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Optimization of High Pressure Coolant Assisted Turning of Inconel 718 withMulti-performance Characteristics

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Abstract
Optimization of process parameters during machining is a very essential task for machining as the process parameters have major influence on performance of a machining process. This becomes even more important while machining heat resistance superalloys. Researchers are taking lot of efforts to investigate new techniques find out optimized process parameters for machining these alloys. This paper presents use of Grey Relational Analysis (GRA) to optimize process parameters for High Pressure Coolant (HPC) assisted turning of Inconel 718.GRA is frequently used for optimization of manufacturing processes which involves analysis of multi-performance characteristics. In present analysis turning of Inconel 718 is carried out using a high pressure coolant which is introduced in the cutting zone with an external pump high pressure coolant system. Here turning process is optimized for response variable such as cutting force, feed force, radial force, surface roughness and tool wear. It is seen from the analysis that GRA is a very useful approach for optimization which can effectively used for machining processes which involves multipleresponse variables. Optimized process parameters found during the investigation are 80 bar coolant pressure,60m/min cutting speed,0.1 mm/rev feed and 1 mm of depth of cut.

Keywords: Grey Relational Analysis, High Pressure Coolant, Surface Roughness, Cutting Forces, Tool Wear, Inconel 718.

Introduction
Inconel 718 is Heat Resistant Super Alloy (HRSA) from Nickel-Chromium group suitable for aerospace applications. It has excellent physical properties like corrosion resistance, high strength, outstanding weldability, extremely good creep–rupture strength and a high fatigue endurance limit. 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 one the most difficult to cut material because of poor thermal conductivity, high temperature strength, high shear strength, presence of abrasive carbide particles in the microstructure, high chemical reactivity to most tool materials, during its machining the cutting tool often supports extreme thermal and mechanical loads close to the cutting edge leading to rapid tool wear, welding and adhesion of worked material onto the cutting tool frequently occur during machining causing severe notching and very high cutting forces due to the material strength which may result in vibration[3-5].Because of above reasons lot of research is going on in the field of machining of Inconel 718 using different techniques like ultrasonic and high temperature-aided cutting[6], Cryogenic machining[7], Air jet assisted machining[8], Ultra High Speed Machining[9]. Also researchers are investigating on use different tool materials and coatings which can minimize the tool wear. Apart from this it is very important to optimize the process parameters while machining Inconel 718 which can give improved results in terms tool wear, surface finish, cutting forces, residual stresses and other surface integrity parameters.

This paper presents use of Grey Relational Analysis to optimize the process parameters for high pressure assisted turning of Inconel 718. In High pressure coolant (HPC) assisted turning, coolant is supplied in machining zone at a very high pressure as compared to conventional flood cooling. Recent studies have reported improved chip control, increased tool life, lower cutting temperature, decreased cutting forces and better surface finish due to use of high pressure coolant during machining [10-13]. While machining of Inconel 718 with high-pressure cooling leads to more efficient chip breaking and usually extends the tool life [14]. The application of high pressure cooling lubrication fluid to the tool-chip interface decreases cutting force components on account of mechanical effect of high pressure coolant and also provides desirable chip breakability, which tends to improve the quality of machined surface [15].The cutting force significantly decreases with increase in pressure of coolant because of better chip segmentation as compared to conventional lubrication [16]. Chip segmentation depends to a greater extent on the coolant pressure employed when machining Inconel 718. Machining with a high coolant pressure produced well segmented C-shape chips [17].

Grey relational analysis is very useful technique to optimize a process with multi response characteristics. Grey relational analysis to solve engineering problems. In GRA grey relational grade is calculated which can provide knowledge of the factors affecting response variables [18].Machining considered as complex process in which the relationship between various factors is unclear. Such systems is often are called grey that give poor, incomplete and uncertain information. To solve such kind of problem, grey relational analysis (GRA) is very useful [19, 20]. In grey relational analysis, black represents having no information and white represents having all information. A grey system has a level of information between black and white [21**].** Through the grey relational analysis, a grey relational grade is obtained to evaluate the multiple performance characteristics. As a result, optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade [22].

Methodology of Grey Relational Analysis

The procedure of Grey relational analysis is as follow [19-21]

Step 1: Data Preprocessing

The first step in grey relational analysis is data preprocessing which is performed to prepare raw data for the analysis where the original sequence is transferred to a comparable sequence between zero and unity which is also called as the grey relational generation .In this investigation "smaller-the-better" criterion is used for normalization of all the responses as:

$$x_i^*(k) = \frac{\max x_i^{(o)}(k) - x_i^{(o)}(k)}{\max x_i^{(o)}(k) - \min x_i^{(o)}(k)} \quad (1)$$

Step 2: Determination of deviation sequence

The deviation sequence$\Delta 0_i(k)$ is the absolute difference between the reference sequence $x_0^*(k)$ and the comparability sequence $x_i^*(k)$after normalization. It is determined using Eq. 2 as:

$$\Delta 0_i(k) = |x_0^*(k) - x_i^*(k)| (2)$$

Step 3: Determination of Grey Relational Coefficient

GRC for all the sequences expresses the relationship between the ideal (best) and actual normalized S/N ratio. If the two sequences agree at all points, then their grey relational coefficient is 1. The grey relational coefficient $\gamma(x_0(k), x_i(k))$ can be expressed by Eq. 3.

$$\gamma(x_0(k), x_i(k)) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(k) + \zeta\Delta_{max}} (3)$$

Where, Δmin is the smallest value of $\Delta 0_i(k) = min_i min_k |x_0^*(k) - x_i^*(k)|$and Δmax is the largest value of $\Delta 0_i(k) = max_i max_k |x_0^*(k) - x_i^*(k)|$,$x_0^*(k)$ is the ideal normalized S/N ratio, $x_i^*(k)$ is the normalized comparability sequence, and ζ is the distinguishing coefficient. The value of ζ can be adjusted with the systematic actual need and defined in the range between 0 and 1; here it is taken as 0.5.

Step 4: Determination of Grey Relational Grade

The overall evaluation of the multiple performance characteristics is based on the grey relational grade. The grey relational grade is an average sum of the grey relational coefficients which is defined as,

$$\gamma \ (x_o, x_i) = \frac{1}{m}\sum_{i=1}^{m} \gamma(x_0(k), x_i(k)) \quad (4)$$

Step 5: Determination of Optimal parameters

The grey relational grade calculated for each sequence is taken as a response for the further analysis. The larger-the-better quality characteristic was used for analyzing the GRG, since a larger value indicates the better performance of the process. The response table of Taguchi method was employed here to calculate the average grey relational grade for each factor level. In this, the grouping of the grey relational grades was done initially by the factor level for each column in the orthogonal array and then by averaging them.

Step 6: Prediction of grey relational grade under optimum parameters

After evaluating the optimal parameter settings, the next step is to predict and verify the improvement of quality characteristics using the optimal parametric combination. The estimated grey relational grade by using the optimal level of the machining parameters can be calculated as

$$\widehat{\gamma} = \gamma_m + \sum_{i=1}^{0} (\bar{\gamma} - \gamma_m) \quad (5)$$

where $\gamma_m$is the total mean grey relational grade, $\bar{\gamma}$ is the mean grey relational grade at the optimal level, and o is the number of the main design parameters that affect the quality characteristics. The predicted or estimated grey relational grade (optimal) is equal to the mean grey relational grade plus the summation of the difference between the overall mean grey relational grade and the mean grey relational grade for each of the factors at optimal level.

Details of Experiments

Experimental Procedure

In this investigation Inconel 718 rods of 40mm in length and 22 mm in diameter with hardness 39HRc are used. The turning length is kept as 15 mm. The experiments are carried out on a MTAB CNC turning center. All the experiments are conducted under high pressure coolant cutting conditions (20 bar, 50 bar, 80 bar). Coolant is 5 % oil water emulsion. The cutting insertsare Sandvik make QM 1105, PVD coated CNMG12 04 08.The experiments are carried out on 27 specimens for every experimental run a fresh insert side is used for making suitable analysis and comparison. During experiment Cutting force components are measured using a Kistler 9257, three-component piezo-electric dynamometer. The whole arrangement of experiment is shown in Figure.1.The surface roughness is measured using a Mitutoyo SJ-210 with cut-off length of 0.8mm. After every turning operation specimen is cleaned and surface roughness is measured with a suitable clamping arrangement. The surface roughness is measured at three points on the specimen and average of that is taken as final roughness value. Tool wear is measured by Mitutoyo make Tool Makers Microscope.

Experimental Design

In this investigation the main focus 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 levels of parameters and their actual values are shown in Table 1.Taguchi orthogonal array was used to design the experiment. The chosen array is L_{27} with four factors at three levels each. Measured responses according to the experimentation carried out with of L_{27} array is are shown in Table. 2

Fig.1.Experimental Set Up

Table 1 Process parameters and Their Levels

Level	P (bar)	V (m/min)	f (mm/rev)	d (mm)
1	20	40	0.1	0.5
2	50	60	0.15	1
3	80	80	0.2	1.5

Table 2 Measured Responses According to L_{27} Array

EN	Fx	Fy	Fz	Ra	TW
1	233.4	191.6	144.8	0.431	30
2	413	225.9	288.1	0.588	30
3	622	309.7	318.3	0.556	40
4	280.7	207.1	144.8	0.837	25
5	534.1	271.3	309.5	1.087	35
6	789.7	310.5	477.3	0.997	30
7	361	246.7	155.1	1.398	35
8	617.1	293	322.2	1.695	30
9	968.6	326.3	539.1	1.46	45
10	291.2	228.9	150.2	0.935	20
11	548.8	272.7	319	1.082	35
12	784.3	282.4	479.7	0.997	30
13	363.9	247.4	162.2	1.03	25
14	638.7	281.1	314.6	1.2	35
15	905.7	323	527.4	1.588	30
16	199.8	173.1	117.1	0.461	35
17	409.4	224.9	294.4	0.983	40
18	580.5	241.4	415.5	0.839	45
19	337.5	213.2	226.1	1.159	15
20	619.9	243.8	256.1	1.301	20
21	836	320.5	440.6	1.259	35
22	164.3	159	93.32	0.4	25
23	326	233.1	145.5	0.449	20
24	479.9	229.3	343.9	0.571	25
25	255.7	198.6	126.5	0.723	20
26	515.8	272.4	309.4	0.929	25
27	752.7	279.9	458.3	1.039	25

Result and Discussions

The measured values of cutting force, radial force, feed force, surface roughness and tool wear (flank wear) are as shown in table. For optimization of these multiple characteristics grey relational analysis is done on the experimental data. Data preprocessing is by using Eq^n .1.here all the measured responses ar transferred in dimensionless entities. After data preprocessing deviation sequences are calculated using Eq^n.2.This normalized data is shown in Table.3

From deviation sequences grey relational coefficients and corresponding grey relational grades are calculated these are shown in Table.4 with their ranks.

Table 3 Normalized data

EN	Normalized Data				
	Fx	Fy	Fz	Ra	TW
1	0.9141	0.8051	0.8845	0.9761	0.5000
2	0.6908	0.6001	0.5631	0.8548	0.5000
3	0.4309	0.0992	0.4953	0.8795	0.1667
4	0.8553	0.7125	0.8845	0.6625	0.6667
5	0.5402	0.3288	0.5151	0.4695	0.3333
6	0.2224	0.0944	0.1386	0.5390	0.5000
7	0.7554	0.4758	0.8614	0.2293	0.3333
8	0.4370	0.1990	0.4866	0.0000	0.5000
9	0.0000	0.0000	0.0000	0.1815	0.0000
10	0.8422	0.5822	0.8724	0.5869	0.8333
11	0.5219	0.3204	0.4937	0.4734	0.3333
12	0.2291	0.2624	0.1332	0.5390	0.5000
13	0.7518	0.4716	0.8455	0.5135	0.6667
14	0.4102	0.2702	0.5036	0.3822	0.3333
15	0.0782	0.0197	0.0262	0.0826	0.5000
16	0.9559	0.9157	0.9467	0.9529	0.3333
17	0.6953	0.6061	0.5489	0.5498	0.1667
18	0.4825	0.5075	0.2773	0.6610	0.0000
19	0.7847	0.6760	0.7021	0.4139	1.0000
20	0.4335	0.4931	0.6348	0.3042	0.8333
21	0.1649	0.0347	0.2210	0.3367	0.3333
22	1.0000	1.0000	1.0000	1.0000	0.6667
23	0.7990	0.5571	0.8829	0.9622	0.8333
24	0.6076	0.5798	0.4379	0.8680	0.6667
25	0.8864	0.7633	0.9256	0.7506	0.8333
26	0.5630	0.3222	0.5153	0.5915	0.6667
27	0.2684	0.2773	0.1813	0.5066	0.6667

From response table and AOM plot of GRG shown in Figure 2, 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. 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 Tables 5.

Table 4 **Grey Relational Coefficients with Grades and Corresponding Ranks**

Exp No	Grey Relational Coefficients					GRG	RANK
	Fx	Fy	Fz	Ra	TW		
1	0.8534	0.7196	0.8124	0.9543	0.5000	0.7679	3
2	0.6179	0.5556	0.5337	0.7750	0.5000	0.5964	10
3	0.4677	0.3569	0.4977	0.8058	0.3750	0.5006	16
4	0.7755	0.6349	0.8124	0.5970	0.6000	0.6840	6
5	0.5210	0.4269	0.5076	0.4852	0.4286	0.4739	17
6	0.3914	0.3557	0.3673	0.5203	0.5000	0.4269	24
7	0.6715	0.4882	0.7830	0.3935	0.4286	0.5530	12
8	0.4704	0.3843	0.4934	0.3333	0.5000	0.4363	23
9	0.3333	0.3333	0.3333	0.3792	0.3333	0.3425	27
10	0.7601	0.5448	0.7967	0.5476	0.7500	0.6798	7
11	0.5112	0.4239	0.4969	0.4870	0.4286	0.4695	18
12	0.3934	0.4040	0.3658	0.5203	0.5000	0.4367	22
13	0.6683	0.4862	0.7639	0.5068	0.6000	0.6051	9
14	0.4588	0.4066	0.5018	0.4473	0.4286	0.4486	21
15	0.3517	0.3378	0.3393	0.3528	0.5000	0.3763	26
16	0.9189	0.8558	0.9036	0.9139	0.4286	0.8041	2
17	0.6213	0.5593	0.5257	0.5262	0.3750	0.5215	15
18	0.4914	0.5038	0.4089	0.5960	0.3333	0.4667	19
19	0.6990	0.6068	0.6267	0.4604	1.0000	0.6786	8
20	0.4688	0.4966	0.5779	0.4181	0.7500	0.5423	13
21	0.3745	0.3412	0.3909	0.4298	0.4286	0.3930	25
22	1.0000	1.0000	1.0000	1.0000	0.6000	**0.9200**	1
23	0.7132	0.5303	0.8103	0.9296	0.7500	0.7467	5
24	0.5603	0.5434	0.4708	0.7911	0.6000	0.5931	11
25	0.8148	0.6787	0.8704	0.6672	0.7500	0.7562	4
26	0.5336	0.4245	0.5078	0.5504	0.6000	0.5232	14
27	0.4060	0.4089	0.3791	0.5033	0.6000	0.4595	20

Table 5 Response Table for GRG

Sr No	Factors	Level 1	Level 2	Level 3	Max-Min	Rank
1	Pressure	0.5313	0.5343	**0.6236**	0.0923	3
2	Speed	0.5628	**0.5861**	0.5403	0.0458	4
3	Feed	**0.6574**	0.5455	0.4862	0.1712	2
4	DoC	**0.7165**	0.5287	0.4439	0.2726	1
Mean Grey Relational Grade = 0.5631						

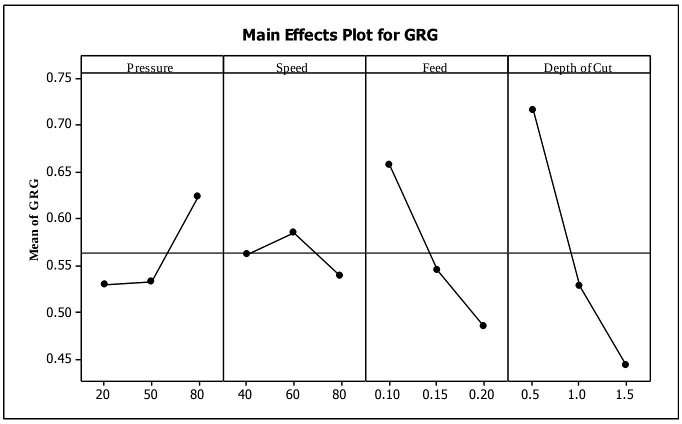

Figure 2. Main Effect plot Grey Relational Grade

Table 6 **Improvement in Grey Relational Grade**

	Initial Parameter Setting	Optimal Parameter	
		Prediction	Experimental
Setting Level	$P_2V_3F_1D_1$	$P_3V_2F_1D_1$	$P_3V_2F_1D_1$
Cutting Force	199.8		164.3
Radial Force	173.1		159
Feed Force	117.1		93.32
Surface Roughness	0.461		0.4
Tool Wear	35		25
GRG	**0.8041**	**0.8945**	**0.9200**
Improvement in Grey Relational Grade= 0.1159			

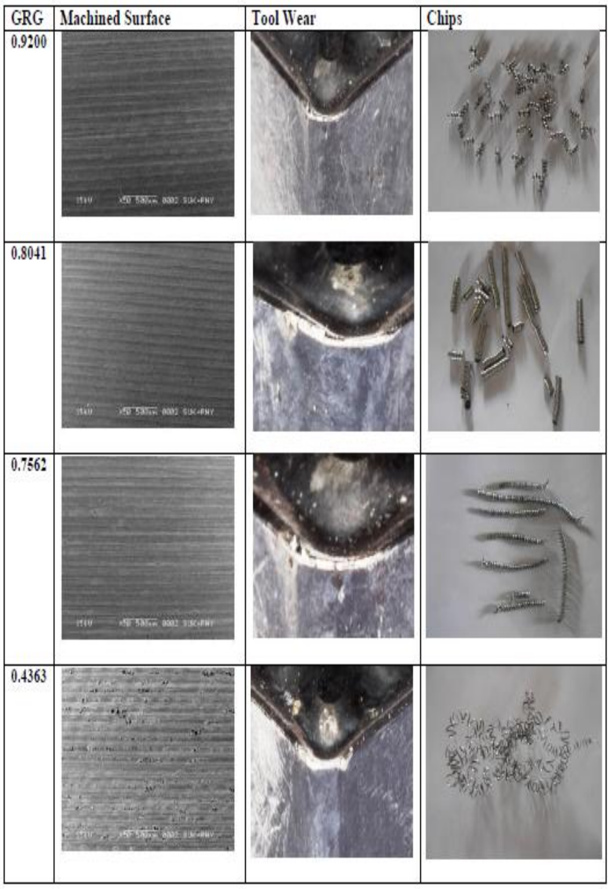

Figure 5 Surface pattern,tool wear and chips obtained for varoius Grey Relational Grades

Once the optimal parametric conditions were obtained the predicted grey relational grade under optimal condition was calculated by using Eq.5.Good agreement was found between predicted (0.8945) and Experimental value (0.9200) as mentioned in Table 6.The improvement of grey relational grade from initial parameter combination i.e. $P_2S_3f_1d_1$ to optimal parameter combination i.e. $P_3V_2f_1d_1$ was 0.1159 i.e. 11.59 %.This indicates that grey relational analysis is a very useful technique to solve optimization problems where the machining processes deals with multiple responses. The main focus of this analysis is pressure of coolant, from analysis of data it was found that with increase in pressure of coolant, magnitude of cutting force components decreases with significant decrease in tool wear and surface roughness.

From Figure 5 it can be seen that,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 favorable 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. Tool wear also decreases with increase in pressure of pressure of coolant.

Coclusion

Optimization of High Pressure Assisted turining of Inconel 718 is presesnted in this paper.Grey relational analysis is used for optimization of the turining process.Cutting forces, Surface roughness and tool wear are the resopnses for which cutting parameters with coolanat pressure has been optimized.Current analysis shows that all the process parameters shows significvant effect on multiple resoposes.Depth of cut is found to have most significant effect on the respose varibles. Depth of cut is followed by feed , pressure of coolant and then speed.From the analysis it is clear that coolant pressure is a very imporatant cosideration during machining of Inconel 718. Increse in coolant pressure promotes curing of chips which results in decrese in cutting forces and tool wear as an effect of decresed frcitionsal conditions at cutting zone.The optimied cutting parmeters from grey relational analysis are 80 bar coolant pressure,60 m/min speed,0.1 mm/rev feed and 0.5mm depth of cut.

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