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ScienceDirect
Procedia Engineering 64 (2013) 1276 – 1282
Procedia Engineering
www.elsevier.com/locate/procedia

International Conference on DESIGN AND MANUFACTURING, IConDM 2013

Optimization of Machining Parameters for End Milling of Inconel 718 Super Alloy Using Taguchi Based Grey Relational Analysis

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Abstract

This study investigated the parameter optimization of end milling operation for Inconel 718 super alloy with multi-response criteria based on the taguchi orthogonal array with the grey relational analysis. Nine experimental runs based on an L_9 orthogonal array of Taguchi method were performed. Cutting speed, feed rate and depth of cut are optimized with considerations of multiple performance characteristics namely surface roughness and material removal rate. A grey relational grade obtained from the grey relational analysis is used to solve the end milling process with the multiple performance characteristics. Additionally, the analysis of variance (ANOVA) is also applied to identify the most significant factor. Finally, confirmation tests were performed to make a comparison between the experimental results and developed model. Experimental results have shown that machining performance in the end milling process can be improved effectively through this approach.

Selection and peer-review under responsibility of the organizing and review committee of IConDM 2013

Keywords: End milling; Inconel super alloy; Machinability; Taguchi Method; Multi-response optimization; Grey relational analysis.

Nomenclature

v	cutting velocity (m/min)
f	feed rate (mm/tooth)
d	depth of cut
SS	sum of squares
DF	degrees of freedom
MS	mean square error
F	Fisher ratio
%C	percentage contribution
Greek symbols	
γ	grey relational grade
ξ	grey coefficient

1. Introduction

Nickel-based super alloys play an extremely important role in space vehicles, rocket engines, experimental aircrafts, nuclear reactors, submarines, steam power plants, petrochemical equipments and other high-temperature applications [2, 10]. Among the nickel-based super alloys, Inconel 718 is the most frequently used. However properties such as low thermal conductivity, rapid work hardening, ability to react with tool materials under atmospheric conditions, formation of built-up edge, weld to the cutting

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Selection and peer-review under responsibility of the organizing and review committee of IConDM 2013
doi:10.1016/j.proeng.2013.09.208

edges and presence of abrasive carbides in their microstructure causes poor machinability of these materials and restrict the wider usage [12, 14]. They are known to be among the most difficult-to-cut materials. Several researchers have studied the effect of cutting conditions in machining of nickel based super alloys [5, 7, 8, 15, 21]. Most of the research on machining Inconel alloy is concentrated mainly on the study of cutting tool wear and wear mechanism [1, 9]. Poor selection of machining parameters causes cutting tools to wear and break quickly as well as economical losses such as damaged work-piece and poor surface quality [13, 16, 20]. Among various machining processes, the end-milling process is one of the most widely used material removal processes in industry. The cutting operations by the end mills can be as simple as a face milling on the top of a flat surface with a rigid cutter or a milling of very complex parts [22].

In the view of above machining problems, the main objective of the present work is to investigate the influence of different machining parameters on end milling of Inconel 718 super alloy. Taguchi design approach is utilized for experimental planning during end milling of Inconel alloy. The results are analyzed to achieve optimal surface roughness and material removal rate. Grey relational analysis was performed to combine the multiple responses in to one numerical score, rank these scores, and determine the optimal machine parameter settings. Confirmation tests were performed by using experiments. ANOVA is performed to investigate the more influencing parameters on the multiple performance characteristics.

2. Experimental details

2.1. Materials and processes

The experimental study was carried out in wet cutting conditions on a Hass-US five-axis, high-speed CNC milling machine equipped with a maximum spindle speed of 12000 rpm, feed rate of 10 m/min and a 25-kW drive motor. CNC part programs for tool paths were created. The workpiece material used was Inconel 718 in the form of a 300mm (length) _ 52mm (width) _ 6mm (height) block. The workpiece material is mounted onto the machine table to provide maximum rigidity. The experimental setup of the workpiece for end mill is shown in Fig. 1. The detailed information on chemical composition and mechanical properties of this Inconel 718 alloy is provided in Tables 1 and 2 respectively. The tool used for performing end milling operation is uncoated tungsten carbide (10mm diameter, 4 -flutes) produced by Sandvik. Tools with four teeth are selected for better surface quality. The same tool was used until maximum flank wear reached $V_B$max _0.2 mm. The machined surface was measured at three different positions using a surf test (Make - Mahr surf test) measuring instrument with the cutoff length 2.5 mm and the average surface roughness (R_a) value is recorded in microns. Material removal rate (MRR) is used as another performance measure to evaluate a machining performance. Material removal rate is expressed as the amount of material removed under a period of machining time and is expressed in mm^3/sec.

(a) (b)

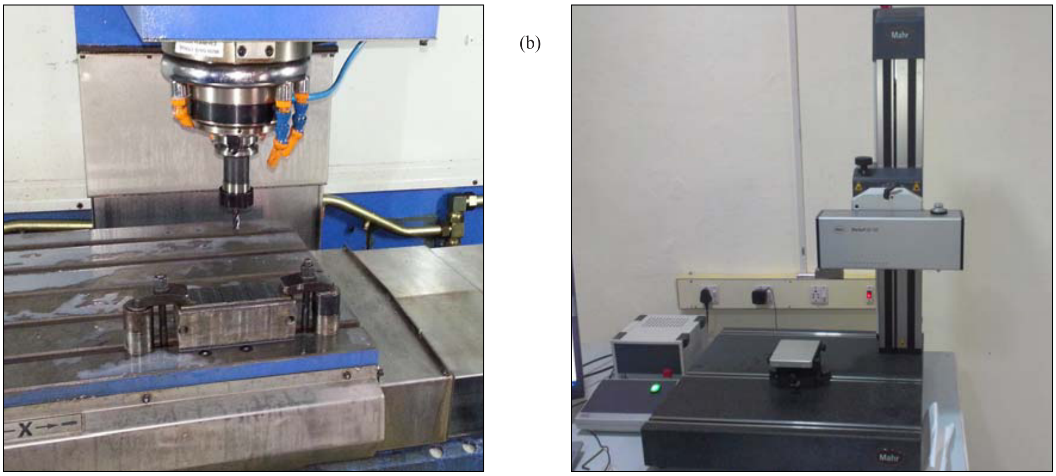

Fig. 1. (a) Experimental set up for end milling operation (b) Set up for surface roughness measurement

Table 1 Chemical composition of Inconel 718 alloy (wt %)

Elements	C	Mn	Si	Ti	Al	Co	Mb	Cb	Fe	Cr	Ni
Percentage	0.08	0.35	0.35	0.6	0.8	1.0	3.0	5.0	17.0	19.0	52.82

Table 2 Mechanical properties of Inconel 718 alloy

Ultimate Strength (MPa)	Yield Point (MPa)	Elongation (%)	Hardness (HRC)
1260 - 1390	1041 - 1160	14 - 19	40 - 45

2.2. *Plan of experiments*

In recent years, the Taguchi method has become a powerful tool for improving productivity during research and development so that high quality products can be produced quickly and at low cost. Taguchi's parameter design is an important tool for robust design. Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments [3, 6, 19]. The methodology of Taguchi for three factors at three levels is used for the implementation of the plan of experiments. The degrees of freedom required for the study is six and Taguchi's L9 orthogonal array is used to define the 9 trial conditions. Only the main effects are of interest and factor interactions are not studied. The process parameters and levels are listed in Table 3. Each of the 9 trials or process designs is replicated twice and the average response values are used for the analysis. Table 4 shows the experimental layout and corresponding average test results.

Table 3 Process parameters and their levels

Parameter	Unit	Level 1	Level 2	Level 3
Cutting velocity (v)	m/min	25	50	75
Feed rate (f)	mm/tooth	0.06	0.09	0.12
Depth of cut (d)	mm	0.2	0.4	0.6

Table 4 Experimental layout using an L9 orthogonal array and corresponding results

Expt. No.	Process parameter			Average Response Values	
	Cutting velocity	Feed rate	Depth of cut	Surface roughness (microns)	Material removal rate (mm^3/sec)
1	1	1	1	0.21	4.308
2	1	2	2	0.25	4.480
3	1	3	3	0.29	4.503
4	2	1	2	0.2	5.643
5	2	2	3	0.27	5.731
6	2	3	1	0.27	5.904
7	3	1	3	0.21	6.906
8	3	2	1	0.23	7.080
9	3	3	2	0.27	7.530

3. Determination of optimal machining parameters

3.1. Grey Relational Analysis (GRA)

In the GRA, data pre-processing is first performed in order to normalize the raw data for the analysis. In the present study, a linear normalization of the experimental results for surface roughness and material removal rate as shown in Table 5 were performed in the range between zero and one, which is also called grey relational generating [4, 17].

The normalized experimental results x_{ij} can be expressed as:

$$x_{ij} = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \tag{1}$$

y_{ij} for the i^{th} experimental results in the j^{th} experiment. Table 5 shows the normalized results for surface roughness and material removal rate. Basically, the larger the normalized results correspond to the better performance and the best-normalized results should be equal to one.

Table 5 Evaluated Grey relational coefficient and Grade values

Exp.	Normalized values		Grey relational coefficients after weighted		Grey relational grade	
No	Surface roughness	Material removal rate	Surface roughness	Material removal rate	Grey grade	Rank
1	0.8889	0.0000	0.8182	0.3333	0.5758	5
2	0.4444	0.0534	0.4737	0.3456	0.4097	8
3	0.0000	0.0604	0.3333	0.3473	0.3403	9
4	1.0000	0.4142	1.0000	0.4605	0.7302	2
5	0.2222	0.4415	0.3913	0.4724	0.4318	7
6	0.2222	0.4952	0.3913	0.4976	0.4445	6
7	0.8889	0.8062	0.8182	0.7206	0.7694	1
8	0.6667	0.8604	0.6000	0.7817	0.6909	4
9	0.2222	1.0000	0.3913	1.0000	0.6957	3

Next, the grey relational coefficient is calculated to express the relationship between the ideal (best) and the actual normalized experimental results. The grey relational coefficient ξ_{ij} can be expressed as:

$$\xi_{ij} = \frac{\min_i \min_j \left| x_i^o - x_{ij} \right| + \xi \max_i \max_j \left| x_i^o - x_{ij} \right|}{\left| x_i^o - x_{ij} \right| + \xi \max_i \max_j \left| x_i^o - x_{ij} \right|} \tag{2}$$

Where x_i^0 is the ideal normalized results for the i^{th} performance characteristics and ξ is the distinguishing coefficient which is defined in the range $0 \le \xi \le 1$. In the present study the value of ξ is assumed as 0.5.

Then, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each performance characteristics. The overall evaluation of the multiple performance characteristics is based on the grey relational grade, that is:

$$\gamma_j = \frac{1}{m} \sum_{i=1}^{m} \xi_{ij} \tag{3}$$

Where γ_j is the grey relational grade for the j^{th} experiment and m is the number of performance characteristics.

Table 5 shows the grey relational grade for each experiment using L9 orthogonal array. Higher the grey relational grade better is the product quality. Therefore, on the basis of grey relational grade, the factor effect can be estimated and the optimal level for each controllable factor can also be determined. The mean of the grey relational grade for each level of the parameter is summarized and shown in Table 6. In addition, the total mean of the grey relational grade for the 9 experiments is also calculated and listed in Table 6. Figure 2 shows the grey relational grade graph for the levels of the processing parameters. Basically, the larger the grey relational grade, the better is the multiple performance characteristics. However, the relative importance among the parameters for the multiple performance characteristics will still need to be known so that the optimal combinations of the process parameter levels can be determined more accurately [18].

Table 6 Response table for the grey relational grade

Process Parameter	Grey relational grade				
	Level 1	Level 2	Level 3	Max-Min	Rank
Cutting velocity	0.4419	0.5355	0.7186*	0.2767	1
Feed rate	0.6918*	0.5108	0.4935	0.1983	2
Depth of cut	0.5704	0.6119*	0.5139	0.0980	3

Total Mean Value of the Grey Relational Grade = 0.5654

* Optimum levels

3.2. Analysis of Variance

The purpose of the analysis of variance is to investigate which machining parameters significantly affect the performance characteristic. This is accomplished by separating the total variability of the grey relational grades, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into contributions by each machining parameter and the error [11]. First, the total sum of the squared deviations SS_T from the total mean of the grey relational grade γ_m can be calculated as:

$$SS_T = \sum_{j=1}^{p} (\gamma_j - \gamma_m)^2 \tag{4}$$

Where p is the number of experiments in the orthogonal array and γ_j is the mean grey relational grade for the j^{th} experiment.

The total sum of the squared deviations SS_T is decomposed in to two sources: the sum of the squared deviations SS_d due to each machining parameter and the sum of the squared error SS_e. The percentage contribution of each of the machining parameter in the total sum of the squared deviations SS_T can be used to evaluate the importance of the machining parameter change on the performance characteristic. In addition, the Fisher's F- test can also be used to determine which machining parameters have a significant effect on the performance characteristic. Usually, the change of the machining parameters has a significant effect on performance characteristic when F is large. Table 7 shows the results of ANOVA analysis.

Table 7 Results of the analysis of variance

Source	DF	SS	MS	F	% C
Cutting velocity	2	0.11887	0.05944	37.193	56.88
Feed rate	2	0.07240	0.03620	22.651	34.64
Depth of cut	2	0.01452	0.00726	4.542	6.95
Error	2	0.00320	0.00160		1.53
Total	8	0.20898			100.00

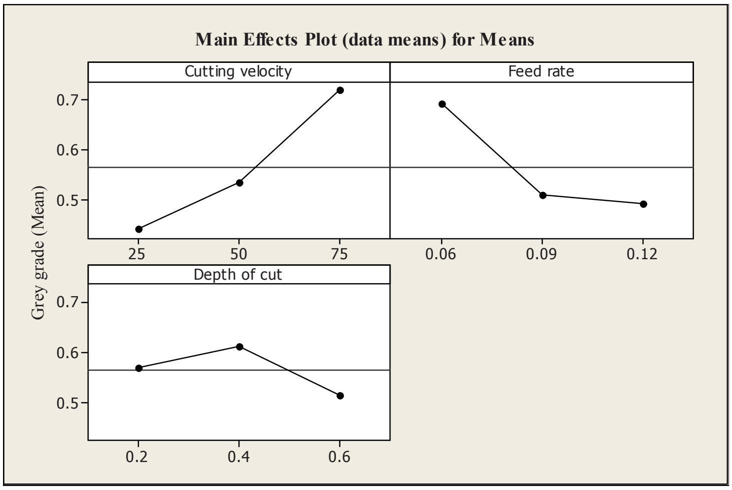

Fig. 2. Main effects plot for Grey relational grade

Results of analysis of variance indicate that cutting velocity is the most significant machining parameter followed by feed rate affecting the multiple performance characteristics.

3.3. Confirmation Experiment

Once the optimal level of machining parameters is selected the final step is to predict and verify the improvement of the performance characteristics using the optimal level of the machining parameters. The estimated grey relational grade $\hat{\gamma}$ using the optimum level of the machining parameters can be calculated as

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q} (\bar{\gamma}_j - \gamma_m) \quad (5)$$

Where γ_m is the total mean of the grey relational grade, $\bar{\gamma}_j$ is the mean of the grey relational grade at the optimum level and q is the number of machining parameters that significantly affects the multiple performance characteristics.

Based on Eq (5) the estimated grey relational grade using the optimal machining parameters can then be obtained. Table 8 shows the results of the confirmation experiment using the optimal machining parameters. The surface roughness (Ra) is improved from 0.21 to 0.19 µm and the material removal rate (MRR) is greatly increased from 4.308 to 7.100 mm^3/sec. It is clearly shown that multiple performance characteristics in the end milling of Inconel 718 are greatly improved through this study.

Table 8 Results of machining performance using initial and optimal machining parameters

	Initial machining parameters	Optimal machining parameters	
		Prediction	Experiment
Setting Level	$A_1B_1C_1$	$A_3B_1C_2$	$A_3B_1C_2$
Surface roughness (Ra)	0.21	0.19	0.19
Material removal rate (MRR)	4.308	7.100	7.21
Grey relational grade	0.5758	0.8915	
Improvement in grey relational grade = 0.3156			

4. Conclusion

It has been established that grey relational analysis is an effective optimization tool for machining of Inconel 718 alloy in end milling. It has been also found that the optimal cutting parameters for the machining process lies at 75m/min for cutting velocity, 0.06 mm/tooth for feed rate and 0.4 mm for depth of cut. Further it has been observed that there is a 64.8%increase in material removal rate and at the same time a 9.52% decrease in surface roughness. This encourages applying the grey concept for optimizing multi response processing with multiple factors. Analysis of variance shows that the cutting velocity is the most significant machining parameter followed by feed rate affecting the multiple performance characteristics with 56.88% and 34.64% influence respectively.

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