	**Feed rate , *f*** (mm/rev)	***Surface roughness, Ra*** (μm)
6	1	1	0.6	0.15	150	1.02
3	2	1	0.2	0.2	200	1.07
10	3	1	0.4	0.15	200	1.11
9	4	1	0.4	0.15	100	0.93
2	5	1	0.6	0.1	200	1.09
11	6	1	0.4	0.15	150	0.89
7	7	1	0.4	0.1	150	1.01
15	8	1	0.4	0.15	150	0.95
8	9	1	0.4	0.2	150	0.96
12	10	1	0.4	0.15	150	0.94
13	11	1	0.4	0.15	150	0.92
4	12	1	0.2	0.1	100	1.04
14	13	1	0.4	0.15	150	0.9
1	14	1	0.6	0.2	100	1.15
5	15	1	0.2	0.15	150	0.95

IV. RESULTS AND DISCUSSION

The results from the machining trials performed as per the experimental plan are shown in Table 1. These results were input into the Design Expert® software (Version: 9.0.6.2) for further analysis. Without conducting any transformation on the response, examination of the fit review output revealed that the quadratic model is significant for surface roughness, *Ra* therefore it will be used for further analysis. Table 2 shows the ANOVA table for response surface quadratic model for surface roughness. The value of "Prob. > *F*" in Table 2 for model is less than 0.05 which indicates that the model is significant, which is desirable as it indicates that the terms in the model have a significant effect on the response.

Table 2. ANOVA table (partial sum of squares) for response surface quadratic model for surface roughness, *Ra*

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value (Prob > F)**	**Significance**
Model	0.089	9	9.871E-003	11.95	0.0069	significant
A-Depth of cut	2.450E-003	1	2.450E-003	2.96	0.1457	-
B-Feed rate	1.250E-003	1	1.250E-003	1.51	0.2734	-
C-Cutting speed	0.016	1	0.016	19.60	0.0068	significant
AB	0.013	1	0.013	15.34	0.0112	significant
AC	3.008E-003	1	3.008E-003	3.64	0.1147	-
BC	8.333E-006	1	8.333E-006	0.010	0.9239	-
A^2	4.823E-003	1	4.823E-003	5.84	0.0604	-
B^2	4.823E-003	1	4.823E-003	5.84	0.0604	-
C^2	0.016	1	0.016	19.23	0.0071	significant
Residual	4.132E-003	5	8.264E-004	-	-	-
Lack of Fit	1.532E-003	1	1.532E-003	2.36	0.1995	not significant
Pure Error	2.600E-003	4	6.500E-004	-	-	-
Cor Total	0.093	14	-	-	-	-
Std. Dev.	0.029	-	R-Squared	0.9556	-	-
Mean	1.00	-	Adj R-Squared	0.8756	-	-
C.V. %	2.89	-	Pred R-Squared	-2.7418	-	-
PRESS	0.35	-	Adeq Precision	10.156	-	-

In the same manner, the main effect of cutting speed (*C*), and second order effect of cutting speed (C^2) are significant model terms. Other model terms are not statistically significant. These insignificant model terms (not counting those required to support hierarchy) can be removed and may result in an improved model. The R^2 value is high which is desirable. The predicted R^2 is in reasonable agreement with the adjusted R^2. The adjusted R^2 value is particularly useful when comparing models with different number of terms. This comparison is however done in the background when model reduction is taking place. Adequate precision compares the range of the predicted values at the design points to the average prediction error.

The following equation (2) is the final empirical model in terms of actual factors for surface roughness, *Ra*.

$$Ra = 2.247 - 1.433\ \text{depth of cut} - 9.702\ \text{feed rate} - (5.80 \times 10^{-3})\ \text{cutting speed} + 9.75\ (\text{depth of cut} \times \text{feed rate}) - (4.75 \times 10^{-3})\ (\text{depth of cut} \times \text{cutting speed}) + (1.0 \times 10^{-3})\ (\text{feed rate} \times \text{cutting speed}) + 1.073\ \text{depth of cut}^2 + 17.176\ \text{feed rate}^2 + (3.117 \times 10^{-5})\ \text{cutting speed}^2 \qquad (2)$$

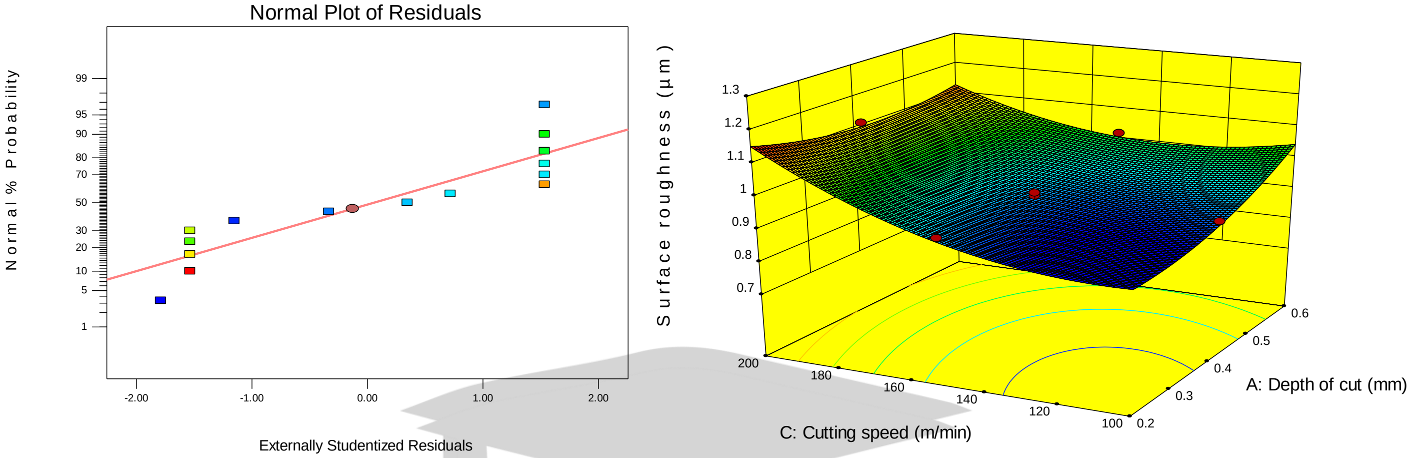
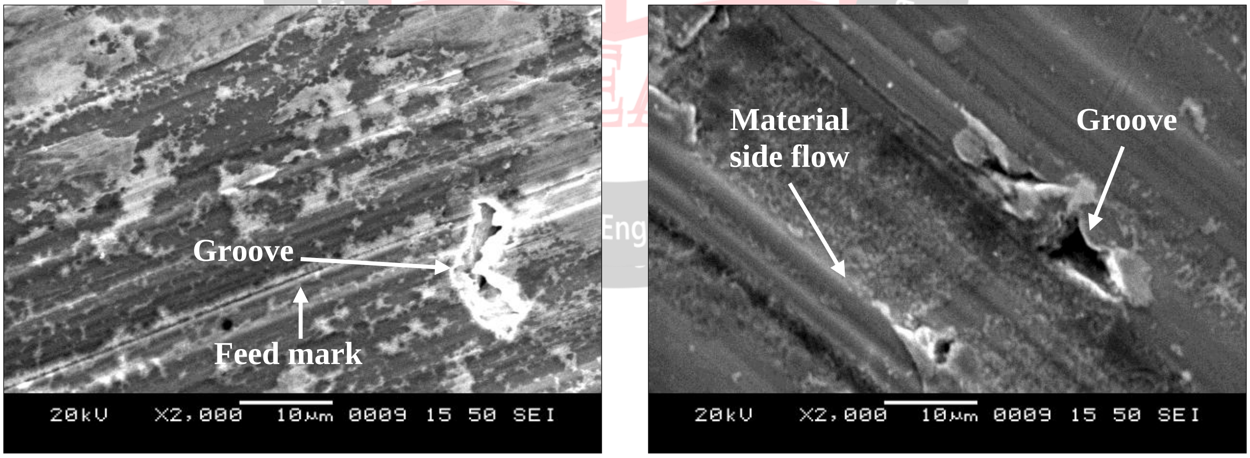


Fig. 2. (a) Normal Probability Plot, and (b) Response Surface 3D Plot for surface roughness, *Ra*

After the formulation of quadratic model of surface roughness (*Ra*), the model adequacy checking was performed in order to verify that the underlying assumption of regression analysis is not violated. The normal probability plot of the residuals for surface roughness is shown in Fig. 2 (a). It illustrates the normal probability plot of the residual, which shows no sign of the violation since each point in the plot follows a straight line pattern implying that the errors are distributed normally. This implies that the models proposed are adequate and there is no reason to suspect any violation of the independence or constant variance assumption. In order to investigate the influence of machining parameters on the surface roughness, the three-dimensional response surface plot is analysed as shown in Fig. 2 (b). It represents the influence of machining parameter cutting speed on the surface roughness during machining. It is found that as the cutting speed increases then surface roughness is also increases. This is attributed to the fact that as the cutting speed is increases the friction between tool and workpiece is also increases and it affects the machined surface accordingly [7].



(a_p=0.2 mm, V_c=200 m/min, f=0.2 mm/rev)
(a)

(a_p=0.4 mm, V_c=150 m/min, f=0.15 mm/rev)
(b)

Fig. 3. (a and b) SEM micrographs of machined surfaces of Nickel alloy

Also Fig. 3 (a and b) shows the SEM micrographs of machined surfaces of Nickel alloy. It is seen that higher cutting speed shows more feed marks on machined surfaces than lower cutting speed.

V. CONCLUSIONS

In this research, the quadratic model for surface roughness (*Ra*) has developed so as to investigate the influences of machining parameters of Nickel alloy. The effect of machining parameters such as depth of cut, feed rate and cutting speed were evaluated by using RSM. The surface roughness increases with increase in cutting speed. This is attributed to the fact that as the cutting speed is increases the friction between tool and workpiece is also increases and it affects the machined surface accordingly. The

ANOVA of surface roughness revealed that cutting speed is influencing the response variable investigated. Also, second order effect of cutting speed (C^2) is significant model term. The R^2 value is high which is desirable. It is seen that higher cutting speed released maximum surfaces alterations with higher surface roughness values and lower cutting speed released minimum surface alterations with lower surface roughness values.

VI. ACKNOWLEDGMENT

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