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OPTIMIZATION OF REAMING PROCESS PARAMETERS FOR TITANIUM TI-6AL-4V ALLOY USING GREY RELATIONAL ANALYSIS

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ABSTRACT

Reaming is one of the finishing processes that have been widely applied in manufacturing industries. Reaming of Titanium Ti-6Al-4V alloy material is an important and current research topic on manufacturing processes. Optimal process parameter setting is an important element in the machinability study of Titanium Ti-6Al-4V alloy. Optimization has most significant importance, particularly for reaming operations. This research work focuses on the multi-response optimization of reaming process parameters using the Taguchi and Grey relational technique to obtain minimum cutting temperature (T), thrust force (F_t), torque (M_t), surface roughness (R_a) and hole quality. The experiments were performed on Titanium Ti-6Al-4V alloy using uncoated carbide straight shank reamer under wet and cryogenic LN_2 conditions. Eighteen experimental runs (L_{18}) based on the Taguchi method of orthogonal arrays were performed to determine the best factor level condition. The environment, cutting speed and feed rate were selected as control factors. Grey relational analysis was used to determine the most significant control factors affecting the output parameters. Grey relational grade obtained from the grey relational analysis was used to solve the reaming process with the optimal levels of the multiple performance characteristics responses were established. The optimum results indicate that the reaming results have been improved in wet coolant than the cryogenic LN_2 condition.

Keywords: optimization, reaming, cryogenic, temperature, thrust force, surface roughness, hole quality.

INTRODUCTION

Titanium and its alloys are most important materials used in automotive components, aerospace, and biomedical applications. The main beneficial properties are low thermal conductivity, light weight, high corrosion resistance and good mechanical properties. Titanium alloys are classified into difficult to cut materials due to an extreme temperature in the cutting zone interface region. A better cooling system can decrease the cutting temperature and increase tool wear resistance [1].

Reaming is one of the finishing operations to enhance the surface integrity and hole quality of the surface. Cutting coolants decrease the contact friction between the workpiece and cutting tool interface region. It also produces less tool wear and better surface finish [2]. Large consumption of cutting fluids used in manufacturing industries affects human workers health, pollution problems, recycling and disposal costs [3]. Cryogenic cooling is a new coolant approach used as a replacement of cutting fluids.

Kilickap et al [4] have optimized the drilling parameters on surface roughness using response surface methodology and genetic algorithm. Feed rate is the most significant parameter which affects surface roughness. Kuram et al [5] used cutting fluids and cutting parameters in the optimization of end milling. Cutting fluids improved the machining performance in end milling. Gaitonde et al [6] proved that cutting speed and feed rate are the most important drilling process parameters which control the output responses. Krishnamoorthy et al [7] applied grey fuzzy logic for the optimization of drilling parameters and found that feed rate is the most significant factor which affects the responses.

Rajmohan et al [8] optimized in drilling by using response surface methodology and reported a lower cutting speed and feed rate which are beneficial in the improvement of surface quality. Feed rate having 56.15% percentage was the most significant factor in ANOVA which affects the drill bit cutting temperature [9]. Better hole quality and minimum processing cost achieved at a lower speed and feed rates when using carbide tools in drilling [10]. Optimization of parameter objectives increases the flexibility to increase productivity and improved surface quality [11]. Taskesen et al [12] reported that optimal combination of process parameters was mainly used to obtain minimum tool wear and better hole quality in drilling. Proper selection of process parameters using optimization technique results in better output responses [13].

Optimal process parameters and cutting conditions in drilling using Taguchi optimization method were more adequate for satisfying the manufacturer's expectations [14]. Minimization of wear of the cutting tool by applying the optimized input process parameters by using various techniques and improving the machining performance [15 – 16]. Manimaran et al [17] reported that cooling environment was the most effective significant factor to improve the performance in machining. Rad et al [18] suggested more future work was required to optimize the process parameters in drilling and reaming operations.

From the best of author's knowledge, there is a lack of studies carried out in the optimization of process parameters in reaming operations under cryogenic LN_2 cooling and wet cooling. Titanium Ti-6Al-4V alloy is used as a workpiece and uncoated straight shank reamer is used as a tool. Cryogenic LN_2 cooling is a unpolluted technology and is better in controlling the cutting zone temperature [19 – 28]. The cutting environment, cutting speeds and feed rates are the critical factors in determining the reaming performance. In the present work, the Grey relational analysis is employed for the optimization of the multi-responses. The experiment is conducted for reaming Titanium Ti-6Al-4V alloy under wet cooling and cryogenic LN_2 cooling. Finally, the confirmation tests have been carried out to confirm the test results.

1. EXPERIMENTAL PROCEDURE

The experiments were conducted in the CNC Vertical Machining Centre (ARIX VMC 100) as shown in the Fig. 1. The uncoated carbide straight shank type reamer tool was used for experimentation with a diameter of 16.3 mm. The titanium alloy work piece material of rectangular block with dimensions of 164 × 80 × 25 mm which are fixed at the upper side of a Kistler 9257B type piezoelectric transducer-based dynamometer. Water soluble oil in the mixing ratio of 1: 15 used as a wet coolant. Cryogenic liquid nitrogen is supplied at a pressure of 4 bar and a flow rate of 0.8 l/min.

Thermocouple (K – type) of 3 mm diameter was used for cutting temperature measurement. The thermocouple was placed on the sidewall of the workpiece and a distance of 0.2 mm between the thermocouple tip and the hole surface was maintained. Zeilmann and Weingaertner [29] have used this technique to measure the cutting temperature in the drilling zone at three different heights. Variation of cutting zone temperature was observed and recorded. Thrust force and torque were measured by using KISTLER dynamometer. The surface roughness was measured by contact type Taylor-Hobson surface tester (Surtronic 3+) with a cutoff length of 0.8 mm and traverse length of 4 mm. Coordinate Measuring Machine (CMM) was used to measure the hole quality viz. Circularity and Cylindricity.

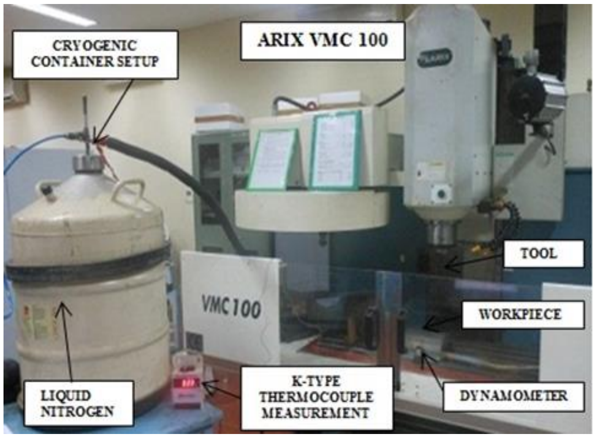


Fig. 1 Experimental setup

1.1 DESIGN OF EXPERIMENTS

Table 1 presents the factors and their levels, considered in this study. Experiments are conducted with three factors, one at two levels and the others at three levels. Hence, a three level orthogonal array (OA) L_{18} is chosen for the experimental trials and the response values obtained are given in Table 2.

Table 1. Factors and levels

S.No.	Factors	Level 1	Level 2	Level 3
1	Environment	Wet	LN_2	-
2	Speed (m/min)	10	20	30
3	Feed (mm/rev)	0.1	0.2	0.3

Table 2. Responses values from L_{18} Orthogonal Array

Env	Speed	Feed	T	F_t	M_t	R_a	Cir	Cyl
1	1	1	26.96	87.5	2.537	0.62	0.011	0.013
1	1	2	32.25	109.4	4.02	0.78	0.022	0.024
1	1	3	37.68	114.6	8.879	0.82	0.13	0.137
1	2	1	29.68	137.3	5.889	0.7	0.012	0.014
1	2	2	36.88	187.4	6.09	0.84	0.058	0.065
1	2	3	41.58	246.7	8.303	0.88	0.207	0.161
1	3	1	36.96	148.4	11.45	0.74	0.013	0.019
1	3	2	43.17	195.6	18.57	0.82	0.079	0.1
1	3	3	44.17	255	22.64	0.98	0.269	0.238
2	1	1	22.11	67	2.192	1.08	0.127	0.124
2	1	2	25.06	70	3.144	1.18	0.16	0.138
2	1	3	27.08	72.1	5.662	1.46	0.245	0.249
2	2	1	24.35	76.5	3.322	1.2	0.14	0.124

2	2	2	26.15	81	4.158	1.28	0.24	0.217
2	2	3	28.74	119.9	6.724	1.62	0.255	0.303
2	3	1	29.06	87.4	4.998	1.06	0.148	0.131
2	3	2	33.39	112.8	6.427	1.36	0.245	0.229
2	3	3	37.68	166.9	11.96	1.7	0.292	0.353

1.2 OPTIMIZATION STEPS USING THE TAGUCHI–GREY RELATIONAL ANALYSIS

In this work, the grey relational analysis is used to investigate the multiple performance characteristics in the optimization of process parameters in cryogenic drilling. The multi-response variables are complicated and complex problems to be solved. The three categories of S/N ratio are 1. Higher the better (HB), 2.Smaller the better (LB) and 3. Nominal the better (NB). In this drilling process, the smaller the better (LB) is used for the temperature, thrust force, surface roughness, circularity, and cylindricity.

Step 1. The output responses are converted into signal to noise (S/N) ratios using eq. 1 for smaller-the-better characteristics.

$$\text{S/N ratio} = -10\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{9} y_{ij}^{2} \quad (1)$$

where, n = number of replications, y_{ij} = observed response value, i =1, 2 ...n, j =1, 2...k

The first step in the Grey relational analysis is data pre-processing. It is normally carried out due to variable units and range used for the different factors of the experiment. The data pre-processing includes transferring the original sequence to a comparable sequence. Eq. (1) is used for the S/N ratio with Smaller the better.

Step 2. The S/N ratios obtained are normalised using Eq. (2) for lower-the-better characteristics

$$z_{ij} = \frac{\max(y_{ij}, i = 1,2,...9) - y_{ij}}{\max(y_{ij}, i = 1,2,...9) - \min(y_{ij}, i = 1,2...9)} \quad (2)$$

where, z_{ij} = Normalised S/N ratio of the output responses

The average value of the grey relational coefficient is called as the grey grade and the multi-response optimization results are based on the grey relational grade. The grey relational coefficient and grey relational grades are computed by the Eq (3) - (4).

Step 3. The grey relational coefficient is calculated with the normalised S/N ratios by using the following equation

$$\gamma_{ij} = \frac{\Delta \min + \psi \Delta \max}{\Delta_{oj}(k) + \psi \Delta \max} \quad (3)$$

where, Ψ is distinguishing coefficient in the range of $0 \le \Psi \le 1$, Δ min = lower normalised value of each output response, Δ max= largest normalised value of each output response, Δ_{oj} = absolute value of each output response (1-z_{ij}), γ_{ij} = Grey relational coefficient

Step 4. The mean Grey relational grade is calculated by using the following equation

$$\overline{\gamma_{ij}} = \frac{1}{k}\sum_{i=1}^{k} \gamma_{ij} \quad (4)$$

where $\overline{\gamma_{ij}}$ = grey relational grade for the jth experiment, k = number of output performance characteristics. A higher grey relational grade implies the parameter closer to the ideal sequence. Therefore, on the basis of the grey relational grade, the factor effect can be estimated and the optimal level for each controllable factor can also be determined.

Step 5. Predict and validate the quality characteristic using the optimal level of the design parameters. The predicted grey relational grade was obtained by using optimal AWJ parameters it can be calculated in the Eq. (5).

$$\gamma_{ij} = y_m + \sum_{i=1}^{q} (\overline{\gamma_i} - \gamma_m) \quad (5)$$

where, γ_m = the mean grey relational grade, $\overline{\gamma_i}$ = denotes the grey relational grade at the optimal level, q = number of drilling process parameters.

The Grey relational coefficient was calculated from the above equations 1 to 5 and rank was assigned to each grade which is shown in table 2.

2. RESULTS AND DISCUSSION

The Grey relational grade and rank of all 18 experimental runs is shown in Table 3 which is based on L_{18} orthogonal array. In 18 values, experiment number 1 has the optimal multi-response characteristic. In this experimental work, 1st experimental run has the optimum value. Accordingly, from the mean response shown in Figure 2, it is observed that the lower V_c = 10 m/min and f = 0.1 mm/rev under wet cooling condition are the optimum levels for Titanium Ti-6Al-4V alloy in reaming. Additionally from the multi-response output, 1st experimental number has a better optimal reaming parameter.

Table 3. Grey Relational Grade and Rank

Exp. No.	**1**	2	3	4	5	6
GRG	**0.9138**	0.7827	0.5887	0.7929	0.6359	0.4930
Rank	**1**	3	12	2	9	16
Exp. No.	7	8	9	10	11	12
GRG	0.7095	0.5359	0.3972	0.7821	0.6837	0.5949
Rank	5	13	18	4	7	11
Exp. No.	13	14	15	16	17	18
GRG	0.7080	0.6209	0.5072	0.6446	0.5186	0.4018
Rank	6	10	15	8	14	17

The cutting temperature 27^{o}C, thrust force 87.5 N, torque 2.537 Nm, surface roughness 0.62 µm, circularity 0.011 mm and cylindricity 0.013 mm are the best response parameters, which are produced by reaming at a cutting speed 10 m/min and feed rate 0.1 mm/rev under wet cooling. The low level process parameters are found to be the best in reaming and the wet cooling is an effective coolant for Titanium Ti-6Al-4V alloy.

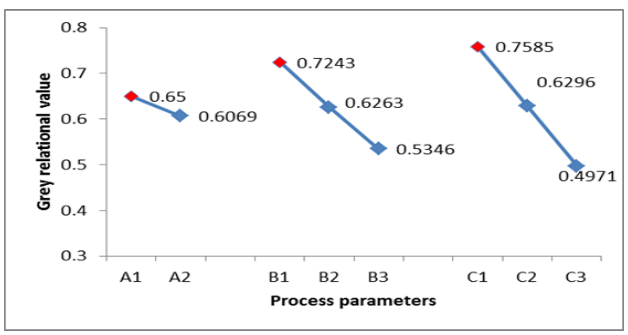
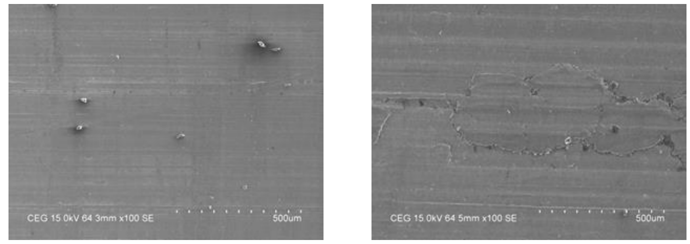


Fig. 2 Mean response values of drilling process parameters

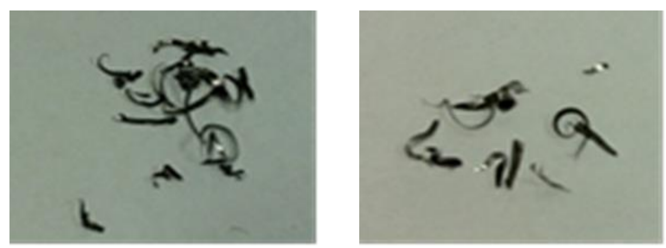
A reduction of 17.98% cutting temperature was observed in cryogenic LN_2 cooling over wet cooling for a similar condition. The reduction in cutting temperature due to heat generated can dissipate quickly from the cutting zone by supplying LN_2 cooling. Thrust force of 23.42% reduction and torque of 13.59% reduction in LN_2 cooling was observed at the tool – chip interface produces a better lubrication and penetration effect over wet cooling. The Cryogenic LN_2 coolant in the cutting zone minimizes the frictional torque between the workpiece and the chip when compared to wet cooling. About 42.59% increase in surface roughness due to chip dragging in the reamed hole surface in cryogenic LN_2 cooling.



Wet cooling LN$_2$ Cooling

Fig. 3 SEM Images of the Cross section of the hole

The SEM image of the cross-section of the hole as shown in Figure 3 reveals how the surface of the hole is affected by chip dragging. Since the hardness of the material increases at the cryogenic temperature, the chip sheared from the material also have high hardness resulting more damage to the hole surface at cryogenic conditions. Circularity increases of 91.02% in cryogenic LN_2 cooling which affects the hole quality with a maximum variation of deviation when compared to a wet cooling. An increase of 89.64% in Cylindricity shows affecting cylindrical surface and maximized the hole enlargement compared with wet cooling. In cryogenic LN_2 cooling, chip breakability was found to be better as shown in Figure 4.



Wet cooling LN$_2$ Cooling

Fig. 4 Images of Chip Morphology

The variation between the maximum and minimum values of the grey relational grade is shown in Table 4. The average grey relational grade for each of the levels was calculated by the following procedure: (1) summing up of the grey relational grade at the factor level for each column in the orthogonal array, and (2) taking its average. The maximum-minimum values of the reaming parameters were 0.2614 for feed rate, 0.1897 for cutting speed and 0.0431 for the environment.

The maximum value of the maximum-minimum is the best effective factor affects the multi- response characteristic of the drilling process. The maximum value of the maximum-minimum is 0.2614, which corresponds to feed rate (control factor). The hierarchy of the important control factors in machining can be listed as feed rate, cutting speed and environments. The output results obviously indicate that the reaming performance was influenced more by a controllable factor, specifically the feed rate. Application of cryogenic LN_2 cooling results in a reduction of cutting temperature, thrust force, torque, but the increase in surface roughness, circularity, and cylindricity. Based on the results obtained from the mean response table for closeness coefficient results, wet cooling is found to be economical in the reaming process.

Table 5 shows the compared test results of the initial setting parameters and optimal process parameters in drilling. Once, the optimal level of the reaming process parameters is found, confirmation test results are carried out to confirm the enhancement in the multi-response characteristics of the reaming process. The confirmation result of the process parameters indicates that the Grey relational grade of the optimal process condition (A1B1C1) is higher than initial process condition (A1B3C3).

Table 4. Response value for the average GRG

Factors	Environment	Speed	Feed
Level 1	**0.6500**	**0.7243**	**0.7585**
Level 2	0.6069	0.6263	0.6296
Level 3	-	0.5346	0.4971
max-min	0.0431	0.1897	0.2614
Rank	3	2	1

Table 5. Confirmation Test Results

Condition	**Setting level**	**Output responses**					
		T (^{o}C)	**F_t (N)**	**M_t (Nm)**	**R_a (μm)**	**Cir (mm)**	**Cyl (mm)**
Initial setting parameters	A1B3C3	27	87.5	2.537	0.62	0.011	0.013
Optimal process parameters	A1B1C1	44	255	22.64	0.98	0.269	0.238

Improvement in Grey Relational Grade: **0.5166**.

3. CONCLUSIONS

In this study, the effect of reaming parameters such as environments, cutting speed and feed rate were studied based on Grey relational analysis with L_{18} orthogonal array. The Grey relational grade was employed to position the output responses based on their significance in reaming of Titanium Ti-6Al-4V alloy.

On the basis of rank obtained from the Grey relational grade, the 1st experimental run gives the optimal value of 0.9138 to obtain minimum temperature, thrust force, and torque. Better chip breakability was found to be in cryogenic LN_2 cooling. The predicted optimum input parameter combinations are Wet cooling, cutting speed = 10 m/min, feed rate = 0.1 mm/rev for reaming of Titanium Ti-6Al-4V alloy.

Optimal results propose that the Grey relational analysis can be employed for improving the reaming performance and the application of wet cooling in the manufacturing industries. It was observed that the projected process parameter Grey relational analysis combination was more effective in solving the multi-response problem in reaming process.

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