Research Paper

EFFECT OF CUTTING CONDITION ON TOOL WEAR AND SURFACE ROUGHNESS DURING MACHINING OF INCONEL 718

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ABSTRACT

In this study, an attempt has been conducted to investigate the effects of cutting parameters on tool wear and surface roughness during hard turning of Inconel 718 material. By taking into account the Analysis of Variance (ANOVA) in accordance to Central Composite Design (CCD); the mathematical model of the flank wear and surface roughness are developed with transformation of the natural logarithm. The experimental results have revealed that the cutting speed is the most significant effect to the flank wear; whereas the surface roughness is strongly influenced by the feed rate and slight related to the tool wear mechanisms. Due to the high pressure at elevated temperature, a micro-welding and built-up-edge are formed even at relatively low cutting speeds of 30-45m/min; it is a disadvantage for the machined surface quality. In particular, the surface roughness tends to decreased with the increased of the cutting speed when the built-up-edge was disappeared. However, the tool wear increased rapidly when the cutting speed increased over 90 m/min. This phenomenon is therefore inevitable affected to the tool life and the machined surface quality.

KEYWORDS Tool wear, surface roughness, Nickel-based super-alloy, Inconel 718, Response surface methodology

1. INTRODUCTION

Nickel-based super-alloys have been widely used in the aircraft and nuclear industry due to their exceptional thermal resistance and their ability to retain mechanical properties at elevated temperatures [1, 2], strong corrosion resistance and excellent thermal fatigue properties as well as thermal stability [3, 4]. Consequently, these alloys are classified to be difficult-to-machine materials [1-3]. The tool wear during machining of the Inconel 718 depends on the combined effect of several factors which is the result of complicated physical, chemical and thermo-mechanical phenomena forming through the different mechanisms such as adhesion, abrasion, diffusion and oxidation [1, 5]. Because of low thermal conductivity, machining of the nickel-based super-alloys in general and the Inconel 718 materials in particular, leads to a significant increase in the cutting temperature and high tresses; the adhesive wear through welding is thus developed rapidly and forming built-up-edge (BUE), it occurs even at a low cutting speed of 20m/min [6].

Several research efforts have been conducted in order to improve the machined surface accuracy, reduce the tool wear and subsequently extend the tool life; which directly affects to the cost of machining and productivity. Some of the solutions have recommended concerning with the cutting tool selection: using PVD coated (TiAlN) cutting tool [6] or multilayer coating of TiAl/TiAlN [7, 8] can be improved the cutting speed up to 100m/min compared to uncoated cutting tool (less than 30m/min). By considering the different coating materials, I. Ucun et al.[8] have reported that the performance of cutting tools coated with AlTiN, TiAlN+AlCrN, and AlCrN are improved, while the coated with TiAlN+WC/C and DLC are more significant against BUE formation. So far, it is also believed that polycrystalline cubic boron nitride (PCBN) tooling [9-11], and ceramic cutting tools [12, 13] allows machining at higher cutting speed in comparison with the coated carbides due to their superior hot hardness and notch wear resistant.

Although machining of the Inconel 718 has been carried out in several various studied; however, most of main characteristics and the results of cutting process such as tool wear, cutting forces, machined surface quality, and performance could only be determined experimentally [14]. The experimental studies should therefore be investigated with any further improvement of the cutting tool, machine design, the workpiece materials or methodology approaches. In the case of cutting process, Response Surface Methodology (RSM); which is a set of sequential experimental design [15] has been already proved in regard to efficient analyzing the effect of cutting conditions on the response factors such of the tool wear [16], surface roughness and cutting force [17, 18]. The relationship between the cutting parameters and the respond factors has mainly analyzed of variables (ANOVA) by using a quadratic regression through transformation of square root.

In this sense, it is thus worthy to use such the response surface methodology within the present framework. Furthermore, with the aim of getting more precise information about the tool wear mechanism and the surface roughness during machining process; the quadratic regression through transformation of natural logarithm will be applied for the first time according to our best knowledge in the field. First of all, the flank wear mechanism during machining of the Inconel 718 steel (hardened ~ 44HRC) using PVD coated cutting tool will be investigated; part of the work is then analyzing effect of the cutting parameters on the flank wear and surface roughness. The machining experiments are performed with assistance of the response surface methodology in accordance to central composite design (CCD). The experimental design was considered three level of each factor for the cutting speed in range of Vc=10-110m/min, feed rate f=0.02-0.12mm/min and depth of cut ap=0.05-0.55mm.

2. EXPERIMENTAL PROCEDURE

2.1. Experimental design

The matrix of the experiment should be well planned to optimize the number of the machining test and evaluate the effects of certain factors on some specific results; as well as quantify the effects of one or more input variables on the response factors. Based on the CCD method, the matrix design for k factor experiment is defined through the level of independent variables and the number of the experiment as given by:

$$n = 2^k + 2k + n_0 \qquad (1)$$

where 2^k are experiments in factorial design; $2k$ are experiments in star design and n_0 is the number of central point. In current experimentation, three experimental factors and six central points have led to twenty of the total runs are considered. The level of independent parameters is then modeled as summarized in the table 1; therein, the lowest and highest values are calculated through the scaled parameter (α). It depends on the number of the factor experiment considered through the relation of formula $\alpha = \left(2^k\right)^{1/4}$; with the three mentioned factors, one obtains α=1.682.

Table 1 level of independent variables for CCD

Levels	Lowest	Low	Medium	High	Highest
Coding	(-α)	(-1)	0	(+1)	(+α)
V_c (m/min)	9.55	30	60	90	110.45
f (mm/rev)	0.02	0.04	0.07	0.1	0.12
a_p (mm)	0.05	0.15	0. 3	0.45	0.55

2.2. Experimental setup

The machining tests were conducted under coolant condition on the CNC Lathe OKUMA – HL20. The workpiece material was Inconel 718, through-hardened at ~44 HRC; with the chemical composition as given in tables 2.

Table 2 chemical composition of the Inconel 718 [22]

wt. %	Ni	Fe	Cr	Nb+Ta	Mo	Ti	Al	Co	Si
	52.94	19.22	17.94	5.11	2.95	0.93	0.53	0.14	0.04
wt. %	Mn	Cu	Ca	Mg	Pb	C	B	S	P
	0.04	<0.1	<0.002	<0.003	<0.001	0.034	<0.005	<0.002	0.009
at. %	Ni	Fe	Cr	Nb	Mo	Ti	Al	Ti+Al/Nb	Ti/Al
	52.58	20.06	20.1	3.2	1.79	1.13	1.14	0.71	0.99

The cutting tool used PVD coated with the grades of TS2000 (Ti,Al)N + TiN; which manufactured by SECO. The specification of the cutting tool as follows: rake angle $\gamma_0 = 6^0$, clearance angle $\alpha = 0^0$, nose radius $r_\epsilon = 0.4$mm and included angle $\varepsilon_r = 80^0$, setting cutting edge angle $\kappa_r = 95°$, Inclination angle $\lambda_s = 6°$.

After each experiment, the surface roughness values Ra were measured using a Mitutoyo SJ-201 roughness tester; while the flank wear values were measured after certain length of the cutting path by using a maker microscope and a high resolution camera. Each test was started with a new cutting edge of the insert.

3. RESULTS AND DISCUSSIONS

Table 3 the matrix of experiment and response factors have achieved

Test	Type	Cutting parameters			Response factors	
		V_c(m/min)	f(mm/rev)	a_p(mm)	Vb(mm)	Ra (μm)
1	Center	60	0.07	0.3	0.149	0.48
2	Factorial	90	0.1	0.45	0.251	1.59
3	Factorial	90	0.04	0.45	0.128	1.12
4	Factorial	30	0.04	0.45	0.108	0.78
5	Factorial	90	0.1	0.15	0.166	1.96
6	Factorial	30	0.04	0.15	0.112	0.48
7	Axial	60	0.02	0.3	0.102	0.41
8	Axial	9.55	0.07	0.3	0.102	0.96
9	Center	60	0.07	0.3	0.104	0.77
10	Axial	60	0.07	0.05	0.112	0.39
11	Factorial	30	0.1	0.15	0.128	1.48
12	Axial	60	0.122	0.3	0.118	2.04
13	Center	60	0.07	0.3	0.119	0.89
14	Factorial	90	0.04	0.15	0.109	1.96
15	Center	60	0.07	0.3	0.126	0.58
16	Center	60	0.07	0.3	0.117	0.81
17	Center	60	0.07	0.3	0.103	0.95
18	Axial	60	0.07	0.55	0.115	0.83
19	Axial	110.45	0.07	0.3	0.287	1.85
20	Factorial	30	0.1	0.45	0.204	1.92

Tool wear is one of the most important criterions for machinability assessment of the cutting process, while surface roughness has widely been considered to be primary indicator of the machined surface quality. In the current work, the experimental matrix and the values of the response factors for the flank wear and surface roughness have achieved during machining of Inconel 718 (table 3). The surface roughness (Ra) was evaluated in a range of 0.39 – 2.04μm, while the flank wear values (Vb) were obtained in the order from 0.102 mm to 0.287mm. These results, in turn, are served to calculate the statistical analysis of variables (ANOVA) for the cutting parameters in order to find the most significant affected cutting parameters with respect to the response factors.

3.1. Development of the mathematical model

The RSM was adopted both the mathematical and the statistical techniques in our present study in order to investigate the influence of the cutting condition on the specific dependents. In fact, several mathematical models have already been developed in various studies; most of them have been performed based on the polynomial regression equation, called first order [17, 19] and the quadratic regression (or in other words, second order) [19-21] through the transformation of polynomial such as square root. These authors have also reported that application of all the developed models is able to be used in their particular experimental systems. In our special case, it seems to us that the polynomial transformation of the conventional square root for the regression model is not suitable to analyze the effect of the cutting condition towards the response factors during hard turning of the Inconel 718. We therefore endeavor to identify a new regression model which fit better our experimental results. We wish next to consider the translation of natural logarithm for the regression model.

To describe the empirical relationship between the cutting parameters and the response factors of the flank wear and the surface roughness during machining process, we propose here a general formula:

$$y = \exp\left[\varphi(V_c, f, a_p)\right] \tag{2}$$

Therein, φ is the responsive function of the cutting parameters which depends on the cutting speed, feed rate and depth of cut. The transformation of the linear regression and quadratic regression for three factors of the cutting parameters are defined by Eqs.3, 4 through transformation of natural logarithm.

$$\varphi_l = \delta_0 + \delta_1 \cdot V_c + \delta_2 \cdot f + \delta_3 \cdot a_p \tag{3}$$

$$\varphi_q = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ii} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 \tag{4}$$

where δ_0 *and* β_0 are the free terms of the regression equation; $\delta_1, \delta_2, \delta_3$ and $\beta_1, \beta_2 \ldots \beta_k$ are the linear terms while the $\beta_{11,} \beta_{22} \ldots \beta_{kk}$ and $\beta_{12,} \beta_{13} \ldots$ are quadratic and interaction term. All these parameters are experimentally determined.

3.2. Effect of cutting parameters on the flank wear

In this paper, the effect of cutting parameters towards the flank wear during machining of Inconel 718 is first investigated based on the ANOVA; which is one of the most useful statistical model methodologies as summarized in table 4.

It is important to recall that the model terms are considered to be significant only in the case where the values of "Prob > F" are less than 0.05. From Table 3, it is observed that influence of the cutting speed Vc(m/min), feed rate f(mm/rev) and V_c^2 on the flank wear are more pronounced in comparison with the other. However, when the F-value contributes to the model by a factor of 8.4307, the cutting speed is the most important factor to the tool wear and its evolution in time as well.

Table 4 the ANOVA results of the experiment for the tool wear

Source	Sum of Squares	df	Mean Square	F-Value	p-value Prob > F	Remarks
Model	1.236024	9	0.13734	2.86359	0.0584	not significant
V_c (m/min)	0.404331	1	0.40433	8.43070	0.0157	
f (mm/rev)	0.325577	1	0.32558	6.78861	0.0262	
a_p (mm)	0.080471	1	0.08047	1.67791	0.2243	
$V_c * f$	0.013166	1	0.01317	0.27452	0.6117	
$V_c * a_p$	0.002607	1	0.00261	0.05437	0.8203	
$f * a_p$	0.071298	1	0.0713	1.48664	0.2507	
V_c^2	0.33185	1	0.33185	6.91941	0.0251	
f^2	0.000416	1	0.00042	0.00867	0.9276	
a_p^2	0.000629	1	0.00063	0.01312	0.9111	
Residual	0.479593	10	0.04796			
Lack of Fit	0.386524	5	0.0773	4.15308	0.0721	not significant
Pure Error	0.093069	5	0.01861			
Cor Total	1.715617	19				

After applying our proposed mathematical model to the experimental results, we obtain a linear and quadratic regression through transformation of natural logarithm as follows:

$$Vb = \exp\left[-2.88789 + 5.73551E - 003 * Vc + 5.14672 * f + 0.51175 * a_p\right] \tag{4.1}$$

$$\begin{aligned} \mathrm{Vb} = \exp(&-1.68609 - 0.018856 * V_c - 3.01585 * f - 1.37372 * a_p \\ &+ 0.045075 * V_c * f + 4.01182E - 003 * V_c * a_p + 20.97889 * f * a_p \\ &+ 1.68608E - 004 * V_c^2 - 5.96874 * f^2 + 0.29373 * {a_p}^2) \end{aligned} \tag{5}$$

Eq.5 allows a 3-D description of the relationship between Vb and the cutting parameters as easily observed in Fig 1. As a result, the flank wear is not only dependent on cutting speed (Fig 1a, b); there is a probability indirectly influenced by the cutting force and temperature concerning feed rate and depth of cut. Indeed, the cutting forces and temperature are increased with the feed rate and depth of cut. However, the effect of the depth of cut is only observed at high feed rate and cutting speed as illustrated in Fig.1 b & c. they are expected results and consistent with our proposed equations.

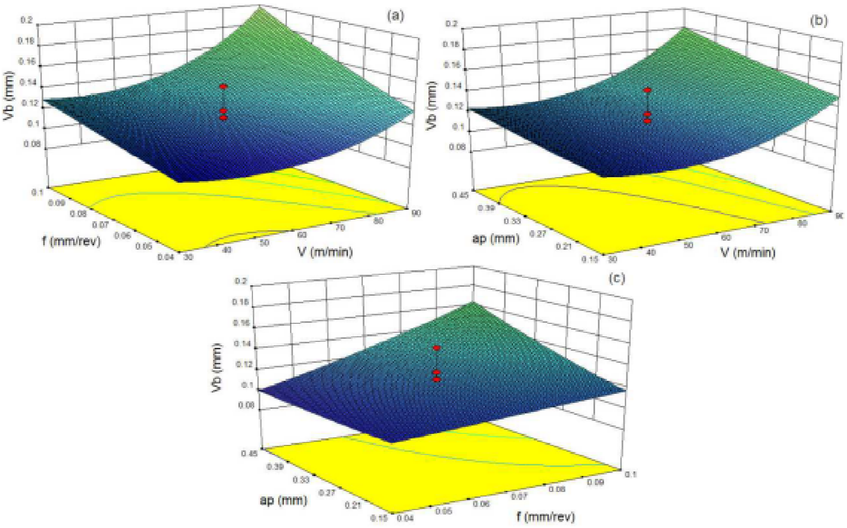

Fig.1. Effect of the cutting parameters on the flank wear.

Accordingly, the increase of cutting forces and temperature has led to a decrease in the material strength; the plastic deformation with micro-welds hence takes place at the tool-work interface due to the low thermal conductive of the workpiece material. It is then subsequently formed the BUE as shown in Fig 2.

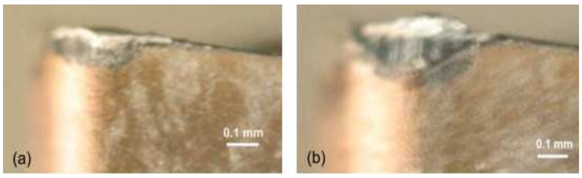

Fig.2. Progressive adhesive wear with BUE during turning of Inconel 718
(a) Vc=30m/min, f = 0.04mm/rev; (b) Vc=45m/min, f = 0.1mm/rev;

The similar plastic deformation during machining of Inconel 718 has recently reported in the literature (Figs.3, 4). Therein, the tool wear failure has been reported to be related to the adhesive wear mechanism. Back to our work, it is interesting to point out that such BUE already occurs at low cutting speed, even smaller than 50 m/min. More interestingly, with increasing the cutting speed up to 75m/min, the built-up-edge disappears as shown in Fig.5. Also the surface roughness is reduced, and then the machined surface quality is obviously improved.

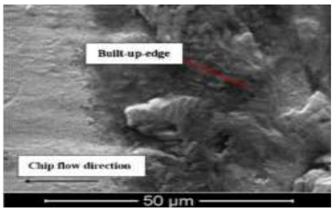

Fig.3. SEM image of the flank wear in machining of Inconel 718 [6]

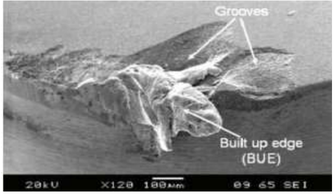

Fig.4. SEM micrograph of the tool wear during machining of Inconel 718 [11]

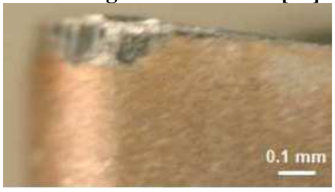

Fig.5. Flank wear during machining of Inconel 718 (Vc=60m/min, f=0.07mm/rev)

However, when the cutting speed increased is high enough (about 90 m/min) the hard particles of the material slide against the cutting tool cause a considerable increase of the tool wear. A combination of complicated physical, chemical, and thermo-mechanical phenomena can be given here for explanation. Different mechanisms of adhesion and abrasion when machining hardened material such of the Inconel 718 may be accounted here. Only abrasive wear mechanism is responsible for the flank wear in this case as shown in Fig 6. The variation of the tool wear mechanisms is thus influenced on the machined surface which will be further discussed in the next coming section.

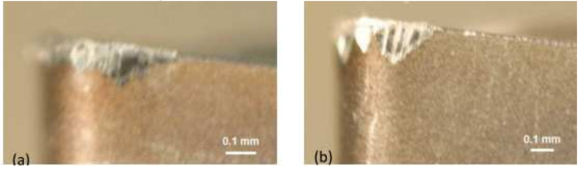

Fig.6. Progressive of the abrasive wear
(a) Vc=90m/min, f = 0.04mm/rev; (b) Vc=110m/min, f = 0.07mm/rev

3.3. Effect of cutting parameters on the Surface roughness

The surface roughness (Ra) is considered as a primary indicator of the machined surface quality. Based on the set of the 20 experiments, the surface roughness during machining of Inconel 718 was analyzed by taking into consideration of the ANOVA as summarized in table 5;

Table 5 Analysis of variance table for the surface roughness (Ra)

Source	Sum of Squares	*df*	Mean Square	F-Value	p-value Prob > F	Remarks
Model	4.7749218	9	0.530547	4.888713	0.0104	significant
V_c (m/min)	0.6434116	1	0.643412	5.928703	0.0352	
f (mm/rev)	1.8864474	1	1.886447	17.38263	0.0019	
a_p (mm)	0.1138971	1	0.113897	1.049503	0.3298	
$V_c * f$	0.3512865	1	0.351286	3.236922	0.1022	
$V_c * a_p$	0.2867581	1	0.286758	2.642327	0.1351	
$f * a_p$	0.0019588	1	0.001959	0.018049	0.8958	
V_c^2	1.2133967	1	1.213397	11.18082	0.0074	
f^2	0.3554653	1	0.355465	3.275428	0.1004	
a_p^2	0.0016682	1	0.001668	0.015371	0.9038	
Residual	1.0852485	10	0.108525			
Lack of Fit	0.7343943	5	0.146879	2.093161	0.2184	not significant
Pure Error	0.3508542	5	0.070171			
Cor. Total	5.8601703	19				

Similar to the tool wear; the cutting speed V_c (m/min), feed rate f (mm/rev) and the V_c^2 are also significant model terms towards the surface roughness. However, the feed rate appears as the most significant factors as a F-value of 17.38263 contributes to the model. It is easily to conclude that the remaining parameters do not play an important role because their P-values are found to be higher than 0.1. As for example, a P-value of 0.3298 clearly indicates that the depth of cut is not really significant. Once again, the general equation 1 has been used to describe the relationship between the surface roughness and the cutting parameters; one gets the following linear and quadratic regressions (Eqs.6, 7):

$$Ra = \varphi_l = \exp\left[-1.51726 + 7.23516E - 003 * Vc + 12.38870 * f + 0.60882 * a_p\right] \tag{6}$$

$$\begin{aligned} Ra = \exp(&-1.50477 - 2.53388E - 003 * V_c + 0.88495 * f + 3.17668 * a_p \\ &- 0.23283 * V_c * f - 0.042073 * V_c * a_p + 3.47724 * f * a_p \\ &+ 3.22409E - 004 * V_c^2 + 174.50371 * f^2 - 0.47818 * a_p^2) \end{aligned} \tag{7}$$

Fig.7 which are generated from Eq.7 provide us with a better interplay between the cutting parameters and the machined surface. The best machined surface quality Ra was achieved at the lowest the feed rate and the medium values of the cutting speed (Fig.7a, b). This point can be explained as follows: Ra indeed increases at low cutting speed of about 30-45m/min. The behaviour is probably due to the effect of BUE. The BUE is no longer observed in the range of the cutting speed from 45 to 75 m/min.

However, when the cutting speed is higher than 90m/min the tool wear dramatically increases and exists under the form of abrasive wear. Fig. 7c indicates that the depth of cut does not have significant effect on the surface roughness. Both the adhesive wear with the BUE and the abrasive wear are responsible for the tool wear mechanisms in the present experimental results; It is therefore inevitable affected to the tool life and the machined surface quality. Such a finding is in a good agreement with our mathematical theory.

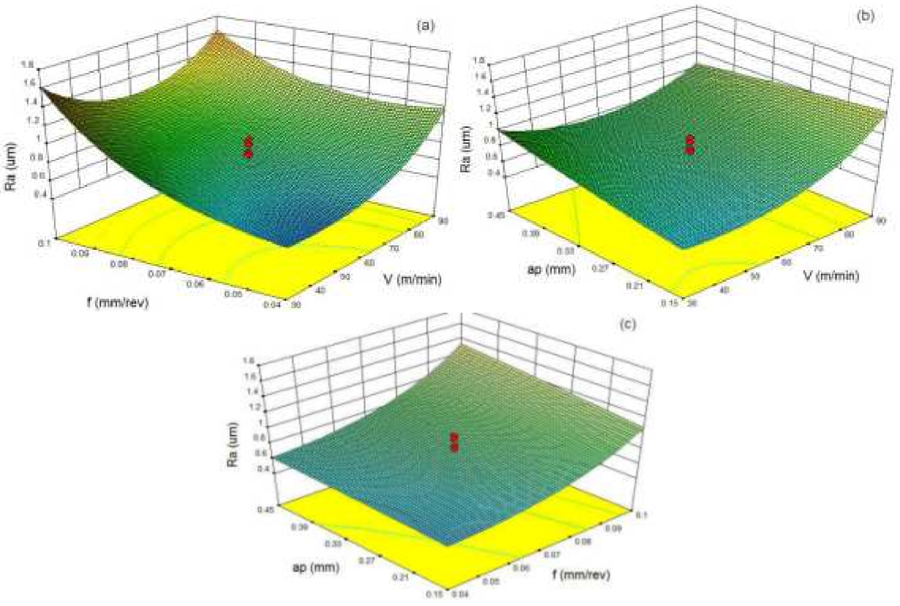

Fig.7. Effect of the cutting parameters on the surface roughness

4. CONCLUSION

In this study, the effect of cutting parameters on the flank wear and the surface roughness during machining of hardened Inconel 718 (~44HRC) has been investigated. Application of the RSM has led to introduce a new mathematical model for a better explanation of both the tool wear and surface roughness through the transformation of natural logarithm. The obtained experimental results as well as the mathematical model strongly suggest that the cutting speed is the most important factor to the flank wear, while the surface roughness is considerably influenced by the feed rate. Besides, the depth of cut plays a minor role for both the flank wear and surface roughness; especially at low feed rate and cutting speed.

Another important point to be underlined is that the tool wear during machining has occurred in both the adhesion and abrasion wear through the different wear mechanisms; which are referred to the thermo-mechanical affects. The observation is explained by an increase of the cutting force and temperature that lead to the formation of micro welds at the tool-work interface. This phenomenon occurs even at relatively low cutting speeds of about 30-45m/min. Reduction in strength of the cutting edge then causes plastic deformation and therefore the built-up-edge is formed.

In particular, when machining at higher cutting speed, around 50-75m/min, the surface roughness is significantly improved due to the disappearance of built-up-edge. However, due to the hard particles of the Inconel 718 material against the cutting tool, the abrasive wear increases rapidly at high cutting speed, more than 90m/min. As evidenced from this paper, in order to achieve a high surface quality with low cutting tool wear, a cutting speed in the range of 50-70 m/min is highly recommended for the hardened Inconel 718 using PVD coated cutting tool.

REFERENCES

1. Zhu, D., X. Zhang, and H. Ding, *Tool wear characteristics in machining of nickel-based superalloys.* International Journal of Machine Tools and Manufacture, 2013. 64(0): p. 60-77.
2. Ulutan, D. and T. Ozel, *Machining induced surface integrity in titanium and nickel alloys: A review.* International Journal of Machine Tools and Manufacture, 2011. 51(3): p. 250-280.
3. Dudzinski, D., et al., *A review of developments towards dry and high speed machining of Inconel 718 alloy.* International Journal of Machine Tools and Manufacture, 2004. 44(4): p. 439-456.
4. Jawaid, A., S. Koksal, and S. Sharif, *Cutting performance and wear characteristics of PVD coated and uncoated carbide tools in face milling Inconel 718 aerospace alloy.* Journal of Materials Processing Technology, 2001. 116(1): p. 2-9.
5. Campbell, F.C., *Superalloys*, in *Manufacturing Technology for Aerospace Structural Materials*. 2006, Elsevier Science: Oxford. p. 211-272.
6. Hao, Z., et al., *New observations on tool wear mechanism in dry machining Inconel718.* International Journal of Machine Tools and Manufacture, 2011. 51(12): p. 973-979.
7. Cantero, J.L., et al., *Analysis of tool wear patterns in finishing turning of Inconel 718.* Wear, 2013. 297(1–2): p. 885-894.
8. Ucun, İ., K. Aslantas, and F. Bedir, *An experimental investigation of the effect of coating material on tool wear in micro milling of Inconel 718 super alloy.* Wear, 2013. 300(1–2): p. 8-19.
9. Bushlya, V., J. Zhou, and J.E. Ståhl, *Effect of Cutting Conditions on Machinability of Superalloy Inconel 718 During High Speed Turning with Coated and Uncoated PCBN Tools.* Procedia CIRP, 2012. 3(0): p. 370-375.
10. M'Saoubi, R., et al., *Surface integrity analysis of machined Inconel 718 over multiple length scales.* CIRP Annals - Manufacturing Technology, 2012. 61(1): p. 99-102.
11. Khan, S.A., et al., *Tool wear/life evaluation when finish turning Inconel 718 using PCBN tooling.* Procedia CIRP, 2012. 1(0): p. 283-288.
12. Li, L., et al., *High speed cutting of Inconel 718 with coated carbide and ceramic inserts.* Journal of Materials Processing Technology, 2002. 129(1–3): p. 127-130.
13. Zhou, J.M., V. Bushlya, and J.E. Stahl, *An investigation of surface damage in the high speed turning of Inconel 718 with use of whisker reinforced ceramic tools.* Journal of Materials Processing Technology, 2012. 212(2): p. 372-384.
14. Viktor, P.A., *Design of experiments in metal cutting tests; Chapter 5*, in *Tribology and Interface Engineering Series*. 2006, Elsevier. p. 276-325.
15. Robert, W., *Response Surface Methodology and Sequential Experimentation*, in *International Encyclopedia of Ergonomics and Human Factors, Second Edition - 3 Volume Set*. 2006, CRC Press.
16. Mandal, N., B. Doloi, and B. Mondal, *Development of flank wear prediction model of Zirconia Toughened Alumina (ZTA) cutting tool using response surface methodology.* International Journal of Refractory Metals and Hard Materials, 2011. 29(2): p. 273-280.
17. Aouici, H., et al., *Analysis of surface roughness and cutting force components in hard turning with CBN tool: Prediction model and cutting conditions optimization.* Measurement, 2012. 45(3): p. 344-353.
18. Choudhury, I.A. and M.A. El-Baradie, *Machinability assessment of inconel 718 by factorial design of experiment coupled with response surface methodology.* Journal of Materials Processing Technology, 1999. 95(1–3): p. 30-39.
19. Routara, B.C., et al., *Response Surface Methodology and Genetic Algorithm used to Optimize the Cutting condition for Surface Roughness Parameters in CNC Turning.* Procedia Engineering, 2012. 38(0): p. 1893-1904.
20. Thangavel, P.S., V;Shanmugam, R, *Application of response surface methodology for predicting flank wear in turning operation.* Journal of engineering manufacture, 2006. 220 no : .
21. Neşeli, S., S. Yaldız, and E. Türkeş, *Optimization of tool geometry parameters for turning operations based on the response surface methodology.* Measurement, 2011. 44(3): p. 580-587.
22. C. Slama , M.A., *Structural characterization of the aged Inconel 718.* Journal of Alloys and Compounds, 2000. 306