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“Investigations on the machinability of Waspaloy under dry environment”

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Abstract. Nickel based superalloy, Waspaloy is extensively used in gas turbine, aerospace and automobile industries because of their unique combination of properties like high strength at elevated temperatures, resistance to chemical degradation and excellent wear resistance in many hostile environments. It is considered as one of the difficult to machine superalloy due to excessive tool wear and poor surface finish. The present paper is an attempt for removing cutting fluids from turning process of Waspaloy and to make the processes environmentally safe. For this purpose, the effect of machining parameters such as cutting speed and feed rate on the cutting force, cutting temperature, surface finish and tool wear were investigated barrier. Consequently, the strength and tool wear resistance and tool life increased significantly. Response Surface Methodology (RSM) has been used for developing and analyzing a mathematical model which describes the relationship between machining parameters and output variables. Subsequently ANOVA was used to check the adequacy of the regression model as well as each machining variables. The optimal cutting parameters were determined based on multi-response optimizations by composite desirability approach in order to minimize cutting force, average surface roughness and maximum flank wear. The results obtained from the experiments shown that machining of Waspaloy using coated carbide tool with special ranges of parameters, cutting fluid could be completely removed from machining process

Key words: Waspaloy; Superalloy; Dry machining; Surface roughness; Tool wear; RSM

1. Introduction

Aerospace superalloys, such as nickel base and titanium alloys as well as other advanced materials like structural ceramics and hardened steel are generally referred to as difficult- to- cut alloys due to their unique combination of properties like high strength at elevated temperatures, resistance to chemical degradation and wear resistance. The Ni based alloys are most widely used super alloy, accounting for 50 wt. % of materials used in an aerospace engine, mainly in gas turbine compartment. They exhibit excellent strength to weight ratio and strong resistance to corrosion, mechanical and thermal fatigue, mechanical and thermal shock, creep and erosion at elevated temperatures [1-3].

Alloy 718 (Inconel 718) and Waspaloy are most widely used Ni based super alloy in various high strength cast and wrought components for high temperature applications. Inconel 718 is widely used in



the hot section of turbine machinery and nuclear reactors whereas waspaloy in aircraft turbine engine as compressor disc, shaft and turbine cases. The maximum service temperature of waspaloy is as high as 750⁰C, but due to the high cobalt content it is an expensive alloy. Therefore cheaper alternate alloy inconel 718 is used whenever possible, which have 650⁰C maximum service temperature [4].

The machining of nickel based alloys are very difficult due to short tool life and severe surface abuse of machined surface. The major part of their strength is retained during the machining process, so that the cutting forces attain high values. Ni based alloys have low thermal conductivity, so the heat generated in cutting is not removed through the chip and dissipates within the tool and workpiece causes rapid tool wear. This affects the machined surface and alters the microstructure of alloy. So that the cutting tool material used for machining superalloys should have adequate hot hardness at elevated temperature [5].

Tool coating plays a major role in tool development, especially for dry machining by acting as a partial substitute of cutting fluid. The AlTiN coated carbide tools performed significantly for dry and MQL machining of stainless steel as well as hardened steel up to 63 HRC because of high hot hardness and wear resistance of coating at elevated temperature associated to an ultra-fine crystallinity [6].

Response Surface Methodology (RSM) has been used for developing and analyzing a mathematical model which describes the relationship between machining parameters and output variables. Researchers found that the developed model by using RSM procedure shows a very good agreement with the experimental values [7-15].

Considering all the above facts the present work aims to investigate the effect of machining parameters such as cutting speed and feed rate on the cutting force, cutting temperature, surface finish and tool wear. Test results were analyzed for understanding the machining difficulties during machining of Waspaloy with AlTiN coated carbide tool insert (KCU25). In this work, RSM was used to determine the relationship between machining parameters and the output response. Then ANOVA was used to test the adequacy of the regression model as well as each machining variables. Finally, composite desirability approach was used to find the optimal cutting parameters.

Table 1.Physical properties of Waspaloy.

Properties	Value
Density	8.20g/cm ³
Melting point	1330-1360 ⁰ C
Specific heat	520J/kg K
Average coefficient of thermal expansion	12μm/mK
Thermal conductivity	11.7 w/m k
Ultimate tensile strength	1241MPa

Table 2. Chemical composition of Waspaloy.

Element	Ni	Cr	Co	Mo	Ti	Al	Fe	Si	C	Zr	Cu	Mn
Wt %	58.97	20.94	13.09	5.74	2.79	1.24	0.78	0.066	0.062	0.058	0.032	0.017

2. Experimental work

2.1. Workpiece material

The workpiece material used was Waspaloy with a length of 220 mm and a diameter of 23 mm. The physical properties and chemical composition of Waspaloy are shown in Table 1 and 2 respectively. The major element in Waspaloy other than Nickel is Chromium which provides high temperature

oxidation resistance. Fig 1 shows the microstructure of Waspaloy and inhomogeneous grain size structure may be observed.

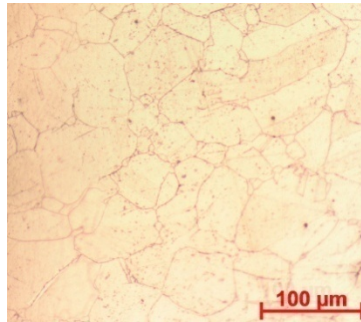


Figure 1. Microstructure of workpiece material.

2.2. Cutting tool

The cutting tool was AlTiN coated tungsten carbide inserts (KCU25). This advanced PVD nano-crystalline coating with high Al content provide better wear protection by increasing the protective surface oxide films after oxidation [7]. The tool radius was 0.4 mm, the rake and clearance angle were -5° and 5° respectively. The tool holder used was MCLNR2525M12 with an approach angle of 95° .

2.3. Experimental set-up and cutting conditions

The machining experiments were performed on a heavy duty lathe (Make- ESTEEM, Model- ETM510) under dry conditions. To investigate the machinability of Waspaloy various experimental trials were performed under a wide range of cutting speeds varying from 30 to 60 m/min, feed rates varying from 0.103 to 0.206 mm/rev and a constant depth of cut (0.5 mm). Machining length, 40 mm was fixed throughout these trials. General full factorial design method was used for designing the experiment.

The cutting force for every test was recorded using kistler piezoelectric dynamometer (model 9257B). Infrared pyrometer with a temperature range of 260 to 2000⁰C was used to measure and record the cutting temperature. The machined samples, average surface roughness (R_a) was measured using MAHR surface profilometer. Three measurements were taken at three different locations and average value was used for in the analysis. Tool wear measurements were taken using a Zeiss optical microscope and analyzed using Axio Vision SE64 software. The experimental data obtained in this study were analyzed by using Minitab 17.

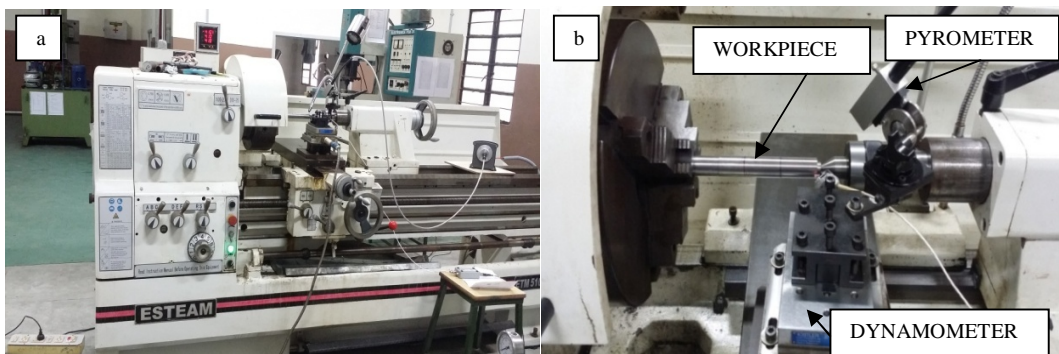


Figure 2. Experimental setup (a) Heavy duty lathe (b) Machining setup with dynamometer and pyrometer arrangement.

Table 3. Cutting parameters and their levels.

Process parameter	Level 1	Level 2	Level 3
Cutting speed , Vc (m/min)	30	45	60
feed , f (mm/rev)	0.103	0.147	0.206

3. Results and discussion

3.1. Analysis of variance (ANOVA)

The relationship between independent input variables (cutting speed and feed rate for constant depth of cut) and output responses (feed force or thrust force or cutting force or cutting temperature or average surface roughness or maximum flank wear (Y)) can be expressed as

$$Y=f(V_c, f) \tag{1}$$

where Y is the desired response and f is the response function. The response surface equation for two factors can be expressed as

$$Y= a_0 + a_1V_c + a_2f + a_{12}V_c f + a_{11}V_c^2 + a_{22}f^2 \tag{2}$$

where Y is the desired response and a_0, a_1, \dots, a_{22} are the regression coefficients for each response Y [7-9].

Table 4. Experimental plan and results for feed force, thrust force, cutting force, cutting temperature, average surface roughness and maximum flank wear.

Run	Cutting parameters		Response factors					
	Vc (m/min)	f (mm/rev)	Feed force (N)	Thrust force (N)	Cutting force (N)	Cutting temperature (°C)	Average surface roughness (µm)	Maximum flank wear (µm)
1	30	0.103	127	183	235	435	0.731	146.7
2	30	0.147	114	150	215	449	0.615	176.66
3	30	0.206	103	140	207	465	0.58	198.5
4	45	0.103	149	224	302	445	1.125	167.4
5	45	0.147	124	174	300	457	0.957	189.43
6	45	0.206	111	156	257	478	0.882	244.93
7	60	0.103	217	231	480	447	1.75	175.6
8	60	0.147	176	202	442	463	1.619	191.5
9	60	0.206	123	172	350	481	1.51	251.99

ANOVA method is used to check the adequacy and significance of the model and variables. F- value is also used to test the adequacy of the model. To find out whether a parameter has an effect in the response ANOVA analysis the P (importance/probability) value should check. If 95% confidence level for intervals is considered, then the P value < 0.05 (5% importance value) indicates that the parameter is effective. Contribution of every parameter on the total variation is on the table as PC (%) [9-11].

The results of ANOVA for identifying the significant factors and its percentage contribution for feed force, thrust force, cutting force, cutting temperature, average surface roughness and maximum flank wear are given in the Table 5 and 6

Table 5 . ANOVA results for feed force, thrust force and cutting force.

Source	DF	Adj SS	Adj MS	F	P	PC (%)	R ² (%)
Feed force							
V _c	1	4316.2	4316.2	97.98	0.002*	39.67	98.79
f	1	4930.7	4930.7	111.93	0.002*	45.33	
V _c ²	1	0.2	0.2	0.01	0.948	0.001	
f ²	1	247.3	247.3	5.61	0.099	2.27	
V _c × f	1	1288.3	1288.29	29.25	0.012*	11.84	
Error	3	132.2	44.05				
Total	8	10877.6					
thrust force.							
Source	DF	Adj SS	Adj MS	F	P	PC (%)	R ² (%)
V _c	1	4858.59	4858.59	70.68	0.004*	59.32	97.48
f	1	2904.00	2904.00	42.25	0.007*	35.45	
V _c ²	1	162.00	162.00	2.36	0.222	1.98	
f ²	1	133.66	133.66	1.94	0.258	1.63	
V _c × f	1	51.12	51.12	0.74	0.452	0.62	
Error	3	206.22	68.74				
Total	8	8190.00					
cutting force.							
Source	DF	Adj SS	Adj MS	F	P	PC (%)	R ² (%)
V _c	1	7367.2	7367.2	34.47	0.010*	9.67	99.16
f	1	63037.5	63037.5	294.95	0.0001*	82.77	
V _c ²	1	382.7	382.7	1.79	0.273	0.50	
f ²	1	813.5	813.5	3.81	0.146	1.07	
V _c × f	1	2752.6	2752.6	12.88	0.037*	3.61	
Error	3	641.2	213.7				
Total	8	76155.6					

DF: degrees of freedom, SS: sum of squares, F: F-test value, P: error variance and PC: percentage contribution.

*At a given response, parameters belonging to the filled cells are effective within 95% reliability interval

The analysis of variance (ANOVA) for cutting force components were performed and shown in Table 5. The coefficient of determination, R² of feed force, thrust force and cutting force is 0.9879, 0.9748 and 0.9916 respectively, which indicating that 98.79%, 97.48% and 99.16 % of the variability in the response can be explained by the model. From the ANOVA results, it is evident that feed rate is the most significant parameter which affecting feed force as well as cutting forces. But in the case of thrust force, cutting velocity is the most significant factor.

The feed force, thrust force and cutting force increases with increase in feed rate and decreases with increase in cutting speed. The most important control factors that can effectively reduce the variations and contribute to the quality characteristics are identified in descending order for feed force feed rate (45.33%) , cutting speed (39.67%), cutting speed x feed rate(11.84%), feed rate²(2.27%) and cutting speed² (0.001%), for thrust force cutting speed (59.32%), feed rate (35.45%) , cutting speed² (1.98%),

feed rate²(1.63%) and cutting speed x feed rate(0.62%) and for cutting force as feed rate (82.77%), cutting speed (9.67%), cutting speed x feed rate(3.61%), feed rate²(1.07%) and cutting speed²(0.5%).

Table 6 . ANOVA results for cutting temperature, average surface roughness and maximum flank wear.

Source	DF	Adj SS	Adj MS	F	P	PC (%)	R ² (%)
Cutting temperature							
V _c	1	1571.79	1571.79	786.37	0.0001*	82.57	99.68
f	1	294.00	294.00	147.09	0.001*	15.44	
V _c ²	1	9.39	9.39	4.70	0.119	0.49	
f ²	1	37.63	37.63	18.82	0.023*	1.98	
V _c × f	1	3.78	3.78	1.89	0.263	0.19	
Error	3	6.00	2.00				
Total	8	1903.56					
average surface roughness							
Source	DF	Adj SS	Adj MS	F	P	PC (%)	R ² (%)
V _c	1	0.06805	0.06805	141.19	0.001*	4.34	99.91
f	1	1.45337	1.45337	3015.44	0.0001*	92.66	
V _c ²	1	0.00213	0.00213	4.43	0.126	0.14	
f ²	1	0.01102	0.01102	22.86	0.017*	0.70	
V _c × f	1	0.00177	0.00177	3.67	0.151	0.11	
Error	3	0.00145	0.00048				
Total	8	1.56844					
maximum flank wear							
Source	DF	Adj SS	Adj MS	F	P	PC (%)	R ² (%)
V _c	1	7144.3	7144.3	64.16	0.004*	72.48	96.52
f	1	1575.6	1575.6	14.15	0.033*	15.98	
V _c ²	1	271.8	271.8	2.44	0.216	2.76	
f ²	1	324.8	324.8	2.92	0.186	3.29	
V _c × f	1	134.6	134.6	1.21	0.352	1.37	
Error	3	334.0	111.3				
Total	8	9587.0					

* At a given response, parameters belonging to the filled cells are effective within 95% reliability interval

From Table 6, cutting speed with PC (%) of 82.57, has the most effect on cutting temperature. Subsequently, the feed rate has a PC (%) of 15.44. The coefficient of determination, R² of cutting temperature is 0.9968, i.e. 99.68% of the variability in the response can be explained by the model. The cutting temperature increases with increase in cutting speed and feed rate.

Feed rate with PC (%) of 92.66 has the most effect on average surface roughness. Here the R² value of the model is 0.9991 and close to 1, which is desirable. The average surface roughness value is increases with increase in feed rate and decrease in cutting speed.

From Table 6, it is evident that the cutting speed with PC (%) of 72.48 has the most significant effect on maximum flank wear. And R² value is 0.9652 which means that model is desirable. The maximum flank wear value is increases with increase in cutting speed and feed rate.

The main effects plot and interaction plot for feed force, thrust force, cutting force, cutting temperature, average surface roughness and maximum flank wear are shown in figure 3 and 4 [12]. It is clearly observed that the cutting speed and feed strongly changes feed force, thrust force, cutting

force, cutting temperature, average surface roughness, maximum flank wear. Both speed and feed rate have an increasing effect in the case of cutting temperature and maximum flank wear. The cutting speed has a decreasing effect in feed force, thrust force, cutting force and average surface roughness, influence value is high and it has much higher levels of contribution.

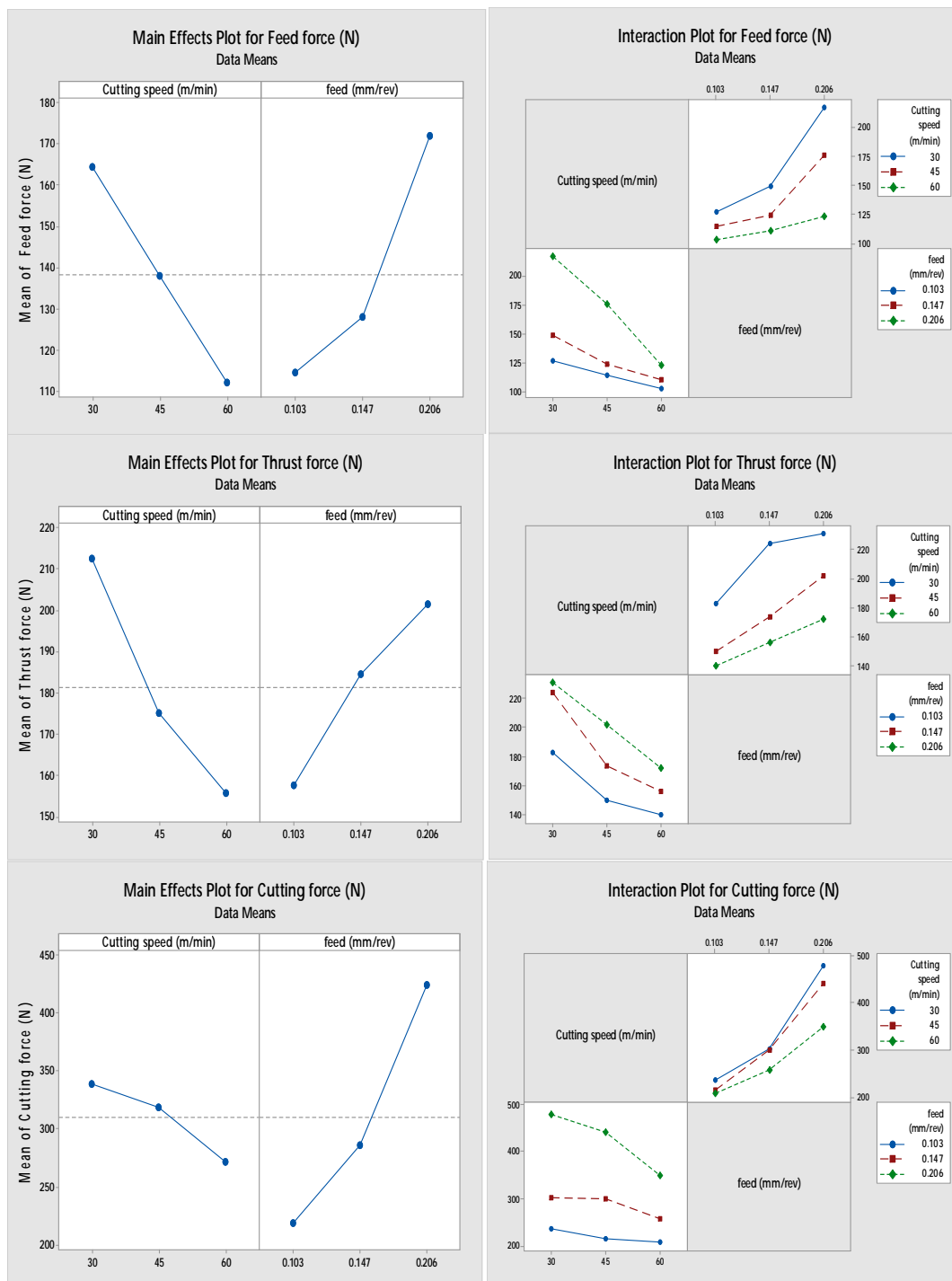


Figure 3. Main effects plot and Interaction plot for feed force, thrust force and cutting force.

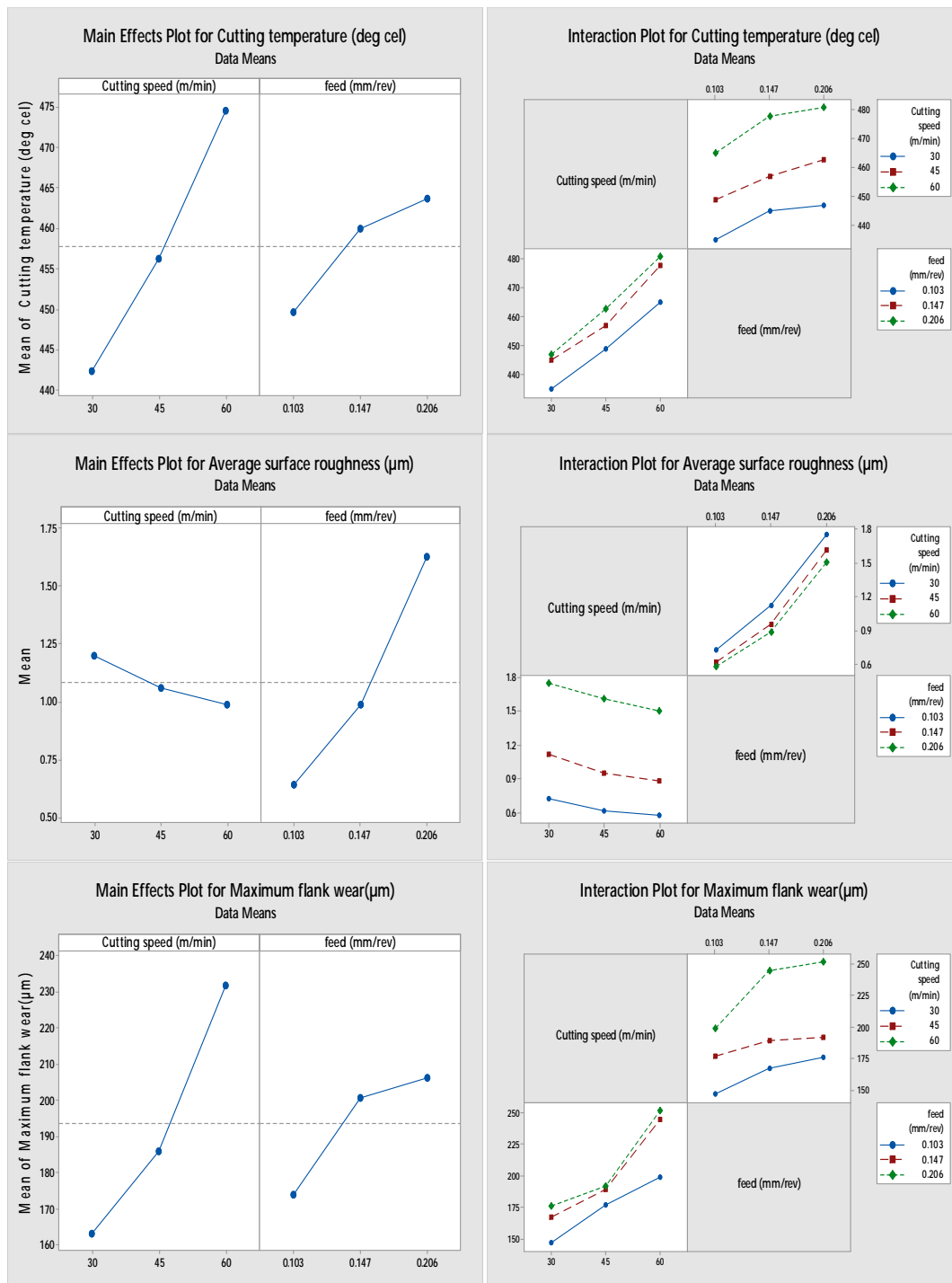


Figure 4. Main effects plot and Interaction plot for cutting temperature, average surface roughness and maximum flank wear.

However, feed rate has an increasing effect feed force, thrust force, cutting force and average surface roughness. Therefore, low feed and higher cutting speed provides lower cutting forces and roughness value. From the interaction plot the variation of feed force, thrust force, cutting force, cutting temperature, average surface roughness, and maximum flank wear with respect to three different speed and feed rate can be understand. There is an increasing trend of maximum flank wear

at all three speed and feed rate. Average surface roughness trend is totally different, it increases with feed and decreases with cutting speed. The combined effect of cutting speed and feed rate is also increasing the cutting temperature.

The developed mathematical model has high determination coefficients which mean that the regression model can be utilized to predict the responses accurately.

Table 7. Regression models

Regression models	R ² %	R ² (adj) %
Feed force = 71.0 + 1.65 V _c + 270 f + 0.0015 V _c ² + 4298 f ² - 23.15 V _c × f	98.79	96.76
Thrust force = 175.1 - 4.79 V _c + 1611 f + 0.0400 V _c ² - 3160 f ² - 4.61 V _c × f	97.48	93.29
Cutting force= -66 + 8.42 V _c + 1104 f - 0.0615 V _c ² + 7796 f ² - 33.84 V _c × f	99.16	97.75
Cutting temperature= 378.2 + 0.020 V _c + 598 f + 0.00963 V _c ² - 1677 f ² + 1.254 V _c × f	99.68	99.16
Average surface roughness= 0.670 - 0.01599 V _c + 1.91 f + 0.000145 V _c ² + 28.69 f ² - 0.0271 V _c × f	99.91	99.75
Maximum flank wear= 82 - 3.51 V _c + 1500 f + 0.0518 V _c ² - 4926 f ² + 7.48 V _c × f	96.52	90.71

Contour plots have a very significant role in the study of the response surface. Circular shaped contour represents the independence of factor effects and elliptical contours may indicate factor interaction. The contours of the responses are shown in figure 5. Feed force, thrust force and cutting force are drastically increases even at low cutting speed values. Cutting temperature and maximum flank wear values are low at low levels of speed and feed. The most effective parameter on average surface roughness was determined as the feed rate. In the combinations of low feed rate and high cutting speed surface roughness gets better.

3.2 Optimization and Confirmation test

The optimal cutting parameters were determined based on multi-response optimizations by desirability function of response surface methodology in order to achieve minimum cutting force, average surface roughness and maximum flank wear. Initially, each response is converted into individual desirability function which varies from 0 to 1. Finally the individual desirability functions are combined to form a single value called composite desirability of the multi response system. The best combination was selected based on the highest desirability value [13-15].

Table 8. Goals and limits for optimization of cutting conditions.

Cutting condition and Response	Goal	Lower limit	Upper limit
Cutting speed (m/min)	In range	30	60
Feed rate (mm/rev)	In range	0.103	0.206
Cutting force (N)	Minimize	207	480
Average surface roughness (µm)	Minimize	0.58	1.75
Maximum flank wear (µm)	Minimize	146.70	251.99

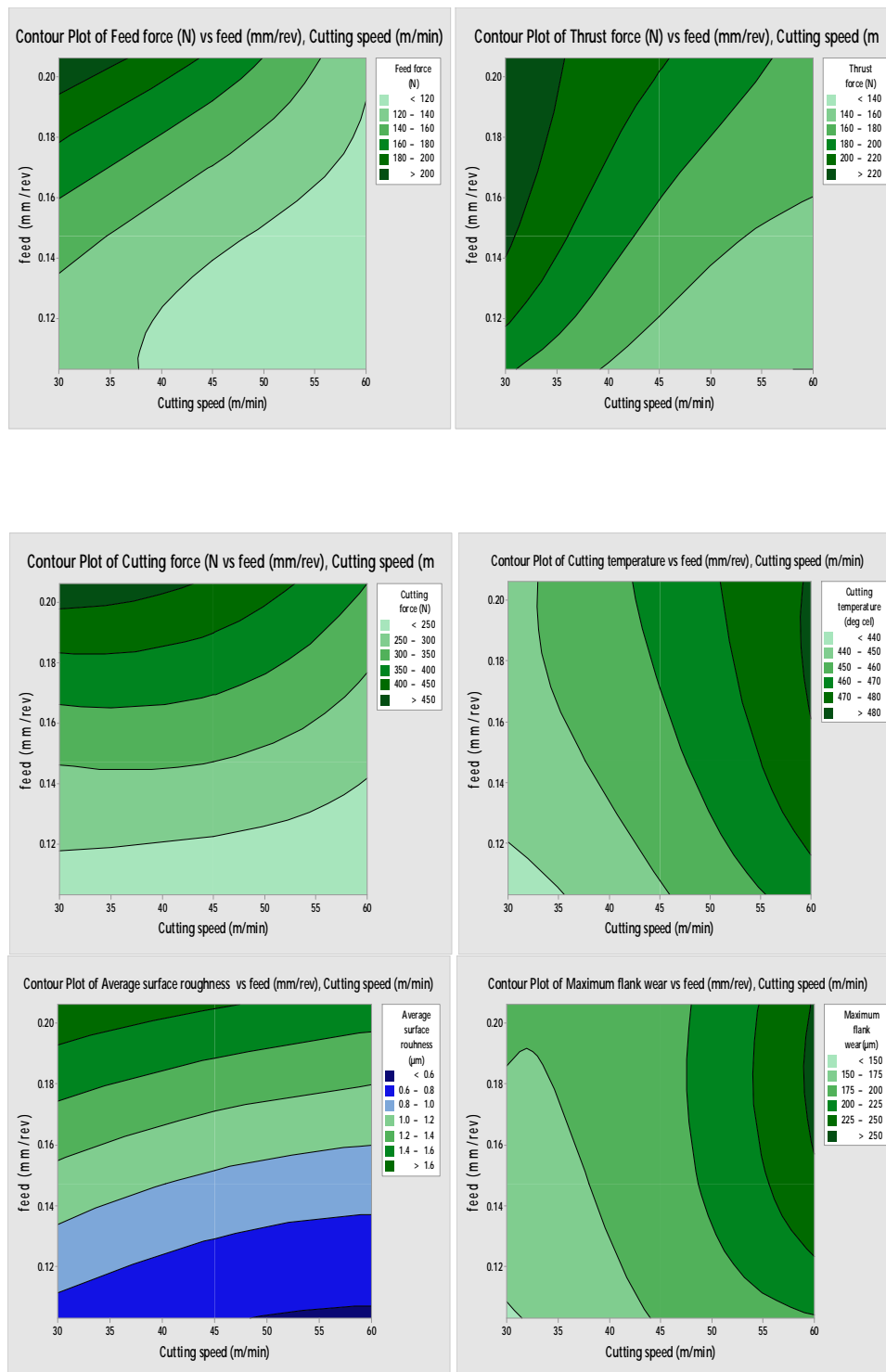


Figure 5. Contour plots showing the interaction effect of control factors on feed force, thrust force, cutting force, cutting temperature, average surface roughness and maximum flank wear.

Table 8 shows the constraints for optimization of cutting parameters for cutting force, average surface roughness and maximum flank wear. The results of RSM optimizations are 31.5152 m/min

cutting speed and 0.103 mm/rev feed rate which has an optimal desirability 0.9266. A confirmation test was carried out to compare the predicted and measured values which are tabulated in Table 9. Optimization plot is shown in figure 6. The optimal configuration was 31.5152 m/min cutting speed and 0.103 mm/rev feed rate which provides the global optimal solution of 225.09 N cutting force, 0.7237 μm average surface roughness and maximum flank wear of 149.72 μm at the corresponding zone for the composite desirability of 92.66%.

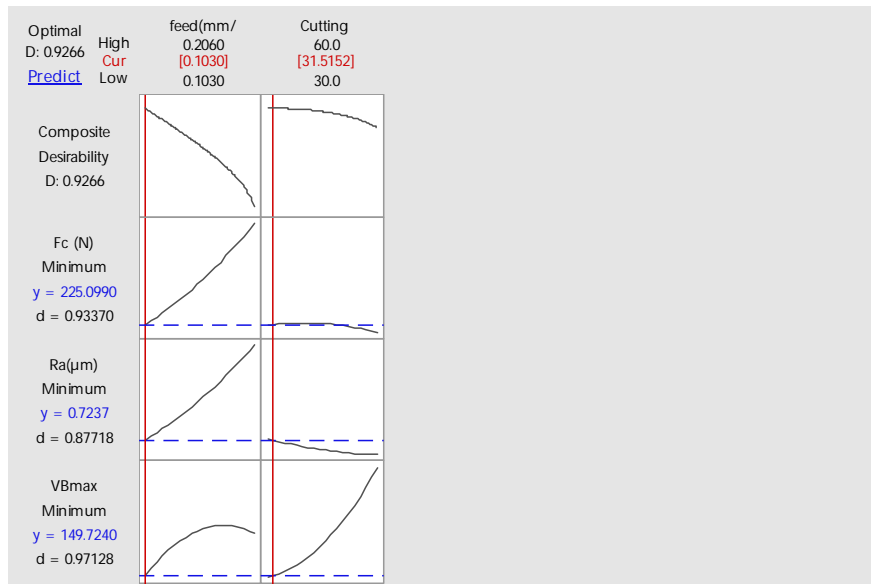


Figure 6. Optimization plot for minimum cutting force, average surface roughness and maximum flank wear.

From table 9, a good agreement between the predicted and measured values show that the developed models can accurately predict the cutting force, cutting temperature, average surface roughness and maximum flank wear within the range of investigation.

Table 9. Comparison between experimental and predicted results at optimum cutting conditions.

Response	Experiment value	Model value	% Error
Feed force (N)	123	122	0.81
Thrust force (N)	182	181	0.55
Cutting force (N)	227	225.1	0.84
Cutting temperature ($^{\circ}\text{C}$)	436	439	-0.68
Average surface roughness (μm)	0.757	0.7237	4.39
Maximum flank wear (μm)	147	149.72	-1.85

4. Conclusions

Response Surface Methodology (RSM) and composite desirability method was used to investigate the influence of cutting speed and feed rate during dry machining of Waspaloy using AlTiN coated carbide tool. The following conclusions were drawn from the present research:

1. Feed rate was found to be the most significant parameter for feed force, cutting force and average surface roughness which accounts the maximum percent contribution of 45.33%, 82.77 % and 92.6 % respectively.
2. Cutting speed was found to be significant parameter for thrust force, cutting temperature and maximum flank wear with %PC of 59.32%, 82.57% and 72.48%.
3. The developed regression equation for feed force, thrust force, cutting force, cutting temperature, surface roughness and maximum flank wear have high determination coefficient (R^2) which explaining 98.79%, 97.48%, 99.16%, 99.68%, 99.91% and 96.52% variability in predicting new observations.
4. Based on the composite desirability approach, the optimum cutting variables for minimum cutting force, average surface roughness and maximum flank wear were cutting speed of 31.5152 m/min and feed rate of 0.103 mm/rev.
5. A good agreement between the predicted and measured values confirm that the developed regression models can accurately predict the cutting force, cutting temperature, average surface roughness and maximum flank wear within the range of investigation.
6. The results obtained from the confirmation test shown that machining of Waspaloy using coated carbide tool with optimum cutting parameters, the cutting fluid could be completely removed from machining process.

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