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STUDY ON THE MACHINABILITY CHARACTERISTICS DURING HIGH-SPEED TURNING OF INCONEL 718 WITH PVD COATED TOOL

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ABSTRACT

Nickel-based Superalloy, Inconel 718 is difficult-to-cut material due to its properties like low thermal conductivity, work hardening etc. and retains its strength at high temperatures. This paper presents an optimization approach for determination of the optimum cutting parameters which minimize the machinability characteristics such as Surface Roughness and Temperature in High Speed turning of Inconel 718 using SECO make PVD coated tungsten carbide tool SNMG 120408 TS 2000. An exhaustive experimental study has been conducted with various cutting parameters like speed, feed and depth of cut with three levels each. Optimization has been carried out by using Taguchi method. Also the significant cutting parameters have been found out for the process optimization by performing an ANOVA. Confirmation tests with the optimal levels of cutting parameters are carried out in order to illustrate the effectiveness of the method. JMP statistical software was used to compare the results. Validations of the modeled equations are proved to be well within the agreement with the experimental data.

Keywords: *Inconel 718, High speed machining and JMP Statistical software*

1. Introduction

A superalloy, or high performance alloy, is an alloy that exhibits excellent mechanical strength and creep resistance at high temperatures, good surface stability and corrosion and oxidation resistance [1]. Super alloys are metallic materials for service at high temperatures, particularly in the hot zones of gas turbines. Superalloys typically have a matrix with an austenitic face-centered cubic crystal structure. A superalloy's base alloying element is usually nickel, cobalt, or nickel-iron. Superalloy development has relied heavily on both chemical and process innovations and has been driven primarily by the aerospace and power industries. Typical applications are in the aerospace, industrial gas turbine and marine turbine industry, e.g. for turbine blades [2] for hot sections of jet engines, and bi-metallic engine valves for use in diesel and automotive applications.

Machining of this alloy is quite difficult for its high strength, work hardening and poor thermal properties. Although these properties are desirable design requirements, they pose a greater challenge to manufacturing engineers due to the high temperature and stresses generated during machining. Hence it is called as "Difficult-to-cut material". Fig.1. shows the high speed cutting ranges in machining of various materials and reveals that when the cutting speed is more than 40m/min it becomes high speed machining for nickel alloys [3-7].

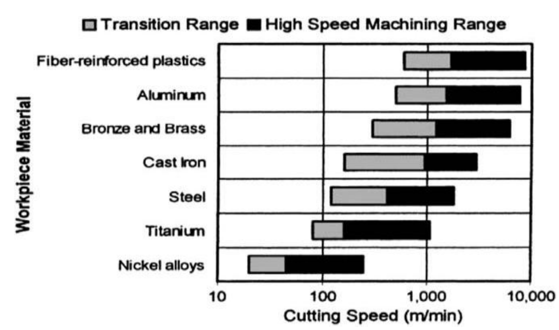

Fig. 1 High-Speed Cutting Ranges in Machining of Various Materials

Coatings improve the performance of carbide tools. Coatings are hard materials and therefore provide a good abrasion resistance. They have excellent high temperature properties such as high resistance to diffusion wear, superior oxidation wear resistance and

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high hot hardness. The good lubricating properties of the coatings minimize friction at the tool-chip and tool-workpiece interfaces, thus in some cases, reduce cutting temperature. Coating material also lowers the forces generated during machining relative to uncoated tools. Higher cutting speeds can be achieved with coated carbide tools when machining aero engine alloys. This area has attracted a lot of research interest and substantial work has been carried out to determine the effects of coatings on tool performance. Typical coating materials used include TiC, TiN, Al_2O_3, TiCN, TiAlN, TiZrN and recently introduced diamond coatings. It is estimated that 40 % of all cutting tools used in the industry are coated and 8 %of them are used for machining purpose. In comparison with the TiN and TiCN coatings, it has been shown that the PVD (TiN, TiAlN) coating is most suitable in dry machining of difficult-to-cut materials such as Inconel 718. Superior oxidation resistance, high temperature chemical stability, high hot hardness and low thermal conductivity are the principal reasons of its performance. Recently, a TiN/AlTiN nanolayer coating gave good results when machining Inconel 718 with low BUE phenomenon and reduced abrasion wear [8].

The applications in which the concept of Signal to Noise (S/N) ratio is useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio is divided into three categories- smaller the better, nominal the best and larger the better. The higher S/N ratio shows the better result [9-10]. The treatment of the experimental result is based on the analysis of average and analysis of Variance (ANOVA) [11-12].

JMP is statistical software [13] that gives a graphical interface to display and analyze data. The mission of JMP is to help researchers to analyze and make discoveries in their data. The main purpose of using JMP software here is to analyze the data with Taguchi design method. By using JMP software the analysis of data can be done in very short period of time and also it generates different graphical plots.

2. Methodology

The present work attempts to understand and evaluate the machinability of Inconel 718 considering the practical difficulties. The process parameters surface roughness and cutting temperature were used as response characteristics and are optimized using Taguachi method. Hence, “lower the better” S/N ratio characteristic was chosen for the process parameters. ANOVA analysis has been done to analyze the effect of cutting parameters on process parameters. A multiple linear regression mathematical model was developed based on the response characteristics cutting temperature and surface roughness. The model was validated by carrying out a confirmation test. The results were compared with JMP statistical software and are justified.

2.1 Machining performance measure

2.1.1 Surface roughness (SR)

The machined surface roughness was measured by a Mitutoyo make Surftest SJ201 (Fig 2) surface roughness tester of sampling length 0.8mm and least count of 0.01µm. The result of the surface roughness depends on the stylus path direction. For this reason the roughness were measured several times and averaged and expressed in microns (µm).

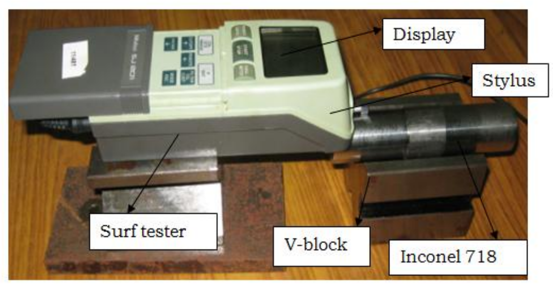

Fig. 2 Surface Roughness Profilometer

2.1.2 Temperature

Temperature measurements were carried out using a non-contact standard K- type thermocouple and specially modified tool holder for placing it in the top portion of the tool holder (Fig 3).

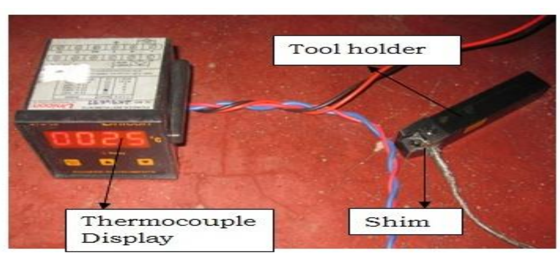

Fig. 3 Temperature Measurement Set Up

3. Design of Experiments

Design of experiment is a powerful tool for analyzing the influence of the process variables over a specific variable, which is an unknown function of these process variables. Taguchi-based method is used for analysis. Design based on Taguchi method design involves selection of response variables, independent variables, their interactions and an orthogonal array. Standard L9 orthogonal array was selected for conducting the experiments**.**

4. Experimental Details

4.1 Tool and work piece

In this work, experiments have been carried out using SECO make PVD coated tungsten carbide cutting tool SNMG 120408 TS 2000 (Table 1). Table 2 shows the tool nomenclature.

Table 1: Specifications of the Cutting Tools

Tool	Specification	Grade	Tool Holder
TiN/TiAlN PVD Coated	SNMG 120408	TS 2000	PSBNR 2020 K12

Table 2: Tool Nomenclature

Rake angle (γ)^0	-6
Clearance Angle (α)^0	6
Inclination angle (λ)^0	-6
Approach angle (ψ)^0	75
Included angle (β)^0	90
Nose radius (r)mm	0.8

The work material used was Inconel 718 (Fig 4). The major elements in the Inconel 718 are (Ni = 54.48 %, Cr = 17.5%, Nb = 4.9%, Al = 0.66 %, Ti = 0.96% balance are Fe and other (Composition was given by the supplier).

Fig. 4 Inconel 718 Bar (Machined)

4.2 Experimental setup and cutting conditions

Machining tests were carried out on a GADEE WEILER LZ350 Conventional Lathe (Fig. 5) under dry cutting conditions by varying cutting parameters such as cutting speed (V_c), feed (f), and depth of cut (d). Based on the preliminary experiments, the parameters and the corresponding levels chosen for the investigations are shown in Table 3.

Fig. 5 Experimental Set-up

Table 3: The Machining Parameters and their Levels

Parameters	LEVEL 1	LEVEL 2	LEVEL 3
Cutting Speed, V_c (m/min)	50	60	70
Feed, f (mm/rev)	0.103	0.137	0.164
Depth of Cut, d(mm)	0.5	0.75	1

5. Experimental Results and Analysis

Table 4 and table 5 show the experimental results of Surface Roughness and Cutting Temperature.

Table 4: Surface Roughness Values

Ex. No	**Surface Roughness (R_a)**		
	Run 1	**Run 2**	**Avg**
1	0.625	0.925	0.775
2	1.075	1.11	1.0925
3	1.29	1.325	1.3075
4	0.75	0.93	0.84
5	0.74	0.825	0.7825
6	0.77	0.94	0.855
7	0.82	0.89	0.855
8	0.76	0.72	0.74
9	1.375	1.405	1.39

Table 5: Cutting Temperature Values

Ex. No	Cutting Temperature (°C)		
	Run 1	**Run 2**	**Avg**
1	472	473	472.5
2	552	554.2	553.1
3	613	611	612
4	531	532.5	531.75
5	595	594	594.5
6	566	568.2	567.1
7	610	608.6	609.3
8	613	615	614
9	649	652.3	650.65

Table 6: Response Table for Signal to Noise Ratio Smaller is Better (Surface roughness)

FACTORS	LEVEL 1	LEVEL 2	LEVEL 3
CUTTING SPEED	-0.3483	1.63344	0.36826
FEED	1.62416	1.32	-1.29082
DEPTH OF CUT	1.994803	-0.72183	0.3804

ANOVA is performed to analyze the results and to find optimal conditions. The results are analyzed theoretically by choosing the 'lower the better' S/N ratio characteristic for Surface Roughness and Temperature. Tables 6 to 9 shows the results of the S/N ratios and ANOVA analysis and indicate that the Feed is the most influencing factor on the Surface roughness and the Cutting speed is the most influencing factor on the Cutting temperature.

Table 7: Analysis of Variance for Surface Roughness

FACTOR	S.S	D.O.F (df)	M.S.S	F-RATIO (Calculated)	S.S'	P
CUTTING SPEED	0.173369	2	0.086685	10.44792	0.156776	15.19478
FEED	0.460386	2	0.230193	27.74465	0.443792	43.01258
DEPTH OF CUT	0.30675	2	0.153376	18.48611	0.290159	28.12236
ERROR	0.09127	11	0.008297	--	0.141046	13.67028
St	1.031774	17	0.478551	--	2.06354	100
MEAN	16.5792	1		--	--	--
ST	17.61098	18		--	--	--

Table 8: Response Table for Signal to Noise Ratio Smaller is Better (Cutting Temperature)

FACTORS	LEVEL 1	LEVEL 2	LEVEL 3
CUTTING SPEED	-54.6931	-55.0235	-55.909
FEED	-54.5663	-55.3675	-55.6917
DEPTH OF CUT	-54.7749	-55.2124	-56.6382

Table 9: Analysis of Variance for Cutting Temperature

FACTOR	S.S	D.O.F (df)	M.S.S	F-RATIO (Calculated)	S.S'	P
CUTTING SPEED	20352.39	2	10176.19	191.9122	20246.34	44.01788
FEED	16290.15	2	8145.074	153.6075	16184.1	35.1861
DEPTH OF CUT	8769.9	2	4384.949	82.69548	8663.847	18.83621
ERROR	583.278	11	53.02525	--	901.4293	1.959812
St	45995.71	17	22759.24	--	45995.71	
MEAN	6020219	1		--	--	--
ST	6066214	18		--	--	--

5.1 Selection of optimum set of conditions

` From the S/N Ratios and ANOVA analysis it is clearly observed that the surface roughness (Ra) is optimum at medium cutting speed and low feed and low depth of cut within the range selected. And at low cutting speed, low feed and low depth of cut the temperature is optimum. Table 10, 11 shows the optimum set of conditions for Surface Roughness and Temperature.

Table 10: Optimum Set of Conditions for Surface Roughness

Control Factor	Cutting Speed	Feed	Depth of Cut
Optimum value	60 (m/min)	0.103 (mm/rev)	0.5 (mm)

Table 11: Optimum Set of Conditions for Cutting Temperature

Control Factor	Cutting Speed	Feed	Depth of Cut
Optimum value	50 (m/min)	0.103 (mm/rev)	0.5 (mm)

5.2 Verification experiment

Confirmation test was conducted with the optimum set of conditions, the predicted and confirmation tests S/N ratios are presented in Tables 12-15. The difference in the value of S/N ratios was with in 0.2 which is very reasonable degree of approximation.

Table 12: S/N Ratio for Surface Roughness

Run 1	Run 2	Avg.	S/N RATIO(dB)
0.59	0.57	0.58	4.730

Table 13: Comparison of S/N Ratios (Surface Roughness)

$\eta_{predicted}$ **(dB)**	4.150
$\eta_{confirmation}$ **(dB)**	4.730

Table 14: S/N Ratio for Cutting Temperature

Run 1	Run 2	Avg.	S/N RATIO(dB)
471	473	472	-53.479

Table 15: Comparison of S/N Ratios (Cutting Temperature)

$\eta_{predicted}$ **(dB)**	-53.94
$\eta_{confirmation}$ **(dB)**	-53.479

5.3 Analysis through JMP statistical software

The Standard Least squares Fit model was selected to analyze the data and the results are shown in the form of tables and figures.

5.3.1 Surface roughness

Table 16 and 17 indicates that the entire model and the factors Speed, Feed, Depth of Cut are significant. From the table values it is concluded that the feed has more influence on the surface roughness followed by depth of cut and speed to get minimum surface roughness.

Table 16: ANOVA Response Table for Surface Roughness (whole model)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	0.47025417	0.078376	44.2940
Error	2	0.00353889	0.001769	Prob > F
C.Total	8	0.47379306		0.0222*

Table 17: Effect Tests (Parameters)

Source	DF	Sum of Squares	F Ratio	Prob > F
Speed	2	0.08668472	24.4949	0.0392*
Feed	2	0.23019306	65.0467	0.0151*
Depth of Cut	2	0.15337639	43.3403	0.0226*

Fig 6-9 shows whole Model Leverage Plot and Factors Effect Leverage Plots for Surface Roughness. Fig. 7 indicates that the model and all factors speed, feed and depth of cut are significant and the data is fit to the model. The effect of factors on the surface roughness is showed by leverage plots. Fig 7-9 shows the leverage plots for speed, feed and depth of cut.

Prediction Profiler plot (Fig. 10) suggests that at medium cutting speed (60 m/min), low feed (0.103 mm/rev) and low depth of cut (0.5 mm) the surface roughness is less.

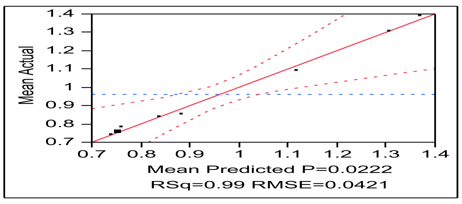

Fig. 6 Actual by Predicted Plot

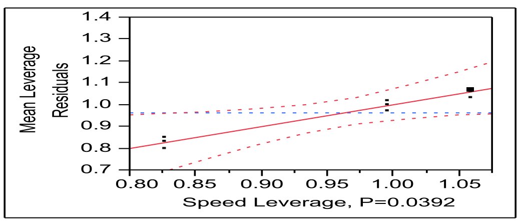

Fig. 7 Leverage Plot for Speed

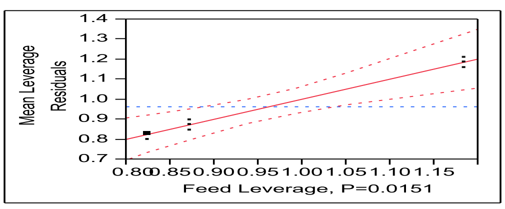

Fig. 8 Leverage Plot for Feed

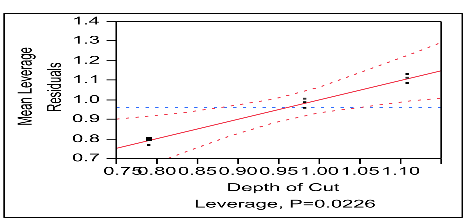

Fig. 9 Leverage Plot for Depth of Cut

Table 18: Optimized Cutting Parameters

Control Factor	Cutting Speed	Feed	Depth of Cut
Optimum value	60 (m/min)	0.103 (mm/rev)	0.5 (mm)

The optimized parameter levels are shown in table 18.

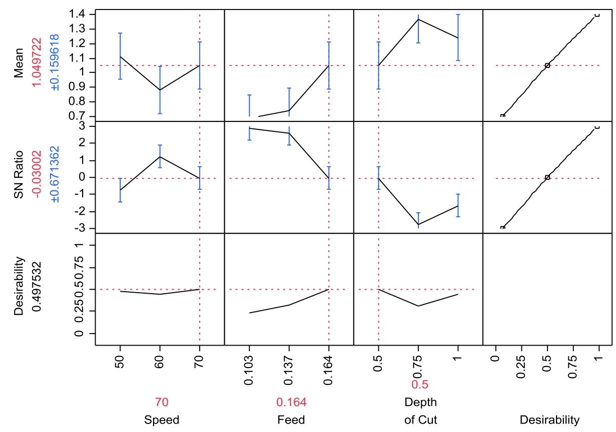

Fig. 10 Prediction Profiler

5.3.2 Cutting temperature

Tables 19 and 20 indicate that the Model and the factors Speed, Feed, Depth of cut are significant. From JMP ANOVA response table values it is concluded that the speed has more influence on cutting temperature followed by feed and depth of cut to get minimum cutting temperature.

Table 19: ANOVA Response Table for Cutting Temperature (whole model)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	23072.967	3845.49	36.8236
Error	2	208.861	104.43	Prob > F
C.Total	8	23281.827		0.0267*

Table 20: Effect Tests (Parameters)

Source	DF	Sum of Squares	F Ratio	Prob > F
Speed	2	9980.6106	47.7860	0.0205*
Feed	2	8290.7406	39.6951	0.0246*
Depth Of Cut	2	4801.6156	22.9896	0.0417*

Fig. 11 indicates that the model and all factors speed, feed and depth of cut are significant and the data is fit to the model. The effect of factors on the Cutting Temperature is showed by leverage plots. Fig 12-14 shows the leverage plots for speed, feed and depth of cut.

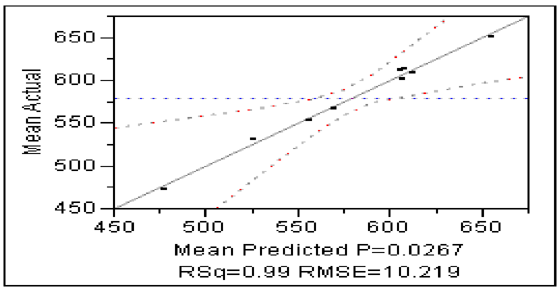

Fig. 11 Actual by Predicted Plot

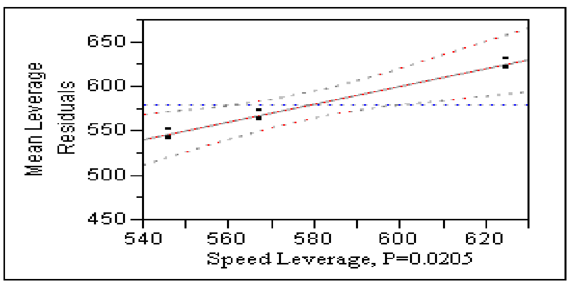

Fig. 12 Leverage Plot for Speed

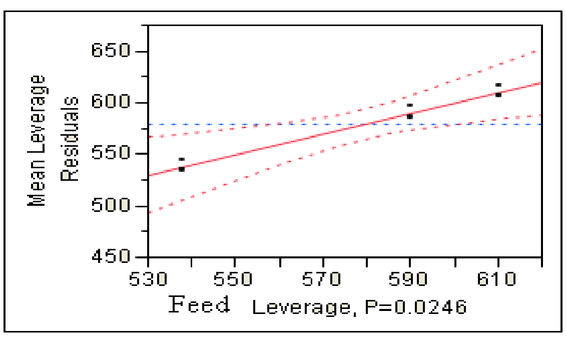

Fig. 13 Leverage Plot for Feed

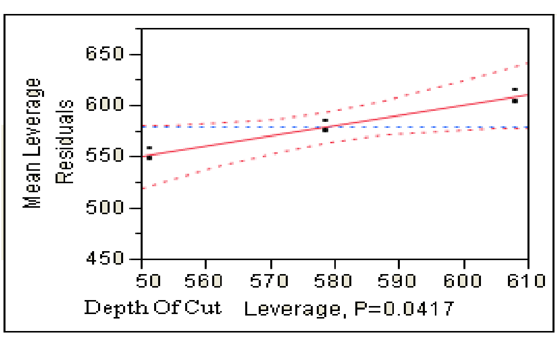

Fig. 14 Leverage Plot for Depth of Cut

Fig 15 suggests that choosing the low cutting speed (50 m/min), low feed (0.103mm/rev) and low depth of cut (0.5mm) based on smaller the better characteristics result in lower cutting temperature.

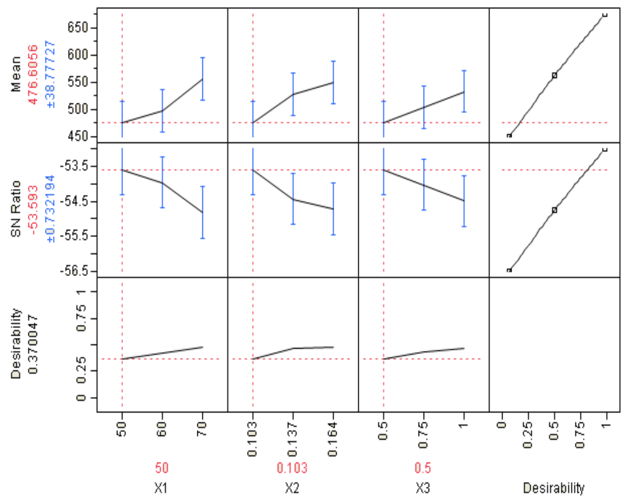

Fig. 15 Prediction Profiler

The optimized parameter levels are shown in table 21.

Table 21: Optimized Cutting Parameters

Control Factor	Cutting Speed	Feed	Depth of Cut
Optimum value	50 (m/min)	0.103 (mm/rev)	0.5 (mm)

5.4 Comparison of contribution of cutting parameters on machinability characteristics from ANOVA (theoretically calculated) and JMP Statistical software

In JMP statistical software, the cutting parameters, which has very low value has higher effect on machinability characteristic. In ANOVA (theoretically calculated), the higher value of the cutting parameter has higher effect on machinability characteristic.

The contribution of cutting parameters on machinability characteristics from ANOVA (theoretically calculated) and JMP statistical software are listed in the table 22. From table 22 and it is concluded that the results are tallied.

Table 22: Comparison of results from ANOVA and JMP statistical software

	JMP(contribution) Prob > F			ANOVA(% of contribution)		
	Speed	**Feed**	**DOC**	**Speed**	**Feed**	**DOC**
Surface Roughness (µm)	0.039 Low	0.015 High	0.022 Medium	15.194 Low	43.012 High	28.122 Medium
Cutting Temperature (°C)	0.027 High	0.033 Medium	0.06 Low	44.017 High	35.186 Medium	18.836 Low

5.5 Regression mathematical model for various parameters

The multiple linear regression equations obtained for Surface Roughness (Eq.-1) and Cutting Temperature (Eq.-2) are as follows:

Surface Roughness, Ra (µm) = 0.09135-0.00276 *(s) +5.724521 *(f) +0.38333* (d) ……………..(1)
R^2= 0.959934

Cutting Temperature, T (°C) = 100.2303+3.93916* (s) +1192.886 * (f) +108.1333 * (d) ………….. (2)
R^2= 0.942632.

5.6 Effect of feed and depth of cut on surface roughness at constant speed 70m/min

ANOVA and JMP conclude Feed has more effect on surface roughness than depth of cut and speed. Fig. 16 shows the influence of feed and depth of cut on surface roughness at constant speed 70m/min during dry turning of Inconel 718. During turning it was observed sometimes higher value of roughness due to the presence of hard carbide particles present in the matrix. The surface roughness increased with higher feed rates in all machining conditions. In general, it is found that surface roughness increases with an increase in the feed rate and depth of cut and a decrease in cutting speed. Roughness is found to reduce drastically up to a particular critical value of surface speed which is attributed to the reduction in size of the built up edge. At this speed, when the effect of the built up edge is considered negligible, the profile of the cutting edge of the tool (pointed or curved) gets imprinted on the work surface, and the surface roughness from this point on depends on the feed rate. A larger depth of cut, or in other words a larger chip cross-sectional area adversely affects surface finish though it is usually not significant until it is large enough to cause chatter. It is noted that the effect of increased feed is more pronounced on surface finish than the effect of an increased depth of cut. Thus, measures for improving machining productivity (increasing feed and depth of cut) work against achieving better surface quality.

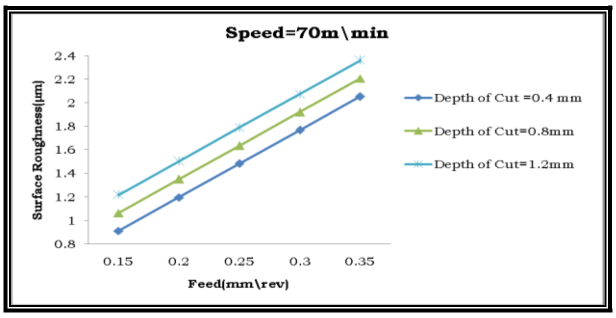

Fig. 16 Influence of Feed on Surface Roughness

5.7 Effect of speed and feed on cutting temperature at depth of cut 0.5mm

Fig. 17 shows the variation of temperature with various cutting speeds and feed rates at constant depth of cut. As the speed and feed increases the temperature is increasing at a constant depth of cut. It is due to the fact that temperatures in the cutting zone considerably affect the stress-strain relationship, fracture and the flow of the work piece material. Generally, increasing temperature decreases the strength of the workpiece material and thus increasing its ductility. When cutting at higher speed, the strain rate in the shear zone would be expected to be high, thus more heat energy would be generated, resulting in a higher temperature at the tool-chip interface. Also, the increase in temperature is more likely due to more energy consumed by the system during cutting, especially at higher cutting speeds. Furthermore, the chip sliding velocity also increased at higher cutting speed resulting in higher temperature generated along the tool-chip interface. Apart from this as the speed increases, the time for heat dissipation decreases and thus temperature rises.

6. Conclusions

In this experimental study, the work material chosen was Superalloy Inconel 718 which is a costly material and has got poor machinability. Therefore, the selections of optimal cutting parameters are important to produce quality components and to minimize the higher unit cost. Keeping in mind the applications of this material, the following conclusions are drawn based on the experimental study and JMP statistical software data analysis.

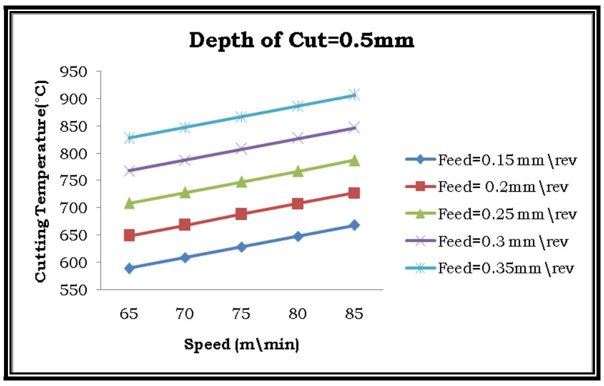

Fig. 17 Influence of Cutting Speed on Surface Roughness

a) The optimal cutting conditions were selected by varying cutting parameters through the Taguchi parameter design method. The results indicated that the Taguchi parameter design was an efficient way of determining the optimal cutting parameters for surface roughness and cutting temperature. JMP statistical software also reveals the same.
b) The optimum set of cutting parameters for surface roughness found are Cutting speed: 60 m/min, Cutting feed: 0.103 mm/rev and Depth of cut: 0.5 mm from the range selected. Feed has much effect on surface roughness than the depth of cut and speed.
c) The optimum set of process parameters for cutting temperature found are Cutting speed: 50 m/min, Cutting feed: 0.103 mm/rev and Depth of cut: 0.5 mm from the range selected. Cutting speed has much effect on cutting temperature than the feed and depth of cut.

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