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An Investigation of the Parametric Effects of Cutting Parameters on Quality Characteristics during the Dry Turning of Inconel 718 Alloy

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Abstract

Objectives: The present study investigated the parametric investigation of machinability parameters on the quality characteristics of force (Fz) and roughness (Ra) during the dry turning of Inconel 718 alloy. **Methods/Statistical Analysis**: Machinability experiments are carried out with PVD coated carbide with (KC5510) and without wiper (KC5525) insert at three speeds (60, 80, 100 m/min), two feed (0.06 and 0.10 mm/rev) and three cutting depth (0.4, 0.8, 1.2 mm) under dry cutting conditions. The experiments are planned based on Taguchi's L_{18} orthogonal array. The percentage contribution of the machinability parameters on quality characteristics is determined using analysis of variance test (ANOVA). Predictive regression equations are developed for the estimation of all the quality characteristics. **Findings:** From the experimental results, the most significant factor in case of both Fz and Ra is cutting depth during the turning of 718 Inconel alloy for both the inserts. The Pearson correlation (r) is evaluated whether the correlation is exists between the machinability parameters (speed; feed and cutting depth) on force and roughness. The results of calculated 'r' show that the cutting depth has a strong correlation with both quality characteristic trailed by the speed. **Application/Improvements:** In addition, the lower magnitude of Ra roughness is observed for KC5010 compared to insert designated with KC5525.

Keywords: Dry Turning, Force, Parametric Investigation, Roughness, Statistical Analysis

1. Introduction

Nickel based Inconel 718 alloy is a high-temperature alloy which is under the scope of present research. It is a corrosion and oxidation resistance that finds a way to high temperatures components. It is often used as a material in automotive and aerospace components due to its good tensile strength, fatigue, creep and rupture strength[1]. In[2] developed artificial neural network (ANN) between responses and machinability parameters in high-speed turning of 718 Inconel alloy using PVD (K10) inserts. The author concluded that neural network model showed good agreement with experimental data sets and suggested that ANN model can be used for complex relationship. In[3] conducted the experiments based on the Taguchi's L_{27} orthogonal array, and the effects are analysed using the statistics test of analysis of variance. Higher cutting speed, lower feed and moderate cutting depth combined with honed cutting edge are the optimum points for resulting residual stress in the turned surface is compressive. In[4] attempted to study the machinability of Inconel 718 using cemented, K20, tungsten carbide cutting tool using Taguchi optimization method. They developed regression model to correlate the machining parameters with the responses such as force, conventional cutting temperature and tool life. In[5] described the GP (genetic algorithm) with ANN (artificial neural network) provides an intelligent optimization method for process

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parameters optimization of Inconel 718. In[6] investigated optimization of surface roughness in turning of 718 Inconel using two coated inserts, which is designated as KC5525 and HK150. In[6] applied the four different analytical methods with a minimization objective for roughness. Comparing with other analytical method, GP found to be superior as a result of lowest overall root mean square error (RMSE) and mean prediction error (MPE). In[7] justified the use of predictive model based on the artificial neural network (ANN) approach to develop relationship between cutting speed and tool wear on turning of Inconel 718, by its capability to detect forecast errors for the highest cutting speed value. In[8] used an orthogonal array coupled with grey-relational analysis (GRA) for process optimization while Inconel 718 alloy turning. Optimal points are determined by the highest value of grey relational grade (GRG) in grey analysis for various quality characteristics. In[9] investigated finish turning of 718 Inconel using TiAlN cutting tool. Experimental data sets tested with variance test. From the statistics test the tool flank wear and roughness are significantly influenced by feed, approach angle and tool nose radius, but speed alone on tool flank wear. In another study by[10] means of the hybrid Grey-Fuzzy approach optimized cutting force and surface roughness. They stated that synchronised improvement in multiple output responses of machining variable is greatly improved by Grey-Fuzzy Logic analysis. In[11] used Fuzzy-Grey relational analysis for design parameter optimization of complex characteristics while WEDM on 825 Inconel, a super alloy. The author suggested that the combined Taguchi-Grey fuzzy logic technique improves the optimization procedure and thereby, yield the best optimal points. In[12] investigated the main effects of machining variables during machining of Inconel 625 with PVD coated carbide tools. Result of analysis of variance (ANOVA) reveals that the feed followed by speed is most significant factor on roughness, Ra. In[13] used Taguchi's L9 experimental array to study the factor effects (cutting depth; speed; and feed rate;) on force and roughness on machining of Inconel 718 using PVD insert. Feed rate followed by speed and cutting depth is the variable factor that affects output responses significantly. In[14] applied the Taguchi optimization method to minimize the two output responses such as roughness; and force. The results reveal that the feed and cutting depth has the most important effect on each response. In[15] investigated the comparison of confidence level of various methods of process optimization techniques on machinability of the Inconel 625. Their results show that roughness; cutting energy; and material removal rate is significantly influenced by the feed; and cutting depth. As Inconel 718 is a critical component for aerospace and increasingly being used, it is necessary to determine the machinability of these materials in order to be able to process them efficiently. This study investigated the effect of machinability parameters on main cutting force and surface roughness using two different inserts on machining of 718 Inconel alloy. The novelty of the present research work lies in the comparison between the main effects of machinability parameters on quality characteristics using of wiper inserts when machining Inconel 718 alloy.

2. Experimental Section

2.1 Cutting Inserts and Measurement

The experiments are planned based on Taguchi's L_{18} orthogonal array on workpiece of Inconel 718. Cylinder bar of diameter 35 mm and length 300 mm is fixed in a medium duty lathe (7.5 kW, 1600 rpm) and a skin cut of 0.5 mm is carried out before actual machining. Coated PVD carbide inserts factory-made by Kennametal is used as cutting tools which has ISO designation of KC5525 and KC5010. The inserts are attached on a tool holder and it's designated by ISO coding as PCLNR 2525M12. Grades of insert are an advanced PVD grade with hard AlTiN coating and fine grained unalloyed substrate. This grade is ideal for machining of one of the most common high-temp alloys like Inconel 718. The fine grained tungsten carbide with 6% cobalt for KC5010 and 10% for KC5525 cobalt substrate provide an excellent toughness; deformation resistance; and inserts edge strength. Cutting force and surface roughness are measured using 9257B type Kistler dynamometer and using the Mahr surf test (Model GD120), respectively.

3. Methods

The experimental design is based on Taguchi's orthogonal array (OA) which involves selecting response variables, independent variables, and their interactions. The following steps are involved in Taguchi's optimization methodology[16-18]:

i. Formulate the objective function of the study with the target specification

ii. Identify the independent variables and responses with factors and levels
iii. Select an appropriate experimental design and conduct experiments
iv. Analyze the results by signal to noise (S/N) ratio or by via variance test (ANOVA).
v. Determine the optimal machinability parameters
vi. Confirmation trials

In this research work, the machinability parameters and their levels used in the experiments are presented in Table 1. The factorial design of experimental strategy with 18 experiments is used for execution of machinability experiments. Experimental trial has been carried out for a machinability length of 30 mm. The average Ra roughness values and Fz force measured and their S/N ratio are listed in Table 2.

Table 1. Parameters and their levels

Parameter, symbol	Units	Levels		
		1	2	3
Cutting speed (A)	m/min	60	80	100
Feed rate (B)	mm/rev	0.06	–	0.10
Cutting depth (C)	mm	0.4	0.8	1.2

Table 2. Pearson correlation analysis among machining parameters

Parametric design parameters	Quality characteristics (KC5010)			
	Fx	Fy	Fz	Ra
	r (p-value)	r (p-value)	r (p-value)	r (p-value)
Cutting speed	−0.084 (0.741)	0.074 (0.771)	−0.163 (0.571)	0.213 (0.395)
Feed rate	−0.078 (0.757)	−0.639 (0.004□)	0.194 (0.439)	0.509 (0.031□)
Depth of cut	0.935 (0.000)	0.082 (0.747)	0.816 (0.000□)	0.198 (0.430)
Parametric design parameters	Quality characteristics (KC5525)			
	Fx	Fy	Fz	Ra
	r (p-value)	r (p-value)	r (p-value)	r (p-value)
Cutting speed	−0.311 (0.209)	0.135 (0.594)	−0.290 (0.242)	−0.188 (0.454)
Feed rate	−0.053 (0.833)	0.290 (0.243)	0.132 (0.601)	−0.040 (0.875)
Depth of cut	0.576 (0.012□)	−0.353 (0.151)	0.460 (0.050□)	0.485 (0.041□)

r: Pearson correlation coefficient, □:Significant effect, p-value<0.05

4. Results and Discussion

4.1 Effect of Parameters on *cutting force (fz)*

The measured values of the main cutting force (Fz) during the dry cutting conditions on Inconel 718 for both PVD inserts (KC5010 and KC5525) are presented in Figure 1. Main cutting forces is increases up to 67% for KC5010 and 54% for KC5525 with the increment of cutting depth. At high level of cutting depth and feed rate, the magnitude of main cutting force is observed as 347 N for KC5010 and 368 N for KC5525. Results reveal that cutting depth is the most variable factor on main cutting force. And it also observed that magnitude of about 394 N for KC 5010 and 518 N for KC 5525 on cutting force at combination of lower speed; and higher cutting depth. The increase in magnitude of Fz force is observed an increasing of cutting depth, for all levels of speed. Further it is perceived that, the maximum Fz force is generated at a lessening of speed. This could be endorsed to the fact that for lessening of speed the coefficient of friction is high between workpiece-tool interfaces when compared to higher cutting speed. From Figure 1, it also perceived that the magnitude of Fz force increased as the feed rate increases, for all levels of speed. Further it is recognized that, the maximum of 241 N for KC5010 and 286 N for KC5525 magnitude of the main Fz cutting force is generated at higher feed and lessening speed. The decrease in values of main cutting force is observed while increases the speed. Zou[16] establish that the feed and cutting depth is the most important factors affecting main cutting forces when dry turning of NiCr20TiAl nickel based alloy using PVD, Al_2O_3/TiN, coated carbide tools. It is clear from the main-effect plot of means is shown in Figure 1 that the lower value of Fz force is obtained at a moderate level of speed with low level of feed-cutting depth.

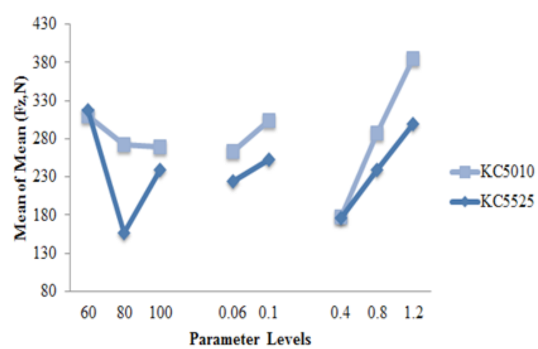

Figure 1. Main effect plots for mean of mean for cutting force (Fz) for KC5010 and KC5525.

4.2 Effect of Parameters on Surface Roughness

The measured values of the surface roughness (Ra) during the dry turning of 718 Inconel for both PVD (KC5010 and KC5525) inserts are presented in Figure 2. From the graphical analysis, the increment of Ra roughness is observed with an increment in the feed for both PVD inserts. But the value of Ra for KC5010 is about 0.47 µm and for KC5525 is about 0.58 µm at high level of feed rate. However, from the plot of main effect, it can be seen that as the speed increases, Ra roughness found to be increase more steadily. The height of ridges is increased at a higher level of feed which consequently resulted in increases the value of Ra. It also noted that at moderate level of cutting depth and low feed results better Ra roughness value for KC5010 but the moderate level of speed and cutting depth is resulted in low Ra roughness for KC5525. It can also be endorsed that higher value of roughness Ra at higher level of cutting depth for both the type of turned insert. From graphical plot (Figure 2), it is also perceived that Ra roughness lessening with an upsurge in depth of cut and speed at moderate value levels for KC5010 insert. At a higher level of cutting depth and speed the surface roughness Ra is found to be higher than low speed and cutting depth for KC5525. It can be comprehended for the both type of PVD inserts that moderate level of cutting depth and their speed contributes the minimum surface roughness Ra.

4.3 Pearson Correlation Coefficient Analysis

The Pearson correlation coefficient (r) is calculated by dividing the covariance of two variables by the multiplication of the standard deviations of these two variables[20]. The correlations between the experimental design parameters and the direction of these correlations are elucidated by calculating the value of r. The Pearson correlation coefficient obtained for each design experimental parameter is given in Table 2. There are positive strong correlations between the cutting depth and feed force; thrust force; cutting force and then with surface roughness. It observed that increases the cutting depth, +0.935 (Fx), +0.816 (Fz) has shown strong linear relationship, results in higher value of feed force, main cutting force whereas increases in depth of cut, +0.082 (Fy), + 0.198 (Ra) has shown weak linear relationship, with thrust force and surface roughness. There are positive strong correlations between the feed rate and surface roughness as well as cutting force, but there is a negative correlation with thrust force. There are negative correlations between the cutting speed and thrust force as well as cutting force, but there is a positive correlation with surface roughness. It is observed that increases the feed rate (+0.509 (Ra), -0.639 (Fy) has shown strong linear relationship) results in higher feed force, surface roughness whereas increases in feed rate (+0.194 (Fz) has shown weak linear relationship) with cutting force. From the Table 2, there is a strong correlation is found between the cutting force (Fz) and feed force (Fx) on the roughness subsequently a 'correlation coefficient' value of 0.224 and 0.201 for KC5525 is obtained. From the force perspective, the strongest correlation is found between feed force and cutting force (+0.896), which delivers that the feed force magnitude is found to be increased as the force Fz is also increased. From the roughness perspective, there is weak correlation is between thrust force and roughness for both the inserts which means that the magnitude of roughness is increased as the thrust force is lessening. Moreover, the Pearson correlation coefficients among the quality characteristics (Fz, and Ra) are calculated and are presented in Table 3. It can be observed that there are positive correlations between the cutting forces and surface roughness, between feed force and cutting force and between the thrust forces and surface roughness for KC55010 and KC5525 Table 3.

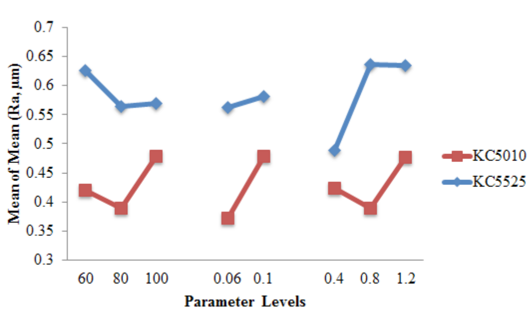

Figure 2. Main effect plots for surface roughness (Ra) for KC5010and KC5525.

5. Regression Equations

Using the experimental data, predictive linear equations for both the inserts are developed for the estimation of the quality characteristics. The determination coefficients (R^2) for cutting force and surface roughness are calculated

Table 3. Pearson correlation analysis among quality characteristics

Responses	Quality characteristics (KC5010)		
	Fx	Fy	Fz
	r (p-value)	r (p-value)	r (p-value)
Fy	0.242 (0.334)	–	–
Fz	0.889 0.000□)	0.235 (0.347)	–
Ra	0.111 (0.662)	−0.105 (0.680)	0.237 (0.345)
Quality characteristics	Quality characteristics (KC5525)		
	Fx	Fy	Fz
	r (p-value)	r (p-value)	r (p-value)
Fy	0.242 (0.334)	–	–
Fz	0.896 (0.000)	0.429 0.076□)	–
Ra	0.224 (0.371)	−0.112 (0.657)	0.201 (0.243)
Responses	Quality characteristics (KC5010)		
	Fx	Fy	Fz
	r (p-value)	r (p-value)	r (p-value)
Fy	0.242 (0.334)	–	–
Fz	0.889 0.000□)	0.235 (0.347)	–
Ra	0.111 (0.662)	−0.105 (0.680)	0.237 (0.345)
Quality characteristics	Quality characteristics (KC5525)		
	Fx	Fy	Fz
	r (p-value)	r (p-value)	r (p-value)
Fy	0.242 (0.334)	–	–
Fz	0.896 (0.000)	0.429 0.076□)	–
Ra	0.224 (0.371)	−0.112 (0.657)	0.201 (0.243)

for KC5010 insert as 71.5% and 83.8 %, respectively (Eqs.4 and 5) and for KC5525 insert as 90.7% and 75.8 %, respectively (Eqs.6 and 7). The differences between measured and predicted responses are refereed as residual. By using these equations (4-7), the responses are predicted and compared with experimental results are shown in Figure 3 (a-b) and 4 (a-b). The developed model shows the model predictive error (MPE) is less than 9%.

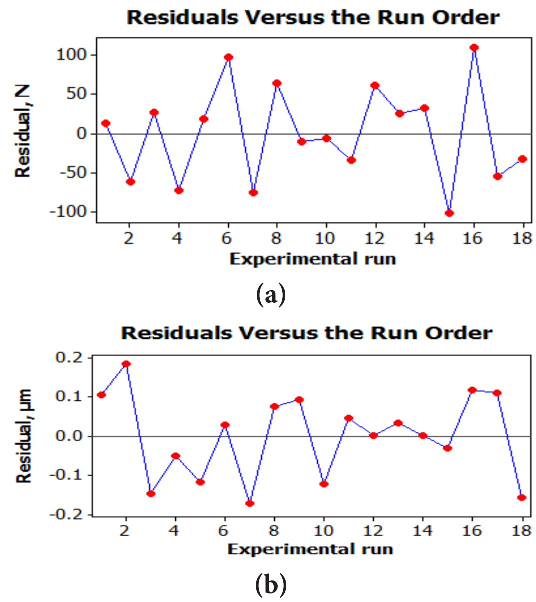

Figure 3. Residuals versus experimental run: a) cutting force (KC5010); b) surface roughness (KC5010).

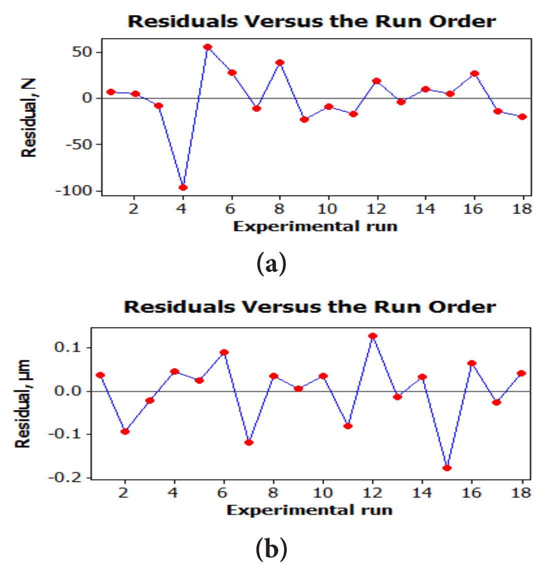

Figure 4. Residuals versus experimental run: a) cutting force (KC5525); b) surface roughness (KC5525).

The cutting force (Fz) model for KC5010 is given in Equation (1).

$$Fz = 701.1 - 8.98 * A - 7026 * B + 282.85 * C + 0.04 * A * A$$
$$- 39.53 * C * C + 52.31 * A * B + 4807 * A * C - 4.38 * B * C \quad (1)$$

The arithmetic mean of roughness (Ra) model for KC5010 is given in Equation (2).

$$Ra = 1.42 - 0.028 * A + 0.09 * B - 0.32 * C - 0.00015 * A * A$$
$$+ 0.38 * C * C + 0.067 * A * B - 3.33 * A * C + 0.005 * B * C \quad (2)$$

Table 4. Analysis of variance for KC5010

Source	DF	SS	MS	F ratio	p-values	PCR
Cutting force (Fz)						
B	1	7260	7260	6.00	0.071	37.8
A	2	6436	3218	2.66	0.184	3.5
C	2	127901	63950	52.83	0.001	66.66
B□A	2	5399	2700	2.23	0.224	2.81
B□C	2	20427	10213	8.44	0.037	10.54
A□C	4 26	19699	4925	4.07	0.101	10.26
Error	4	4822	4842			2.510
Total	17	191965				
Surface roughness (Ra)						
B	1	0.0582	0.0588	4.79	0.054	25.91
A	2	0.0252	0.0126	1.03	0.437	11.11
C	2	0.0242	0.0121	0.98	0.450	10.6
B□A	2	0.0344	0.0172	1.40	0.354	15.19
B□C	2	0.0087	0.0053	0.35	0.721	3.84
A□C	4 26	0.026	0.0066	10.54	0.717	11.7
Error	4	0.049	0.0123			21.6
Total	17	0.2271				

Table 5. Analysis of variance for KC55525

Source	DF	SS	MS	F ratio	p-values	PCR
Cutting force (Fz) for KC5525						
B	1	3799	3799	1.92	0.238	1.75
A	2	77738	38869	19.63	0.009	35.7
C	2	45947	22974	11.60	0.022	21.1
B□A	2	6235	3118	1.57	0.313	2.86
B□C	2	8838	4419	2.24	0.223	4.06
A□C	4	67063	16766	8.47	0.031	30.8
Error	4	7921	1980			3.64
Total	17	217543				
Surface roughness (Ra) for KC5525						
B	1	0.0004	0.0004	0.18	0.695	1.52
A	2	0.0143	0.0072	2.90	0.166	5.22
C	2	0.0868	0.0434	17.61	0.010	31.7
B□A	2	0.0125	0.0062	2.54	0.194	4.55
B□C	2	0.0096	0.0048	1.96	0.255	3.55
A□C	4	0.1398	0.0034	14.18	0.012	51.1
Error	4	0.0098	0.0002			0.36
Total	17	0.2734				

The cutting force (Fz) model for KC5525 is given in Equation (3)

$$Fz = 1241.96 - 42.07 * A + 6345.5 * B + 829.6 * C + 0.34 * A * A - 6.91 * C * C + 47.52 * A * B - 2271.87 * A * C - 6.02 * B * C \quad (3)$$

The arithmetic mean of roughness (Ra) model for KC5525 is given in Equation (4).

$$Ra = 2.36 - 7.3 * B - 0.03 * A - 0.48 * C - 0.008 * A * A + 0.46 * C * C + 0.060 * A * B - 2.78 * A * C + 0.014 * B * C \quad (4)$$

6. Conclusion

The present study investigated the effects of speed, feed and cutting depth on quality characteristics such as forces and roughness during dry turning of 718 Inconel using PVD coated carbide inserts. The results are presented below: Increment in cutting speed resulted in cutting forces decreased whereas an increment of cutting depth increases the main cutting force. The low value of main cutting force is attained at a moderate level of speed; low level of feed and cutting depth for both the PVD coated carbide inserts. The lower value of Ra surface roughness is observed for KC5010 compared to insert designated with KC5525. From analysis of variance and Pearson correlation analysis (r), the cutting depth is the most machining factor affecting the machined Ra roughness and Fz main cutting force. The correlation coefficient (R^2) of the predictive second order regression equations developed using the collected experimental data are deliberate as 71.5% and 83.8 % for insert type of KC55010 and 90.7% and 75.8 %, for insert type of KC5525 for Fz main force and Ra roughness, respectively.

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