Finite Element Investigation and Optimization of Tool Wear in Drilling Process of Difficult-to-Cut Nickel-Based Superalloy using Response Surface Methodology

M. Kolahdoozan*
Department of Mechanical Engineering,
Najafabad Branch, Islamic Azad University, Isfahan, Iran
E-mail: kolahdoozan@pmc.iaun.ac.ir
*Corresponding author

F. Azimifar & S. Rismani Yazdi
Department of Mechanical Engineering,
Majlesi Branch, Islamic Azad University, Isfahan, Iran
E-mail: f.azimifar@iaumajlesi.ac.ir, saeed-rismani@smc.iaun.ac.ir

Received: 10 May 2013, Revised: 3 November 2013, Accepted: 22 April 2014

Abstract: This research deals with monitoring tool wear through the chip formations, forces, and edge temperature of drill while drilling in superalloy plate to optimize effective parameters which lead to facilitate machining process to improve tool life, and enhance productivity. Inconel 718 superalloy material, and cemented coated carbide tool were selected in this study to investigate tool wear mechanism. Mathematical models were deduced by Minitab software to display the influence of the main cutting variables such as cutting speed, feed rate and tool diameter on tool wear. A wear process model of twist drill is established based on finite element method. The 3D FEA model established here, provides a new approach to study the mechanism of drill wear. The predictive models in this study are believed to produce values of tool wear close to those readings recorded experimentally with 95% confidence interval, verified using ANOVA. The simulation results were in accordance with experimental and predictive values from RSM with error rate of 4-6%, proving the ability of the tool wear model to correctly forecast it. In addition, the experimental results demonstrated that cutting speed as the main parameter followed by feed rate, contribute significantly the tool wear of drill bit.

Keywords: ANOVA, Response Surface Methodology, Simulation, Tool Wear

Reference: Kolahdoozan, M., Azimifar, F., and Rismani Yazdi, S., “Finite Element Investigation and Optimization of Tool Wear in Drilling Process of Difficult-to-Cut Nickel-based Superalloy using Response Surface Methodology”, Int J of Advanced Design and Manufacturing Technology, Vol. 7/ No. 2, 2014, pp. 67-76.

Biographical notes: M. Kolahdoozan is assistant professor of Mechanical Engineering at Islamic Azad University, Najafabad Branch, Isfahan, Iran. He received his PhD in Advanced Manufacturing from Islamic Azad University, Science and Research Branch. Their current research interest includes Machining & Advanced Mechatronics. **F. Azimifar,** and **S. Rismani Yazdi** are lecturer of Mechanical Engineering at Islamic Azad University, Majlesi Branch, Isfahan, Iran. They received their MSc in Machining & Advanced Mechatronics, and Advanced Sheet Metal Forming from Isfahan University of Technology. Their current research interest includes Machining & Advanced Metal Forming Process.

1 INTRODUCTION

Drilling is one of the most demanded machining processes and is highly important economically in the industry. It has been utilized in different industries and accounts for 40–60% of the total material remove processes. Nevertheless, in contrast to other machining processes, researches using finite element simulation on drilling are limited and not reported frequently in particular for heat resistant superalloys employed in aeronautic and aerospace applications. The overall objective of this study is to provide a predictive capability in drilling of nickel-based superalloys to enable optimization of the process parameters and drill bit geometry while taking into account work piece quality and tool wear.

Tool wear plays an important role in drilling process research and affects significantly the economics of the machining operations. It affects the tool life, quality of machined surface, cutting parameters such as cutting force, cutting temperature, cutting vibration, and cutting power. Machining Inconel 718 shows its difficulty into two basic problems: short lifespan of tool and harsh surface abuse of machined surface [1-3]. During machining Inconel 718, great thermal and mechanical loads close to the cutting edge is often supported by the cutting tool which leads to quick wear of the tool. The machined surface is affected by both heat generation and plastic deformation which were brought about during machining, causing rapid tool wear [4]. Tool wear is generally affected by several different mechanisms: material adhesion, abrasion, erosion, diffusive wear, corrosion and fracture. These phenomena are usually presented in combination, even if only one or few of them are dominant (Fig. 1).

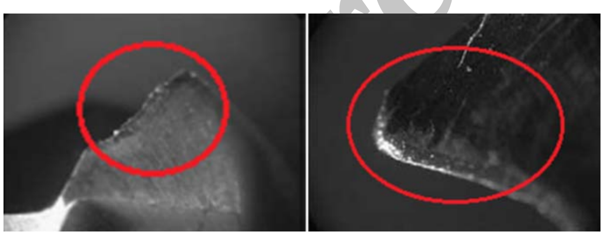

Fig. 1 Wear locations on drill bit

Functional elements that affect the wear of a cutting tool are classifieds into four major groups, as shown in Fig. 2 [5]. When tool wear reaches a certain value, the life of the cutting tool comes to an end because surface integrity is deteriorated, and dimension error becomes greater than tolerance as a result of increasing cutting force, vibration and temperature. Then the cutting tool should be replaced or grounded that interrupts the cutting process. Tool replacement and adjusting machine settings, increases the cost and time and decrease the productivity. Therefore, one can find a lot of investigations regarding tool wear in the literature, however, it is of great importance for the optimization of cutting process to predict tool wear [6-8].

Fig. 2 Four functional elements influencing tool wear in machining processes

Changing cutting parameters and optimizing cutting conditions are what the traditional methods are concerned with in studying tool wear rules. When using this method, experiments should be repeated to obtain reasonable accuracy; this will result in high costs being imposed on the industry manufacturer worldwide regarding time demanding, human energy and work material, respectively. Besides, there will be a need for advanced detection of analytical instruments and testing measures. Simulation technology has turned into an important device in analyzing cutting process, and this makes it possible to study cutting process and the relationship among different parameters through using numerical simulation [9]. Due to free flow of material that occurs over free boundaries, the numerical simulation of cutting process can be extremely difficult. Therefore, most of the previous analyses which used simple models such as rigid-plastic/elastic-plastic and non-hardening material behaviour, or empirical models depending on experimental data, overlooked interfacial friction and tool wear on the cutting process [10].

2 TOOL WEAR MODEL

Tool wear models include Taylor’s model, Hasting’s model, Takeyama & Murata’s model and Usui’s model. The first two models associate with experience formula, especially Taylor's model is widely used in experience scene to predict tool life. The last two models interrelate with discrete formula, there into Usui’s model originated from Shaw formula. Thus, in this paper, Usui's model is used to predict tool wear. By this research, authors have proved that Usui's model is generally better for continuous processes such as metal cutting where diffusion is a major contributor to wear. There is also another model which named Archard's model, however, it is better suited for discrete processes such as cold or hot forging. In these cases, abrasive wear is the dominant wear mode. There are two classifications for wear model: the first one is cutting parameter-tool life type which focuses on optimizing machining operation, such as the famous Taylor's equation which sets up the simple relationship between the cutting speed V_c and tool life T. The other type is cutting process variable-wear rate type which is often according to one or several wear mechanisms such as E. Usui's wear model resulting from adhesive wear, describing wear rate as a function of cutting process variables, e.g., normal stress, contact temperature, and relative sliding velocity on tool face, and supplying approaches for tool wear estimate with numerical methods. If the tool wear rate model is seen as a function of output state variables (T, V, σ, n and so on), Usui's model of wear rate during simulation calculation can be used.

$$\frac{dW}{dt} = A\sigma_n V_s \exp\left(-\frac{B}{T}\right) \tag{1}$$

Where dW/dt is wear rate which is the wear volume per unit area and unit time. σ_n is normal stress [MPa], V_s the sliding velocity at the interface between tool and chip [mm/s], T is cutting temperature [K], A and B are constants determined for the combination of tool and work material. The latter study [11] shows that this equation is able to describe flank wear as well, which mainly results from abrasive wear. The simulation software provides the values of normal stress (σ), sliding velocity (V) and temperature (T) in their local values. A and B constants were set according to the procedure reported in Ref. [10] where experimental tests coupled with FEM simulations are used to calibrate the Usui et al., parameters in order to minimize the tool crater depth error, i.e. the difference between experimental and simulated crater depth.

In this research, A and B constants were estimated considering the experimental data and the results obtained from finite element modeling. Therefore, for drilling process of difficult-to-cut materials such as Inconel 718, the value of A and B is determined by lots of simulation tests, considering A equal to 2.0 E-7 and B equal to1000.

3 FINITE ELEMENT MODEL

The Finite Element Method (FEM) was successfully applied to simulate various cutting processes in the last decade [13-17]. The FEM cutting simulation can be used to estimate the process variables not directly measurable or very difficult to measure during a cutting operation; variables like normal stress and temperature on the tool face, chip temperature, and chip sliding velocity along the tool rake face. Knowing these process variables, may help to better understand the fundamental cutting mechanics and to enable the engineering analysis of tool wear. Moreover, the correlations between such variables and the tool life may enable researchers to employ a systematic approach for the process optimization.

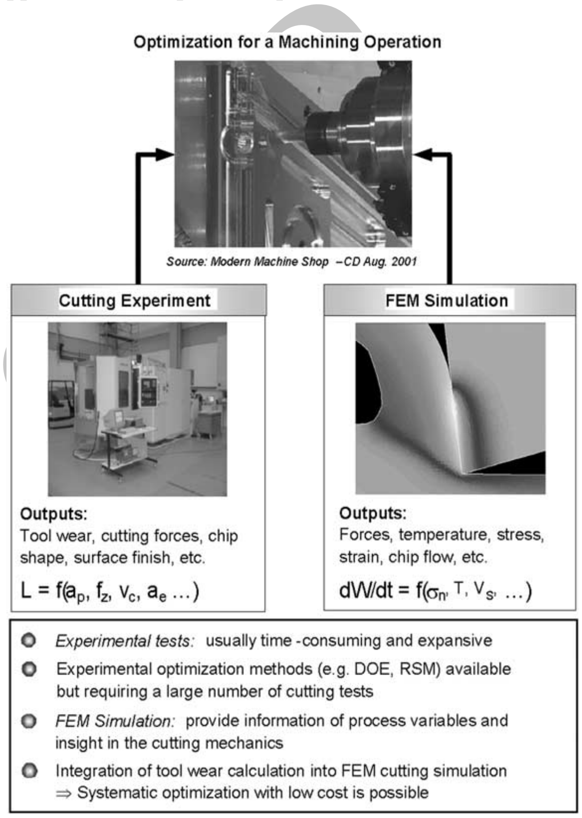

Fig. 3 Comparison between experimental testing and FEM simulation for machining analysis

2D FEM codes which employ tool wear models can be found in the literature [18], but their biggest obstacle is that they have the ability of forecasting tool crater and flank wear only under orthogonal cutting conditions. Using 3D FEM for drilling process, the authors have overcome these limitations. The developed model is new and creative, because not only it provides the wear rate distribution, but also it can consider the tool geometry modification resulted from the wear rate and how its distribution changes with the change in the tool geometry. This made a tool wear simulative model the closest to the actual situation in which along with the change in the tool shape, the cutting conditions change as well. In the current study, drilling of Inconel 718 has been investigated using a 3D Lagrangian finite element model. The interaction between drill and workpiece is integrated by explicit dynamic analysis, where for validation purposes, experimental tests were carried out and compared to FE results.

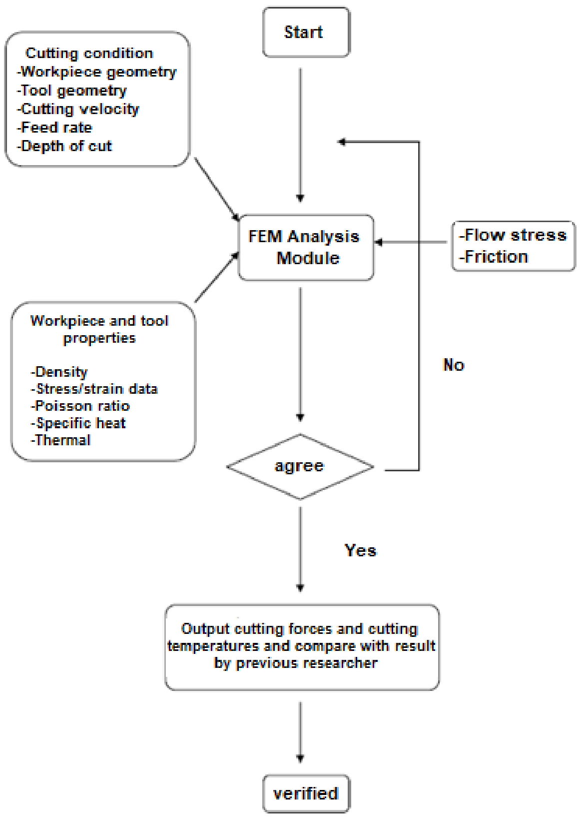

Fig. 4 Chip formation, initial geometry and mesh

The FEM software DEFORM-3D is used in the present study as the simulation tool. It is a robust simulation tool that uses the FEM to model complex machining process in three dimensions. It is available in both Lagrangian (Transient) and arbitrary Lagrangian and the Eularian (ALE Steady-State) modeling. The simulation results on cutting forces and temperatures, and tool wear were compared with experimental data in order to indicate the consistency and accuracy of the results when conducting the comparison. To simulate the chip formation a remeshing procedure was performed frequently so that the workpiece mesh was frequently updated and modified to follow the tool progress. The minimum element size is determined by the feed. For a two-flute drill with 0.15mm feed/revolution, the feed per cutting edge is 0.075mm. A minimum element size of 0.04mm (0.0375 rounded up) was used to get two elements in the chip thickness. Tool was meshed with more than 20,000 tetrahedral element mesh, weighted towards the cutting tip. In order to save calculation time, only a part of the cutting tool near cutting edge joins in the chip formation modeling. Correct configuration of surface types and reasonable adaptive meshing control parameters, which depend on tool edge geometry, will ensures the smooth implementation of chip separation as depicted in Fig. 4.

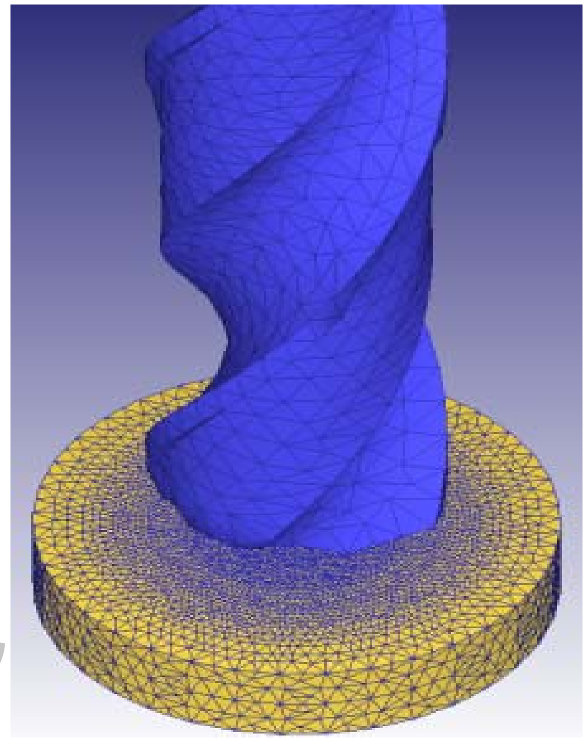

Fig. 5 Stress field (MPa) in workpiece during drilling process

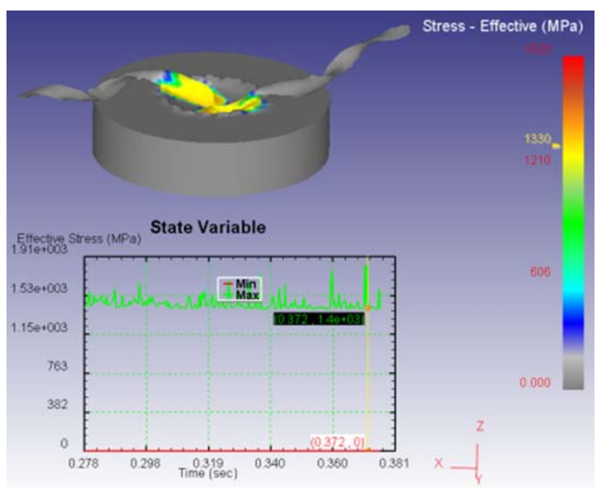

Fig. 6 Process flow chart for simulation

Using DEFORM-3D FEM, the distribution of temperature, stress, strain and strain rate can be plotted on the object's surfaces as well as their inside as shown in Fig. 5. A qualitative analysis of these parameters shows their realistic distribution (close to the theoretical predictions) during the simulation process. The proposed work concentrates on the development model of Finite Element Analysis (FEA) procedures to get to the abovementioned research objectives. The flow of this simulation is depicted in the flow chart in Fig. 6 [10]. Fig. 7 is the steady-state simulation result of the temperature distribution in cutting process. It can be seen that in the place of tool bit where tool contacts with workpiece and chip, violent extrusion and friction occur. This makes the metal close to the rake face fibrosis, and the cutting temperature in this place is considered as the highest so that the most serious wear appears in this place. Fundamental work for the data extraction, such as cutting temperature, contact pressure, and relative friction speed, is provided by the results of steady-state analysis in the prediction of tool wear.The finite element model is composed of a deformable workpiece and a rigid tool. Overall, there have been a series of cutting test to carry out simulation in varies machining parameters of cutting speed, feed rate, and depth of cut. Furthermore, the chip formation and the stress, strain and strain rate distribution in the chip and workpiece as well as the temperature fields in the workpiece, chip, and tool are determined.

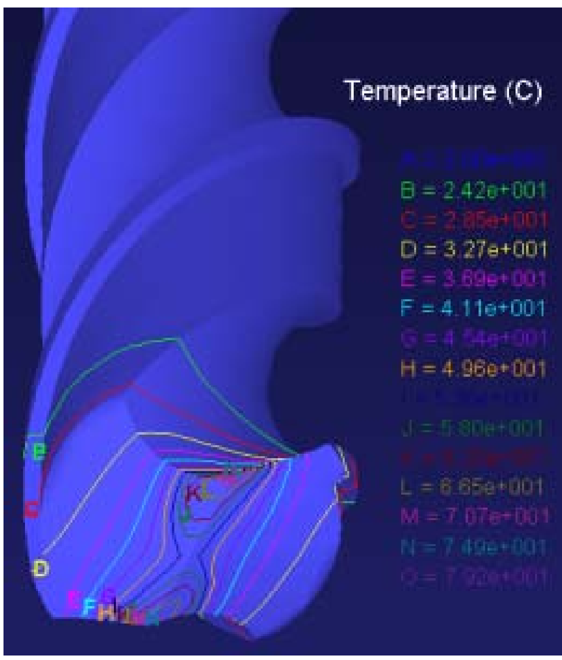

Fig. 7 Most potential wear region, and variation of tool temperatures near the contact areas

The authors applied various cutting speed (ranging from 400 to 600 rpm), feed rate (from 0.1 to 0.14 mm), and tool diameter (5, 10, 15 mm), with constant depth of cut to evaluate the effect of input parameters. Fig. 8 shows the results of tool wear in various cutting speeds. It was observed that increasing cutting speed resulted in a faster tool wear. Tests were repeated by changing the feed rates to observe the influence of feed on tool wear. According to the experimental and FEM data, using higher feeds entails an increase in tool wear.

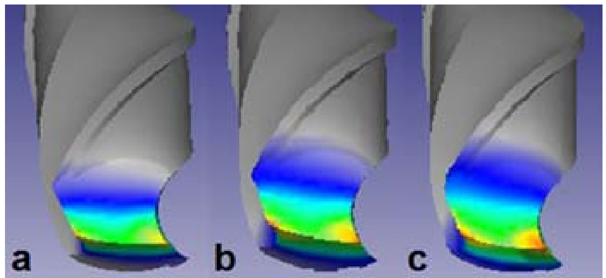

Fig. 8 Predicted results of the wear distribution after 3 min machining at different cutting speeds of a) 400, b) 500, c) 600 rpm

4 EXPERIMENTATION AND ANALYSIS

The experiments were conducted on a conventional drill machine. In the cutting tests, nickel-based superalloy, Inconel 718 alloy with hardness of 40–45 HRC was used as workpiece material. The chemical composition of Inconel 718 is shown in Table 1. Cemented carbide coated tool (TiAIN) was used for the FEM and experimental tests. The cutting forces were measured using Kistler dynamometers. Tool wear was measured with a travelling microscope connected to a digital readout device at a magnification of X25.

Table 1 Chemical composition of the investigated material

Element(per)	min	max
Nickel	50.00	55.00
Chromium	17.00	21.00
Columbium+tantalum	4.75	5.50
Molybdenum	2.80	3.30
Titanium	0.65	1.15
Aluminium	0.20	0.80
Cobalt	-	1.00
Carbon	-	0.08
Manganese	-	0.35
Silicon	-	0.35
Phosphorus	-	0.015
Sulfur	-	0.015
Boron	-	0.006
Copper	-	0.30
Iron	remainder	

4.1. SOE and RSM

It is essential to have a proper design of experiments, for it has a significant effect on the number of experiments needed. Response surface methodology (RSM) was selected in this work so that all interactions among the independent variables can be investigated. Response surface methodology or RSM is a collection of mathematical and statistical techniques that are useful for modeling and analysis of problems in which response of interest is influenced by several variables and the objective is to optimize the response. The version 15 of the Minitab software was used to develop the experimental plan for RSM. The range of cutting parameters was set at three different levels of low, medium, and high based on industrial practice (Table 2).

In the present work, the significant parameters were used to develop mathematical models using response surface methodology. These models are of great use during optimization of the process variables. RSM methodology is practical, economical and relatively easy to use.

Table 2 Levels of input independent variables

S. No.	Parameter	Symbol	Low -1	Medium 0	High +1
1	Speed, (rpm)	V	400	500	600
2	Feed rate, (mm/rev)	f	0.1	0.12	0.1 4
3	Tool diameter, (mm)	D	5	10	15

The experimental results were used to build first-order and second-order models by the multiple regression methods. The purpose of developing mathematical models is to understand the combined effect of involved parameters and to facilitate optimization of the machining process. In these experiments twenty tests were carried out with parameters at different levels which are shown in Table 3.

Table 3 Conditions of cutting experiments according to response surface method

Exp. Number	Cutting speed, V (rpm)	Feed, f (mm/rev)	Tool diameter, D (mm)	Tool wear Experimental	Tool wear Minitab	Tool wear FEM
1	400	0.14	5.0	0.170	0.165	0.181
2	600	0.10	15.0	0.220	0.213	0.211
3	400	0.10	15.0	0.160	0.153	0.164
4	600	0.14	15.0	0.240	0.233	0.232
5	400	0.10	5.0	0.150	0.153	0.144
6	500	0.12	10.0	0.180	0.189	0.176
7	600	0.14	5.0	0.230	0.225	0.239
8	500	0.12	10.0	0.180	0.189	0.176
9	500	0.14	0.5	0.190	0.195	0.193
10	500	0.12	10.0	0.180	0.198	0.176
11	600	0.10	5.0	0.210	0.204	0.222
12	400	0.14	15.0	0.175	0.173	0.164
13	500	0.12	5.0	0.175	0.184	0.182
14	500	0.10	10.0	0.170	0.179	0.178
15	500	0.12	10.0	0.190	0.189	0.195
16	400	0.12	10.0	0.160	0.159	0.153
17	500	0.12	15.0	0.185	0.193	0.175
18	400	0.12	0.5	0.155	0.154	0.167
19	500	0.12	10.0	0.180	0.189	0.176
20	600	0.12	10.0	0.220	0.219	0.233

DOE features of Minitab were utilized that determined the coefficients in the response surface regression model, where the values of these coefficients are presented in Table 4.

The results of ANOVA for tool wear are shown in Table 5. This table also illustrates interaction of each factor in addition to the sum of squares, mean squares, degree of freedom, and F values. Examination of F values in this table indicates that the variables such as cutting speed, feed rate, and tool diameter are significant at 95% confidence level, since P values associated with these terms are less than 0.05. However, the terms containing DD, VF, VD, and FD enjoy P values greater than 0.05 indicating that these terms do not significantly affect the tool wear. It is also clear from the results that cutting speed & feed rate are the dominant factors determining the tool wear followed by tool diameter.

4.2. Mathematical Modeling

The best fitted equations with the regression coefficient of 0.95 for tool wear were obtained. These equations present the expected values of the tool wear for any combination of factor level. The RSM model fitted for tool wear is represented by Eq. (2). The values of RSM model for input parameters are shown in Table 4. The results from the finite element model were in agreement with RSM experimental and predictive values with error value of 4-6%.

$$\text{Tool Wear} = 0.180152 + (V \times 0.030581) + (F \times 0.009844) + (D \times 0.004487) + (VV \times 0.010440) + (FF \times 0.002564) + (DD \times 0.000970) + (VF \times 0.000625) + (VD \times 0.000433) - (FD \times 0.000834) \quad (2)$$

Eq. 3 shows the regression model for tool wear.

$$\text{Tool Wear} = -0.0314 + 0.000301 \times V + 0.512 \times F + 0.000780 \times D \quad (3)$$

The adequacy of the model was also verified using the analysis of variance (ANOVA). At the level of confidence of 95%, the model was checked for its adequacy and the results are presented in Table 5. The model is adequate as the P values of the lack-of-fit are not significant. This implies that the model could fit and it is adequate.

The effects of cutting speed, feed rate, and tool diameter on tool wear as predicted by equation 1 are indicated graphically in Fig. 1 as contour plot. Fig. 9 shows the response graph for two varying parameters of cutting speed and feed rate (v×f) by keeping the third parameter tool diameter at constant average level which indicates that increase of cutting speed is followed by increase of the tool wear.

Referring to the plot it may be seen that the tool wear increases as cutting speed and feed rate increase. Figure 10 shows the effect of cutting speed, feed rate, tool diameter, and their interaction and contribution of each source on results of tool wear. The normal probability plot of residuals as shown in Fig. 11 also lies fairly close to a straight line suggesting that the errors are normally distributed and the regression model is well fitted with the observed values. In terms of the cost of the machining process, authors recommend the cutting speed and the feed rate values to be selected between 400 and 430 rpm, and 0.1 and 0.12 mm/rev, respectively with tool diameter of 10 mm (Fig. 12).

Table 4 Regression analysis for tool wear

Term	Coef.	SE Coef.	T	P
Constant	0.180152	0.000783	230.067	0.000
V	0.030581	0.000654	46.746	0.000
F	0.009844	0.000694	14.187	0.000
D	0.004487	0.000638	7.031	0.000
V×V	0.010440	0.001157	9.027	0.000
F×F	0.002564	0.001203	2.132	0.059
D×D	0.000970	0.000663	1.462	0.174
V×F	0.000625	0.000740	0.844	0.418
V×D	0.000433	0.000700	0.619	0.550
F×D	-0.00083	0.000691	-1.206	0.256
R-Sq = 99.64%		**R-Sq(adj) = 99.32%**		

Table 5 Analysis of variance for tool wear

Source of variance	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.012220	0.012220	0.001358	309.75	0.000
Linear	3	0.011432	0.011016	0.003672	837.73	0.000
Square	3	0.000778	0.000767	0.000256	58.32	0.000
Interaction	3	0.000011	0.000011	0.000004	0.81	0.515
Residual Error	10	0.000044	0.000044	0.000004		
Lack-of-Fit	6	0.000024	0.000024	0.000004	0.79	0.619
Pure Error	4	0.000020	0.000020	0.000005		
Total	19	0.012264				

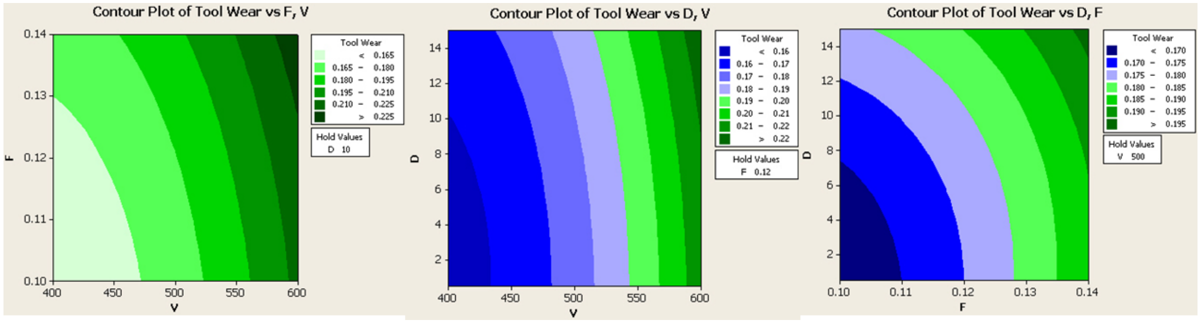

Fig. 9 Contour plot of tool wear

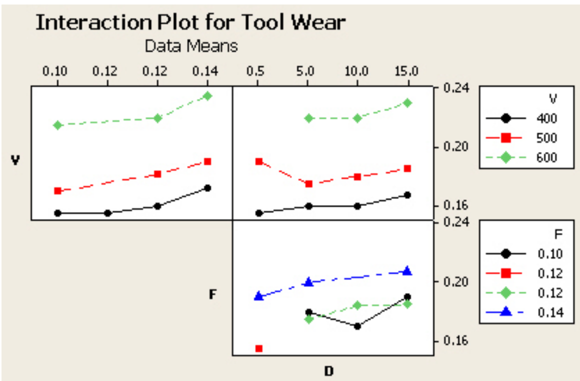

Fig. 10 Interaction plot for tool wear

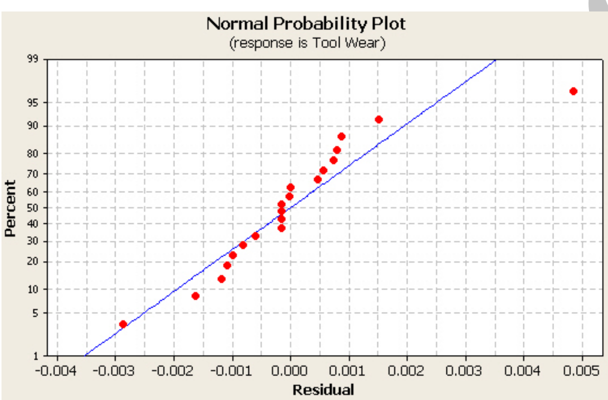

Fig. 11 Normal probability plot of residuals for tool wear

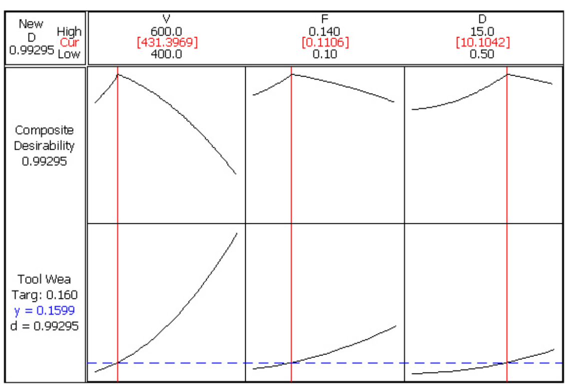

Fig. 12 Optimization plot for tool wear

5 CONCLUSION

Analyzing the tool wear during drilling, this paper, adopted Usui wear rate model, and established the cutting model during steady-state cutting process in order to predict the tool life. Mathematical models were deduced by Minitab software (multiple linear regression and response surface methodology) in order to demonstrate the influence of the main cutting variables such as cutting speed, feed rate and tool diameter on tool wear. The main conclusions drawn from the results of the current work are as follows :

This research work is performed to compare machining output data from FEM Deform-3D software with experimental results and results of RSM model using numerical model to simulate and investigate the wear mechanisms in drilling Inconel 718 alloy by coated carbide tool.

Response surface methodology offered a simple, systematic approach and reduced the number of experiments to optimize design for performance, quality and manufacturing cost. It is a scientifically disciplined mechanism for evaluating and implementing improvements in products, processes, materials, equipments and facilities. Small central composite design (CCD) was employed in developing the tool life model in relation to primary cutting parameters such as cutting speed, axial depth of cut and feed.

Analysis of variance showed levels of the obtained correlations to be highly confident. The experimental values agreed with the predicted results thus proved suitability of the models. These showed the adequacy of the derived models to predict tool wear within ranges of parameters that have been investigated during the experiments. The derived models, particularly, could be used to optimize practical cutting conditions. The proposed empirical model predicts tool wear within confidence level of 95%.

The experimental results in this study demonstrated that the cutting speed as the main parameter and feed rate as the secondary, influence the tool wear of drill bit. The tool life model obtained from RSM showed that among the machining parameters, cutting speed has the most dominant effect on tool wear, followed by the feed rate. Increasing these two cutting variables leads to reduction of tool life. With increasing the tool wear or tear, the rising of cutting force and cutting temperature could be monitored clearly, resulting in deterioration of machine quality.

The tool life can be improved simultaneously through DOE approach instead of using Engineering judgment. The confirmation experiments were conducted to verify optimal cutting parameters. The developed model has been validated experimentally and exhibited negligible error. The proposed model can be utilized to predict the corresponding tool wear in drilling process of Inconel 718 concerning different parameters. This can contribute optimizing metal cutting process, increasing productivity, and reducing manufacturing costs. The Deform-3D results were agreed with experimental and predictive values from RSM with 4-6% error.

Response surface methodology has proved to be a successful method that can be used to predict tool wear drilling of Inconel 718 with Cemented carbide coated tool. The first and second order equations developed by RSM using Minitab are able to provide accurately predicted results for the tool wear close to those values found in the experiments. The equations were checked for their adequacy with a confidence level of 95%. Both equations proved the cutting speed to be the most dominant cutting factor on the tool wear, followed by the feed rate, and tool diameter.

A good combination of cutting speed, feed rate, and tool diameter can generate minimum tool wear through drilling Inconel 718. According to Minitab, the optimum values for these parameters are 430 rpm, 0.11 mm, and 10 mm for cutting speed, feed rate, and tool diameter, respectively. Most of the simulation results were in line with the experimental results, while some were quite far from the experimental ones. To reach more accurate results from the simulation, some modification should be applied to mesh parameters and coefficients used in FEM.

ACKNOWLEDGEMENTS

The author would like to thank the Islamic Azad University, Najafabad branch, for funding and technical support of the project.

REFERENCES

[1] Ezugwu, E. O., Wang, Z. M., and Machado, A. R., "The machinability of nickel-based alloys: a review", Journal of Materials Processing Technology, Vol. 86, 1998, pp. 1-16.

[2] Martin, E., Ildiko, M., "Monitoring of Drilling Process for Highly Stressed Aeroengine Components", 5th CIRP Conference on High Performance Cutting 2012, Procedia CIRP, 2012, pp. 587-92.

[3] Gregor, K., Christoph, H., Mark, H., Martin, W., and Marc, B., "modern machining of advanced aerospace alloys-enabler for quality and performance", 5th CIRP Conference on High Performance Cutting 2012, Procedia CIRP 1, 2012, pp. 28-43.

[4] Kitagawa, T., Kubo, A., and Maekawa, K., "Temperature and wear of cutting tools in high-speed machining of inconel 718 and Ti-6Al-6V-2Sn", Wear Journal, Vol. 202, 1997, pp. 142-148.

[5] Yen, Y. C., Söhner, J., Lilly, B., and Altan, T., "Estimation of tool wear in orthogonal cutting using the finite element analysis", Journal of Materials Processing Technology, Vol. 146, 2004, pp. 82-91.

[6] Liew, W. Y. H., Ding, X., "Wear progression of carbide tool in low-speed end milling of stainless steel", Wear Journal, Vol. 265, 2008, pp.155-166.

[7] Fox-Rabinovich, G. S., Yamamoto, K., Kovalev, A. I., Veldhuis, S. C., Ning, L., Shuster, L. S., and Elfizy, A., "Wear behavior of adaptive nano-multilayered tialcrn/nbn coatings under dry high performance machining conditions", Surface and Coatings Technology, Vol. 202, 2008, pp. 2015-2022.

[8] Coelho, R. T., Ng, E. G., and Elbestawi, M. A., "Tool wear when turning hardened AISI 4340 with coated PCBN tools using finishing cutting condition", International Journal of Machine Tools and Manufacture, Vol. 47, 2007, pp. 263-272.

[9] Yan, F. G., Yue, C. X., Liu, X. L., Li, Y. F., and Ji, S. Y., "2D FEM estimate of tool wear in hard cutting operation: tool wear and simulation of hard cutting process under steady state", Advanced Materials Research. Vols. 69-70, 2009, pp. 306-310.

[10] Zukeri, M., Zaim, M., "Study on cutting Operation in turning process by 3d simulation using deform 3D", Master's Thesis, Universiti Tun Hussein Onn Malaysia, 2010.

[11] Kitagawa, T., Maekawa, K., Shirakashi, T., and Usui, E., "Analytical prediction of flank wear of carbide tools in turning plain carbon steels (Part 1) -characteristic equation of flank wear", Bull. Jpn. Soc. Prec. Eng., Vol. 22, 1988, pp. 263-269.

[12] Attanasio, A., Ceretti, E., and Giardini, C., "Simulation of tool wear in 3D FEM environment considering the tool geometry update: the developed algorithm", 11th CIRP International Workshop on Modeling of Machining Operations, Gaithersburg, MD USA, Settembre, 2008, pp.199-206.

[13] Strenkowski, J. S., Carroll, J. T., "A finite element model of orthogonal metal cutting", ASME Journal of Engineering for Industry, Vol. 107, 1985, pp. 349-354.

[14] Ceretti, E., Fallböhmer, P., Wu, W. T., and Altan, T., "Application of 2D FEM to chip formation in

orthogonal cutting", Journal of Materials Processing Technology, Vol. 59, 1996, pp. 169-180.

[15] Jawahir, I. S., Dillon, O. W., Balaji, A. K., Redetzky, M., and Fang, N., "Predictive modeling of machining performance in turning operations", Proceedings of the CIRP International Workshop on Modeling of Machining Operations, Atlanta, GA, USA, May 19, 1998, pp. 161-176.

[16] O¨zel, T., Lucchi, M., Rodriguez, C., and Altan, T., "Prediction of chip formation and cutting forces in flat end milling", Comparison of Process Simulation with Experiments, Trans, NAMRI/SME. Vol. XXVI, 1998, pp. 231-236.

[17] Shatla, M., Yen, Y. C., and Altan, T., "Tool-workpiece interface in orthogonal cutting-application of FEM modeling", Trans, NAMRI/SME, Vol. XXVIII, 2000, pp.173-178.

[18] Xie, L. J., Schmidt, J., Schmidt, C., and Biesinger. F., "2D FEM estimate of tool wear in turning operation", Wear Journal, Vol. 258, 2005, pp. 1479-1490.

