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Effect of geometry parameters on the cutting force and temperature in dry machining of Inconel 718

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Abstract

Nickel based superalloy Inconel 718 is having application in aerospace, automotive and nuclear industry. Super alloy is difficult to process due to its superior properties like high strain hardening tendency, tool-work piece material affinity and high strength at elevated temperature. In this work, the effects of geometry parameters (approach angle and tool nose radius), cutting conditions (cutting speed and feed rate) on cutting force and cutting temperature were investigated during turning of Inconel 718 with TiAlN-coated and uncoated carbide insert under dry condition. The experimental results were analyzed using center composite design response surface methodology (RSM). Statistical analysis of variance and prediction of the mathematical models were proposed. The outcomes indicate that the performance of coated carbide tools better in all conditions. The optimum cutting conditions are presented to achieve the desired results. .

Keywords-Cutting temperature, Cutting force, Approach angle, Nose Radius, Carbide Inserts

1. Introduction

This Inconel 718 is a nickel based super alloy which is usually recognized for its high strength, toughness and corrosion resistance at high temperature [1]. Due to these incredible properties, the Inconel 718 alloy is used in wide application such as gas turbine components, nuclear, marine and energy sectors. However, unique features for instance hardening tendency, low thermal conductivity, and high strength are considered as the cause of low machinability of Inconel 718. It also leads to elevating the cutting temperature at the rake face [2]. It is also known as most difficult-to-machine materials due to the rapid work hardening, tendency to weld, the formation of built-up edge with the tool material and the presence of hard carbides in their microstructure [3, 4]. These several attributes cause the shorter tool life, increase forces and power consumption, lower production efficiency and various surface damages. Cutting expertise for the nickel superalloy Inconel 718 in the manufacturing fields is a hotspot and challenging trouble [5, 6]. Therefore, to resolve the issues mentioned above, various development and research efforts are proposed to ensure the efficient and economical machining of Inconel 718. To achieve an acceptable tool life, minimum cutting force, better surface quality, researchers used different machining related parameters such as tool material, tool coating, tool geometry and cutting parameters.

At present, a significant portion of metal cutting process belongs to the turning operations. A proper selection of the cutting condition such as cutting fluid, cutting speed, feed rate, depth of cut and cutting tool play a major role in the successful completion of turning process. Furthermore, the study of the cutting forces is very essential, since cutting forces correlate strongly with cutting performance such as surface roughness, cutting temperature, tool wear, tool breakage, and forced vibration. Hence, proper selection and range of cutting parameters are essential for machining nickel-based Inconel 718 alloy.

Many researchers analysed cutting forces and temperature developed during machining. Devillez et al. [7] investigated the cutting force and tool wear in dry machining of Inconel 718 with coated carbide tools. The authors found that the cutting force ratio was an interesting indicator of tool wear. A good correlation was analysed between the cutting forces and the tool wear observations. Shinde et al. [8] studied the cutting force during machining of Inconel 718 using three levels of cutting speeds, feed rates, and tungsten carbide inserts. The lowest cutting force was observed with TiAlN-coated insert. In 2014, Davoodi and Tazehkandi [9] studied the cutting forces and surface roughness in turning of Inconel 738 and presented the optimum condition to minimize the cutting forces and maximize the surface finish. Zhang et al. [10] executed experiment with minimal cutting fluid and dry condition for machining of Inconel 718 to study the variation of tool life and cutting force. The results reported that minimum quantity cooling lubrication significantly improved the machinability by a reduction in cutting forces and addition of tool life. Thakur et al. [11] carried out experiments on superalloy Inconel 718 with tungsten carbide insert (K20) tool to investigate the effect of cutting parameters on the cutting force, specific cutting pressure, cutting temperature, tool wear, and surface finish. They also optimized cutting parameters by measuring forces.

To resolve the machining related problems of Ni-based superalloys Inconel 718, it is necessary to investigate different options. Firstly, the proper selection of cutting tool geometry could play a crucial role to minimize the cutting force and temperature. A variety of geometrical parameters is tool nose radius, rake angle, chamfer angle, honing radius and approach angle. In machining, approach angle (side cutting edge angle) is the angle between the cutting edge line of tool and the longitudinal axis of the workpiece. When approach angle has low value, the length of the cutting edge is in contact with the workpiece is increased. Force and temperature are distributed over the considerable length of cutting edge and in consequence stress and temperature are diminished.

In this regard, El-Wardany et al. [12] found that an increase of side cutting edge angle would lead to a lower heat generation and improve tool performance. Sharman et al. [13] conducted the machining of Inconel 718 using different nose radii ranging between 2 to 6 mm. The change in nose radius resulted in high thrust forces. Nalbant et al. [14] conducted the machining of Inconel 718 to see the effects of cutting speed and tool geometry on cutting forces. The results of the experimental investigation indicated that the lowest main cutting force depends on tool geometry. Rahman et al. [15] analysed the influence of tool geometry, cutting speed and feed rate on turning of Inconel 718. Machining forces, surface roughness, and flank wear were considered as the performance indicators for tool life.

Recently to improve the performance of Inconel 718, variously coated carbide; ceramic and cubic boron nitride (CBN) cutting tools were used by the different researchers [16, 17]. The use of coated cutting inserts is another approach could also be used to enhance the machinability of Ni-based superalloy Inconel 718. In this regard, Jindal et al. [18] conducted the machining of Inconel 718 using three different PVD coatings. The low thermal conductivity and compressive residual stress of coating significantly improved tool performance. According to Ezugwu et al. [19], the preferred cutting tool for superalloy is carbide tool sustaining high temperature generated at the chip-tool interface. Settineri et al. [20] analysed the performances and characteristics of novel coated tools in machining of Inconel 718 and noticed that coated tools were better than uncoated inserts. Thakur et al. [21] used nickel-based superalloys as a workpiece to finding the effect of cutting tools and cutting variables on-chip feature and wear of tool. The results indicated that multilayer coated tools exhibited the best performance. In another experiment Ucun et al. [22] analysed uncoated, and DLC coated ultra-fine carbide inserts performance on Inconel 718. The DLC-coated ultra-fine carbide led to an increase in surface finish and a decrease of tool wear.

The largest part of the published work confirms that the cutting tools like coated carbide inserts, ceramic tools (like Al_2O_3/TiC ceramics, Si_3N_4 ceramics, Al_2O_3 ceramics), Cubic boron nitride (CBN) cutting tools, better regarding superior hot hardness than carbide tools. Though the tools described above are better regarding performance, their expenditure factor limits the use in manufacturing applications, especially for high-class materials. Cemented carbides tools have been utilized for a long time, and the uses of coated carbide cutting tools have improved the performance of nickel-based alloys. The coating on the cutting tool increases the wear resistance and life of the tool.

The most of the work has reported the performance of tool coating and geometry. Still, there is need to examine coated carbide tools performance on Inconel 718. Therefore, the basis of this work was to observe combined study of tool geometry parameters (approach angle and tool nose radius) and machining conditions (cutting speed and feed rate) on cutting force and temperature with uncoated and TiAlN-coated carbide inserts under dry condition. RSM has been used to develop the model and for optimization. Regression analysis checked the acceptability of the model. Further significance of parameters was judged by analysis of variance (ANOVA). Finally, an optimum cutting condition has been suggested for low cutting temperature and minimum cutting force.

2. Experimental Details

In this research work, the Inconel 718 was selected for experimentation. It is being used in aero engines, specifically for turbine blades. A bar of diameter 60 mm and 350 mm length has been chosen as a test specimen to maintain L/D ratio less than ten as per ISO 3685 standards [23]. Inconel 718 is having a hardness value of 37±1 HRC. The chemical composition of Inconel 718 was as follows (wt %): 53.50 Ni; 18.60 Cr; 2.95 Mo; 5.15 Nb; 17.30 Fe; 0.97 Ti; 0.19 Co; 0.59 Al; 0.024 V; 0.140 Cu; 0.59 C and other. The depth of cut 0.2 mm was held constant. Both uncoated as well as TiAlN-coated fine-grained high cobalt carbide inserts with Grade KC5525 (made by Kennametal) of different radii, were selected. The ISO designations of the inserts used were CNMG1204. Tool holder with ISO description MCLNR2525M12 has been chosen.

2.1 Selection of process parameters

For experimental study, several parameters influence the performance. The main relevant parameters are the cutting conditions, tool materials, and tool geometry. The tool geometry parameters such as approach angles were selected as 30, 45, 60, 75, 90 deg, while tool nose radius was changed as 0.2, 0.4, 0.8, 1.2, 1.6 mm.

Table-1: Selected machining parameters and its levels

Factors	Symbol	Level-1 (+2)	Level-2 (+1)	Level-3 (0)	Level-4 (-1)	Level-5 (-2)
Cutting Speed	v (m/min)	30	50	70	90	110
Feed Rate	f (mm/rev)	0.075	0.10	0.125	0.150	0.175
Approach angle	α (deg.)	30	45	60	75	90
Tool nose radius	r (mm)	0.2	0.4	0.8	1.2	1.6

Therefore, in this research work, cutting speed (v), feed rate (f), tool nose radius (r) and approach angle (α) are selected as input variables. The levels of the input variables are selected based on the previous research papers and machining handbook. The cutting force and cutting temperature are selected as the performance parameters. Selected machining parameters/conditions and its levels are presented in Table 1

2.2 Experimental Procedure

The experiments were performed with a high precision HMT made a lathe. The performances of inserts were recorded online using TeLC, Germany, a high-precision lathe tool dynamometer regarding main cutting force and power consumption. The infrared thermometer (make: HTC-IRX-66, range -30°C to 1550°C and an optical resolution of 30:1) is used for measuring the cutting temperature.

2.3 Design of experiment and statistical modelling

The effect of process variables in the turning of Inconel 718 was investigated by applying response surface methodology (RSM). RSM design of the experiment is an arithmetic and numerical tool used for modelling and investigation of critical mathematical problems. The mathematical models are to be developed using parameters which influence the process [24]. For experimental study, process parameters selected were cutting speed (v), feed rate (f), tool nose radius (r) and approach angle (α). ANOVA is a statistical technique that relates the control variables to the response. Based on central composite design (CCD), 30 experiments were performed both with uncoated and TiAlN coated carbide tools using a combination of different levels of factors. In this work, cutting force and cutting temperature is the response variable. The mathematical model is represented as;

$$y = \phi (v, f, \alpha, r) + \epsilon \quad (1)$$

Where y is the response value, ϕ is the function of reply, and v, f, α, r is the cutting speed, feed rate, approach angle, and nose radius is the independent variable. 'ϵ' is the experimental error. This error is usually distributed with zero means according to the observed response. Hence, the first order linear mathematical model represented by Eq. (2)

$$y_1 = y - \epsilon = b_0x_0 + b_1x_2 + b_2x_2 + b_3x_3 + b_4x_4 \quad (2)$$

Where y_1 represents the response of the first order model; x_1, x_2, x_3, and x_4 are cutting speed, feed rate, approach angle and nose radius; b_0, b_1, b_2, b_3 and b_4 are the set of regression coefficients estimated by least squares. If the first order mathematical model is not adequate to signify the process, then the second order model is established. Eq. (3), illustrate the general second order model;

$$y_2 = y - \epsilon = b_0x_0 + b_1x_2 + b_2x_2 + b_3x_3 + b_4x_4 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{34}x_3x_4 + b_{11}x_{12} + b_{22}x_{22} + b_{33}x_{32} + b_{44}x_{42} \quad (3)$$

Where y_2 is the responses based on second order model; ϵ is the experimental error. b_0, b_1, b_2, b_3, b_4, b_{12}, b_{13}, b_{14}, b_{23}, b_{24}, b_{34}, b_{11}, b_{22}, b_{33} and b_{44} values are the set of regression coefficients estimated by least squares.

3. Results and Discussion

Based on central composite design (CCD), a total of 30 experiments were performed both with uncoated and PVD coated tools using a combination of different levels of factors. Experiments were conducted to analyse the effect of cutting speed, feed rate, and approach angle and tool nose radius on cutting force and cutting temperature during machining of Inconel 718. ANOVA was conducted to analyse the importance of the process variables. The ANOVA tables for reduced quadratic models for cutting force and cutting temperature are shown as in Table 2 and Table 3. The F-test are performed at 95%, and 99 % confidence level in ANOVA indicates that the model values were significant.

Table -2: Analysis of variance (ANOVA) for cutting force

Source	**SS**	**DF**	**MS**	F_{Cal}	$F_{0.05}$	$F_{0.01}$	**% C**
Model	32872.39	13	2528.645	735.884	2.104	2.868	
v	5310.375	1	5310.375	1545.422	4.182	7.597	16.12
f	9009.375	1	9009.375	2621.902	4.182	7.597	27.36
α	6240.375	1	6240.375	1816.07	4.182	7.597	19.01
r	4788.375	1	4788.375	1393.51	4.182	7.597	14.54
vα	430.562	1	430.562	125.302	4.182	7.597	1.30
vr	264.062	1	264.062	76.847	4.182	7.597	0.89
fα	915.062	1	915.062	266.301	4.182	7.597	2.78
fr	95.062	1	95.062	27.665	4.182	7.597	0.29
αr	297.562	1	297.562	86.596	4.182	7.597	0.91
v^2	2299.527	1	2299.527	669.206	4.182	7.597	6.98
f^2	694.312	1	694.312	202.0584	4.182	7.597	2.11
α^2	2899.313	1	2899.313	843.756	4.182	7.597	8.81
r^2	1714.527	1	1714.527	498.960	4.182	7.597	5.21
Residual error	54.979	16	3.436	0.838	2.01	2.69	0.003
Total	32927.37	29					

Table-3: Analysis of variance (ANOVA) for cutting temperature

Source	SS	DF	MS	F CAL	$F_{0.05}$	$F_{0.01}$	% C
Model	373371.9	13	28720.91	537.585	2.104	2.868	
v	54245.04	1	54245.04	1015.335	4.182	7.597	14.50
f	85323.38	1	85323.38	1597.045	4.182	7.597	22.81
α	57330.38	1	57330.38	1073.084	4.182	7.597	15.32
r	28085.04	1	28085.04	525.683	4.182	7.597	7.52
vf	663.06	1	663.06	12.4109	4.182	7.597	0.18
vα	770.06	1	770.06	14.4137	4.182	7.597	0.22
vr	315.06	1	315.06	5.897	4.182	7.597	0.08
fα	517.56	1	517.56	9.688	4.182	7.597	0.13
αr	2525.06	1	2525.06	47.263	4.182	7.597	0.67
v^2	39325.07	1	39325.07	736.069	4.182	7.597	10.51
f^2	67178.57	1	67178.57	1257.419	4.182	7.597	17.92
α^2	44137.5	1	44137.5	826.146	4.182	7.597	11.73
r^2	53076.57	1	53076.57	993.464	4.182	7.597	14.17
Residual error	854.81	16	53.43		2.01	2.69	
Total	374226.7	29					

The F-values of model 735.884 and 537.585 justifies, significant model. The experimental outcomes (cutting forces and cutting temperatures) and input process variables (cutting speed, feed rate, and approach angle and nose radius) are utilized to formulate the mathematical models. The developed mathematical model illustrates the relationship between input and output variables. The second order mathematical models developed for cutting force with TiAlN-coated carbide tool are as follows;

$$\text{Cutting Force} = 654.279-5.392v+167.5f-5.823\alpha-162.578r+0.017v\alpha+0.507vr-20.167f\alpha-243.750fr+0.718\alpha r+0.022v^2+0.805f^2+0.046\alpha^2+49.414r^2 \quad (4)$$

Eq. (5) represents second order mathematical models for cutting temperature with TiAlN-coated carbide tool;

$$\text{Cutting Temperature} = 2469.862 -14.316v -192f -19.975\alpha -438.620r +12.875vf +0.023v\alpha +0.554vr -15.166f\alpha -2.09375\alpha r +0.094v^2 +79183.33f^2 +0.178\alpha^2 +274.93r^2 \quad (5)$$

To analyse the performance of TiAlN coated carbide tools during machining, Eqs. 4 and 5 are used to predict the functioned relationship between input variables and response variables. The variation of cutting force and cutting temperature with process variables are shown in Fig. (1), Fig. (2), Fig. (3) and Fig. (4).

3.1 Effect of Cutting Speed

Fig. 1 (a) and (b) illustrates the variation of cutting force and cutting temperature with cutting speed. The results indicate that cutting force is decreased with increase in cutting speed and temperature increase with an increase in cutting speed. It is due to the reason that with the increase in speed, the time for which the chip remains in contact with tool decreases and the heat is not carried out by the chip, which causes the increase in temperature at the cutting zone.

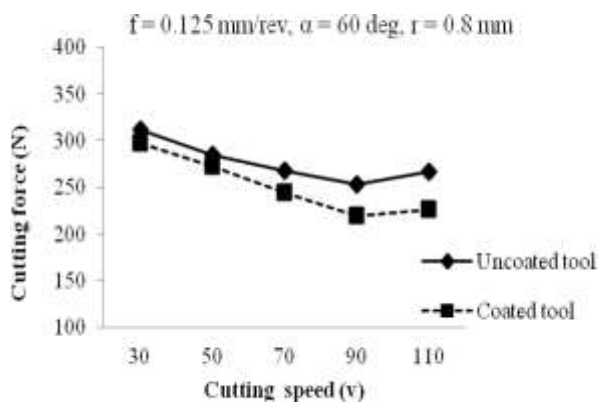

Fig -1(a): Variations of Cutting force with cutting speed

The high-temperature generation causes the upper layer of the material to deform plastically leads to decrease in cutting force. The cutting force seems to be good in the cutting speed range of 75–85 m/min. After 90 m/min, the trend appears to be increasing due to rapid tool wear rate and deformation of cutting edge due to more heat generation rate. It has also been observed from the plots that the performance of TiAlN-coated carbide is superior to uncoated carbide tool. It is because at high temperature the TiAlN decomposes and act as a lubricant, which results in a decrease in frictional heat generation at tool-workpiece and tool-chip interface.

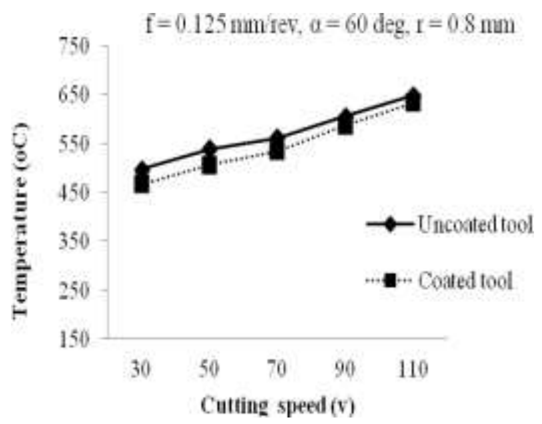

Fig -1(b): Variations of cutting temperature with cutting speed

3.2 Effect of feed rate

Fig. 2 (a) and (b) shows the effect of feed rate on cutting force and cutting temperature. From the figures, it has been understood that cutting force is increased with increase in feed rate. It is because the extra energy is required per revolution with an increase in feed rate which resulted in an increase in cutting force.

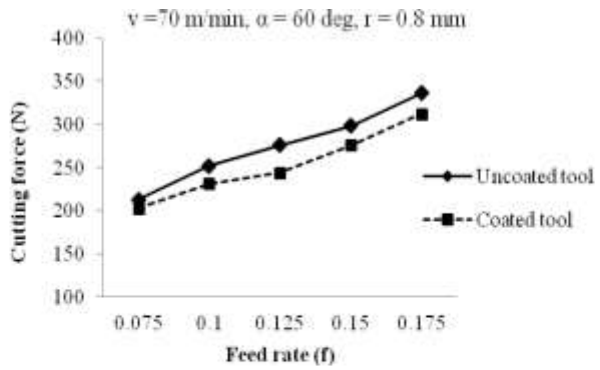

Fig -2(a): Variations of Cutting force with feed rate

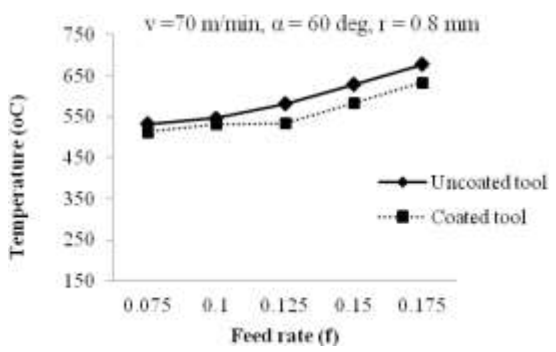

Fig -2(b): Variations of Cutting temperature with feed rate

Also, with an increase in feed rate area in contact between chip and tool is also increases, which tends to increase the friction force between material and flank of the tool. It causes the high heat of generation at the cutting zone and increases the temperature. Figures revealed that performance of TiAlN coated tool is superior to uncoated carbide tools. It is because the TiAlN-coating decomposes at high temperature and provides lubrication at the tool-workpiece interface, which tends to reduce friction; as a result, the temperature recorded with TiAlN-coated carbide tool is less than uncoated carbide tool during machining.

3.3 Effect of approach angle

The variation of cutting force and cutting temperature with approach angle is represented in Fig. 3 (a) and (b). Both cutting force and temperature decrease with increase of approach angle. It is because, with an increase in the approach angle, the contact length of cutting tool tip on work material is less, which further decreases the friction between tool and workpiece, which lead to low heat generation, causing low tool wear which tends to decrease cutting forces. However, at 90 deg approach angles the cutting force and temperature is high due sudden loading and unloading of the cutting tool which increases the vibration. The minimum cutting force and the cutting temperature are observed at 65-75 deg approach angle.

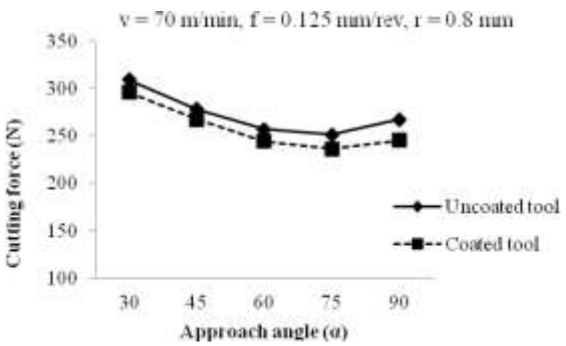

Fig -3(a): Variations of Cutting force with approach angle

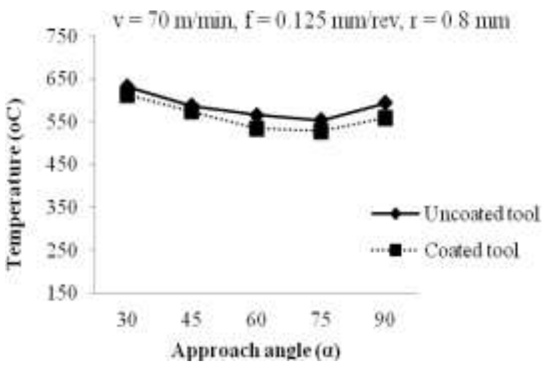

Fig-3(b): Variations of Cutting temperature with approach angle

3.4 Effect of nose radius

Fig. 4 (a) and (b) represent the variation of tool nose radius on cutting force and cutting temperature. The result of the plot revealed that at 0.2 mm of tool nose radius value of cutting force and temperature is high. It is because at 0.2 mm tool nose radius the small contact area available for cutting tool to conduct the heat. It leads to increase in temperature along the cutting edge; causes earlier tool wear rate as results cutting force is also increased. Also, with an increase in tool nose radius, the cutting force is decreased due to increase in area to contact between tool-workpiece interfaces. Consequently, extra area is available for conduction and cutting temperature is also decreased. The minimum value of cutting force and interact temperature is observed at tool nose radius 1.2 mm. After 1.2 mm the cutting force and interface temperature increases due to a large area of contact which causes high friction at tool and workpiece interface, resulting in an increase in cutting force and interface temperature.

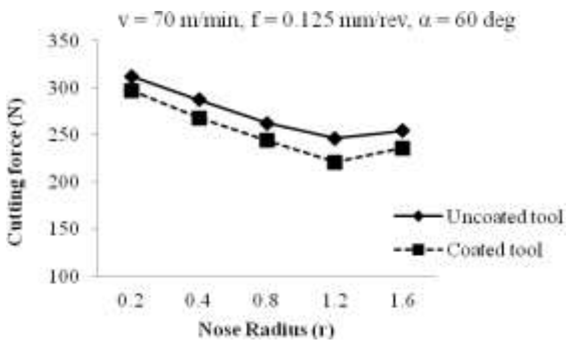

Fig -4(a): Variations of Cutting force with nose radius

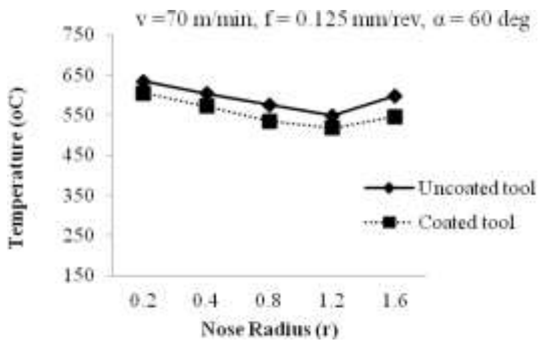

Fig-4(b): Variations of Cutting temperature with nose radius

4. Prediction of Optimum Results

In the present research work, cutting speed, feed rate, nose radius and approach angle was selected as process parameters, and cutting force, and interface temperature were taken as a response variable when machining Inconel 718 with PVD TiAlN-coated and uncoated carbide tools. The desirability function of the RSM was employed for the optimization of the process parameters. The purpose was to find the best arrangement of the process parameters that would provide maximum desirability. The highest cutting speed, low feed rate, maximum tool nose radius and approach angle were fixed as constraints for optimization. The optimum results are given in Table 4 for decreasing the desirability level.

Table-4: Optimization results

Sol No.	v	f	α	r	Cutting force	Cutting temp.	Desirability	Remarks
1.	90.00	0.1	73.0	1.2	197.65	530.57	0.897	Selected
2.	90.00	0.1	75.0	1.2	199.03	535.56	0.897	
3.	82.62	0.1	73.26	1.2	198.09	534.30	0.896	
4.	87.6	0.1	71.79	1.14	196.78	535.21	0.894	
5.	89.66	0.1	73.42	1.11	198.90	536.66	0.888	
6.	78.72	0.1	75	1.2	199.44	538.85	0.887	
7.	89.31	0.11	70.27	1.2	198.23	547.54	0.880	
8.	79.79	0.1	66.86	1.2	192.39	543.47	0.876	
9.	84.03	0.1	74.99	0.95	196.69	543.76	0.852	
10.	75.33	0.1	75	1.04	196.79	545.65	0.851	

It was observed that the desirability level was stable up to solution no. 2. The desirability was lesser with a change in any of the process parameter. Therefore, the selected optimum values of process parameters which gave minimum cutting force and minimum cutting temperature were 90 m/min of cutting speed, 0.1 mm/rev of feed rate, 1.2 mm of nose radius and 73 deg approach angle.

5. Conclusions

In this research work, the performance of TiAlN coated carbide tools are evaluated during machining of Inconel 718. The process variables were taken as approach angle, tool nose radius, cutting speed, and feed rate. The performance parameters were cutting force and cutting temperature. The following conclusions are drawn.

- The mathematical models were developed using response surface methodology. The results indicate that for better machining performance obtained at 90 m/min of cutting speed with 0.1mm/rev of feed rate, 73 deg approach angle and 1.2 mm of nose radius.
- The values of cutting force and cutting temperature are observed low at tool nose radius 1.2 mm. The 10-15% reduction in cutting force was seen with TiAlN-coated carbide tool than uncoated carbide tool.
- The RSM quadratic model obtained is practically perfect. The study indicates that feed rate is a most vital factor influencing the cutting force and temperature, followed by approach angle and nose radius. The geometrical parameter approach angle having contribution of (19.01 and 15.32%).

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