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Performance Evaluation of Inconel 718 Machining With Geometory Parameters

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Abstract: Nickel-based Inconel 718 superalloy is having wide application in aerospace, petrochemical, automotive, marine and nuclear sectors. They are hard to machine because of unique features like low thermal conductivity, high strength at elevated temperatures and high chemical reactivity. Machining of this material is challenge for manufacturers and causes problem of heat generation at the cutting region. Hence, cooling of the cutting zone is significant importance for component in service towards the safety, reliability, and durability. To meet the demands of the ecological and human health, minimum quantity lubrication (MQL) technique was selected. A comparison of its performance with dry and flood coolant machining has been investigated In this work, the effect of machining parameters (cutting speed, feed rate, approach angle and tool nose radius) on cutting force and cutting temperature were investigated during turning of Inconel 718 with TiAlN-coated carbide tool. Mathematical model for cutting force and cutting temperature has been developed using response surface methodology. A statistical analysis of variance was used to find the validity of the developed model. It has been observed that MQL technique showed significant performance. Further Chip formation is studied to get better result.

Keywords: Inconel 718, MQL technique, cutting force, cutting temperature, carbide tool

I. Introduction

High-temperature exotic alloys such as nickel-based alloys are used for application of gas turbine engine components, aerospace industry, and power plants. Nickel-based alloy Inconel 718 is most commonly used material due to its superior high-temperature mechanical properties like high material strength, creep and corrosion resistance. However, machining of the nickel-based alloy is tough due to its high work hardening tendency, small heat conduction, the presence of hard abrasive carbides in their microstructures and high chemical affinity with tool materials. This limits their machining efficiency and leads to high temperature and forces. Due to such unique features, Inconel 718 is well-known as difficult-to-machine alloy [1-2].

The property of low thermal conductivity of Inconel 718 and high level of hardness leads to develop high cutting temperature at the cutting zone. The high cutting forces acting in the shearing zones also promote high friction with high heat generation and consequently develop a high temperature. The generation of high temperatures along with high cutting forces usually led to short cutting tool life and deteriorates the surface quality.

The machining industry has been trying to use various cooling and lubrication techniques such as minimum quantity lubricant (MQL), cryogenic spray cooling, cryogenic pre-treatment, and high-pressure air, oil-based or water-based emulsion cutting fluids, etc., to cool and lubricate the machining process [3-5]. Different studies have been conducted to determine cutting force and cutting temperature when machining Inconel 718 [6-7]. In the past, the investigation has shown that a small reduction in the cutting temperature highly increases the tool life [8].

The application of cutting fluids during machining is the primary function of cooling and lubrication, reducing friction and, consequently, heat generation. The flooded cooling is one of the conventional ways to reduce temperature generated in the cutting region to improve tool life and surface quality. The main advantages of cooling technology include significant improvement in tool life, effective chip segmentation and efficient cooling and lubrication, but it also reduces the power consumptions. However, the application of conventional cutting fluids could prove to be ineffective in the cutting, as it creates both health and environmental problems, and also increase production costs [9].

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To overcome this issue, the use of MQL technique is of great importance in combination between large cutting fluid application and dry machining. In MQL, a minute quantity of coolant along with compressed air is directly applied to the machining area through the set of nozzles in the form of drop by drop and mist. The minute quantity of coolant is not only less waste polluted, but also subjected to several other economic advantages such as reduction in the quantity of coolant used, reduction in the overall cleansing time of machine tool. While machining Inconel 718, the MQL technique has been focused by several researchers showing good results regarding reduction in tool wear, cutting force, temperature, and improvement in surface integrity [10-12].

A examine of current literature provides some studies which are primarily focusing on MQL technique in various machining operations. In a research study, Thakur et al. [13] investigated and optimized the lubrication parameters during high-speed turning of Inconel 718 on cutting temperature, flank wear and cutting forces. Their results indicated that the use of optimized minimum quantity lubrication parameters led to minimizing the cutting forces, cutting temperature and flank wear. Kadam and Pawade [14] conducted high-speed turning of Inconel 718 under dry, flood coolant and water vapor machining environments, at varying material removal rate (MRR) levels depicting productivity rates, surface roughness, residual stresses and surface damage. Water vapor machining environment gives the highest product sustainability index of 82.92% at medium MRR. The water vapor acted as one of best eco-friendly machining method for cooling and lubrication in machining and also a better green manufacturing tool. Gupta et al. [15] conducted an experiment on titanium alloy with RSM and PSO method under MQL conditions. They concluded that the application of MQL in machining of titanium alloy successfully decreased the tangential force, tool wear, surface roughness, and tool-chip contact length. It is noticeable from the current literature that, an application of MQL process shows beneficial results in terms of reducing tool wear, cutting forces, cutting temperature and surface roughness of the machined part, respectively.

Also, for an adequate tool life, minimum cutting force and better surface quality the other parameters, such as tool and tool coating materials, tool geometry, machining strategy, cutting speed, feed rate, depth of cut, etc., must be controlled and selected. Sagnam et al. [16] investigated the cutting forces while turning titanium (grade-2) alloy under MQL conditions using cutting parameters such as cutting speed, feed rate, and approach angle. Nalbant et al. [17] conducted the machining of Inconel 718 to study the influence of cutting speed and tool geometry on cutting forces. The results of the experimental investigation indicated that the cutting force also depends on tool geometry.

Thus, various published works have manifested the machining of Inconel 718, but till date, very few studies have been reported the combined impact of tool geometry, machining conditions and machining variables. Therefore, the present study takes into account the combined study of machining parameters (cutting speed and feed rate) and tool geometry (tool nose radius and approach angle) during the machining of Inconel 718 with TiAlN-coated carbide tool under dry, wet and MQL conditions. An application of the response surface methodology (RSM) was applied to analyzing and optimizing the performance parameters (cutting force and cutting temperature). Secondly, the ANOVA tests have been performed to check the adequacy and significance of process parameters. Then, the theoretical evaluation of cutting force and temperature is carried out and validated with the experimental value. In the end, the effect of each process parameter on responses followed by optimization using desirability approach has been done.

II. METHODOLOGY

A. SELECTION OF PROCESS PARAMETERS

The performance of a machining system is measured regarding cutting forces, cutting temperature, surface finish, and tools wear. The cutting conditions, tool geometry and the type of lubricant are main important parameters affecting the performance of the components.

Table 1 Selected machining parameters and its levels

Actual Factors	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
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 (degree)	30	45	60	75	90
Nose radius, r (mm)	0.2	0.4	0.8	1.2	1.6

In this study, four parameters namely cutting speed, feed rate, approach angle and the nose radius of the cutting tool were selected for the experimentation. Each parameter with five levels has been selected as shown in Table 1.

B. Work piece and cutting tool materials

Work piece material selected during experimentation was Inconel 718. Inconel 718 is having a hardness value of 37±1 HRC. This material is used for aircraft components such as turbine disks and shafts. During experimentation, work piece of 60 mm diameter (D) and 350 mm length (L) are selected to maintain L/D ratio less than ten as per ISO 3685 standards 1993 [18]. 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. A TiAlN-coated fine-grained high cobalt carbide with Grade KC5525 inserts (made by Kennametal) of different radii was selected. ISO designations of the inserts used were CNMG1204. ISO designation of tool holder was MCLNR2525M12. A depth of cut 0.2 mm was kept constant.

C. Experimental detail

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 -30oC to 1550oC and an optical resolution of 30:1) is used for measuring the cutting temperature. Each experiment is performed with new cutting edge. Soluble cutting oil was selected as a lubricant. Before actual experimentation, a trial run was performed by varying the different mass flow rate of lubricant at 50 ml/h, 100 ml/h, 150 ml/h and 200 ml/h. Low cutting force and surface roughness were obtained at 150 ml/h. Hence, 150 ml/h mass flow rate of lubricant was selected for experimentation.

D. Design of experiment and statistical modelling

Response surface methodology (RSM) plays a significant role in modelling and analysis. In RSM, the response is influenced by a large number of variables. The experiments were designed and performed using central composite design (CCD) response surface methodology (RSM) design. According to the central composite design, 30 tests were performed. In this experimental work, cutting speed, feed rate, approach angle, and nose radius were selected as process parameters. The cutting force and cutting temperature were the response variables. The objective is to investigate the outcome of these parameters on responses and consequently optimize these responses [19]. The mathematical model is represented as;

$$z = \phi\,(v, f, \alpha, r) + \epsilon \qquad (1)$$

Where z is machining response, ø is the response function, v, f, α and r are the cutting speed, feed rate, approach angle and tool nose radius, ϵ is the experimental error. In most cases of RSM, the main step is to get the relationship between response and process variables. Hence, the first order linear mathematical model represented by Eq. (2)

$$z_1 = z-\epsilon = k_0x_0+k_1x_2+k_2x_2+k_3x_3+k_4x_4 \qquad (2)$$

Where z_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; k_0, k_1, k_2, k_3 and k_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:

$$z_2 = z-\epsilon = k_0x_0+k_1x_2+k_2x_2+k_3x_3+k_4x_4+k_{12}x_1x_2+k_{13}x_1x_3 +k_{14}x_1x_4+k_{23}x_2x_3+k_{24}x_2x_4+k_{34}x_3x_4+k_{11}x_{12}+k_{22}x_{22}+k_{33}x_{32} +k_{44}x_{42} \qquad (3)$$

Where z_2 is the responses based on second order model; ϵ is the experimental error. k_0, k_1, k_2, k_3, k_4, k_{12}, k_{13}, k_{14}, k_{23}, k_{24}, k_{34}, k_{11}, k_{22}, k_{33} and k_{44} values are the set of regression coefficients estimated by least squares.

III. RESULTS AND DISCUSSION

A. Analysis of cutting force and temperature

During machining, generation of heat develops high temperature at the cutting region and leads to poor surface quality and early cutting tool edge failure. So, for the overall improvement of the process, the cutting zone temperature has to be managed within the acceptable limits. Hence, in this study, use of coolant/MQL is an alternative for effective control of cutting zone temperature. In this work, cutting force and temperature were selected as the response parameters. For performing the experiments, a design of experiment plays a very significant role. Based on central composite design (CCD), 30 experiments were performed with the dry, wet and MQL technique. The significance of the process parameters was done by performing a variance analysis (ANOVA) for cutting force and cutting temperature. The objective is to analyze the influence of cutting speed, feed, approach angle and nose radius on the results.

The Table 2 & 3 represents the result of ANOVA respectively, for cutting force and cutting temperature. These tables show the percentage contribution of each parameter and their interactions. The significance of the process variables was taken at 95% and 99% confidence level. Table 2 presents (ANOVA) result for cutting force. It can be seen that the feed rate (f) is the most important factor affecting cutting force. Its contribution is 31.67%. The next largest factor influencing force is approach

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angle (α) with 18.31% contribution. The nose radius (r) with 13.76% contribution has the least significant effect. Similarly, the interactions are significant. ANOVA result for the cutting temperature is indicated in Table 3. It can be noted that the contribution of feed is 25.36%. The approach angle, cutting speed and nose radius is significant. Respectively, their contributions are (16.12; 15.46 and 7.80) %.

Table 2 ANOVA for cutting force under MQL condition

Source	Sum of sq.	df	Mean sq.	F_{cal}	% cont.
Model	37477.6	14	2676.9	1014.4	
v	6733.5	1	6733.5	2551.6	17.9
f	11881.5	1	11881.	4502.4	31.6
α	6868.1	1	6868.1	2602.6	18.3
r	5162.6	1	5162.6	1956.3	13.7
v*f	9	1	9	3.41	0.2
v*α	420.2	1	420.2	159.2	1.12
v*r	420.2	1	420.2	159.2	1.12
f*α	600.2	1	600.2	227.4	1.60
f*r	12.2	1	12.2	4.642	0.32
α*r	225	1	225	85.2	0.61
v^2	2110.0	1	2110.0	799.5	5.62
f^2	500.2	1	500.2	189.5	1.33
$α^2$	2552.0	1	2552.0	967.0	6.80
r^2	1876.2	1	1876.2	711.	5.00
Residual	39.5	15	2.6		
Lack of Fit	28.7	10	2.8	1.32	0.07
Pure Error	10.8	5	2.1		
Cor Total	37517	29			

Quadratic regression modeled the relationship between the cutting parameters and the performance measures. The regression equations obtained with MQL technique were as follows. The second order cutting force model thus developed is given below in Eq. (4). Its coefficient of determination (R^2) is 98.35%.

$$\text{Cutting force} = 593.088-5.257*v +336.667*f -5.926*\alpha -190.781*r -1.5*v*f+0.017*v*\alpha +0.640*v*r -16.333*f*\alpha +0.625*\alpha*r-87.5*f*r +0.022*v^2 +6883.333*f^2 +0.043*\alpha^2+51.692*r^2 \quad (4)$$

The cutting temperature model with MQL machining is given by Eq. (5) with a determination coefficient (R^2) of 97.63%.

$$\text{Cutting temperature} = 2109.661-13.001*v -17615*f -17.231*\alpha -376.302*r +16*v*f +0.021*v*\alpha +0.515*v*r -15.333*f*\alpha-125*f*r -2.270*\alpha*r +0.083*v^2 +72433.333*f^2 +0.157*\alpha^2 +254.817*r^2 \quad (5)$$

Table 3 ANOVA for cutting temperature under MQL condition

Source	Sum of sq.	df	Mean sq.	F_{cal}	% cont.
Model	350069.	14	25004.9	2017.4	
v	54150	1	54150	4368.8	15.4
f	88816.6	1	88816.6	7165.8	25.3
α	56454	1	56454	4554.7	16.1
r	27337.5	1	27337.5	2205.6	7.8
v*f	1024	1	1024	82.6	0.29
v*α	650.2	1	650.2	52.4	0.19
v*r	272.2	1	272.2	21.9	0.08
f*α	529	1	529	42.6	0.15
f*r	25	1	25	2.02	0.02
α*r	2970.2	1	2970.2	239.6	0.85
v^2	30590.5	1	30590.5	2468.0	8.73
f^2	56213.4	1	56213.4	4535.3	16.0
$α^2$	34364.2	1	34364.2	2772.5	9.81
r^2	45593.4	1	45593.4	3678.5	13.0
Residual	185.9	15	12.3		
Lack of Fit	146.5	10	14.6	1.86	0.04
Pure Error	39.3	5	7.8		
Cor Total	350255.	29			

Figure 2 (a) and (b) illustrate the normal probability plot of distribution in the case of cutting force and temperature. The normal plots show that for the residuals follow a normal distribution, as residual follows a straight line. The comparison between actual and predicted responses for cutting force and cutting temperature is illustrated in Figure 3 (a) and (b) respectively. The comparison indicated that predicted value close to those readings recorded experimentally with a 95% confidence interval. This reflects the good agreement between experimental values and predicted values obtained with models shown in Eq. (4) moreover, (5).

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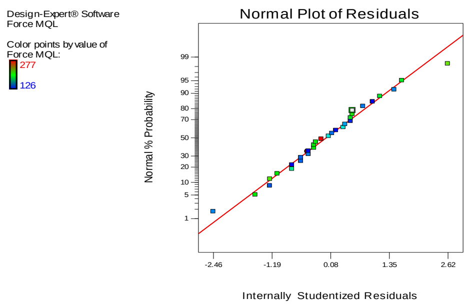

Figure 2 (a) Normal plots of residuals for cutting force

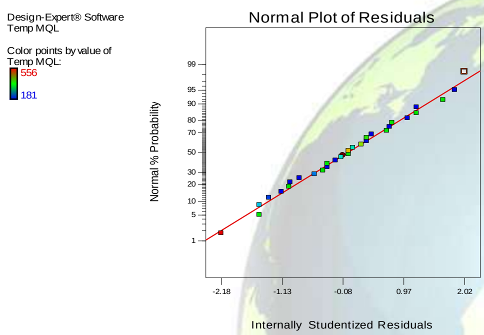

Figure 2 (b) Normal plots of residuals for cutting temperature

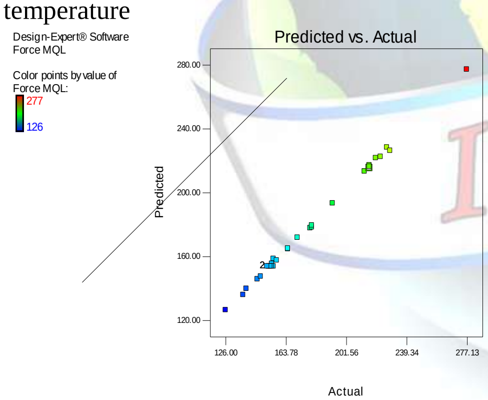

Figure 3 (a) Comparison between measured and predicted value of cutting force

B. Effect of Cutting Speed

Fig. 4 (a) and (b) show the effect of cutting speed on cutting force and cutting temperature during machining of Inconel 718. Examination of Figure 4 (a) shows a tendency for decrease in cutting force with an increase of cutting speed. In parallel to increased cutting speed, cutting temperature rises as represented in figure 4(b), facilitate the plastic deformation in deformation zone. This has helped in decreasing the surface roughness and chip flow.

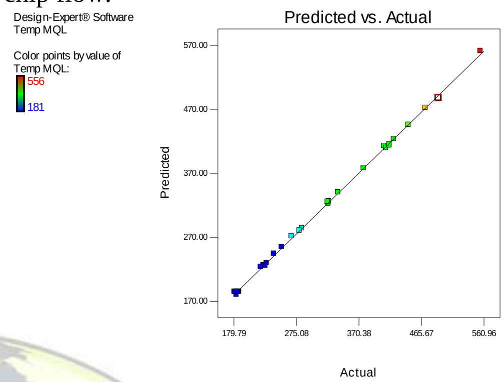

Figure 3 (b) Comparison between measured and predicted value of cutting temperatures

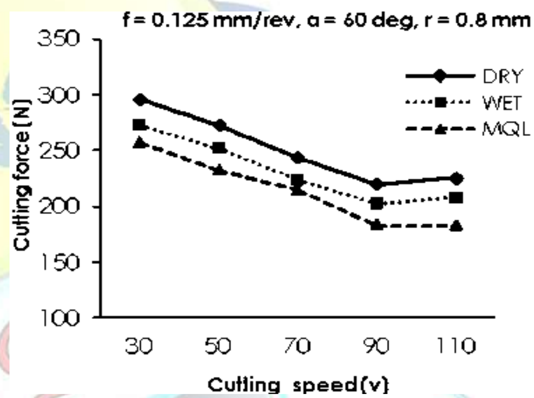

Figure 4 (a) Variations of Cutting force with cutting speed

The possible reason is that the average coefficient of friction at the tool face decreases with decreasing contact length indicating that the friction force decreases. 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. Results showed that less cutting force and the temperature was obtained with MQL in comparison to dry machining. It is attributed that, with a proper MQL technique, the film of lubricant is developed at the tool-chip interface. This thin film of lubricant facilitates the slipping of chips over tool by reducing the friction coefficient, which results in the generation of lower temperature and cutting forces.

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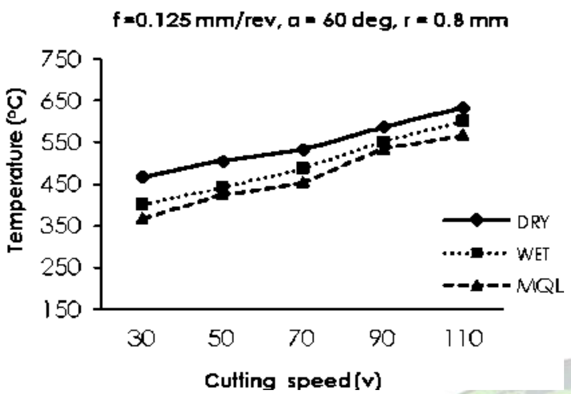

Figure 4 (b) Variations of cutting temperature with cutting speed

C. Effect of feed rate

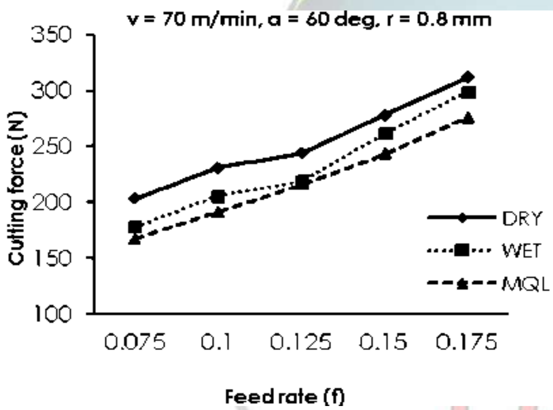

Figure 5 (a) Variations of Cutting force with feed rate

Fig. 5 (a) and (b) shows the variation of cutting force and cutting temperature with feed rate. From figures, it can be seen that increase in the feed rate increases the cutting force and cutting temperature with poor surface quality. This is well known due to fundamental of metal cutting that any increase in the feed rate increases the cross-section and corresponding deforming volume [20]. The increase in feed results in a significant increase in chip-tool contact and coefficient of friction which increases the cutting force and temperature. Due to high friction between cutting edge of the tool and cutting surface of the workpiece, heat is generated due to poor machinability of Inconel 718 results in the severe rise in temperature in cutting region. Consequently, detached pieces of chips are welded to the cutting edge of the tool named as a built-up edge. Sometimes increasing feed rate and formation of the built-up edge produce grooves on machined surface and plastic deformation of work piece [21]. However, applying MQL in the cutting zone can detach chips away from the machining surface and reduces the temperature.

D. Effect of approach angle

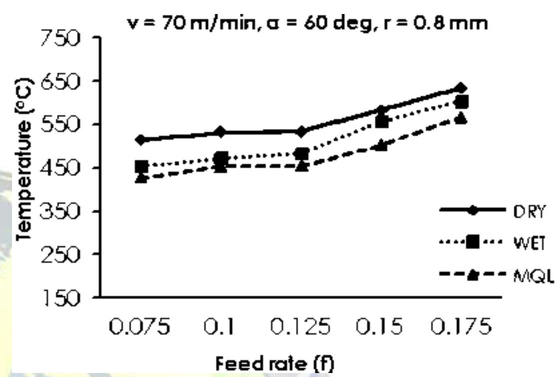

Figure 5 (b) Variations of cutting temperature with feed rates

Fig. 6 (a) and (b) show the variation of cutting force and temperature with approach angle. With an increase in approach angle (from 30^0 to 65^0), the cutting force and temperature decrease. 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 and cutting temperature. However, at 90^0 approach angle, the cutting force and temperature are 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 65^0-75^0 approach angles due to the distribution of the heat over a greater length of the cutting edge. This also reduces the cutting forces and improves tool life.

E. Effect of tool Nose radius

Cutting force and temperature variation with tool nose radius are plotted in Figure 7 (a) and (b). Figures show that at 0.2 mm of tool nose radius the value of cutting force and interface 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

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cutting force is decreased due to increase in area to contact between tool-workpiece interfaces.

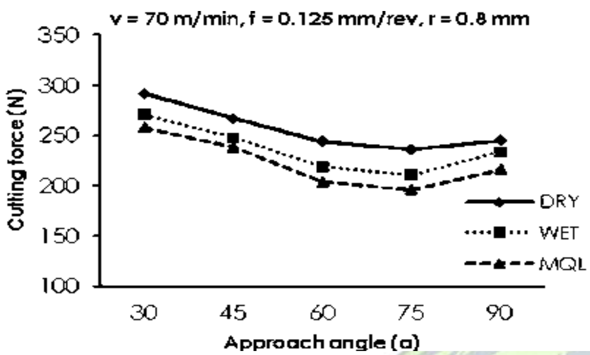

Figure 6 (a) Variations of Cutting force with approach angle

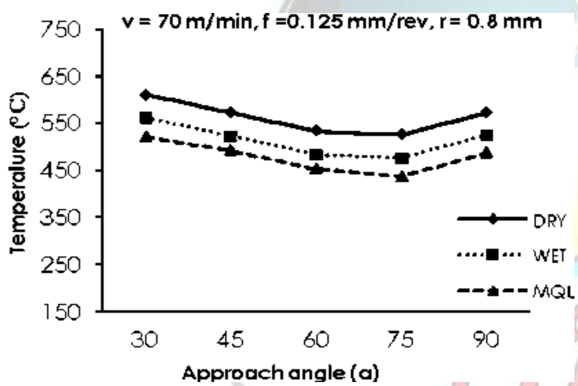

Figure 6 (b) Variations of cutting temperature with approach angles

Consequently, extra area is available for conduction and cutting temperature is also decreased. The minimum value of cutting force and machining temperature is observed at tool nose radius 1.2 mm. After 1.2 mm the cutting force and interface temperature increase due to a large area of contact which causes chatter, vibration and high friction at tool and workpiece interface, resulting in an increase in cutting force and interface temperature.

When compared to the wet condition, the MQL presented an average reduction in the cutting force of 10-12%. The MQL contributes to reduce friction and chip-tool-work piece contact areas allowing better surface finish and improve tool lives.

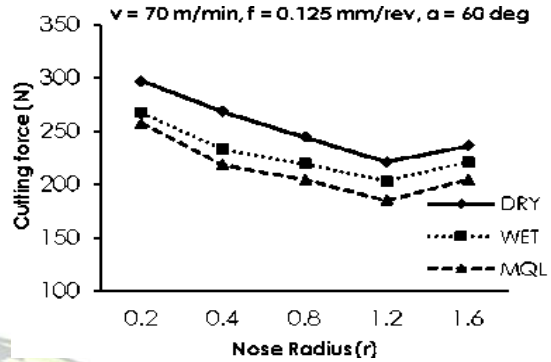

Figure 7 (a) Variation of Cutting force with nose radius

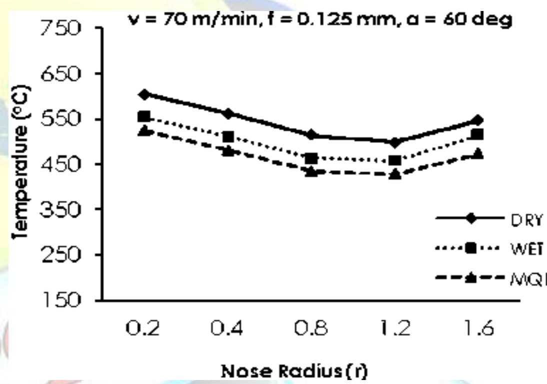

Figure 7 (b) Variation of temperature with nose radiuses

F. Optimization of process parameters

In the present research work, four different machining parameters were used. It has been tried to optimize the machinability aspect with an aim to minimize the value of cutting force and cutting temperature. In order to optimize the process, the machining parameters were selected to be "in the range" for each type of parameters, whereas cutting force and cutting temperature were selected "minimize" so as to achieve the best results. Moreover, the optimal solutions are reported in Table 4 in order of decreasing desirability level, and the highest desirability value is selected for the best solution. It is evident from the optimal conditions that the maximum desirability of 0.985 is achieved (v = 74.72 m/min, f = 0.1 mm/rev, α = 61.5 degree and r = 1.06 mm).

Table 4 Response optimization for cutting force and temperature

Sol. No.	1.	2.	3.	4.	5.
v	74.72	74.72	73.45	74.67	75.23
f	0.1	0.1	0.1	0.1	0.1
α	61.5	61.5	62.3	62.0	62.8
r	1.06	1.06	1.04	1.05	1.02
Cutting force	183.2	183.2	183.4	183.8	184.2
Cutting temperature	436.0	436.0	436.4	436.8	437.3
Desirability	0.985	0.985	0.985	0.984	0.983
Remarks	Selected				

IV. Conclusion

In this research work, the turning of nickel-based Inconel alloy 718 was investigated to determine the effects of machining parameters on machinability aspect (cutting force and cutting temperature). MQL machining was compared with the dry and wet condition. RSM and ANOVA method was used to analyse the results. Eventually, optimized parameters for obtaining lowest cutting forces and temperature were proposed. The findings of this research works as follows:

It was shown that there was a good agreement between experimental and predicted values by quadratic models. MQL machining reported low cutting force and temperature than wet and dry condition while machining of Inconel 718 with TiAlN-coated carbide tools. So, this methodology offers 10-12% reduction in cutting force.

- Feed rate, approach angle and Nose radius had a significant effect on the performance measures. The cutting force and the cutting temperature are strongly influenced by the feed, (30.88%) and (25.33%) respectively. Additionally, the approach angle has a contribution of 21.05% and 16.20% during machining with solid lubricants.
- This experimental investigation helped in explaining the chip micrograph of Inconel 718 during machining, which will give valuable knowledge to manufacturers in the proper selection of cutting parameters. This work also predicted that cutting conditions and tool geometry is vital for achieving the overall performance.
- Based on optimization process, the optimal experimental condition for minimizing cutting force and the temperature is obtained at 74.72m/min cutting speed, 0.1 mm/rev feed rate, 61.49 approach angle and 1.06 mm nose radius, respectively.

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