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An experimental analysis of effective high speed turning of superalloy Inconel 718

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Abstract Superalloy, Inconel 718 is widely used in the sophisticated applications due to its unique properties. However, machining of such superior material is difficult and costly due its peculiar characteristics. The present article is an attempt to suggest Taguchi optimization technique to study the machinability of Inconel 718 with respect to cutting force, cutting temperature, and tool life in high speed turning of Inconel 718 using cemented tungsten carbide (K20) cutting tool. Therefore, the objective of this work is divided into two phases: (i) to demonstrate a correlation between cutting speed, feed, and depth of cut with respect to cutting force, cutting temperature, and tool life in a process control of high speed turning of Inconel 718 in order to identify the optimum combination of cutting parameters; (ii) to show the effect of high speed cutting parameters on the tool wear mechanism and chip analysis. These correlations were obtained by multiple linear regressions. The confirmation tests were carried out to make a comparison between the experimental results and mathematical models proposed. The proposed models agree well with the experimental results.

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Introduction

Turning process is a widely used operation in the engineering industry. Mostly the cutting parameters are selected based on the experience or by use of handbook. However, this does not guarantee that the selected parameters are optimal one. Selection of wrong or non optimal parameters leads to the wastage of raw material, man power, electricity, cutting fluid, cutting tools, etc. Hence, there is an increase in manufacturing cost of the product.

Most of the literature advocates the various mathematical models to select the cutting parameters properly based on the statistical regression techniques or neural computing techniques. All these techniques require in-depth knowledge and experience to formulate the model. At the same time it requires sufficient data to validate the model. Thus, the formulation of model becomes costly in terms of time and material.

Taguchi method is a powerful design of experiment (DOE) tool for manufacturing/engineering optimization of a process. 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 characteristics are divided into three categories when the characteristic is continuous: (i) smaller the better characteristics, (ii) larger the better characteristics, and (iii) nominal the best characteristics. For each type of the characteristics, with the above S/N ratio transformation, the higher the S/N ratio the better is the result [1, 2].

Nickel and nickel-based alloys especially Inconel 718 is widely used in many industries, owing to its unique properties such as high oxidation resistance, corrosion resistance even at very high temperatures, and retains a high mechanical strength under these conditions as well [3]. However, Inconel 718 is considered to have poor machinability due to a peculiar characteristic such as lower thermal conductivity, work hardening, presence of abrasive carbide particles, hardness, affinity to react with tool material, etc., which makes it difficult to machine and consequently more expensive to machine than steels of equivalent hardness.

Most of the literature advocates that the use of different tool materials such as ceramic tool materials like Al_2O_3/TiC mixed ceramics, Si_3N_4 ceramics:Sialon, latest SiC whisker-reinforced Al_2O_3 ceramics (≈25% SiC whiskers), multi-layer (TiN/TiCN/TiN) coated carbide tools produced by the physical vapor deposition (PVD) technique, Cubic boron nitride (CBN) cutting tools, etc., appears to give better overall performance than cemented tungsten carbides while machining nickel-based alloys [4–7]. Though the performance wise for the above mentioned tools are better, their cost limits the use in the engineering applications.

Cemented tungsten carbide cutting tools are the oldest among the hard cutting tool materials. Cemented tungsten carbide tools are mainly used for continuous cutting operations. Over the years, the use of carbides for cutting tools has been established. Carbide tools are used to machine Inconel 718 in the speed range of 10–30 m/min. However, with the increasing demand to achieve fast material removal rate and better surface quality, high speed machining was introduced. For nickel-based alloys, the concept of high speed machining refers to speeds approximately over 40 m/min [8]. Considerable research and development efforts are directed worldwide toward improving the machining operations to ensure efficient and economic machining of Inconel 718 by proper understanding of the behavior of this exotic material while machining at high cutting conditions. However, machining of Inconel 718 remained a difficult problem. An effective approach is still not available.

Therefore, the objective of this work is divided into two phases: (i) to demonstrate a correlation between cutting speed (V_c), feed (f), and depth of cut (d) with cutting force (Fc), cutting temperature (CT), and tool life (TL) in a process control of high speed turning of Inconel 718 in order to identify the optimum combination of cutting parameters; (ii) to show the effect of high speed cutting parameters on the tool wear mechanism and chip analysis.

Taguchi method consists of a plan of experiments with the objective of acquiring data in a controlled way, executing these experiments, and analyzing data, in order to obtain information about the behavior of a given process. These techniques use orthogonal arrays to define the experimental plans. The treatment of the experimental result is based on the analysis of average and the analysis of variance (ANOVA) [9–11].

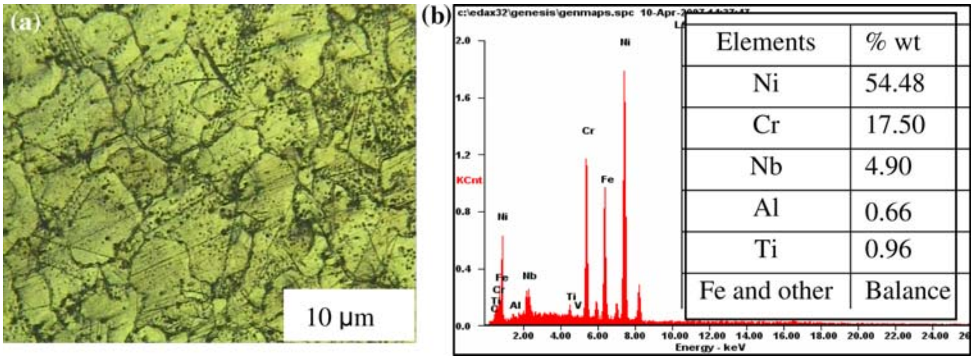
Multiple response characteristics such as Fc, CT, and TL were chosen as output parameters to understand thoroughly the machinability of Inconel 718 at high speed with cemented tungsten carbide (K20) insert tool.

Experimental details

The work material used was Inconel 718. Machining tests were carried out on a precision high speed VDF lathe under dry conditions. The microstructure (100×) and EDAX profile of Inconel 718 are shown in the Fig. 1a and b, respectively.

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 L8 orthogonal array was selected. Screening experiments were conducted so as to identify the suitable process parameters and their levels. The parameters and the corresponding levels chosen for the investigations are shown in Table 1.

The Fc was measured online during turning of Inconel 718 at high speed with a sensitive three component Kistler type dynamometer connected to a charge amplifier and a computer using a data acquisition card. Cutting temperature (CT) was measured using specially modified tool holder arrangement for placing an alumel/chromel thermocouple in



Elements	% wt
Ni	54.48
Cr	17.50
Nb	4.90
Al	0.66
Ti	0.96
Fe and other	Balance

Fig. 1 **a** Microstructure of Inconel 718; **b** EDAX profile of Inconel 718

Table 1 Parameters and their levels

Parameters	Levels	
	1	2
Cutting speed, V_c (m/min)	40	65
Feed, f (mm/rev)	0.08	0.125
Depth of cut, d (mm)	0.5	1

the top portion of the cutting tool holder. Thermocouple measuring point was 1–1.5 mm away from the cutting edge of the insert. This method was found to be far better than the work-tool thermocouple technique. The alumel/chromel thermocouple is capable of measuring temperature up to 1200 °C. The schematic arrangement of temperature measurement setup is shown in Fig. 2.

Design of experiment

Design of experiment is a powerful analysis tool for modeling and analyzing the influence of the process variables over some specific variable, which is an unknown function of these process variables. The major step in the Taguchi method is the selection of the factors affecting the performance measures [9–12]. The selected factors and their levels are mentioned in the Table 1. The performance measures selected for the experimentation were Fc, CT, and TL. The output parameters such as Fc, CT, and TL are the vital machinability indices in the machining of materials, hence selected for the analysis. Analysis of variance (ANOVA) is used to study the effect of process parameters and establish correlation among the V_c, f, and d respect to Fc, CT, and TL. Also tool wear and chip analysis were carried out. Experimental results are provided to confirm the effectiveness of Taguchi technique for high speed turning of Inconel 718.

Experimental results and data analysis

The objective of the experiments are to show the relationship between the high speed cutting parameters like V_c, f, and d and to optimize the high speed turning of Inconel 718 parameters to get lower Fc, CT, and higher TL. Interaction effects of the process parameters were also studied. Based on the analysis mathematical models were developed considering the interaction effects of the cutting parameters. The developed models were validated through the experimental confirmation tests. Table 2 shows standard L8 orthogonal array (OA) to obtain Fc, CT, and TL, respectively. L8 orthogonal array and cutting parameter

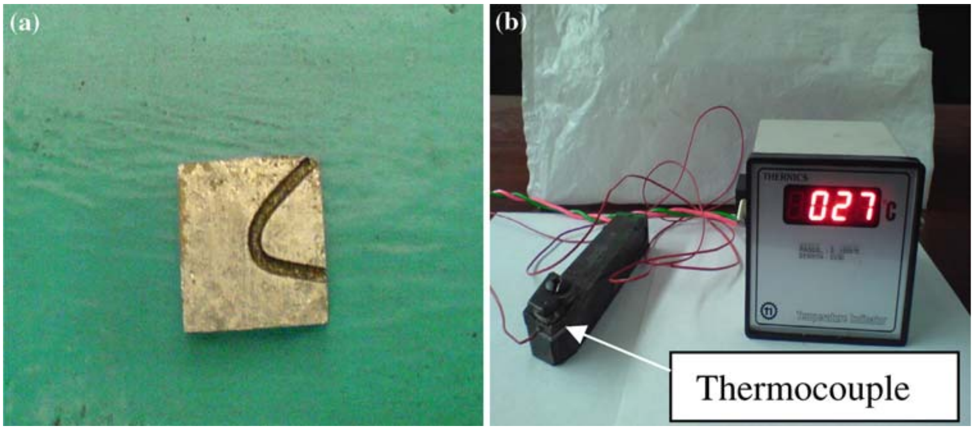


Fig. 2 Temperature measurement setup. **a** Modified shim, **b** Temperature measurement

Table 2 L8 orthogonal array of Taguchi for average of two replications for Fc, CT, and TL

Experiment Number	V_c (m/min)	f (mm/rev)	d (mm)	Fc (N)	CT (°C)	TL (s)
1	40	0.080	0.5	394	411	311
2	40	0.080	1.0	432	486	209
3	65	0.125	0.5	359	583	179
4	65	0.125	1.0	411	617	306
5	40	0.125	0.5	438	507	273
6	40	0.125	1.0	487	567	249
7	65	0.080	0.5	341	530	193
8	65	0.080	1.0	379	573	311

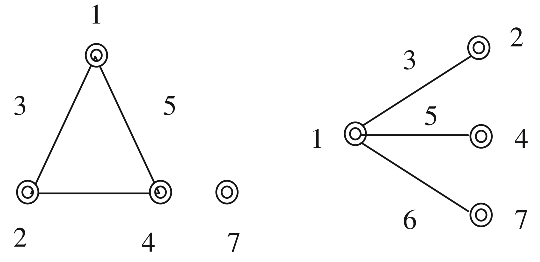


Fig. 3 Standard Linear graph for L8 OA

ranges were selected based on the exhaustive preliminary experimentation and knowledge of literature. A standard linear graph for L8 OA is shown in Fig. 3. The linear graphs are the graphic representations of interaction information in a matrix experiment. They make handy tools in the assignment of the different main factors and their interactions to the different columns of orthogonal arrays.

Cutting force analysis

The experimental results were analyzed with ANOVA, which is used for identifying the factors significantly affecting the performance measures [1, 2]. The results of ANOVA with the Fc, CT, and TL are shown in Tables 3, 4, and 5, respectively. This analysis was carried out for a significance level of $\alpha = 0.05$, i.e., for a confidence level of 95%. The parameters with a *p*-value less than 0.05 are considered to have a statistically significant contribution to the performance measures.

Analysis of variance for Fc using adjusted sum of squares (Adj SS) for tests is shown in Table 3.

Table 3 indicates that V_c, *f*, and *d* are more significant parameters which influence the Fc as their *p*-values are less than that of a significance level of $\alpha = 0.05$, i.e., for a confidence level of 95%. Among all three parameters more influencing parameter is V_c compared to *f* rate and *d*. Also looking at the interaction effect of ANOVA analysis the pair of V_c and *f* is more influential parameter. Figure 4 shows the effect of cutting parameters and their interaction effect on Fc.

Table 3 Analysis of variance for cutting force (N), using adjusted SS for tests

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*p*
Cutting speed, (V_c) (m/min)	1	8515.1	8515.13	8515.13	7569.00	0.007
Feed, *f* (mm/rev)	1	2775.1	2775.13	2775.13	2466.78	0.013
DoC, *d* (mm)	1	3916.1	3916.13	3916.13	3481.00	0.011
$V_c * f$	1	300.1	300.13	300.13	266.78	0.039
$V_c * d$	1	1.1	1.12	1.12	1.00	0.500
$f * d$	1	78.1	78.1	78.13	69.44	0.076
Residual error	1	1.1	1.13	1.13		
Total	7	15586.9				

DF degree of freedom, *p* statistical significance value

Table 4 Analysis of variance for cutting temperature (°C), using adjusted SS for tests

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*p*
Cutting speed, (V_c) (m/min)	1	13778.0	13778.0	13778.0	3061.78	0.012
Feed, *f* (mm/rev)	1	9384.5	9384.5	9384.5	2085.44	0.014
DoC, *d* (mm)	1	5618	5618	5618	1248.44	0.018
$V_c * f$	1	800.0	800.0	800.0	177.78	0.048
$V_c * d$	1	420.5	420.5	420.5	93.44	0.066
$f * d$	1	72.0	72.0	72.0	16.00	0.156
Residual error	1	4.5	4.5	4.5		
Total	7	30077.5				

Table 5 Analysis of variance for tool life, using adjusted SS for tests

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*p*
Cutting speed, (V_c) (m/min)	1	19900.1	19900.1	19900.1	165.66	0.049
Feed, *f* (mm/rev)	1	1953.1	1953.1	1953.1	16.26	0.155
DoC, *d* (mm)	1	2701.1	2701.1	2701.1	22.49	0.132
$V_c * f$	1	36.1	36.1	36.1	0.30	0.681
$V_c * d$	1	78.1	78.1	78.1	0.65	0.568
$f * d$	1	55.1	55.1	55.1	0.46	0.621
Residual error	1	120.1	120.1	120.1		
Total	7	24843.9				

Figure 5 response suggests that choosing the highest V_c (65 m/min) and lowest *f* (0.08 mm/rev) and *d* (0.5 mm) based on smaller the better characteristics result in lower Fc.

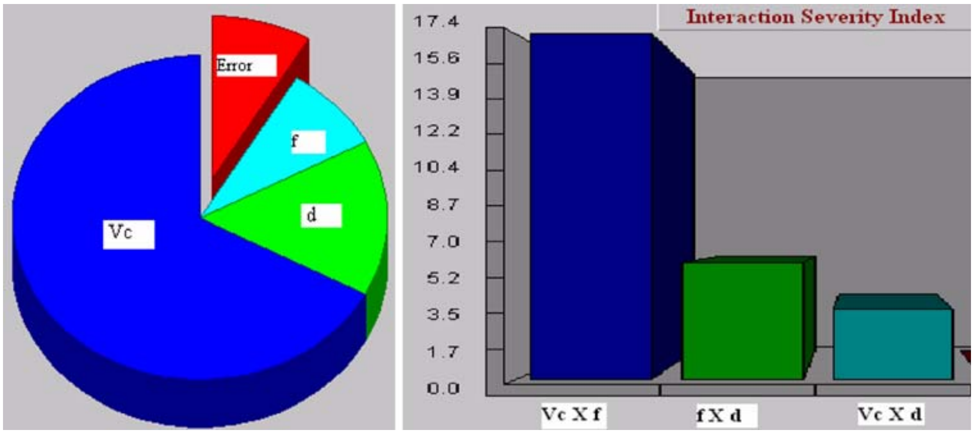
Cutting temperature analysis

Inconel 718 has low thermal conductivity (11.4 W/m K) and specific heat which leads to most of the problems associated with the machining of Inconel 718. The problems are attributed to the generation of CT during machining of Inconel 718 and hence early failure of the component such as fatigue, thereby reducing life of the component. Optimizations of the performance parameter are most important so as to minimize the possible problems associated with the machining of Inconel 718.

Analysis of variance for CT using adjusted sum of squares (Adj SS) for tests is shown in Table 4.

Table 4 indicates that the *p*-values of V_c, *f*, and *d* are less than $\alpha = 0.05$. It means that these parameters are statistically significant parameters. Also interaction effect between V_c

Fig. 4 Effect of cutting parameters and their interaction on cutting force



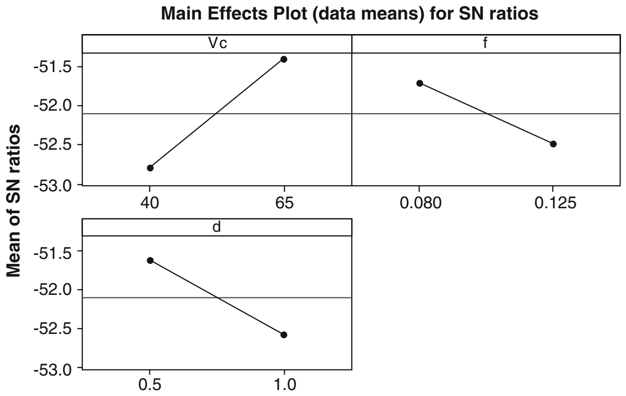


Fig. 5 Signal to noise (S/N) ratio graph for cutting force. Signal-to-noise: Smaller is better

and *f* are also statistically significant than that of V_c and *d*. The interaction effect between V_c and *d* have more *p*-value than that of $\alpha = 0.05$. The effect of cutting parameters and their interaction effect on CT is shown in Fig. 6.

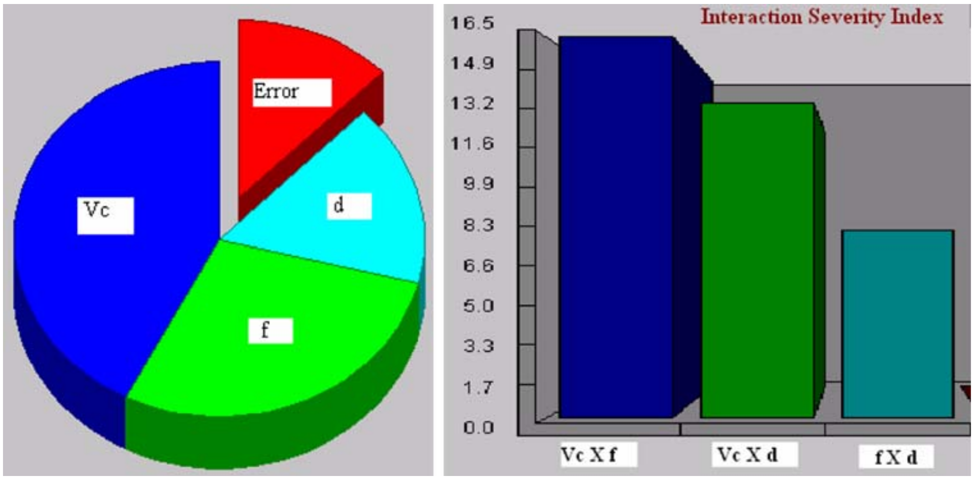
The S/N response graph is shown in Fig. 7. The CT with smaller the better quality characteristics suggests to get lower temperature with lowest V_c (40 m/min), *f* (0.05 mm/min), and lowest *d* (0.5 mm).

Tool life analysis

The cutting parameters such as the V_c, *f*, and *d* have different effects onto the cutting forces, tool life, tool wear, and surface quality.

From the ANOVA results (Table 5), it can be seen that the effect of process parameters such as the *f* and *d* is very negligent as its *p*-value is greater than 0.05. The most statistically significant factor is V_c. Among the two way interactions, the interaction effect in the decreasing order are (V_c * *d*), (*f* * *d*), and (V_c * *f*). Also their effect is negligible on TL. The evaluated result agrees with the metal cutting theory that the V_c greatly affects the TL. Figure 8 shows the S/N response graph for TL. The slope of the V_c is steep compared to *f* and *d* indicating the influence of V_c on TL. Therefore, based on the S/N and ANOVA analyses, the optimal cutting parameters for TL are V_c at level 1, *f* at level 1, and *d* at level 1.

Fig. 6 Effect of cutting parameters and their interaction on the cutting temperature



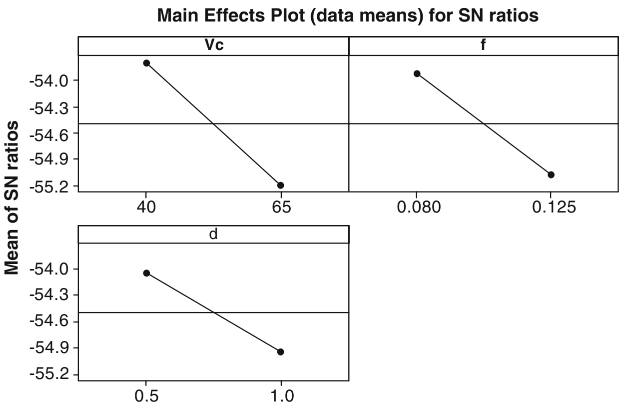


Fig. 7 Signal to noise (S/N) ratio graph for cutting temperature. Signal-to-noise: Smaller is better

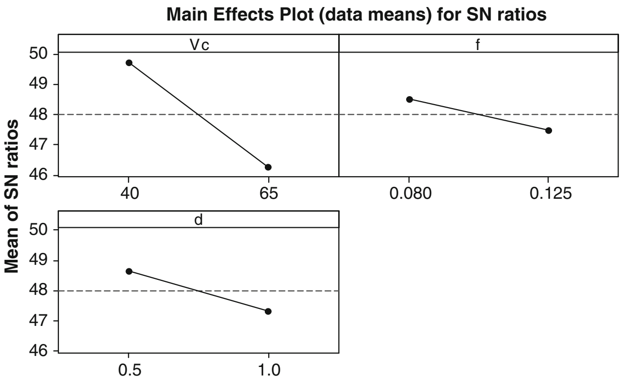


Fig. 8 Signal to noise (S/N) ratio graph for tool life. Signal-to-noise: Smaller is better

Correlations and confirmation tests

Once the optimal level of the design parameters have been selected, the final step is to predict and verify the improvement of the quality characteristic using the optimal level of the design parameters. The correlations between the factors (V_c, f, and d) and the measured Fc, CT, and TL were obtained by multiple linear regression analysis. The quality characteristics used for the Fc and CT is lower the better whereas for TL it is higher the better.

The regression equations obtained were as follows:

$$\text{Cutting force } (N) = 278 - 0.468\,V_c + 1971 f + 82.2\,d - 21.8\,V_c{}^{*} f \quad [\text{Adj. } R^2 = 0.99] \qquad (1)$$

$$\text{Cutting temperature } (^{\circ}\text{C}) = -158 + 8.70\,V_c + 3389 f + 228\,d - 35.6\,V_c{}^{*} f - 2.32\,V_c{}^{*} d \quad [\text{Adj. } R^2 = 0.99] \qquad (2)$$

$$\text{Tool life } (s) = 593 - 3.99\,V_c - 694 f - 73.5\,d \quad [\text{Adj. } R^2 = 0.98] \qquad (3)$$

Table 6 Cutting conditions used in turning of Inconel 718 tests

Test No.	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)
A	45	0.08	0.5
B	55	0.09	0.75
C	60	0.1	1

The above equations include only those interaction effects which have got major influence on the process parameters.

The cutting conditions and confirmation test results for Fc, CT, and TL are shown in Tables 6 and 7, respectively.

From Table 7 it was observed that the calculated error is greater especially for the Fc with maximum value of 9.5% and minimum value of 5.5% whereas CT with maximum value of 13.5% and minimum value of 5.3%. Thus, it is proved that the Eqs. 1 and 2, respectively, correlate the evaluation of the Fc and CT to perform the machining operation at higher V_c with the cutting conditions (V_c, f, and d) with a reasonable degree of approximation.

The mathematical model proposed for TL also shows the minimum percentage error between the experimental and model value. Hence, the proposed mathematical model can be effectively used for evaluating TL.

Tool wear mechanisms

During machining operation, there are several types of wear mechanisms, namely, abrasion, adhesion, diffusion, fatigue, and chemical wear may occur simultaneously or one of them may dominate the process due to the friction between the tool and work-piece. In dry machining of Inconel 718, the wear and damage of cutting tools can be of various forms.

Figure 9 show the SEM micrographs of tool after high speed turning operation at different cutting parameters. In this study, abrasion wear and chipping of the flank wear were the main wear mechanism. In some cases depth of cut notch wear was also observed. Furthermore, built-up-edge BUE formation caused by adhesion of work-piece to tool can be observed from (Fig. 10). Abrasion wear and chipping wear appears to be major wear mechanisms. Also, the damage is caused by adhesion of the machined material on the tool surface. Therefore, tool geometry can seriously change with consequent on the machined surface quality and the required geometrical tolerances.

The flank wear rate was rapid at higher V_c of 65 m/min for a d of 0.5 mm and 1 mm, especially when cutting under dry conditions. A short contact area at the chip–tool interface was observed at high V_c and low d parameter. The

Table 7 Experimental plan and confirmation results for high speed turning of Inconel 718

Test	Cutting force (N)			Cutting temperature (°C)			Tool life (s)		
	Expt. value	Model value	% Error	Expt. value	Model value	% Error	Expt. value	Model value	% Error
A	403	377	6.4	506	438	13.5	345	21	7.0
B	450	408	9.5	553	524	5.3	291	255	12.3
C	422	398	5.9	633	578	8.7	234	210	10.2
Mean			7.26			9.16			9.93

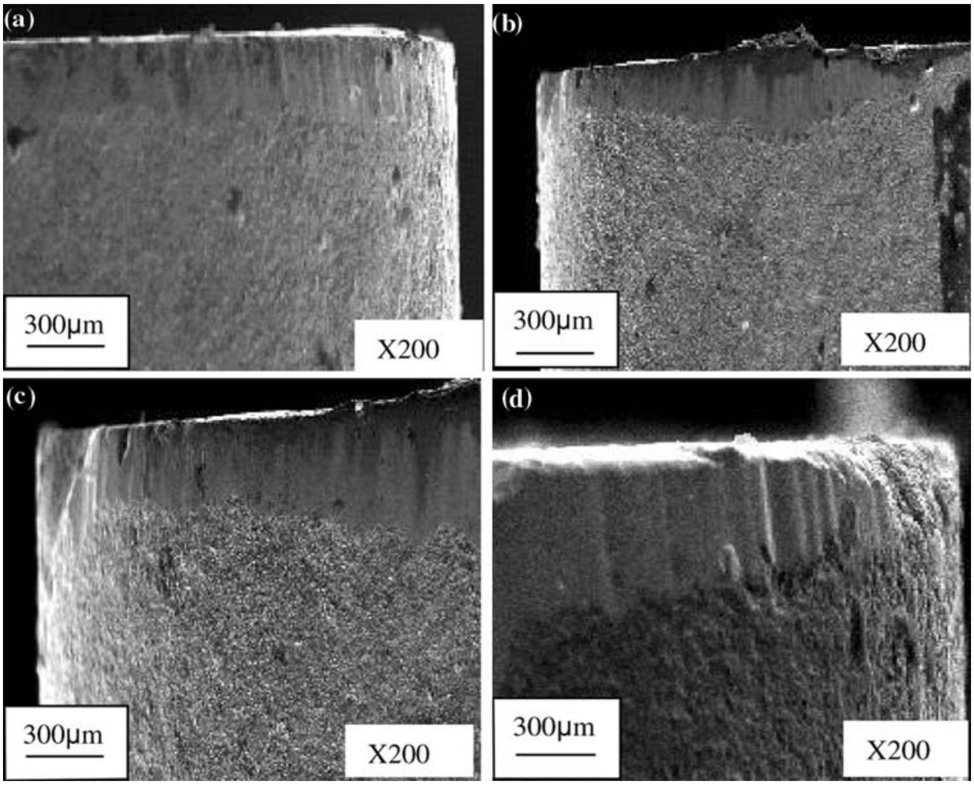


Fig. 9 SEM images of flank wear at various cutting conditions: **a** $V_c = 40$ m/min, $f = 0.08$ mm/rev, $d = 0.5$ mm; **b** $V_c = 40$ m/min, $f = 0.08$ mm/rev, $d = 1$ mm; **c** $V_c = 65$ m/min, $f = 0.08$ mm/rev, $d = 0.5$ mm; and **d** $V_c = 65$ m/min, $f = 0.08$ mm/rev, $d = 1$ mm

greater CT and stresses generated on the flank face close to the nose area probably caused the yield strength of the tools to reduce. This eventually resulted in a greater wear rate at nose area. Almost all the worn surfaces showed similar characteristics at higher values of V_c, f, and d.

Figure 9c and d shows chipping at the cutting edge closer to nose after cutting Inconel 718 at 65 m/min for a d of 0.5 and 1 mm, respectively.

Chip analysis

The mechanism of chip formation and separation is due to the extremely high strain rate in the machining process. As the cutting condition reaches a critical value at which serrated chips are formed, the plastic deformation rate becomes high and the tool-workpiece friction becomes more severe, increasing rate of heat generation. In case of the cutting of Inconel 718 due to the lower thermal conductivity characteristics of the material, temperature can be very high locally in some areas of the workpiece, resulting in further thermal softening of workpiece.

The chips produced under various cutting conditions were collected and their SEM images are shown in Fig. 11. At low cutting condition the chip is a continuous type but when the cutting parameter is increased, it is changed to “saw-tooth” type. It was observed that the higher the cutting parameters, the more noticeable the saw-tooth chips (Fig. 11d). The formation of “saw-tooth” chips is due to periodic formation of cracks ahead of the tool. Saw tooth or segmented chips are produced due to catastrophic strain localization above some critical cutting parameters. According to recent observations, the frequency of shear localized saw-tooth shape chips is very high. The cutting edge is subjected to a high frequency force variation. The

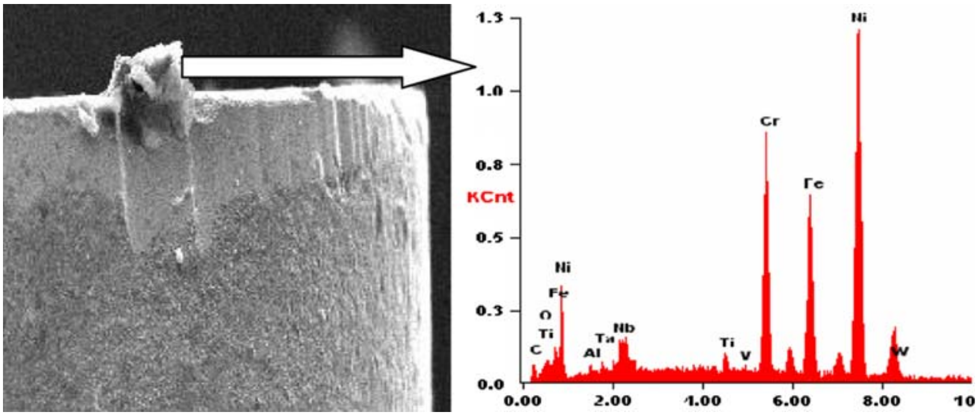


Fig. 10 SEM image and EDAX profile of built up edge formation

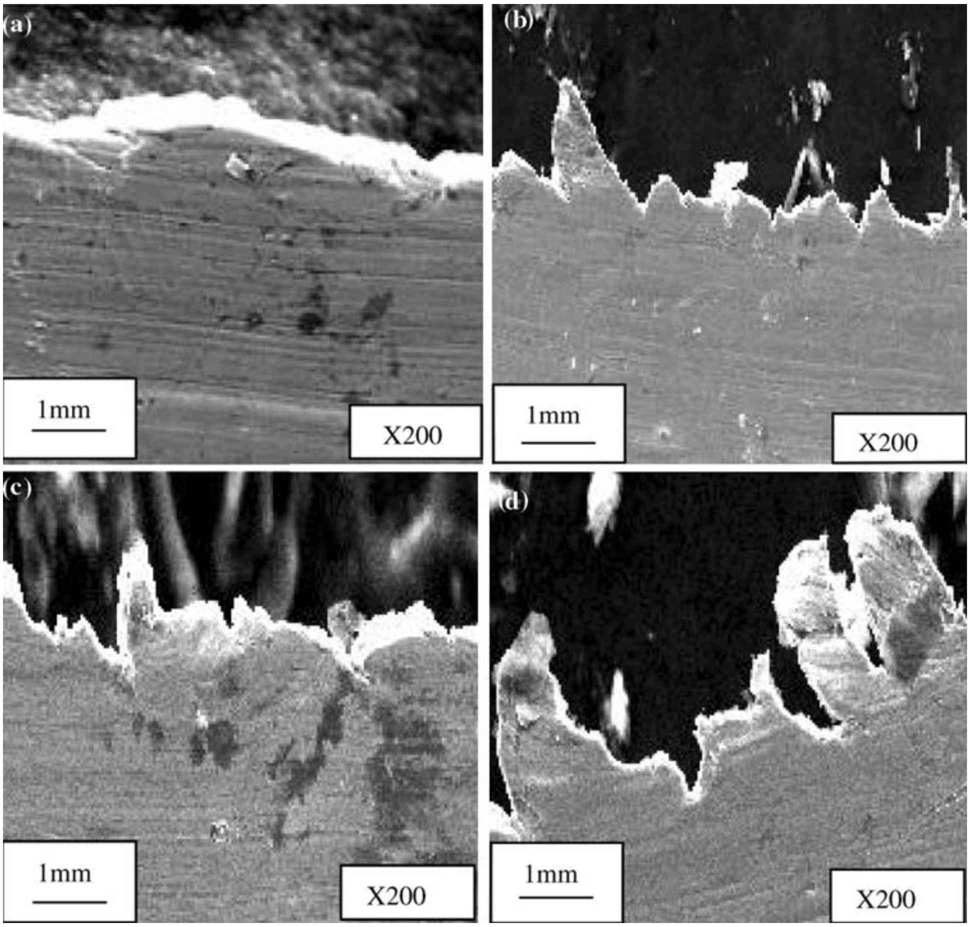


Fig. 11 SEM images of chips obtained at various cutting conditions: **a** $V_c = 40$ m/min, $f = 0.08$ mm/rev, $d = 0.5$ mm; **b** $V_c = 40$ m/min, $f = 0.08$ mm/rev, $d = 1$ mm; **c** $V_c = 65$ m/min, $f = 0.08$ mm/rev, $d = 0.5$ mm; and **d** $V_c = 65$ m/min, $f = 0.08$ mm/rev, $d = 1$ mm

transition of continuous chip to saw-tooth chip is from low cutting parameters to high cutting parameters.

Conclusions

The experimental investigation of high speed turning of Inconel 718 using Taguchi optimization technique leads to the following conclusions:

- In this study the optimal cutting condition was 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 Fc, CT, and TL.
- The experimental results indicated that V_c, f, and d and interaction effect between V_c and f influence the Fc and CT. The study indicated that TL is only influenced by the V_c alone.

- The relationship between the factors and the performance measures are expressed by multiple regression equations, which can be used to estimate the expected values of the performance level for any factor levels. The R^2-values for the regression equations are considerable enough to obtain reliable estimates. The results obtained with the equations confirmed that predictions by means of this model have an associated error much lower than the one obtained by the geometric theoretical model.
- The improvement of Fc, CT and TL from initial cutting parameters to the optimal cutting parameters is about 235, 316, and 155%, respectively.
- Abrasion, chipping, and adhesive wear were recorded as the main wear mechanisms for investigated tools. Finally, BUE formation was observed at all V_c's but its size decreased with increased V_c.

It is clearly seen from the above conclusions that by proper selection of the cutting parameters it is possible to improve the machinability of difficult to machine material, Inconel 718 with high quality with minimum number of experiments.

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