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Modeling and Optimization of Cutting Parameters in Dry Turning of Inconel 718 using Coated Carbide Inserts

R.Ramanujam[1*], K. Venkatesan[1], Vimal Saxena[1], Philip Joseph[1]

[1]School of Mechanical and Building Science, VIT University, Vellore – 632 014. India

Abstract

This work presents a statistical approach for optimization of dry turning parameters of Inconel 718. Based on Taguchi's L9 orthogonal array, turning experiments were carried out at various levels of cutting parameters to evaluate the performance measures such as cutting force, surface roughness and tool wear. The turning operations were carried out in a medium duty lathe machine with PVD coated carbide cutting insert. The optimal cutting conditions were determined using the Taguchi's Signal to Noise (S/N) ratio which was calculated for R_a, R_t, R_z and F_z according to the "smaller-the-better" criteria. Tool wear was analyzed using scanning electron micrograph. The statistical analysis of results using ANOVA reveals that feed rate and depth of cut has maximum weightage for affecting the responses. The mathematical model for the individual responses has been developed using regression analysis as a function of the cutting parameters as independent variables. The developed regression model shows a high determination coefficient i.e., $R^2 = 0.912$ for R_a, R_t, 0.943 for $R_z$and 0.882 for $F_z$which proves the model accuracy. The predicted value from the developed model and experimental values are found to be very close to each other justifying the significance of the model. Confirmation experiments were conducted on the optimum cutting conditions to illustrate the effectiveness of Taguchi's optimization technique.

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Keywords:: Inconel 718; Machinability; Optimization,;Taguchi method; ANOVA;Signal to Noise ratio

1. Introduction

Nickel-based alloys have widespread applications in the nuclear and aerospace industry owing to their superior thermal properties and the ability to retain their mechanical properties at elevated working temperatures (~700°C) by Ezugwu et. al. (2003). Among all other nickel based alloys, Inconel 718 has the unique attribute of combined corrosion resistance and high strength at elevated temperature. The high temperature strength is due to the effects of the submicron gamma double prime precipitates and also to a minor extend, the effect of gamma prime precipitates

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by Attia et. al. (2008). The other desirable characteristics of the alloy are high thermal fatigue resistance, resistance to thermal shock and high melting temperature makes an ideal material for use in aerospace, automotive and corrosive applications such as marine equipment, nuclear reactors, petrochemical plants, food processing equipment and pollution control apparatus by Choudhury et. al. (1998).

Even though required from design perspective, these properties pose a serious challenge to the manufacturing sector. Properties such as low thermal conductivity, generation of high temperature at cutting zone up to 1200 °C, high work hardening tendency and high tool-workpiece affinity which lead to the formation of built-up edge on the cutting tool material and hence they are categorized as "difficult-to-cut" materials by Gessinger et. al.(1998), Ezugwu et. al. (1998), Reddy et. al. (1991) and Arunachalam et. al. (2002). Several problems that arise while machining of nickel based super alloys are surface cracking, plastic deformation, metallurgical transformations, increased micro hardness, and the formation of tensile residual stresses which result in significant loss in production by Braghini et. al. (2004) and Chao Xue et. al (2011).

Many research works have been carried out on turning of Inconel 718 to improve machinability by choosing different characteristics such as application of new generation cutting tools, optimization of tool geometry and use of nontraditional machining processes. Generally, coated carbide tools, CBN and whisker reinforced ceramic tools are used for machining of Inconel 718. Cubic Boron Nitride (CBN) cutting give good performance in terms of tool life and surface roughness at higher cutting speed compared to ceramic tools in dry turning tools by Arunachalam et. al. (2004) and Costes et. al. (2007). According to Bushlya et al. (2012), PCBN tools offer excellent performance during machining of Inconel 718 but their costs are relatively high as compared to carbide tools. At lower cutting speeds say 30 m/min, HSS and uncoated carbide inserts are usually preferred by Devillez et. al. (2007). Due to the advancement in coating technology, high cutting speed of up to 100 m/min is achievable with coated cemented carbides and is widely used in the industries by Dudzinski et. al. (2005). However, the extent of their effectiveness has been critically analyzed by researchers in terms of performance metrics. Itakura et al. [1999] investigated the application of TiN/TiC multilayered coating and found better performance up to 30 m/min and at higher speed, adhesion wear was found to be the dominant wear. Jindal et al. (1999) found that TiAlN coated inserts exhibit good performance both at low and high cutting speeds due to the effect of low thermal conductivity and act as protecting layer for the tool surface from heat transfer and for resistance to the BUE formation. Ducros et. al. (2003) investigated the use of multilayer and nano layer coatings (especially TiN/AlTiN) on dry turning of Inconel 718 resulting significant productivity improvement where as the abrasive wear is the main dominant tool failure.

However, it is necessary to determine optimal cutting parameters in order to attain minimal costs and production time. In recent years, research has been done on statistical and Taguchi's method of experimental studies to determine the effects of cutting parameters on various quality characteristics relating to turning operation on various materials. Pawade et. al. (2007) used four factor and three-level fractional factorial design to study the effect of process and tool dependent parameters to determine optimal performance indices. According to his observations, the surface roughness reached a minimum value with the tool edge geometry angle of 30° at higher cutting speeds. Similarly, with the increase in cutting speed, cutting force was found to decrease and vice versa. Few studies has been carried out on the effect of cutting fluids and the results shows no significant improvement on machining performance by Ezugwu et. al. (2005).

From the review of literature, it is observed that only few investigations have been carried out for the optimization and statistical modeling of process parameters in dry turning of Inconel 718. To overcome the above shortcoming, the present work has been focused to attain the following objectives:

i. Planning of experimental design according to the choice of factors, its levels.
ii. To conduct the machining experiments on Inconel 718 under dry turning using new generation cutting insert (AlTiN - PVD coated carbide insert).
iii. To predict the optimum process parameter using Taguchi's experimental design procedure.
iv. To develop a statistical model and validate the results obtained using taguchi method.
v. To conduct the confirmation test at optimum levels to compare the predicted results and to analyze the tool wear patterns using SEM images.

2. Experimental Methods

The details of test specimen, cutting conditions, measurements and methodology adopted for the present study are described in the following sections.

2.1 Test specimen, Cutting insert and measurements

Dry turning operations based on Taguchi's L9 experimental array were carried out on Inconel 718 bar of diameter 35mm and length 600mm in a medium duty lathe (7.5kW, 1600rpm). The chemical composition of Inconel 718 in wt% is listed in Table 1. Each machining trial has been carried out on a new fresh cutting edge. Prior to experimental trials, a skin cut of 1.5mm thickness is done in order to avoid any deformities on the surface.The cutting tool used was PVD coated carbide insert (KC5525) manufactured by Kennametal. Grade KC5525 is an advanced PVD coated fine-grain tungsten carbide insert specifically designed for machining high-temperature alloys. Its substrate has 10% cobalt for excellent toughness and deformation resistance. The inserts used were of ISO coding CNMG 120408-MS (80° diamond shaped insert) with negative rake angle and nose radius of 0.8 mm and were mounted on a tool holder designated by ISO coding PCLNR 2525M12. Surface roughness measures (Ra, Rt, Rz) and cutting force (Fz) were considered as performance characteristics and measured by Mahr surf test and Kistler dynamometer respectively. To measure roughness of the surface the cutoff length has been fixed as 1.75 mm and 4 mm as assessment length. The measurement was taken at three locations (90° apart) around the circumference of the workpiece and repeated thrice at each point on the face of the machined surface and the average values were recorded. The cutting force values were recorded using a digital indicator via data acquisition system. The resultant cutting force was then considered to evaluate the machining performance in this study.

Table 1. Chemical composition (wt %) of Inconel 718 alloy

Elements	C	Mn	Si	Ti	Al	Co	Mb	Cb	Fe	Cr	Ni
Percentage	0.08	0.35	0.35	0.6	0.8	1.0	3.0	5.0	17.0	19.0	52.82

2.2 Methodology

The experimental design was based on Taguchi's orthogonal array which involves selecting response variables, independent variables, and their interactions. The process flow chart of the experimental steps and optimization procedure are shown in Fig. 1. The levels of the process parameters were selected in order to cover a sufficiently wide range of possible cutting conditions. The parameters and the corresponding levels chosen for this experimentation were given in Table 2. The Taguchi method uses Signal-to-Noise (*S/N)* ratio to measure the variations of experimental design. The word 'signal' indicates the desirable value and the word 'noise' indicates the undesirable value. The formulae for signal-to-noise ratio are designed such that the experimentalist can always select the factor level settings which maximize the S/N ratio to optimize the quality characteristics of an experiment. Then, the selection of calculating the signal-to-noise ratio depends on the characteristics such as smaller-the-better, larger-the-better or nominal-the-better. The objective of the present work is to optimize the process parameter for the minimization of surface roughness (R_a, R_t and R_z) and cutting force (F_z) values. Therefore, in this work a smaller-the-better characteristic has been taken to calculate the signal-to-noise ratio. The cutting force (Fz) and surface roughness (Ra, Rt and Rz) values were measured from the experimental trials and their corresponding S/N ratio values are listed in Table 3.

Table 2. Process parameter and their levels used in the experiments

Process parameter	Unit	Level 1	Level 2	Level 3
Cutting Speed (A)	m/min	30	50	70
Feed rate (B)	mm/rev	0.103	0.206	0.294
Depth of cut (C)	Mm	0.2	0.3	0.4

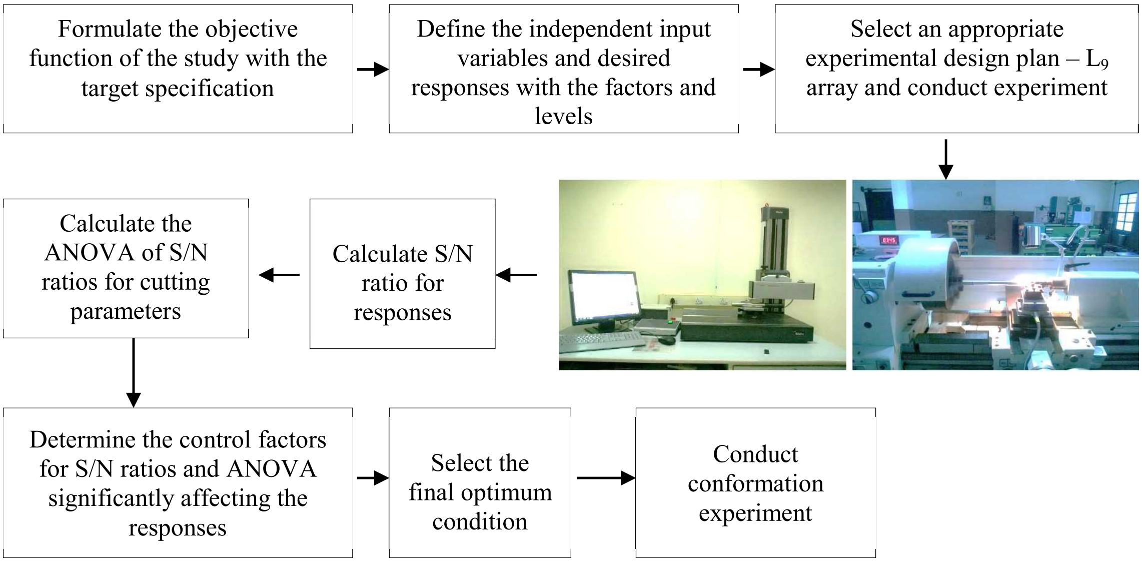


Fig.1 Process flowchart for Experimental

The S/N ratio for cutting force (Fz) and surface roughness (Ra) is calculated by taking into the consideration smaller-the-better characteristics (in decibel) and is given by

$$S/N(\eta) = -10x\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

Where ‘n’is the number of measurements in a row, n=3 and
‘y_i’ is the i^{th} measured value in a row.

The mean S/N ratio of each parameter level has been calculated by averaging their corresponding levels in orthogonal array. The optimal parameters were chosen based on higher S/N ratio as the signal represents the desirable value and noise represents the undesirable value. Next, statistical analysis of variance (ANOVA) was conducted to study the significance of process parameters on responses based on their P-value and F-value at 95% confidence level. Finally, the optimal parameters are verified by conducting some confirmation runs.

3. Results and discussion

The influence of machining parameters and its effects on surface roughness (Ra, Rt and Rz) and cutting force (Fz) on dry turning of Inconel 718 with PVD coated carbide inserts has been discussed in this section.

3.1 Analysis of S/N ratio and ANOVA for surface roughness and cutting force

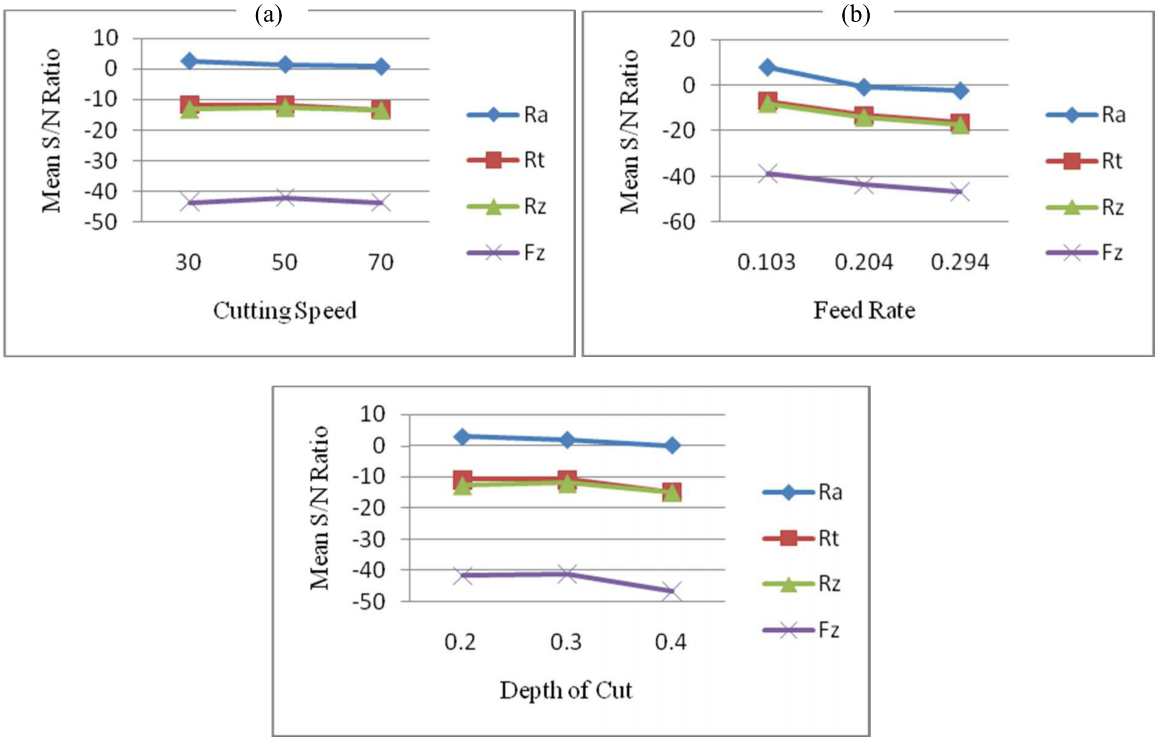
The cutting force (Fz) and surface roughness (Ra, Rt and Rz) values were measured from the experimental trials and their corresponding S/N ratio values are listed in Table 3.Then the mean S/N ratios at each level of process parameters are obtained by computing the average at corresponding levels. Based on the analysis of the S/N ratio, the optimal levels of cutting condition for the process parameters are listed in Table 4.The response plots of S/N ratio results for the surface roughness (Ra, Rt and Rz) and cutting force (Fz) are shown in Fig. 3.

Table 3 Experimental results and single to noise ratio for Inconel 718

Exp. No.	Cutting Parameters			Experimental results				Single to noise ratio			
	speed (m/min)	feed (mm/rev)	doc (mm)	Ra µm	Rt µm	Rz µm	Fz (kN)	Ra dB	Rt dB	Ra dB	Fz dB
1	30	0.103	0.2	0.275	1.610	2.284	87.18	-2.738	-18.935	-18.219	-38.808
2	30	0.206	0.4	1.098	4.427	4.878	133.2	-1.515	-15.028	-14.457	-42.490
3	30	0.294	0.6	1.356	8.147	8.846	288.9	-3.121	-18.108	-17.472	-49.215
4	50	0.103	0.4	0.392	1.702	1.982	49.69	-0.812	-13.766	-4.822	-33.925
5	50	0.206	0.6	1.167	5.226	5.498	240.8	8.148	-5.9491	-4.622	-47.633
6	50	0.294	0.2	1.331	6.359	7.263	173.6	-1.886	-16.480	-15.179	-44.791
7	70	0.103	0.6	0.618	4.128	3.547	140.6	10.818	-7.190	-4.138	-42.959
8	70	0.206	0.2	1.018	4.177	4.796	114.8	-2.494	-17.223	-16.068	-41.198
9	70	0.294	0.4	1.225	5.738	6.488	213.9	-0.155	-13.630	-12.418	-46.604

Table 4 Analysis of S/N ratio

Cutting Parameters	Mean S/N ratio (dB)			Max – Min	Rank
	Level 1	Level 2	Level 3		
Surface Roughness (R_a)					
Cutting Speed (A)	2.583*	1.437	0.752	1.831	3
Feed rate (B)	7.845*	-0.773	-2.297	10.142	1
Depth of cut (C)	2.857*	1.854	0.062	2.795	2
	Total Mean to S/N ratio (η) = 0.694		*Optimum Level= A1B1C1		
Surface Roughness (R_t)					
Cutting Speed (A)	-11.760	-11.684*	-13.304	1.620	3
Feed rate (B)	-7.024*	-13.325	-16.488	9.464	1
Depth of cut (C)	-10.874*	-10.906	-14.967	4.093	2
	Total Mean to S/N ratio (η) = -14.037		*Optimum Level= A2B1C1		
Surface Roughness (R_z)					
Cutting Speed (A)	-13.291	-12.656*	-13.620	0.963	3
Feed rate (B)	-8.038*	-14.063	-17.467	9.429	1
Depth of cut (C)	-12.672	-11.983*	-14.913	2.930	2
	Total Mean to S/N ratio (η) = -11.933		*Optimum Level= A2B3C2		
Cutting Force (F_z)					
Cutting Speed	-43.50	-42.128*	-43.59	1.47	3
Feed rate	-38.56*	-43.77	-46.87	8.31	1
Depth of cut	-41.60	-41.01*	-46.60	5.60	2
	Total Mean to S/N ratio (η) = -43.0695		*Optimum Level= A2B1C1		



(c)

Fig. 2 Response plot for S/N ratio (a) Cutting speed; (b) Feed rate; (b) Depth of cut

The results of analysis of variance for identifying significant factors and its percentage contribution are given in Table 5. From the ANOVA results for Ra, Rt, Rz and Fz, it is evident that the feed rate is the most significant parameter for affecting surface roughness and cutting force while the P-value (Probability of significance) is less than 0.05 at 95% confidence level, followed by depth of cut. The cutting force increases with increase in feed rate and depth of cut. However, cutting speed is found to be insignificant in the experiments for affecting both the responses in the experimental region. From the above S/N ratio results for surface roughness (Ra), the optimum conditions arrived are:(i) Cutting speed (30 m/min),(ii) Depth of cut (0.2 mm) and (iv) Feed rate (0.3 mm/rev) shown in Table 4. From the above S/N ratio results for cutting force (Fz), the optimum conditions arrived are:(i) Cutting speed (50 m/min),(ii) Depth of cut (0.2 mm) and (iv) Feed rate (0.3 mm/rev) shown in Table 4. Results of analysis of means indicate that feed rate cut is the most significant machining parameter followed by depth of cut and cutting velocity affecting the cutting force performance characteristics. The optimum process parameter evolved with respect to minimization of surface roughness and cutting force leads to two different combinations such as A1B1C1 and A2B1C1 respectively.

From the result of the analysis of variance shown in Table 5, the variations caused by each control factor on the cutting parameters as well as the effect of the control factors on the quality characteristic variation can be observed. The main control factors that can effectively reduce the variations and contribute to the quality characteristics are identified in descending order for Ra as feed rate (91.8%), depth of cut (3.72%) and cutting speed (0.36%) and for Fz feed rate (88.8%), depth of cut (9.72%) and cutting speed (0.81%).

Table 5 ANOVA Analysis

Source	DF	SS	MS	F ratio	P	%P
Surface Roughness (R_a)						
Cutting Speed (A)	2	0.00493	0.00246	0.19	0.840	0.36
Feed rate (B)	2	1.25512	0.6275	48.52	0.020	91.8
Depth of cut (C)	2	0.05086	0.02543	1.97	0.337	3.72
Error	8	0.02587	0.01293			1.89
Total	9	1.3367				
Notes: S = 0.113731 R-Sq = 98.06% R-Sq(adj) = 92.26%						
Surface Roughness (R_t)						
Cutting Speed (A)	2	0.1553	0.0776	0.17	0.857	0.44
Feed rate (B)	2	27.328	13.6642	29.38	0.330	77.77
Depth of cut (C)	2	6.7231	3.3616	7.33	0.122	19.13
Error	8	0.9300	0.4650			2.64
Total	9	35.136				
Notes: S = 0.681916 R-Sq = 97.35% R-Sq(adj) = 89.41%						
Surface Roughness (R_z)						
Cutting Speed (A)	2	0.3326	0.1663	0.78	0.563	0.81
Feed rate (B)	2	36.4349	18.2175	85.20	0.012	88.8
Depth of cut (C)	2	3.8035	1.9018	8.89	0.101	9.77
Error	8	0.4276	0.2138			1.04
Total	9	40.9986				
Notes: S = 0.462393 R-Sq = 98.96% R-Sq(adj) = 95.83%						
Cutting Force (F_z)						
Cutting Speed (A)	2	407.5	203.8	0.22	0.821	0.38
Feed rate (B)	2	26555.5	13277.7	14.23	0.066	56.69
Depth of cut (C)	2	18013.1	9006.3	9.65	0.094	38.46
Error	8	1865.9	932.9			3.98
Total	9	46841				
Notes: S = 30.5440 R-Sq = 96.02% R-Sq(adj) = 84.07%						

3.2 Regression model for Surface roughness and cutting force

A linear regression model was carried on the dependent variable R_a, R_t, R_z and F_z and cutting speed, feed rate depth of cut are considered as the predictor variable in the experimental data for selected PVD coated tungsten carbide inserts. In addition to linear regression equations and coefficient of determination (R^2) has been utilized to study the significance of regression model developed. Usually, the R^2 value lies in the range of 0 to 1 (i.e. $0 \le R^2 \le 1$). When R^2 value approaches to unity, it is taken as a better prediction of responses and fitting of the model with the experimental data. If R^2 value is 85%, it means that this model explains about 85% of the variability in predicting new observations. Therefore, the following regression equations are obtained for both cutting force and surface roughness

R_a = - 0.218 + 0.00110 Cutting Speed + 4.64 Feed rate + 0.431 Depth of cut (2)
R^2 = 91.8% R^2 (adj) = 86.9%
R_t = - 1.60 - 0.0012 Cutting Speed + 22.3 Feed rate + 4.46 Depth of cut (3)
R^2 = 91.2% R^2(adj) = 86.0%
R_z = - 0.80 - 0.0098 Cutting Speed + 25.7 Feed rate + 2.96 Depth of cut (4)
R^2 = 94.3% R2 (adj) = 91.0%
F_z = - 61.2 + 0.333 Cutting Speed + 696 Feed rate + 246 Depth of cut (5)
R^2= 88.2% R^2(adj) = 81.1%

The developed mathematical models has presented a high determination coefficients by explaining 91.8%, 91.2%, 94.3% and 88.2% variance for R_a, R_t, R_z and F_z. This model indicates that it fits well and accurately explains the linear relationship between the dependent and the predictor variable as shown in Fig. 3. The maximum residual for F_z, R_a, R_t and R_z are found to be 0.021 and 0.142 respectively and within the reasonable limit implying the significance of the model developed. Thus, the model developed using linear regression analysis can be utilized to predict accurately the cutting force and surface roughness in dry machining of Inconel 718.

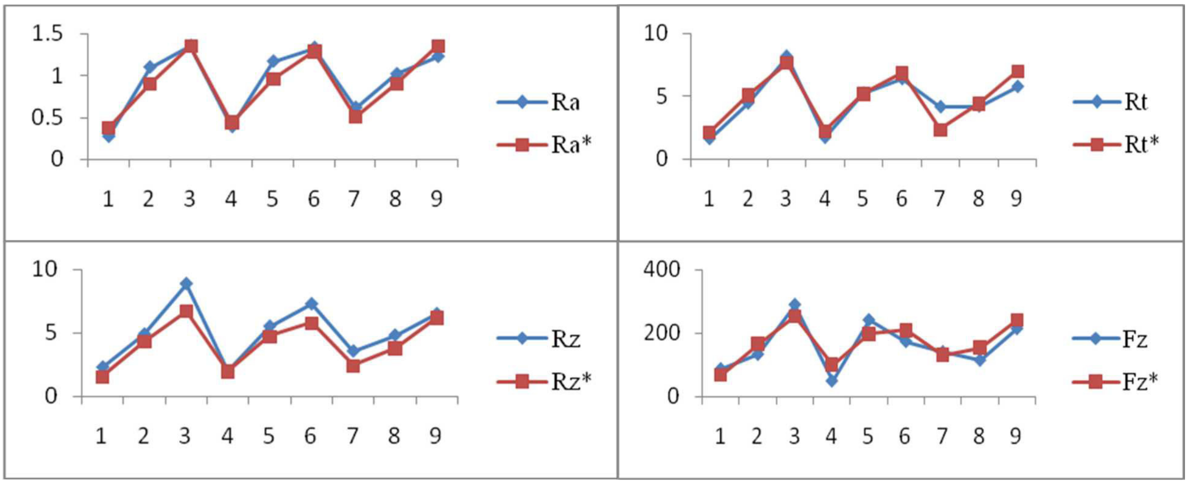


Fig 3 Comparison of Experimental vs Predicted Results for Ra, Rt, Rz and Fz.

3.3 Confirmation experiment

Tool wear analyses were carried on the optimal parameters obtained. The results of the confirmation experiments was listed in Table 6. Three different cutting tools were used and experiments were conducted for a cutting length of 150mm. Tools were examined under SEM. The progression of tool wear was recorded for every 30mm length and is depicted in Fig 4. It was observed that tool 1 (Ra) underwent a maximum wear a 0.216Vb at the end of the run which was within the acceptable limit (0.3Vb) where as tool 2 (Rt) and tool showed a maximum wear of 0.5337Vb and 0.34765Vb. The coated layer is abraded off first. It is followed by flank wear and chipping in tool 2 at the outer cutting edge. Similarly, for the tool 3 (fz) carters wear at the cutting edges is evidenced by the SEM examinations, were found to be responsible for the cutting force values. The SEM of the tool flanks at V=30 m/min, 50 m/min, and 70 m/min are shown by Fig. 4 (a), (b), and (c), respectively. It is observed from SEM images that at lower cutting speed, the tool wear was found mainly on the rake face and flank face. Fig. 4 (a) shows rake surface wear at cutting speed V= 30 m/min and feed rate f=0.103 mm/rev. From Fig. 4 (a), it was found that bright brand at the cutting edge is flank wear of about at the cutting length of 150 mm is 0.217 mm. As the cutting length is very short, there is not substantial growth of wear was found on the rake and flank face at this low cutting speed. However, as cutting speed increased from 50 m/min to 70 m/min, non- uniform wears at the flank face of the cutting insert was observed. At v= 50 m/min, the wear on the tool looks like a cater Fig. 4 (a). But when examine through SEM image, the rake face of the picture Fig. 4 (b), shows there of some micro cracks around the carter region, which means micro chipping at the cutting edge may be happened before carter wear. This indicates the welding of the work piece material may be happened between the flank face of tool and machined work piece surface. The welded material may be taken by the work piece, which makes the wear on flank face is bright. It also clear from the cutting edge, the edge chipping is due to the abrasion wear of the cutting tool are spreading over the flank face. Fig 4(c) shows the carter wear at cutting speed v=70m/min and f=0.296 m/min. At cutting speed increases from 30 min to 70 m/min, the flank wear gradually increase from 0.271 mm to 0.348 mm which indicates different wear pattern and surface roughness. It can be found that the surface roughness changes gradually with the increasing of cutting speed. At V=30 m/min the flank surface appears very coarse, while at V=50 m/min the flank surface seems much better than that at V=70 m/min.

(a) (b) (c)

Fig. 4 a) Tool wear at V=50 m/min: wear on rake and flank face
b) Tool wear at V=70 m/min: edge chipping on flank and rake face;
c) Tool wear at V=70 m/min: crater wear on rake and flank face.

Table 6 Conformation Experiments

Length of cut	30	60	90	120	150
Surface Roughness (R_a)					
Ra	0.324	0.356	0.385	0.443	0.469
Tool Wear	0.108	0.137	0.151	0.193	0.217
				Note: At Optimal Condition A1B1C1	
Surface Roughness (R_t)					
Rt	2.451	2.789	3.455	3.746	4.367
Tool Wear	0.122	0.131	0.139	0.143	0.534
				Note: At Optimal Condition A2B1C1	
Surface Roughness (R_z)					
Rz	2.576	2.802	2.962	3.893	4.398
Tool Wear	0.138	0.234	0.273	0.334	0.348
				Note: At Optimal Condition A2B3C2	
Cutting Force (F_z)					
Fz	60.64	116.3	66.21	96.97	58.5
Tool Wear	0.122	0.131	0.139	0.143	0.534
				Note: At Optimal Condition A2B1C1	

4. Conclusion

This paper discussed about the modeling and optimization of dry machining of Inconel 718 using coated tungsten carbide insert. L_9 orthogonal array, S/N ratio and ANOVA were adopted for finding the optimal process parameter for the performance measures of cutting force and surface roughness. Linear regression model was developed for surface roughness and cutting force to check the model adequacy. The following conclusions were drawn from the present research:

- Based on the response table, response graph and ANOVA analysis, the optimal cutting parameter for Ra, Rt, Rz and Fz were A2B1C2, i.e. cutting speed at 50 m/min, feed at 0.103 mm/rev and depth of cut at 0.4 mm respectively.
- Feed rate was found to be the most significant parameter for Ra, Rt, Rz which accounts the maximum percent contribution of 91.8%, 77.7%, 88.8% followed by depth of cut 3.72%, 19.13%, 9.77%. Cutting speed has the insignificant effect on surface roughness.
- Feed rate and depth of cut was found to be significant parameters for Fz with 56.69% and 38.46%.
- The developed regression equation for both cutting force and surface roughness have high determination coefficient (R^2) which explaining 91.8%, 91.2, 94.3% and 88.2% and shows that the developed model has high significant on the responses.
- At cutting speed V=30 m/min, the tool wear is on obvious due to low cutting temperature and short cutting length. The dominant wear mechanism is edge chipping and fracture. This may be happened due to the vibration of cutting force, segmented chip and welding of contacting of materials between the workpiece and cutting tool. At cutting speed from 30 m/min to 70 m/min, the predominant tool wear mechanisms are abrasion, oxidation and edge chipping due to the friction and thermal softening.

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