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Influence of Cryogenic Reaming Process Parameters on Titanium Alloy by Using Grey Relational Analysis

Optimization of process parameters in reaming operation is used mainly to reduce the production cost in industries. The current study focuses on the optimization effect of process parameters in cryogenic reaming of Titanium alloy. The input factors considered are cooling environment, cutting speed and feed rate. The effects of reaming parameters are cutting temperature, thrust force, torque, surface roughness, circularity and cylindricity. Multi response optimization – Grey relational analysis is used to optimize the process parameters. The smaller the better is used to minimize the better output responses and to find out the most significant factor affecting the reaming operation. As a result, the lower level parameter cutting speed 10 m/min and feed rate 0.1 mm/rev under cryogenic LN_2 *cooling are found to be optimal conditions. The most significant factors (higher to lower) which affect the reaming operations are feed rate, cutting speed and cooling environment.*

Keywords: *Titanium, Optimization, Reaming, Temperature, Force, Roughness, Hole quality.*

1. 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 produce 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 [4–7].

Kilickap et al. [8] 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. [9] used cutting fluids and cutting parameters in optimization of end milling. Cutting fluids improved the machining performance in end milling. Krishnamoorthy et al. [10] applied grey fuzzy logic for the optimization of drilling parameters and found that feed rate is the most significant factor which affects the responses [10].

Rajmohan and Palanikumar [11] optimized in drilling by using response surface methodology and reported a lower cutting speed and feed rate which are beneficial in improvement of surface quality. Feed rate having 56.15% percentage was the most significant factor in ANOVA which affects the drill bit cutting temperature [12]. Better hole quality and minimum processing cost achieved at lower speed and feed rates when using carbide tools in drilling. Optimization of parameter objectives increase the flexibility to increase productivity and improved surface quality [13]. Taskesen et al. [14] 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 [15].

Optimal process parameters and cutting conditions in drilling using Taguchi optimization method were more adequate for satisfying the manufacturer’s expectations [16–22]. Minimization of wear of the cutting tool by applying the optimized input process parameters by using various techniques and improving the machining performance [23–25]. Manimaran et al. [26] reported that cooling environment was the most effective significant factor to improve the performance in machining.

From the best of author’s knowledge, there is lack of studies carried out in optimization of process parameters in reaming operations under cryogenic LN_2 cooling and wet cooling. Titanium grade 2 alloy is used as a workpiece and uncoated straight shank reamer is used as a tool. Cryogenic LN_2 cooling is an unpolluted technology and is better in controlling the cutting zone temperature [27]. The cutting environment, cutting speeds and feed rates are the critical factors in determining the reaming performance. In the present work, the Grey

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relational analysis is employed for the optimization of the multi responses. The experiment is conducted for reaming Titanium alloy under wet cooling and cryogenic LN_2 cooling. Finally the confirmation tests have been carried out to confirm the test results.

2. MATERIALS AND METHODS

The experiments were conducted in the CNC Vertical Machining Centre (ARIX VMC 100) as shown in the Figure 1. The uncoated carbide straight shank type reamer tool was used for experimentation with a diameter of 16.3 mm. 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. It is supplied at a pressure of 3 bar. Cryogenic liquid nitrogen is supplied at a pressure of 3 bar and a flow rate of 0.6 l/min.

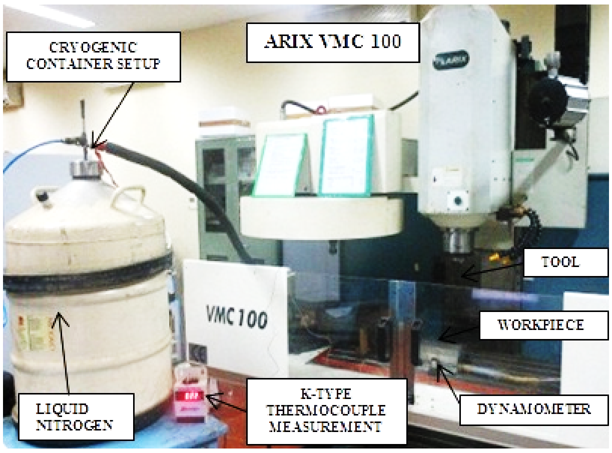


Figure 1. Experimental setup

Thermocouple (K – type) of 3 mm diameter was used for cutting temperature measurement. The thermocouple was placed on the sidewall of the workpiece at a height of 18 mm and a distance of 0.2 mm between the thermocouple tip and the hole surface was maintained. Zeilmann and Weingaertner [28] 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. Microhardness of the reamed surface was measured by using Vicker's microhardness tester.

2.1 Design of Experiments

The factors and their corresponding levels are shown in Table 1. Reaming experiments were conducted with one factor at two levels, with two factors at three levels. Hence, a three level L_{18} orthogonal array have been chosen for the multi response optimization, and the corresponding response values obtained are shown 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 Response values from L18 Orthogonal Array

S.No.	Environment		Speed		Feed	
1	1	WET	1	10	1	0.1
2	1		1	10	2	0.2
3	1		1	10	3	0.3
4	1		2	20	1	0.1
5	1		2	20	2	0.2
6	1		2	20	3	0.3
7	1		3	30	1	0.1
8	1		3	30	2	0.2
9	1		3	30	3	0.3
10	2	LN_2	1	10	1	0.1
11	2		1	10	2	0.2
12	2		1	10	3	0.3
13	2		2	20	1	0.1
14	2		2	20	2	0.2
15	2		2	20	3	0.3
16	2		3	30	1	0.1
17	2		3	30	2	0.2
18	2		3	30	3	0.3

2.2 OPTIMIZATION STEPS USING THE GREY RELATIONAL ANALYSIS

In this research work, the grey relational analysis was used to investigate the multiple performance characteristics in the optimization of process parameters in cryogenic reaming.

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 reaming operation, the smaller the better (LB) is used for the cutting temperature, thrust force, torque, 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.

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

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 considering variable units and range used for the different factors of the experiment. The data pre-processing includes transformation of the original sequence to a comparable one.

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

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

where, z_{ij} = Normalised S/N ratio of the output responses. The average value of the grey relational coefficient is referred to as the grey grade. 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:

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

where, Ψ is distinguishing coefficient in the range of 0≤Ψ≤1, Δmin = lower normalised value of each output response, Δmax = largest normalised value of each output response, Δ_{oj} = absolute value of each output response (1-zij), γij = Grey relational coefficient. The normalized response values for S/N ratio is shown in Table 3.

Table 3 Normalized Response values for the S/N ratio with Smaller the better

S.No	Normalized Responses					
1	0.86905	0.85486	0.96891	1	1	1
2	0.68278	0.69893	0.71305	0.76744	0.85326	0.85294
3	0.39321	0.53119	0.49875	0.67441	0.67934	0.67941
4	0.68745	0.74446	0.86301	0.95348	0.98913	0.99117
5	0.44777	0.52591	0.62709	0.67441	0.80978	0.82352
6	0.22915	0.22788	0.35993	0.48837	0.50543	0.47058
7	0.53585	0.59786	0.83791	0.81395	0.98097	0.97058
8	0.30436	0.35345	0.45918	0.59302	0.71739	0.76176
9	0	0	0	0.27906	0.13315	0.09117
10	1	1	1	0.90697	0.98641	0.99705
11	0.83826	0.90061	0.81878	0.69767	0.80978	0.82058
12	0.65822	0.66756	0.60415	0.58139	0.44565	0.39117
13	0.85268	0.92254	0.95594	0.72093	0.98097	0.99117
14	0.66835	0.7783	0.69243	0.48837	0.80163	0.78235
15	0.40179	0.43237	0.49526	0.32558	0.3913	0.29117
16	0.70382	0.71658	0.86101	0.65116	0.91304	0.95
17	0.48246	0.51815	0.59916	0.30232	0.67391	0.72058
18	0.31527	0.2272	0.23408	0	0	0

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

$$\overline{\gamma_{ij}} = \frac{1}{k}\sum_{i=1}^{k}\gamma_{ij} \tag{4}$$

Table 4 Grey Relational Grade values

S. No	Grey Relational co-efficient values						Grey Relational Grade
1	0.79246	0.77503	0.94146	1.00000	1.00000	1.00000	0.91816
2	0.61183	0.62417	0.63536	0.68254	0.77311	0.77273	0.68329
3	0.45176	0.51610	0.49938	0.60563	0.60927	0.60932	0.54857
4	0.61535	0.66178	0.78494	0.91488	0.97872	0.98265	0.82305
5	0.47518	0.51330	0.57280	0.60563	0.72441	0.73912	0.60507
6	0.39344	0.39304	0.43857	0.49425	0.50273	0.48571	0.45129
7	0.51859	0.55424	0.75518	0.72881	0.96334	0.94443	0.74410
8	0.41819	0.43609	0.48039	0.55128	0.63889	0.67729	0.53369
9	0.33333	0.33333	0.33333	0.40952	0.36580	0.35490	0.35504
10	1.00000	1.00000	1.00000	0.84313	0.97354	0.99413	0.96847
11	0.75558	0.83418	0.73398	0.62318	0.72441	0.73592	0.73454
12	0.59398	0.60064	0.55813	0.54430	0.47423	0.45093	0.53703
13	0.77242	0.86586	0.91902	0.64179	0.96334	0.98265	0.85751
14	0.60121	0.69281	0.61914	0.49425	0.71595	0.69672	0.63668
15	0.45529	0.46833	0.49764	0.42574	0.45098	0.41362	0.45193
16	0.62800	0.63823	0.78248	0.58904	0.85185	0.90909	0.73311
17	0.49138	0.50924	0.55504	0.41747	0.60526	0.64150	0.53665
18	0.42204	0.39283	0.39497	0.33333	0.33333	0.33333	0.36831

where $\overline{\gamma_{ij}}$ = grey relational grade for the jth experiment, k = number of output performance characteristics. A higher grey relational grade implies the location of 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. The grey relational co-efficient values and grades are shown in Table 4.

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 reaming parameters. It can be calculated by Eq. (5).

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

where, γ_m = the mean grey relational grade, $\overline{\gamma_{ij}}$ = 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 5.

Table 5 Grey Relational Grade and Rank

S.No.	Environment A	Speed B	Feed C	Grey Relational Grade	Rank
1	1	1	1	0.91816	2
2	1	1	2	0.68329	8
3	1	1	3	0.54857	11
4	1	2	1	0.82305	4
5	1	2	2	0.60507	10
6	1	2	3	0.45129	16
7	1	3	1	0.74410	5
8	1	3	2	0.53369	14
9	1	3	3	0.35504	18
10	2	1	1	0.96847	1
11	2	1	2	0.73454	6
12	2	1	3	0.53703	12
13	2	2	1	0.85751	3
14	2	2	2	0.63668	9
15	2	2	3	0.45193	15
16	2	3	1	0.73311	7
17	2	3	2	0.53665	13
18	2	3	3	0.36831	17

3. RESULTS AND DISCUSSION

The Grey relational grade and rank of all the 18 experimental runs are shown in Table 5 which is based on L_{18} orthogonal array. Among the 18 values, experiment number 10 has the optimal multi response characteristic. In this experimental work, 10th experimental run has the optimum value. Accordingly, from the mean response as shown in Figure 2, the lower cutting speed (10 m/min) and feed rate (0.1 mm/rev) under cryogenic LN_2 cooling condition are observed as the optimum levels for Titanium alloy. Additionally from the multi response output, 10th experimental number is the better optimal reaming parameter.

The corresponding output values of experiment number 10 are cutting temperature (T) 17.11°C, thrust force (F_t) 29.65 N, torque (M_t) 1.046 Nm surface roughness (R_a) 1.2 µm, circularity (Cir) 0.016 mm and cylindricity (Cyl) 0.015 mm respectively.

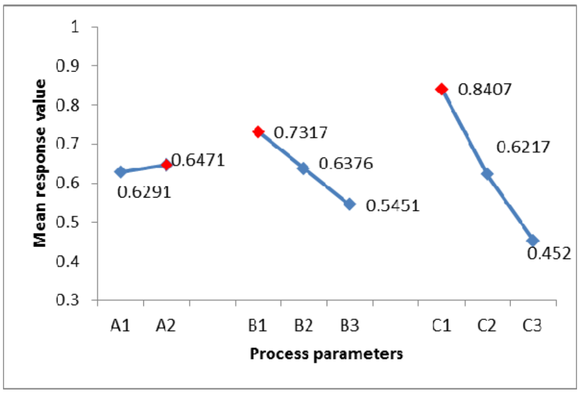
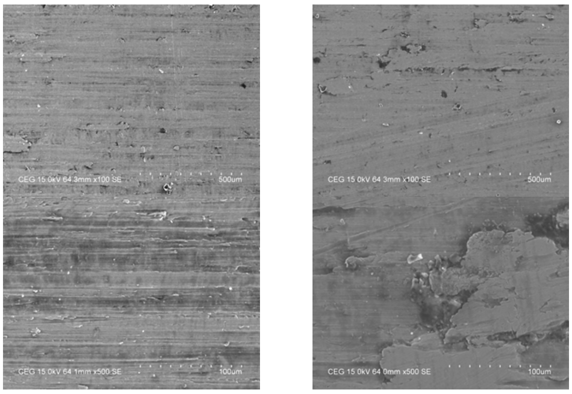


Figure 2. Mean response values of reaming process parameters

A reduction of 16% in cutting temperature was observed in cryogenic LN_2 cooling over wet cooling for a similar condition. Thus reduction at the cutting zone is due to rapid heat dissipation by supplying LN_2 cooling. A 30% thrust force decrease in cryogenic LN_2 cooling was observed at the tool – chip interface produces a better lubrication effect over wet cooling. A 15.17% reduction in torque in cryogenic LN_2 cooling over wet cooling is observed. The advantage of cryogenic LN_2 cooling arising out of the decrease in the friction between chip – tool interface results in better cushioning effect. Surface roughness increases by 6.67% due to chip dragging in the reamed hole surface in cryogenic LN_2 cooling.

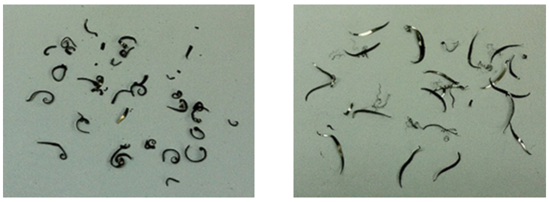


Wet cooling **LN_2 Cooling**

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

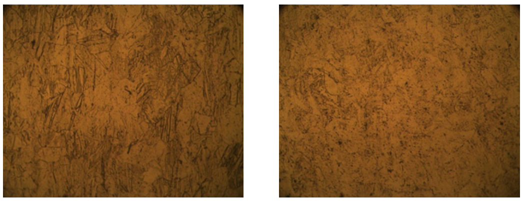
The cross section of the reamed surface was analyzed through SEM image as shown in Figure 3 reveals how the surface of the hole is affected by chip dragging. Since the hardness of the material increases at the cryogenic temperature, the chip sheared from the material also has high hardness resulting in more damage to the hole surface at cryogenic conditions. A circularity increase of 35.58% in cryogenic LN_2 cooling is seen which affects the hole quality with a maximum variation of deviation when compared to wet cooling. A cylindricity increase of 8.55% shows damage of cylindrical surface maximizing the hole enlargement compared with wet cooling.

Chip breakability was found to be better in wet cooling over cryogenic LN_2 cooling as shown in Figure 4. Chip is discontinuous at lower cutting speed, width of the chip is less and non-uniform in flood cooling. It is discontinuous and of larger width of the chip with uniform pattern observed in cryogenic LN_2 cooling. In cryogenic LN_2 cooling condition, the penetration effect is very less when compared to wet cooling. Cooling effect is distinct due to insufficient penetration of LN_2 cooling into the in-depth of the reamed surface of the hole.



Wet cooling **LN_2 Cooling**

Figure 4. Chip images



Wet cooling **LN_2 Cooling**

Figure 5. Microstructure of the reamed surface

The microhardness of the reamed surface under wet and cryogenic LN_2 cooling is compared. In cryogenic LN_2 cooling, the microhardness of the hole surface increases by 13.47% over wet cooling. The main reason for increase in microhardness is due to the decrease of the cutting temperature in the cryogenic LN_2 cooling. The Microstructures of reamed surface have almost of same grain size in both cryogenic LN_2 cooling and wet cooling as shown in Figure 5. During the reaming operation, cutting temperature increases with increase of feed rate under both coolant conditions. In comparison with both coolants, no drastic changes in the microstructures were observed.

Table 6 Response value for the average Grey Relational Grade

Factors	Environment A	Speed B	Feed C
Level 1	0.6291	0.7371	0.8407
Level 2	0.6471	0.6376	0.6217
Level 3	-	0.5451	0.4520
max-min	0.0180	0.1866	0.3887
Rank	3	2	1

The average grey relational grade values for each level of the parameter were calculated, and are shown in Table 6. 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 variation between the maximum and minimum values of the grey relational grade is shown in Table 4. The maximum-minimum values of the reaming parameters were 0.3887 for feed rate, 0.1866 for cutting speed and 0.0180 for environment.

The maximum value of the maximum-minimum is the best effective factor affecting the multi- response characteristic of the reaming process. The maximum value of the maximum-minimum is 0.3887, which corresponds to the feed rate (control factor). The hierarchy of the important control factors in machining can be listed as feed rate, cutting speed and environment. The output results indicate that reaming performance influenced more by controllable factor, specifically the feed rate. Application of cryogenic LN_2 cooling results in reduction of cutting temperature, thrust force and torque, but increase of surface roughness, circularity and cylindricity. Based on the results obtained from the mean response table for closeness coefficient result, cryogenic LN_2 cooling is found to be economical in reaming process.

The significant factors of the study were determined from the ANOVA on the basis of grey relational grade. The factors, feed rate and cutting speed are significant for the experiment. The values of the ANOVA are presented in Table 7.

Table 7. ANOVA (Analysis of Variance)

Factor notation	Factor	Sum of Squares	Degrees of freedom	Mean Squares	F Value	% Contribution
A	Environments	0.00146	1	0.00146	5.94	0.26
B	Cutting speed	0.10435	2	0.05217	211.89	18.49
C	Feed rate	0.45575	2	0.22788	925.42[a]	80.75
	Error	0.00295	12	0.00025		0.52
	Total	0.56452	17			100

[a] **Significant at 95% confidence level**

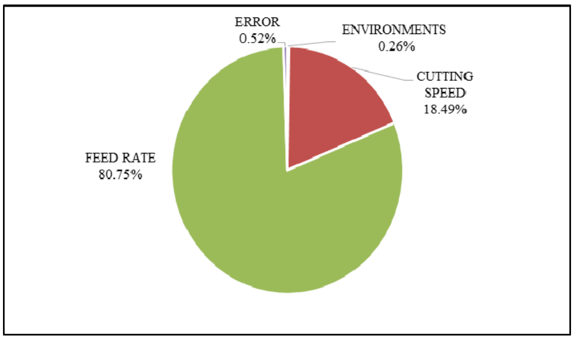


Figure 6. Percentage contributions of parameters

The percentage contributions of the parameters are shown in Figure 6. The feed rate with 80.75% contribution was found to have more influence on the reaming performance of the Titanium Grade 2 Alloy. The contribution of cutting speed and environments are 18.49% and 0.26% respectively. The cutting temperature 17.11 °C, thrust force 29.65 N, torque 1.046 Nm, surface roughness 1.2 µm, circularity 0.016 mm and cylindricity 0.015 mm are the best response parameters produced by reaming at a cutting speed 10 m/min and feed rate 0.1 mm/rev under cryogenic cooling.

Table 8. Confirmation Test Results

Condition	**Initial setting parameters**	**Optimal process parameters**
Setting level	A1B3C3	A2B1C1
T (°C)	42.77	17.11
F_t (N)	118.6	29.65
M_t(Nm)	7.061	1.046
R_a (µm)	1.74	1.20
Cir (mm)	0.330	0.016
Cyl (mm)	0.323	0.015
GRG	**0.35504**	**0.96847**

Improvement in Grey Relational Grade: **0.61343**. Table 8 shows comparison test results of the initial setting parameters and optimal process parameters in reaming. Once, the optimal level reaming process parameters are found, confirmation test results are carried out to confirm the enhancement in the multi response characteristic of the reaming process. The confirmation result of the process parameters indicates that the Grey relational grade of the optimal process condition (A2B1C1) is higher than the initial process condition (A1B3C3). The low-level process parameters were found to be the best in reaming and cryogenic cooling as an effective coolant.

4. CONCLUSION

In this work, the effect of process parameters in reaming such as environment, cutting speed (V_c) and feed rate (f) 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 alloy.

On the basis of rank obtained from the Grey relational grade, the 10th experimental run gives the optimal value of 0.96847 to obtain minimum cutting temperature (T), thrust force (F_t) and torque (M_t). Chip breakability was found to be better in wet cooling. Increase in microhardness is observed in the cryogenic LN_2 cooling condition. No drastic changes are observed in both wet and cryogenic LN_2 cooling conditions. The predicted optimum input parameter combinations are cryogenic LN_2 cooling, cutting speed (V_c) (10 m/min), feed rate (f) (0.1 mm/rev) for reaming Titanium alloy.

Optimal results indicate that the Grey relational analysis can be employed for improving reaming performance with the application of cryogenic LN_2 cooling in manufacturing units. The projected process parameter Grey relational analysis combination was found to be more effective in solving multi response problem in reaming process.

REFERENCES

[1] Ahmed, L.S. and Kumar, M.P.: Cryogenic drilling of Ti–6Al–4V alloy under liquid nitrogen cooling, Materials and Manufacturing Processes, Vol. 31, No. 7, pp. 951-959, 2016.

[2] Bhowmick, S and Alpas, A.T.: Minimum quantity lubrication drilling of aluminium-silicon alloys in water using diamond-like carbon coated drills, Int J Mach Tools Manuf., Vol. 48, pp. 1429–1443, 2008.

[3] Ahmed, L.S., Kumar, M.P.: Performance evaluation of cryogenic cooling in reaming titanium alloy, Materials and Manufacturing Processes, Vol. 32, No. 3, pp. 302-308, 2016.

[4] Ahmed, L.S., Govindaraju. N., Kumar, M.P.: Experimental investigations on cryogenic cooling in the drilling of titanium alloy, Materials and Manufacturing Processes, Vol. 31, No. 5, pp. 603-607, 2016.

[5] Ahmed, L.S., Kumar, M.P.: Investigation of cryogenic cooling effect in reaming Ti-6AL-4V alloy, Materials and Manufacturing Processes, Vol. 32, No. 9, pp. 970-978, 2017.

[6] Govindaraju, N., Ahmed, L.S, Kumar, M.P.: Experimental investigations on cryogenic cooling in the drilling of AISI 1045 steel, Materials and Manufacturing Processes, Vol. 29, No. 11-12, pp. 1417-1421, 2014.

[7] Govindaraju, N, Ahmed, L.S. and Kumar, M.P.: Experimental investigations on cryogenic cooling in drilling of aluminium alloy, Applied Mechanics and Materials, Vol. 592, pp. 316-320, 2014.

[8] Kilickap, E., Huseyinoglu, M. and Yardimeden, A.: Optimization of drilling parameters on surface roughness in drilling of AISI 1045 using response surface methodology and genetic algorithm, Int J Adv Manuf Tech, Vol. 52, No. 1-4, pp. 79–88, 2011.

[9] Kuram, E., Ozcelik, B., Bayramoglu, M., Demirbas, E., Simsek, B.T.: Optimization of cutting fluids and cutting parameters during end milling by using D-optimal design of experiments, Journal of Cleaner Production, Vol. 42, pp. 159–166, 2013.

[10] Krishnamoorthy, A., Boopathy, S.R., Palanikumar, K. and Paulo Davim, J.: Application of grey fuzzy logic for the optimization of drilling parameters for CFRP composites with multiple performance characteristics, Measurement: Journal of the International Measurement Confederation, Vol. 45, No. 5, pp. 1286–1296, 2012.

[11] Rajmohan, T., Palanikumar, K.: Application of the central composite design in optimization of machining parameters in drilling hybrid metal matrix composites, Measurement, Vol. 46, No. 4, pp. 1470–1481, 2013.

[12] Cakiroglu, R. and Acir, A.: Optimization of cutting parameters on drill bit temperature in drilling by Taguchi method, Measurement: Journal of the International Measurement Confederation, Vol. 46, No. 9, pp. 3525–3531, 2013.

[13] Sardinas, R.Q., Reis, P. and Davim, J.P.: Multi-objective optimization of cutting parameters for drilling laminate composite materials by using genetic algorithms, Composites Science and Technology, Vol. 66, No. 15, pp. 3083–3088, 2006.

[14] Taskesen, A., Kutukde, K.: Analysis and optimization of drilling parameters for tool wear and hole dimensional accuracy in B4C reinforced Al-alloy, Transactions of Nonferrous Metals Society of China, Vol. 23, No. 9, pp. 2524–2536, 2013.

[15] Saravanan, M., Ramalingam, D., Manikandan, G., Kaarthikeyen, R.R.: Multi objective optimization of drilling parameters using genetic algorithm, Procedia Engineering, Vol. 38, pp. 197–207, 2012.

[16] Balaji, K., Rao, N.V., Rao, M. and Murthy, B.S.N.: Optimization of drilling parameters for drilling of Ti-6Al-4V based on surface roughness, flank wear and drill vibration, Measurement, 2017.

[17] Goel, B., Singh, S., Sarepaka, G.V.: Optimisation of machining parameters for single point diamond turning of chromium zirconium copper alloy C18150 using Taguchi and grey relational analysis, Int. J. of Machining and Machinability of Materials, Vol. 19, No. 2, pp. 95 – 109, 2017.

[18] Ganta, V., Sagar, K.S. and Chakradhar, D.: Multi objective optimisation of thermally enhanced machining parameters of Inconel 718 using grey relational analysis, Int. J. Machining and Machinability of Materials, Vol. 19, No. 1, pp. 57–75, 2017.

[19] Sivaiah, P. and Chakradhar, D.: Multi-objective optimisation of cryogenic turning process using Taguchi-based grey relational analysis, Int. J. Machining and Machinability of Materials, Vol. 19, No. 4, pp. 297-312, 2017.

[20] Sibalija, T.V. and Majstorović.: New Approach to Process Optimization for Multiple Intermediate Exits, FME Transactions, Vol. 38, No. 1, pp. 39-48, 2010.

[21] Waleed, W., Chathriyan, A. and Vimal, S.S.R.: Experimental investigation of the influence of the parameters of the thermal drilling process on composites with a metal matrix, FME Transactions, Vol. 46, No. 2, pp. 171-176, 2018.

[22] Shakeel Ahmed, L. and Pradeep Kumar, M.: Multiresponse optimization of cryogenic drilling on Ti-6Al-4V alloy using topsis method, J Mech Sci Technol, Vol. 30, No. 4, pp. 1835-1841, 2016.

[23] Lu, H.S., Chang, C.K., Hwang, N.C. and Chung, C.T.: Grey relational analysis coupled with principal component analysis for optimization design of the cutting parameters in high-speed end milling, Journal of Materials Processing Technology, Vol. 209, No. 8, pp. 3808–3817, 2009.

[24] Jayabal, S., Natarajan, U.: Optimization of thrust force, torque, and tool wear in drilling of coir fiber-reinforced composites using Nelder-Mead and genetic algorithm methods, International Journal of Advanced Manufacturing Technology, Vol. 51, No. 1-4, pp. 371–381, 2010.

[25] Kurt, M., Bagci, E. and Kaynak, Y.: Application of Taguchi methods in the optimization of cutting parameters for surface finish and hole diameter accuracy in dry drilling processes, International Journal of Advanced Manufacturing Technology, Vol. 40, No. 5-6, pp. 458–469, 2009.

[26] Manimaran, G., Kumar, M.P.: Multiresponse Optimization of Grinding AISI 316 Stainless Steel Using Grey Relational Analysis, Materials and Manufacturing Processes, Vol. 28, No. 4, pp. 418–423, 2013.

[27] Shokrani, A., Dhokia, V., Munoz Escalona, P. and Newman, S.T.: State of the art cryogenic machining and processing, Int J Comp Int Manuf., Vol. 26, No. 7, pp. 1-35, 2013.

[28] Zeilmann, R.P., Weingaertner, W.L.: Analysis of temperature during drilling of Ti6Al4V with minimal quantity of lubricant, J Mat. Proc. Tech., Vol. 179, No. 1-3, pp. 124–127, 2006.

NOMENCLATURE

T	Cutting Temperature
Ft	Thrust Force
Mt	Torque

Ra	Surface Roughness
Cir	Circularity
Cyl	Cylindricity

Superscripts

^{o}	Temperature

УТИЦАЈ ПОСТУПКА КРИОГЕНОГ РАЗВРТАЊА РУПА НА ЛЕГУРУ ТИТАНИЈУМА ПРИМЕНОМ ГРЕЈОВЕ РЕЛАЦИОНЕ АНАЛИЗЕ

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Оптимизација процесних параметара код поступка развртања углавном се користи у циљу смањења трошкова производње у индустрији. Рад се бави оптимизацијом утицаја процесних параметара на легуру титанијума код криогеног развртања. Разматрају се улазни параметри: расхладна средина, брзина резања и брзина помоћног кретања. Утицајни параметри развртања су: температура резања, потисна сила, обртни момент, храпавост површине, кружност и цилиндричност. Вишеодзивна оптимизација – Грејова релациона анализа се користи за оптимизацију процесних параметара. Што се мањи број параметара користи за минимизацију то су излазни одзиви бољи и лакше је утврдити који фактор има највећи утицај на поступак развртања. Оптимални услови се постижу када параметар резања има мању брзину (10 m/min) и када је брзина помоћног кретања 0,1 mm/rev у условима хлађења са LN_2 . Фактори од највећег утицаја на поступак развртања су брзина помоћног кретања, брзина резања и расхладна средина.