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Multi-objective Optimization using Box-Behken of Response Surface Methodology for High-Speed Machining of Inconel 718

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Abstract. This study was carried out to investigate how the high-speed milling of Inconel 718 using ball nose end mill could enhance the productivity and quality of the finish parts. The experimental work was carried out through Response Surface Methodology via Box-Behnken design. The effect of prominent milling parameters, namely cutting speed, feed rate, depth of cut (DOC), and width of cut (WOC) were studied to evaluate their effects on tool life, surface roughness and cutting force. In this study, the cutting speed, feed rate, DOC, and WOC were in the range of 100 - 140 m/min, 0.1 - 0.2 mm/tooth, 0.5 - 1.0 mm and 0.2 - 1.8 mm, respectively. In order to reduce the effect of heat generated during the high speed milling operation, minimum quantity lubrication of 50 ml/hr was used. The effect of input factors on the responds was identified by mean of ANOVA. The response of tool life, surface roughness and cutting force together with calculated material removal rate were then simultaneously optimized and further described by perturbation graph. Interaction between WOC with other factors was found to be the most dominating factor of all responds. The optimum cutting parameter which obtained the longest tool life of 60 mins, minimum surface roughness of 0.262 μm and resultant force of 221 N was at cutting speed of 100 m/min, feed rate of 0.15 mm/tooth, DOC 0.5 m and WOC 0.66 mm.

Introduction

Inconel is prominently known as the material hard to machine. It possesses good mechanical properties where it is stable to creep, thermal fatigue and thermal shock at extreme temperature operation condition. Hence it is widely used in aircraft turbine engine [1]. High speed machining to cut nickel based super alloy Inconel 718 has long been researched to increase the cutting process productivity. The challenge and difficulty to machine Inconel 718 is due to its profound characteristics such as high sheer strength, tendency to weld and form build-up edge, low thermal conductivity and high chemical affinity [2]. Inconel 718 also has the tendency to work harden and retain major part of its strength during machining [3]. These unfavorable characteristics, coupled with dry cutting condition, causes severe and rapid tool wear when machining Inconel 718 [4]. For this reason, machining Inconel 718 is still performed at low cutting speed, using coated carbide tool with cutting fluid to cool the tool and work-piece [5]. Usually, the cutting speed employed under dry condition is in the range of 20 - 50 m/min for uncoated carbide tools where the feed rates are 0.10 - 0.20 mm/rev in turning [8]. Higher cutting speed, up to 100 m/min may be achieved with coated carbide tools [6]. Much higher speeds are also possible using ceramics tools, Polycrystalline Cubic Boron Nitride (PCBN) and diamond.

Response Surface Methodology (RSM) is a versatile statistical and mathematical tool for optimization purposes. RSM is able to estimate the optimization of factors of process parameters, material formulations, managing systems as well as factors for biological growth towards various responses whether in a complex or a simple system. RSM was used by researchers to determine the optimization of input process parameters for impact of yield. With numerous efforts to understand machinability of Inconel 718, many attempts have been made to generate mathematical models for the machinability of Inconel 718. Machinability model can be defined as a functional relationship between input of independent cutting variables (cutting speed, feed rate, cutting depth, etc.) and the outputs of the cutting process [7, 8]. Various parameter selections have been experimented and many results, either positive or negative, have been reported. The response data collected from properly designed and planned experiment works using design of experiments such as Central Composite Design and RSM were normally employed to generate tool life modeling [9]. Other methods such as Artificial Neural Networks have also been reported [10]. Prete et al. attempted to study on turning operation optimization on Inconel 718 [11]. However, multi-objective optimization of Inconel 718 related machining process using Box-Behnken RSM was found to be less in literature.

This study takes into account the effects of cutting speed, feed rate, DOC and WOC on tool life, surface roughness, cutting force and material removal rate (MRR). In this study, the multi-objective optimization using Box-Behnken RSM was described.

Methodology

The experiments of end milling were conducted using a DMC 635 V Eco CNC milling machine with a maximum spindle speed of 8,000 revolutions/minute. The work piece was an aged block of Inconel 718. The chemical compositions of this material are 53 wt.% Ni, 18.30 wt.% Cr, 18.7 wt.% Fe, 5.05 wt.% Nb, 3.05 wt.% Mo, 1.05 wt.% Ti, 0.23 wt.% Mn, and C balance. The selected cutting tools were Sumitomo QPMT 10T335PPEN with TiAlN PVD coating on fine grain tungsten carbide (10 wt.% Co). A tool overhang of 60 mm is maintained throughout the experiment and the measured tool run out has a radial measurement of 10 µm to 50 µm and an axial measurement of 5 µm to 30 µm [12]. Four machining input parameters, i.e. (cutting speed, Vc; feed rate, fz, depth of cut, ap and width of cut, ae) were selected. The effects of these input parameters on the output parameters were studied for tool life (min), surface roughness (µm) and cutting force (N). The weightage of each criterion is assumed equal during optimization. Details of variable input are shown in Table 1.

Minimum quantity lubrication was used in this experiment with constant flow rate of 50 ml/hr. The Box Behnken RSM approach was used for design of experiments, thus the total 29 test runs were randomly performed. For the statistical data analysis, Design expert software has been used for ANOVA and optimization process.

Table 1: Input parameter

Term	Factors	Range
A	Cutting speed, Vc	100, 120, 140 m/min
B	Feed rate, fz	0.1, 0.15, 0.2 mm/tooth
C	Depth of cut, ap	0.5, 0.75, 1.0 mm
D	Width of cut, ae	0.2 , 1,1.8 mm

Result and Discussion

Analysis of variance (ANOVA) was performed to identify the significant factor for each response. The factor was considered significant when its p-value is less than 5%. On occasions that the p-value is too small, the F-value was used to rank the factor. Table 2 shows the most factors contributed to tool life. It was dominated by factor D, followed by A, B and C. The sole parent term in ANOVA shows that the model is in linear form.

Table 2: ANOVA results tool life

Source	Sum of squares	DF	Mean square	F-Value	P-Value
Model	53.8637	4	13.47	129.65	< 0.0001
A	6.308559	1	6.31	60.74	< 0.0001
B	3.620952	1	3.62	34.86	< 0.0001
C	1.303902	1	1.30	12.55	0.0017
D	42.63028	1	42.63	410.44	< 0.0001
Residual	2.49278	24	0.10		
Lack of fit	2.025236	20	0.10	0.87	0.6397
Error	0.467544	4	0.12		
Cor Total	56.35648	28			

Table 3 shows the factor contributed to surface roughness. It was dominated by factor interaction of BD, followed by A, D2, CD, C2, D, AD, A2, AC and B2. The combination of parent and the interaction term in ANOVA shows that the model is in quadratic form.

Table 3: ANOVA results surface roughness

Source	Sum of squares	DF	Mean square	F-Value	P-Value
Model	0.087077	12	0.007256	31.9753	< 0.0001
A	0.015194	1	0.015194	66.95402	< 0.0001
B	0.000482	1	0.000482	2.122181	0.1645
C	0.002654	1	0.002654	11.69406	0.0035
D	0.006924	1	0.006924	30.51133	< 0.0001
A^2	0.002645	1	0.002645	11.65476	0.0036
B^2	0.001112	1	0.001112	4.89953	0.0417
C^2	0.007577	1	0.007577	33.38918	< 0.0001
D^2	0.009359	1	0.009359	41.24057	< 0.0001
AC	0.001383	1	0.001383	6.095386	0.0252
AD	0.003312	1	0.003312	14.5949	0.0015
BD	0.024353	1	0.024353	107.3091	< 0.0001
CD	0.008093	1	0.008093	35.65952	< 0.0001
Residual	0.003631	16	0.000227		
Lack of fit	0.003429	12	0.000286	5.645055	0.0541
Error	0.000202	4	5.06E-05		
Cor Total	0.090708	28			

Table 4 shows the factor contributed to resultant force. It was dominated by factor of D, followed by C, B, D2, BD, CD and BC. Factor A was found to be insignificant and removed from the model.

Table 4: ANOVA results cutting force

Source	Sum of squares	DF	Mean square	F-Value	P-Value
Model	188469.7	7	26924.25	245.52	< 0.0001
B	47238.58	1	47238.58	430.76	< 0.0001
C	55248.76	1	55248.76	503.8	< 0.0001
D	69490.95	1	69490.95	633.67	< 0.0001
D^2	10444.39	1	10444.39	95.24	< 0.0001
BC	1226.974	1	1226.97	11.20	0.0031
BD	3602.47	1	3602.47	32.85	< 0.0001
CD	1217.633	1	1217.63	11.10	0.0032
Residual	2302.932	21	109.66		
Lack of fit	1676.142	17	98.6	0.63	0.7774
Error	626.7894	4	156.6974		
Cor Total	190772.7	28			

Based on ANOVA from Table 2 to Table 4, compilation of factors significant for each response is shown in Table 5. It shows that WOC significantly contributed to most of the responses. Perturbation plot was used in determining combination of cutting parameter within the design space. It also shows the trend of each factor to response. Fig. 1(a to d) shows the perturbation plot of tool life, surface roughness, cutting force and MRR as it deviates from optimization point for all factors.

Table 5: Dominating factors for each response

Rank	Tool life (min)	Surface roughness (µm)	Cutting force (N)
1	WOC	Interaction feed rate and WOC	WOC
2	Cutting speed	Cutting speed	DOC
3	Feed rate		Feed rate

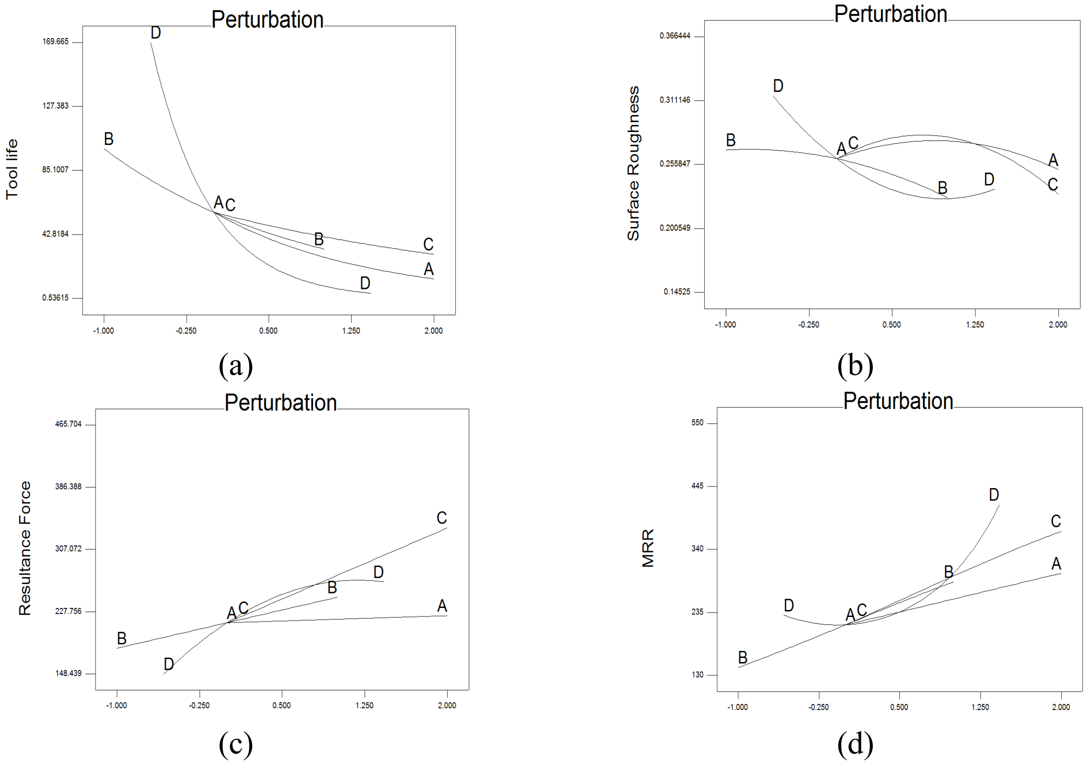

Figure 1: Perturbation plot for various responses (a) tool life, (b) surface roughness, (c) resultance force, (d) MRR

The figures depict that optimization point of this system occurs at the minimum level for both Factor A and C in all responses. However, it is vice versa for Factor B and D whereby the optimization point occurs in between the minimum and maximum level. These indicate that further decrement in the minimum level of Factor A and C may result in different optimization point which could occur at lower value for these two factors. Table 5 shows the list of solutions for process optimization. The predicted value was generated by design expert software based on desirability method. The criteria to be fulfilled were maximum tool life, minimum surface roughness and minimum resultant force. It was ranked by the highest desirability index. Considering maximum material successfully removed combination, No. 10 was selected.

Table 5: List of optimization solution

No.	Cutting speed, Vc	Feed rate, fz	WOC, ap	DOC, ae	MRR	Tool life	Surface roughness, Ra	Resultant force	Max material removed
	m/min	mm/ gigi	mm	mm	mm^3/ min	min	µm	N	mm^3
1	100	0.18	0.98	0.2	94	63.5	0.178	283	5974
2	114.4	0.1	0.5	1.28	225	13.7	0.169	216	3087
3	140	0.1	0.5	1.05	226	9.3	0.151	207	2098
4	140	0.1	0.5	0.9	194	13.2	0.184	200	2553
5	139.5	0.1	0.53	1	225	10.3	0.168	209	2311
6	110.39	0.2	0.5	0.2	68	67.2	0.262	174	4559
7	140	0.15	1	0.2	111	20.4	0.181	255	2275
8	140	0.12	1	0.22	98	27.5	0.222	224	2698
9	139.97	0.1	0.62	1.17	299	6.0	0.145	232	1778
10	**100**	**0.15**	**0.5**	**0.66**	**152**	**59.4**	**0.262**	**221**	**9029**

In Fig.1(a), the tool life decreases as all factors move to maximum level. The degree of curvature for each curve shows the level of decrement, which occurs in a log or linear pattern. The highest contribution factor towards the decrement in tool life is WOC (Factor D). The increment in WOC imposes higher pressure on the cutting tool. It accelerates the progress to fatigue failure and consequently shorten the tool life. For surface roughness in Fig. 1(b), Factor A and C contribute to the highest increment of surface roughness compared to Factor B and D. However, the increment in surface roughness by Factor A and C is a negative quadratic model where it increases until a certain level is achieved and then, decreases. As with tool life, WOC plays the major role in the decrement of surface roughness of the cutting substrate. For resultant force in Fig. 1(c), all factors show linear perturbation as it deviates from optimization point except for Factor D. The resultant force increases with the increment in levels of all factors. However, the highest contribution to the increase in resultant force is Factor C (DOC) followed by Factor D (WOC). However the resultant force for Factor D shows a negative quadratic model. The MRR in Fig. 1(d) shows almost similar pattern with a resultant force where all factors increase the MRR as its level increases from minimum to maximum level. The highest contribution towards positive values of MRR is from Factor D (WOC) with a positive quadratic model.

Conclusion

The RSM was conducted to evaluate the process parameter affecting tool performance, surface roughness and resultant force. However, the optimum parameter is chosen based on the productivity with trade-off the best combination of tool life, surface roughness and cutting force individually. The optimum parameter can be achieved by the combination of Vc = 100 m/min, fz = 0.15mm/tooth, ap = 0.15 mm and ae = 0.66 mm as to achieve maximum productivity of 9029 mm3, 60 min of tool life, Ra = 0.262 μm and resultant force of 221 N.

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