Optimization of High Pressure Coolant Assisted Turning of Inconel 718 using TOPSIS

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Abstract: Optimization of process parameters for machining Heat Resistant Super Alloys (HRSA) is a very challenging task for researchers. Many techniques are being used to find out optimized process parameters for machining these alloys. This paper presents the use of Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to optimize process parameters for High-Pressure Coolant (HPC) assisted turning of Inconel 718.Inconel 718 is one of heat resistance superalloy from nickel-chromium group suitable for aerospace applications.TOPSIS is used for optimization of manufacturing processes which involves analysis of multi-performance characteristics. In the present analysis, high-pressure coolant is introduced into the cutting zone while machining Inconel 718.The performance of the machining is optimized for response variables namely cutting force, radial force, feed force and surface roughness. It is seen from the analysis that TOPSIS is a very striking approach for multiobjective optimization which can be effectively used for machining processes which always involves many process parameters. Optimized process parameters found during the investigation are 80 bar coolant pressure, 60m/min cutting speed, 0.1 mm/rev feed and 0.5 mm of the depth of cut.

Keywords: ***TOPSIS, High Pressure Coolant, Surface Roughness, Cutting Forces, Inconel 718***

1 Introduction

Inconel 718 is one of the Heat Resistant Super Alloy (HRSA) from Nickel-Chromium group suitable for aerospace applications. Apart from Nickel and Chromium it comprises of Iron, Niobium, Molybdenum, Aluminum and Titanium. It has outstanding physical properties like corrosion resistance, strength, weldability. Inconel 718 is commonly used in hot sections of gas turbines, rocket engines, spacecraft structural components, nuclear reactors, pumps, tooling, in the manufacture of components for aircraft turbine engines, cryogenic tankage and nuclear industries [1,2].

Inconel is considered as difficult to cut material because of poor thermal conductivity, high temperature strength, high shear strength and presence of abrasive carbide particles in the microstructure. During its machining the cutting tool often gets subjected to very high thermal and mechanical loads which cause rapid tool wear. Welding and sticking of worked material onto the cutting tool is a major problem during machining of Inconel 718 which causes rigorous notching and high cutting forces generates vibration while machining [3-5]. Because of above reasons lot of research is going on in the field of machining of Inconel 718 using different techniques like Cryogenic machining, Air jet assisted machining, Ultra High Speed Machining. Also researchers are investigating on use different tool materials and coatings which can minimize the tool wear. Apart from this it is extremely necessary to optimize the process parameters while machining Inconel 718 which can give improved performance of various responses during machining.

In High pressure coolant (HPC) assisted turning, coolant is supplied in machining zone at a very high pressure. When coolant is supplied at high pressure in cutting zone it can decrease cutting forces, increase life of cutting and provide superior machined surface. While machining of Inconel 718 with high-pressure coolant produces very small chips and offer extended tool life [6]. High pressure coolant can give enhanced machined surface with lower cutting forces because of better chip [7, 8]. Chip segmentation is greatly influenced by coolant pressure used while machining Inconel 718. Well segmented C-shaped chips can be produced with high pressure coolant [9].

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This paper presents use of Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to optimize the process parameters for high pressure assisted turning of Inconel 718.TOPSIS can be conveniently used for optimization of variety manufacturing processes which involves multi criteria decision making. Recently many researchers have used TOPSIS for multiobjective optimization of machining processes parameters.

Tripathy and Tripathy [10] implemented TOPSIS for multi-attribute optimization of Powder Mixed Electro-Discharge Machining (PMEDM).They found TOPSIS is appropriate to find out best possible solution for the set of input parameters which will give required performance characteristics. Singaravel and Selvaraj [11] determined optimum machining parameters in turning operation of EN25 steel with coated carbide tools using TOPSIS. In their investigation they used TOPSIS for finding out best set of machining parameters from available alternatives and Analytic Hierarchy Process (AHP) method was used to determine the weights of various attributes according to their objectives. According to Parida and Routara [12] TOPSIS approach can provide more reliable solutions as exact experimental values are used to represent the process. Also in TOPSIS simple statistical calculation are used to get the appreciable result.

2 Details of Experiments

2.1 Experimental Procedure

The experimental details are mentioned in Table 1

Table 1 Experimental Details

Workpiece Material and Specifications	Inconel 718 rods (39 HRc.) (40 mm length and 22 mm diameter), Cutting Length= 15 mm.
Machine	CNC Turning Center (Experimental Set-up and Machined components are shown in Fig. 1 and 2 respectively)
Cutting Tool Insert	Sandvik make QM 1105, PVD coated CNMG 12 04 08
High Pressure Coolant System	A plunger type pump of maximum delivery pressure 100 bar is used in the system. The maximum coolant flow rate of the pump is 7 liters per minute (LPM).The nozzle is fixed to turret of machine with a suitable fixture (Shown in Fig.1).Coolant is 5 % oil water emulsion
Force Measurement (Cutting force-Fx, Radial force-Fy and Feed force-Fz)	Kistler 9257, three-component piezo-electric dynamometer
Surface Roughness Measurement	Mitutoyo SJ-210 with cut-off length of 0.8 mm. (With suitable clamping arrangement shown in Fig.3)

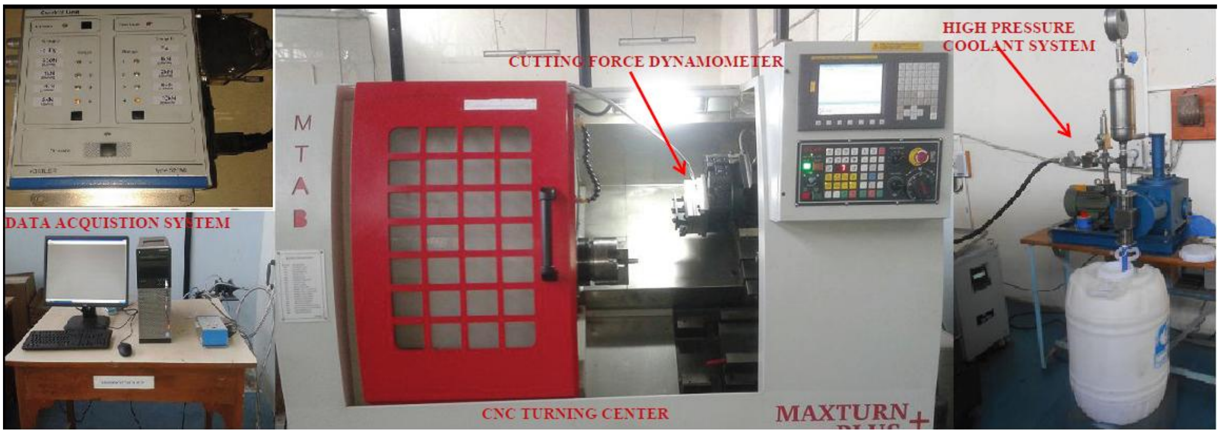

Fig. 1. Experimental Set-up with High Pressure Coolant System and Cutting Force Dynamometer

Fig. 2. Machined Components

Fig. 3. Surface Roughness Measurement

2.2 Experimental Design

In this investigation Taguchi orthogonal array was used to design the experiment. The main focus of the investigation is on pressure of coolant, so apart from speed, feed, depth of cut, pressure of coolant is also taken as process parameter. Based on some trial experiment, available literature and from the insert manufacturer catalogue the levels of process parameters are selected. The parameters with their real values are shown in Table 2. The chosen array is L_{27} with four factors at three levels each. The details of L_{27} array is as shown in Table 3.

Table 2 Levels of parameters with their real values

Levels	Pressure (P) bar	Speed (V) m/min	Feed (f) mm/rev	Depth of Cut (d) mm
1	20	40	0.1	0.5
2	50	60	0.15	1
3	80	80	0.2	1.5

Table 3 Taguchi L_{27} array

Exp. No	Pressure	Speed	Feed	DoC	Fx (N)	Fy(N)	Fz (N)	Ra (µm)
1	20	40	0.1	0.5	233.4	191.6	144.8	0.431
2	20	40	0.1	1	413	225.9	288.1	0.588
3	20	40	0.1	1.5	622	309.7	318.3	0.556
4	20	60	0.15	0.5	280.7	207.1	144.8	0.837
5	20	60	0.15	1	534.1	271.3	309.5	1.087
6	20	60	0.15	1.5	789.7	310.5	477.3	0.997
7	20	80	0.2	0.5	361	246.7	155.1	1.398
8	20	80	0.2	1	617.1	293	322.2	1.695
9	20	80	0.2	1.5	968.6	326.3	539.1	1.46
10	50	40	0.15	0.5	291.2	228.9	150.2	0.935
11	50	40	0.15	1	548.8	272.7	319	1.082
12	50	40	0.15	1.5	784.3	282.4	479.7	0.997
13	50	60	0.2	0.5	363.9	247.4	162.2	1.03
14	50	60	0.2	1	638.7	281.1	314.6	1.2
15	50	60	0.2	1.5	905.7	323	527.4	1.588

16	50	80	0.1	0.5	199.8	173.1	117.1	0.461
17	50	80	0.1	1	409.4	224.9	294.4	0.983
18	50	80	0.1	1.5	580.5	241.4	415.5	0.839
19	80	40	0.2	0.5	337.5	213.2	226.1	1.159
20	80	40	0.2	1	619.9	243.8	256.1	1.301
21	80	40	0.2	1.5	836	320.5	440.6	1.259
22	80	60	0.1	0.5	164.3	159	93.32	0.4
23	80	60	0.1	1	326	233.1	145.5	0.449
24	80	60	0.1	1.5	479.9	229.3	343.9	0.571
25	80	80	0.15	0.5	255.7	198.6	126.5	0.723
26	80	80	0.15	1	515.8	272.4	309.4	0.929
27	80	80	0.15	1.5	752.7	279.9	458.3	1.039

3 Methodology of Optimization using TOPSIS [10-13]

Step 1 Formulation of Decision Matrix: A decision matrix is formed from the given set of attributes. Here each row indicates an alternative and each column indicates an attribute. Therefore, an element h_{ij} of the decision table provide real values the value of the j^{th} attribute in for the i^{th} alternative.
The decision matrix D_m can be given as

$$D_m = \begin{bmatrix} h_{11} & h_{12} & h_{13} & .. & .. & h_{1n} \\ h_{21} & h_{22} & h_{23} & .. & .. & h_{2n} \\ h_{31} & h_{32} & h_{33} & .. & .. & h_{3n} \\ : & : & : & .. & .. & : \\ : & : & : & .. & .. & : \\ h_{m1} & h_{m2} & h_{m3} & .. & .. & h_{mn} \end{bmatrix}$$

Step 2 Normalization of Decision Matrix: After formation of decision matrix all the elements are normalized by using equation and a normalized decision matrix r_{ij} is obtained

$$r_{ij} = \frac{h_{ij}}{\sqrt{\sum_{i=1}^{m} h_{ij}^2}} \quad (1)$$

Step 3 Weight for each response is calculated: Depending on the relative importance of each response, weight can be assigned to each attribute .A set of weights to all attributes is decided such that summation all weights must be one.

Step 4 Formation of Weighted Normalized matrix: A Weighted Normalized matrix is the formed by multiplying each column of normalized matrix r_{ij} with the corresponding weights. A weighted Normalized matrix is given as

$$V = w_j r_{ij} \quad (2)$$

$$\sum_{j=1}^{n} w_j = 1$$

Step 5 Determination of Positive and Negative Ideal Solutions: A positive ideal solution is given as

$$V^{+} = \left\{ \left(\sum\nolimits_{i}^{max} v_{ij} \mid j \in J\right), \left(\sum\nolimits_{i|}^{min} j \in J \mid i=1,2,.....m\right) \right\}$$

$$= \left\{ v_1^{+}, v_2^{+}, v_3^{+} ...., v_n^{+} \right\} \quad (3)$$

V^{+}indicates the best value of the attribute among the values of all attribute for different alternatives under investigation.

A negative ideal solution is given as

$$V^{-} = \left\{ \left(\sum\nolimits_{i}^{min} v_{ij} \mid j \in J\right), \left(\sum\nolimits_{i|}^{max} j \in J \mid i=1,2,.....m\right) \right\}$$

$$= \left\{ v_1^{-}, v_2^{-}, v_3^{-} ...., v_n^{+} \right\} \quad (4)$$

V^{-}Indicates the worst value of the attribute among the values of all attribute for different alternatives under investigation

Table 4 Decision Matrix and Corresponding Separation Measure from Positive and Negative ideal solution with Relative Closeness Coefficient

Decision Matrix

D =

233.4	191.6	144.8	0.431
413	225.9	288.1	0.588
622	309.7	318.3	0.556
280.7	207.1	144.8	0.837
534.1	271.3	309.5	1.087
789.7	310.5	477.3	0.997
361	246.7	155.1	1.398
617.1	293	322.2	1.695
968.6	326.3	539.1	1.46
291.2	228.9	150.2	0.935
548.8	272.7	319	1.082
784.3	282.4	479.7	0.997
363.9	247.4	162.2	1.03
638.7	281.1	314.6	1.2
905.7	323	527.4	1.588
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409.4	224.9	294.4	0.983
580.5	241.4	415.5	0.839
337.5	213.2	226.1	1.159
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836	320.5	440.6	1.259
164.3	159	93.32	0.4
326	233.1	145.5	0.449
479.9	229.3	343.9	0.571
255.7	198.6	126.5	0.723
515.8	272.4	309.4	0.929
752.7	279.9	458.3	1.039

Exp. No	S_i^{+}	S_i^{-}	P_i	Rank
1	0.0116	0.1080	0.9031	3
2	0.0393	0.0823	0.6765	9
3	0.0596	0.0699	0.5398	15
4	0.0256	0.0955	0.7889	6
5	0.0595	0.0592	0.4988	16
6	0.0884	0.0377	0.2992	24
7	0.0531	0.0803	0.6021	12
8	0.0837	0.0446	0.3479	21
9	0.1128	0.0115	0.0926	26
10	0.0314	0.0917	0.7451	7
11	0.0609	0.0577	0.4862	17
12	0.0868	0.0386	0.3076	23
13	0.0392	0.0842	0.6822	8
14	0.0685	0.0505	0.4245	20
15	0.1112	0.0076	0.0643	27
16	0.0060	0.1121	0.9490	2
17	0.0474	0.0717	0.6019	13
18	0.0654	0.0577	0.4687	19
19	0.0445	0.0789	0.6395	10
20	0.0645	0.0573	0.4701	18
21	0.0927	0.0280	0.2317	25
22	0.0003	0.1181	0.9974	1
23	0.0213	0.1014	0.8264	5
24	0.0489	0.0758	0.6080	11
25	0.0191	0.1012	0.8412	4

26	0.0550	0.0641	0.5380	14
27	0.0835	0.0391	0.3187	22

Step 6: Calculation of separation measure from positive and negative ideal solution: - Separation Measure from Positive and Negative ideal is given by

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)2} \quad , i=1,2,3,.......m \tag{5}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)2} \quad , i=1,2,3,.......m \tag{6}$$

Step 7: Calculation of Relative Closeness Coefficient of each alternative:-The relative closeness coefficient of each alternative is given by

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{7}$$

4 Results and Discussion

The measured values of cutting force, radial force, feed force, surface roughness and tool wear (flank wear) are as shown in Table 3. For optimization of these multiple characteristics TOPSIS analysis is done on the experimental data. A decision matrix is formulated for all responses which is shown in Table 4. After formation of decision matrix it is normalized by using equation 1. Weight for each response is assigned arbitrarily, since in this investigation four responses are there for every response a weight of 0.25 is assigned. After this, weighted normalized matrix is the formed by using equation 2. It is formed by multiplying each column of normalized matrixwith the corresponding weights. Positive and Negative Ideal Solutions are determined by equations 3 and 4 respectively. Separation measures are derived from positive and negative ideal solution using equations 5 and 6.Finally Relative Closeness Coefficient of all alternative are determined with equation 7. After calculations of relative closeness coefficients analysis is done to find out optimum process parameters and their significance on relative closeness coefficients. For this purpose Response table, ANOVA and AOM plot for relative closeness coefficient is used. Fig. 4 indicates AOM plot for relative closeness coefficient, Table 5 and 6 shows response table and ANOVA for relative closeness coefficient respectively.

The main focus of this analysis is pressure of coolant, from analysis of data it is found that with increase in pressure of coolant, magnitude of cutting force components decreases with significant decrease in surface roughness.At high pressure chips found are more curled and spring type also high pressure of coolant is able to break the chips into small pieces and keeps them away from cutting zone which also decreases the length of contact with the tool which lowers the friction. This reduction in friction causes the cutting force to decrease. It is observed that a favourable decrease in cutting force ranging from 50 to 150 N can be achieved by increasing the coolant pressure upto 80 bar. Similarly radial force and feed force may decrease up to 80 N and 60 N respectively with increase in coolant pressure.

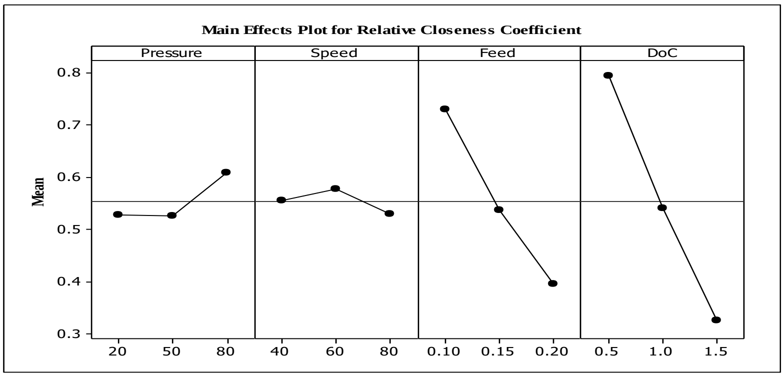

Fig. 4. AOM plot for Relative Closeness Coefficient

From response table 5 ANOVA and AOM plots it can be clearly seen that depth of cut has highest influence on all response variables. It is followed by feed, pressure of coolant and speed. From ANOVA it is clear that all depth of cut, feed and pressure of coolant are found to be significant at 95% confidence level for relative closeness coefficient. From response table of relative closeness coefficient it is clear that the optimal factor setting is $P_3V_2f_1d_1$, i.e. coolant pressure at level 3 (80 bar) cutting speed at level 2 (60 m/min), feed rate at level 1 (0.1 mm/rev), depth of cut at level 1 (0.5 mm). The sequence of significance for all parameters is shown in Table 5. At this optimized cutting parameters Cutting force is 164.3 N, Radial Force is 159 N, Feed Force is 93.32 N and Surface roughness is 0.4 µm.

Table 5 Response Table for Relative Closeness Coefficient

Sr No	Factors	Level 1	Level 2	Level 3	Max-Min	Rank
1	Pressure	0.5277	0.5255	0.6079	0.0824	3
2	Speed	0.5555	0.5766	0.5289	0.0477	4
3	Feed	0.7301	0.5360	0.3950	0.3351	2
4	DoC	0.7943	0.5411	0.3256	0.4687	1

Table 6 ANOVA for Relative Closeness Coefficient

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pressure	2	0.0397	0.0397	0.0198	9.31	**0.002**
Speed	2	0.0103	0.0103	0.0052	2.42	**0.118**
Feed	2	0.5096	0.5096	0.2548	119.54	**0.000**
Depth of cut	2	0.9905	0.9905	0.4953	232.37	**0.000**
Error	18	0.0384	0.0384	0.0021		
Total	26	1.58839				
R-Sq = 97.58%			**R-Sq(adj) = 96.51%**			

5 Conclusions

Optimization of Turning of Inconel 718 with high pressure coolant is presented in this paper. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is used for optimization purpose. Cutting force, Radial force, Feed force and Surface roughness are the responses for which cutting parameters with coolant pressure has been optimized. For the parameters under investigation depth of cut, feed and coolant pressure shows significant effect on multiple responses. Depth of cut is found to have most significant effect on the response variables. Depth of cut is followed by feed, pressure of coolant. However speed does not show significant effect on responses. From the analysis it is clear that coolant pressure is a very important consideration during machining of Inconel 718.The optimized parameters obtained from TOPSIS are 80 bar coolant pressure,60 m/min speed,0.1 mm/rev feed and 0.5 mm depth of cut.

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