Studies on the effects of deep cryogenic treated WC–Co insert on turning of Al6063 using multi-objective optimization

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Abstract

To improve the machining performance manufacturers adopt various methods to improve the tool life which influences production cost and the degree of the surface finish. Recently cryogenic treatment is used to improve the machining performances. In the present work, the tungsten carbide-cobalt (WC–Co) cutting tool is cryogenically treated at -196°C for a soaking time of 24 h and tempered to 200°C for 2 h. The machinability attributes such as Tool Wear Rate, Surface profile roughness (R_a), of the Cryo Treated (CT) cutting tool, are measured on turning operation with different parametric conditions on the Al6063 alloy and compared with an Untreated Tool (UT). The results show that the CT tool improves the tool life with an acceptable surface finish. Taguchi's coupled multi-objective optimization methods such as Grey Relational Analysis (TC-GRA) and Technique for Order Preference by Similarity to Ideal Solution (TC-TOPSIS) were actualized to enhance the turning performance of CT tool. The outcomes revealed that TC-TOPSIS acquired ideal condition is improving the exhibition than the TC-GRA. Furthermore, the interaction impact of cutting parameters is analyzed through 3D surface plots.

Keywords Cryogenic treatment · TC-TOPSIS · TC-GRA · Tool wear rate · Surface finish

1 Introduction

The primary goal for the manufacturing industries is to make a product with less machining time by accomplishing a higher amount of Material Removal Rate (MRR) with an acceptable range of R_a . The higher amount of MRR prompts excess TWR, the abundance quantity of metal is evacuated as hot chips with high machining temperature. Repeto et al. [1] stated that aluminium alloys have good machinability qualities compared with ferrous materials. According to Pattnaik et al. [2], excessive crater wear was noticed while machining non-ferrous materials because of continuous chip flow over the outside of the tool. Javidikia et al. [3] revealed that a larger contact region of the tool-chip builds the chip thickness proportion that prompts to have higher cutting temperatures. Likewise, it induces a

higher cutting force that prompts an effective utilization of the machine. Furthermore, the long chips adhere to the tool and the work piece will prompt in providing the rough surface finish with the most extreme tool wear.

Khanna et al. [4] performed the high-speed orthogonal cutting on titanium alloy and revealed that the continuous chips, high cutting temperature progress to have excess TWR. Bayraktar et al. [5] found an excess TWR on aluminium composites due to the presence of hard silica particles in the composite. Allu et al. [6] declared that low thermal conductivity, strain-hardening, and a higher percent of Nickel arrangement in the material prompts to have high tool wear. The hot hardness of the tool material was assumed to play a key role in deciding the tool life. Varghese et al. [7] examined some techniques such as cutting liquid, coolant oil, hard coating for improving the tool life,

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unfortunately, these systems required more noteworthy control of the activity during the machining. Katoch et al. [8] stated that cryogenic treatment based on various soaking time and different temperatures were implemented to improve the hardness, wear resistance, and toughness property of the tool. Singla et al. [9] suggested that cryogenically treated cutting tools have improved wear resistance, hot hardness, microstructural property, and fatigue life. By the exploratory investigation of Kumar et al. [10] on tempering heat treatment of the cutting tool followed to the cryogenic treatment, confirms the absence of residual stress and will have improved the tool property.

Weng et al. [11] revealed that WC–Co inserts treated with cryogenic fluid have improved tool fracture strength. Das et al. [12] by the trial study affirmed that cryogenic treatment followed by tempering tool shows an excellent wear resistance property while machining hard AISI 4340 steel. Halim et al. [13] reported that CT improves the tool life by 152% on machining of Inconel 718 and the study confirms that the chipping actions during machining were considerably reduced. Celik et al. [14] affirmed that performance characteristics of deeply cryo-treated tungsten carbide inserts showed improved properties on the machining of Ti6Al4V alloy. Palanisamy et al. [15], revealed that cryogenic treated WC–Co inserts show a superior Ra on the workpiece compared with the UT tool. Also, the rate of the desperation of heat was reduced significantly.

There are different kinds of multi-model enhancements based on decision making, such as the Analytic Hierarchy Process (AHP), GRA, and TOPSIS are used to solve the multi-response problems. Sivaiah et al. [16] expressed that Taguchi's optimization was a suitable technique for predicting the ideal condition for a single objective problem. Das et al. [17] conducted turning studies on Al/SiC composite for different operating conditions and preferred to use Taguchi's optimization technique for deciding suitable conditions. Debnath et al. [18] studies focused to locate the optimum condition by using Taguchi's optimization during turning of mild steel at different independent parameters. Balamurugan et al. [19] stated that Taguchi's coupled GRA was a suitable technique to optimize the small datasets of machining condition. Arunkarthikeyan et al. [20] obtained improved outcomes in the machining of AISI 1018 low carbon steel by using Taguchi's GRA. Thangavel et al. [21] adopted the different optimization techniques likewise GRA and TOPSIS for enhancing the machining condition in Electric Discharge Machining (EDM) and concludes Taguchi's TOPSIS has improved results compared with GRA.

From the literature survey, it is reported that advanced metal cutting industries are meant to achieve higher efficiency with less manufacturing costs through operating the machine with the ideal condition. The machining

performance of CT tools for non-ferrous alloys, particularly aluminium alloy is limited. Additionally, the improvement mechanism for the CT tools is still not quantified due to the different cryogenic processing sequence and composition of treating materials. Therefore an attempt has been made to evaluate the improvement in the microstructural and turning performance of cryo-treated WC–Co inserts and compared with UT inserts. Multi-response optimization namely TC-GRA and TC-TOPSIS, are performed for improving the economy of machining. However, one optimization technique is not adequate to predict the ideal condition for engineering problems. The current work is to also locate the ideal turning condition on Al6063 using cryo processed WC–Co inserts as tool material through multi-response Taguchi's GRA and TOPSIS approach.

2 Experimental details

2.1 Sample preparation

The process diagram is shown in Fig. 1. The accompanying procedures are taken for setting up the CT inserts, which is graphically shown in Fig. 2.

Step 1 Reduce the surrounding temperature to -196°C at a constant rate of 2°C per minute.

Step 2 Soaked in a temperature of -196°C for and keep up it for 24-h.

Fig. 1 Flow chart for the experimental study

Fig. 2 Cryogenic treatment procedure

Step 3 Raise the temperature consistently from $-96\text{ }^{\circ}\text{C}$ to surrounding temperature by $2\text{ }^{\circ}\text{C}$ per minute.

Step 4 Once the ambient condition is reached, raise the temperature to $200\text{ }^{\circ}\text{C}$ at a slow rate of $2\text{ }^{\circ}\text{C}$ per min, and keep up it for 2-h.

Step 5 Reduce the temperature to ambient conditions at a controlled rate of $2\text{ }^{\circ}\text{C}$ per minute.

Commercially available Al6063 alloy is used as the machining material and CT tungsten carbide cobalt insert as the tool material. The tool and workpiece material specifications are shown in Table 1. The machine type and the

cutting conditions are shown in Table 2. The micro-hardness test is performed using the Mitutoyo made micro-hardness analyzer. A test weight of 300 g is applied to the samples for a dwell period of 10 s and observations were repeated in three distinct areas and the repeated observation is recorded. The experimental setup for the study is displayed in Fig. 3.

The machinability performance of the CT and untreated WC-Co inserts are measured in terms of TWR and Ra at different turning machining conditions. The wear rate of the tool is estimated by the weight reduction technique and is measured using Eq. (1).

Table 1 Workpiece and tool specification

Workpiece		
Composition	AA6063 (Si—0.04%, Mg—0.70%, Mn—0.10%, Fe—0.35%, Zn—0.10%, Ti—0.10%, Cr—0.1%, Cu—0.10%, remaining Al	
Dimensions	Length = 400 mm, Diameter = 100 mm	
Tool holder	PSBNR2020K-11	
Cutting insert geometry	Material	WC-Co
	Insert style	DNMG 150,608
	Clearance angle	0 deg
	Included angle	55 deg
	Thickness	4.8 mm
	Shape	Diamond
	Corner radius	1.20 mm

Table 2 Machining conditions

Parameters	Cutting velocity(CV) (m/min)	Feed rate(FR) (mm/rev)	Depth of cut (DOC) (mm)
Levels	79	0.102	0.4
	121	0.143	0.6
	188	0.191	0.8
Machining	Dry turning		
Machining time	3 min		
Machine	NAGMATI 175 semi-automated lathe		

$$TWR = \frac{T(b) - T(a)}{T(t)} \quad (1)$$

T(b)—Weight of the WC–Co insert before machining in mg, T(a)—Weight of the WC–Co insert in the after of machining in mg, T(t)—Machining time in min, TWR—Tool Wear Rate in mg/min.

Turning experiments were performed for Taguchi's L27 Orthogonal Array (OA) experimental design and the enhancement study is conducted for a multi-response as needs are on the cryo treated WC–Co inserts. These responses are estimated for determining the optimum cutting conditions. Taguchi's in correlation with Grey Relational Analysis (TC-GRA) and Taguchi's associated TOPSIS (TC-TOPSIS) have proceeded as a multi-response optimization problem.

Fig. 3 Experimental setups for **a** Turning **b** Cutting insert **c** Surface roughness **d** Micro-hardness

2.2 Process involved in Tc-GRA and TC-TOPSIS

2.2.1 Steps in TC-GRA

The following steps were followed to convert the multiple responses into a single response in TC-GRA.

Stage 1 Transformation of yield reactions into Signal to Noise (S/N) proportion

$$\frac{S}{N} \text{ratio} = -10 \log \left(\frac{1}{n} \right) \sum_{i=1}^n \frac{1}{Y_{ij}^2} \quad (\text{Larger the best}) \quad (2)$$

$$\frac{S}{N} \text{ratio} = -10 \log \left(\frac{1}{n} \right) \sum_{i=1}^n \frac{1}{Y_{ij}^2} \quad (\text{Smaller the best}) \quad (3)$$

Stage 2 Normalization of S/N value

$$Z_{ij} = \frac{Y_{ij} - \min(Y_{ij}, i = 1, 2, \dots, n)}{\max(Y_{ij}, i = 1, 2, \dots, n) - \min(Y_{ij}, i = 1, 2, \dots, n)} \quad (\text{Larger the best}) \quad (4)$$

$$Z_{ij} = \frac{\max(Y_{ij}, i = 1, 2, \dots, n) - Y_{ij}}{\max(Y_{ij}, i = 1, 2, \dots, n) - \min(Y_{ij}, i = 1, 2, \dots, n)} \quad (\text{Smaller the best}) \quad (5)$$

Stage 3 Computation of the Grey Relational Coefficient (GRC)

$$GRC_{ij} = \frac{\Delta \min + \gamma \Delta \max}{\Delta_{ij} + \gamma \Delta \max}, \quad \{i, j = 1, 2, \dots, n\} \quad (6)$$

GRC_{ij} —GRC for the i th experimental run and j th dependent variable, Δ —Quality loss or absolute difference between the Y_{0j} and Y_{ij} , γ —Coefficient ($0 \leq \gamma \leq 1$).

Stage 4 Computation of the Grey Relational Grade (GRG)

$$GRG_i = (1/m) \sum (GRC_{ij}, i, j = 1, 2, \dots, n) \quad (7)$$

m —Number of responses.

Stage 5 Ranking the qualities dependent on the GRG in the plunging request.

2.2.2 Steps in TC-TOPSIS

The following statistical steps are used to find the best alternative from the finite number of alternatives in the TC-TOPSIS method.

Step 1 To shape the decision matrix which has n qualities and option can be represented as follows.

$$D_m = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & \cdots & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\ a_{m1} & a_{m2} & a_{m3} & \cdots & \cdots & a_{mn} \end{bmatrix} \quad (8)$$

a_{ij} is the performance of i th alternative concerning the j th attribute.

Step 2 To form the normalized matrix

$$N_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^m Q_{ij}^2}} \quad (\text{Beneficial}) \quad (9)$$

$$N_{ij} = 1 - \frac{a_{ij}}{\sqrt{\sum_{i=1}^m Q_{ij}^2}} \quad (\text{Non-beneficial}) \quad (10)$$

Step 3 To form the weighted normalized decision matrix $U = [U_{ij}]$

$$U = W_j N_{ij} \quad (11)$$

$$W_j (j = 1, 2, \dots, n)$$

where $\sum_{j=1}^n W_j = 1$.

Step 4 To decide the positive best solution and the negative best solution for the perfect arrangements.

$$U^+ = \left\{ \left(\sum_i^{\max} U_{ij} | j \in J \right), \sum_i^{\min} j | j \in J | i = 1, 2, \dots, m \right\} \quad (12)$$

$$U = \{u_1^+, u_2^+, u_3^+ \dots, u_n^+\}$$

$$U^- = \left\{ \left(\sum_i^{\min} U_{ij} | j \in J \right), \sum_i^{\max} j | j \in J | i = 1, 2, \dots, m \right\} \quad (13)$$

$$U = \{u_1^-, u_2^-, u_3^- \dots, u_n^-\}$$

Step 5 Separation measurement between the positive best solutions to the ideal solution

$$S_i^+ = \sqrt{\sum_{j=1}^n (U_{ij} + U_j^+)^2}, i = 1, 2 \dots m \quad (14)$$

Step 6 Separation measurement between the negative best solutions to the ideal solution

$$S_i^- = \sqrt{\sum_{j=1}^n (U_{ij} - U_j^-)^2}, i = 1, 2 \dots m \quad (15)$$

Step 7 Relative closeness (CC) of the distinct alternative to the positive best solution

$$CC = \frac{S_i^-}{S_i^+ + S_i^-}, i = 1, 2, \dots m \quad (16)$$

Step 8 Ranking the Closeness Coefficient (CC) values descending order. Finding the most and least preferred solutions.

3 Result and Discussion

3.1 Microstructural and Micro-hardness examination

Cryogenic treatment assists to form fine η (eta) structures carbide particles with development in WC grain size in WC-Co insert. Subsequently, improvement in the thermal conductivity of the cutting tool due to fine grain structure will decrease the TWR and improves the tool life.

Arunkarthikeyan et al. [22] found fine η -eta carbide formation on 24 h cryo treated tool whereas the increase of cryo treated insert beyond 24-h will reduce

Table 3 Hardness of Cryo treated and un-treated WC-Co

S.No	Treatment	Vicker's Hardness (N/mm ²)
1	Cryo treated WC-Co insert	1686.5
2	Untreated WC-Co insert	1596.1

the development of η -eta carbide particles. The course of action with a η -eta carbide has been recorded excess for 24-h cryo treated WC-Co compared with the UT tool, is confirmed by Fig. 4a, and b.

CT at the primary stage forms the coarser η -eta carbide particles inside the tool, which in turn brings about brittleness property. The post hardening through heat treatment to 200 °C slightly improves the tool toughness and relieves the internal residual stress. Along these, the void formed by the irregular WC is occupied with fine η -eta carbides. The SEM microscopic image for cryo treated WC-Co insert is confirmed that the dispersion of η -eta carbides and variation in grain shape is found in the 24-h CT insert. According to Li et al., [23], the post hardening process will enable scattered η -eta carbide particles and it was allowed to situate around the surface of the tool and fills the void regions.

Table 3 outlines the micro-hardness of the CT and untreated WC-Co tools. CT inserts have better hardness compared with UT samples owing to the structural rearrangements and refinement of η -eta carbides which can be verified by SEM images. The cryo processed inserts have an improved micro-hardness by 5.7% compared with UT insert. Khan et al. [24] detailed that the finely scattered carbides will enhance the tool hardness and wear resistance without influencing the toughness.

Fig. 4 SEM image for **a** Untreated, **b** Cryo treated WC-Co inserts

Table 4 TWR and Ra reduction percentages

Exp. no	Cutting velocity (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Cryo treated tool (CT)	
				TWR reduction (%)	Ra reduction (%)
E1	79	0.102	0.4	19.0	11.5
E2	79	0.102	0.4	17.6	21.2
E3	79	0.102	0.4	21.1	20.6
E4	79	0.143	0.6	20.8	13.2
E5	79	0.143	0.6	15.0	11.7
E6	79	0.143	0.6	15.8	17.0
E7	79	0.191	0.8	14.3	14.3
E8	79	0.191	0.8	8.3	16.1
E9	79	0.191	0.8	10.7	14.2
E10	121	0.102	0.6	18.2	16.9
E11	121	0.102	0.6	27.8	12.4
E12	121	0.102	0.6	10.5	2.6
E13	121	0.143	0.8	12.5	14.0
E14	121	0.143	0.8	21.7	16.3
E15	121	0.143	0.8	32.0	21.4
E16	121	0.191	0.4	20.8	16.0
E17	121	0.191	0.4	14.3	16.3
E18	121	0.191	0.4	22.2	12.2
E19	188	0.102	0.8	17.6	4.7
E20	188	0.102	0.8	22.7	6.3
E21	188	0.102	0.8	16.7	14.9
E22	188	0.143	0.4	25.0	11.2
E23	188	0.143	0.4	21.1	0.9
E24	188	0.143	0.4	20.0	13.5
E25	188	0.191	0.6	19.2	11.2
E26	188	0.191	0.6	32.1	10.6
E27	188	0.191	0.6	17.4	16.9

Table 5 ANOVA for Cryo treated tool (TWR)

Source/TWR	DOF	Adj.SS	Adj.MS	F-value	Contribution (%)
Cutting velocity (CV)	2	0.2866	0.1433	43	12
Feed rate (FR)	2	1.7866	0.8933	268	75.5
Depth of cut (DOC)	2	0.2066	0.1033	31	8
Error	20	0.0666	0.0033		2.3
Lack of fit	2	0.0066	0.0033	1	0.2
Pure error	18	0.0600	0.0033		2
Total	26				100

phase), cobalt binder (β -beta phase), and a blend of two phases (η -eta phase) are the significant phases. Stewart [26] study reported that the improvement in wear behavior is acknowledged due to densification in Co after the treatment where Naveena et al. [27] identified the tool wear resistance with the changes in the WC grains size after the cryo treatment. From Table 4, it is confirmed that TWR is reduced for CT insert compared with UT inserts. The decrease rate on TWR for CT insert is in the range of 8.3 to 32.1%.

TWR decreases at the low-level CV operating conditions and it is noticed in the 'E8' test trail. Similar observations are noticed by Nursel et al. [28], as the higher levels of FR and lower levels of CV show a 24% improvement in the WC-Co tool life. The maximum and the minimum TWR for the CT insert are acquired for 'E9' and 'E23' experimental trails and the wear rates are 2.4, and 1.4 mg/min respectively. The higher level of DOC and FR essentially reduces the tool life and produces the thicker chips during machining that persistently flow over the tool surface which increases the wear rate. Figure 5 shows the TWR correlation at different turning conditions and it is observed that CT insert shows the less TWR.

ANOVA study on TWR to the tool life characteristics acquired from turning of CT insert and it is shown in Table 5. The contribution of FR is more on TWR, trailed by CV and the contribution percentages are 75.5, and 12%, respectively. DOC is extremely less and the rate is

3.2 Tool wear rate and Surface profile roughness

Deep Liquid Nitrogen soaked WC-Co insert shows less tool to wear because of the arrangement and conveyance of the η -eta carbides. Arunkarthikeyan et al. [25] detailed WC-Co inserts are the blend of tungsten carbide (α -alpha

Fig. 5 TWR variation for cryo treated (CT) and untreated (UT) WC-Co

Fig. 6 Surface plot analysis of (a–c) TWR and (d–f) Ra characteristics of treated WC–Co

8% alone. The R^2 is 97.16%, and it shows an excellent correlation between the parameters of the input and output parameters.

Figure 6 shows the surface plots for the interaction of each machining parameter to comprehend the significance of each machining parameter on the output

responses, such as TWR and Ra. For 24 h of CT inserts, the effect of the different interaction of cutting parameters is shown in Figs. 6a–c. FR plays a significant role in tool life and it can be verified from Figs. 6b and c. TWR increases with an increase of FR and DOC, which can be confirmed

Fig. 7 Ra variation for cryo treated (CT) and untreated (UT) WC–Co

in Fig. 6c. Summarily, FR is found to be the dominating factor on TWR to a greater degree for cryo processed insert.

The Al6063 alloy is machined in different turning conditions and the CT inserts display least Ra compared with UT insert and it is shown in Fig. 7. The level of decrease in Ra is determined through the UT insert. From Table 4, it is identified that the CT insert shows better observation for Ra with 21.4% and it is witnessed from the 'E15' experimental run. Kara et al. [28] reported a 45% reduction in Ra by using a cryo-treated tool. The 'E23' experimental condition shows decrease Ra as maximum CV supports the continuous chips flow on the machined surface that prompts an unacceptable surface finish. Ciftci [30] studies confirmed that the chip flow action and the high cutting temperature becomes unavoidable at the high levels of a CV which will significantly affect Ra.

The maximum and minimum Ra is recorded for 'E20' and 'E18' trial runs and the values are 1.785, 0.252 μm, respectively. The maximum level of CV and DOC is attributable to the maximum value of Ra, which creates a high cutting temperature at the machining zone and it prompts to tool nose instability. From the Ra study, it can be concluded that higher levels of CV in correlation with lower levels of DOC, and FR will have improved surface finish. From the observations, it has been presumed that cryo treated WC–Co insert gives a better surface finish.

Table 6 ANOVA for Cryo treated tool (Ra)

Source/Ra	DOF	Adj. SS	Adj. MS	F-value	Contribution (%)
Cutting velocity (CV)	2	2.4646	1.2323	171.17	38
Feed rate (FR)	2	0.0977	0.0489	6.79	1.42
Depth of cut (DOC)	2	3.4583	1.7291	240.19	56
Error	20	0.1439	0.0072		2.3
Lack of fit	2	0.1393	0.0696	267.42	2.2
Pure error	18	0.0046	0.0002		0.08
Total	26				100

To understand the contribution of process variables, an ANOVA study is conducted for CT inserts and shown in Table 6. DOC and CV have a significant role in Ra and the contributions of the parameters are 56, and 38%, respectively. The impact of FR on surface profile at CT tool is seen to be low. The contribution between the independent and the dependent factors have positive relationships as the residual square is found to be 97.66%.

Surface plot assessment on Ra is performed to understand the combined effect of different independent parameters on the dependent parameter. Figure 6d–f shows the interaction impact of cutting parameters and it is stated that the DOC has a significant impact on Ra. Ra increments are recorded for the high levels of DOC and CV and it is confirmed from Figs. 6d and e. The results of the CT insert input parameters on Ra is in the accompanying order: DOC, CV, and FR. A higher level of cutting parameters increases Ra.

3.3 Multi response optimization using TC-GRA and TC-TOPSIS

The statistical software (MINITAB 17.0) is used to compute the methods for the GRG in individual levels of the input parameters and the outcomes have appeared in Table 7. DOC is the most impacting factor on S/N of the GRG, trailed by FR and the CV is the third one. The maximum means for S/N proportion is taken as optimum and the corresponding machining condition (CV3-FR3-DOC3) is chosen for validation, which is appeared in Table 8. The methods for the S/N ratio for 3 input factors and 3 levels have been graphically shown in Fig. 8.

Confirmation turning experimentation is conducted to validate the optimum conditions predicted from the TC-GRA (CV3-FR3-DOC3) technique. Equation (17) has been used to decide the predicted GRG value and it is ordered in Table 9. As distinguished that TC-GRA predictable cutting conditions reduce the TWR 1.8 mg/min to 1.6 mg/min, and Ra increments from 0.475 μm to 1.778 μm. The improvement of GRG is 22.88%. The obtained outcomes

Table 7 Performance characteristics in GRA

S.N	S/N ratio		Normalized S/N		Grey coefficient		Grey grade	GRG S/N	Rank order
	TWR	Ra	TWR	Ra	TWR	Ra			
1	-4.0824	9.0445	0.2477	0.1722	0.5707	0.5471	0.559	-5.053	25
2	-3.5218	8.6595	0.1280	0.1948	0.5342	0.5540	0.544	-5.287	26
3	-3.5218	9.1934	0.1280	0.1634	0.5342	0.5445	0.539	-5.363	27
4	-4.6090	6.1431	0.3602	0.3428	0.6098	0.6034	0.607	-4.342	23
5	-4.6090	6.6137	0.3602	0.3151	0.6098	0.5935	0.602	-4.413	24
6	-5.1055	6.4661	0.4663	0.3238	0.6520	0.5966	0.624	-4.092	20
7	-7.2346	0.1049	0.9210	0.6979	0.9268	0.7680	0.847	-1.438	3
8	-7.2346	0.0174	0.9210	0.7030	0.9268	0.7710	0.849	-1.423	2
9	-7.6042	0.0785	1.0000	0.6994	1.0000	0.7689	0.884	-1.067	1
10	-3.5218	1.0808	0.1280	0.6405	0.5342	0.7356	0.635	-3.946	18
11	-3.5218	1.1996	0.1280	0.6335	0.5342	0.7318	0.633	-3.972	19
12	-4.0824	1.1301	0.2477	0.6376	0.5707	0.7340	0.652	-3.711	15
13	-5.5751	-2.9597	0.5666	0.8781	0.6976	0.8913	0.794	-1.998	5
14	-5.1055	-2.5161	0.4663	0.8520	0.6520	0.8711	0.762	-2.366	11
15	-5.1055	-2.4574	0.4663	0.8486	0.6520	0.8685	0.760	-2.381	12
16	-6.4444	11.6009	0.7523	0.0218	0.8014	0.5055	0.653	-3.695	14
17	-6.4444	11.8352	0.7523	0.0080	0.8014	0.5020	0.652	-3.719	16
18	-6.8485	11.9720	0.8386	0.0000	0.8610	0.5000	0.681	-3.343	13
19	-3.5218	-4.9889	0.1280	0.9974	0.5342	0.9974	0.766	-2.318	9
20	-4.0824	-5.0328	0.2477	1.0000	0.5707	1.0000	0.785	-2.099	6
21	-3.5218	-4.9742	0.1280	0.9966	0.5342	0.9966	0.765	-2.322	10
22	-3.5218	0.9830	0.1280	0.6462	0.5342	0.7387	0.636	-3.925	17
23	-2.9226	1.0415	0.0000	0.6428	0.5000	0.7368	0.618	-4.175	21
24	-2.9226	1.0808	0.0000	0.6405	0.5000	0.7356	0.618	-4.183	22
25	-5.5751	-2.4443	0.5666	0.8478	0.6976	0.8679	0.783	-2.127	8
26	-6.0206	-2.4836	0.6617	0.8501	0.7472	0.8696	0.808	-1.847	4
27	-5.5751	-2.4640	0.5666	0.8489	0.6976	0.8688	0.783	-2.123	7

The CV3-FR3-DOC3 combined machining condition is predicted as an optimum process parameter. The predictable parameters are CV3 = 188 m/min, FR3 = 0.191 mm/rev, DOC3 = 0.8 mm

Table 8 S/N ratio Means (GRG)

Factors	Grey relational grade (GRG)				
	Level-1	Level-2	Level-3	Delta	Rank
CV	-3.612	-3.240	-2.795	0.817	3
FR	-3.789	-3.544	-2.313	1.476	2
DOC	-4.308	-3.399	-1.939	2.369	1

are well in concurrence with the outcomes from the past writing [19, 20].

$$\beta_{predicted} = \beta_m + \sum_{i=1}^n (\beta_o - \beta_m) \quad (17)$$

β_m = Average of total GRG. β_o = Mean of the GRG at the optimal levels, n = Total number of machining factors

The performance characteristics of the TOPSIS approach for the turning operation is shown in Table 10. Taguchi's

Fig. 8 Means of S/N ratio (TC-GRA)

S/N is resolved depends on the goal of larger the better one for closeness coefficient value and it is graphically shown in Fig. 9. The methods for the S/N for the process parameters levels were determined and are appeared in Table 11. The predicted optimal parameter combination is

Table 9 Validation of GRG optimum condition

	Input machining conditions	Optimized process parameters using GRA	
		Predicted	Experiment
Levels	CV ₁ -FR ₂ -DOC ₂	CV ₃ -FR ₃ -DOC ₃	CV ₃ -FR ₃ -DOC ₃
TWR (mg/min)	1.8		1.6
Ra (μm)	0.475		1.778
GRG	0.6243	0.9059	0.7672
The improvement in GRG = 0.1429			
The percentage improvement in GRG = 22.88%			

CV1-FR1-DOC1 and their particular levels are CV1 = 79 m/min, FR1 = 0.102 mm/rev, and DOC1 = 0.4 mm.

Confirmation turning experimentation is conducted to validate the optimum conditions predicted from the TC-TOPSIS (CV3-FR3-DOC3) technique.

Equation (18) has been used to determine the predicted Coefficient of Closeness value and it is tabulated in Table 12. It is referred that TWR and Ra are decreased from

1.8 to 1.4 mg/min, 0.475 to 0.373 μm, individually. The rate of improvement in the closeness coefficient is 1.2%.

$$\lambda_{predicted} = \lambda m + \sum_{i=1}^n (\lambda o - \lambda m) \quad (18)$$

λm = Average of total Coefficient of Closeness, λo = Mean of the Coefficient of Closeness at the optimal levels, n = Total number of machining factors.

3.4 Comparitive approach of TC-GRA and TC-TOPSIS

The confirmation test results for TC-GRA and TC-TOPSIS at the optimal testing conditions are measured and summed up in Table 13. In the present study, Linear Normalization for TC-TOPSIS and Linear Normalization based on maximum-minimum for TC-GRA were used may result in contradiction results. Tripathy et al. [31] obtained similar observations on the use of GRA and TOPSIS.

The significant levels of FR and the associated impact of FR and DOC are the elements affecting the Ra adequately.

Table 10 Performance characteristics in TOPSIS

S.N	Normalized data		Weighted data		Separation measures		Closeness coefficient	S/N ratio	Rank order
	TWR	Ra	TWR	Ra	TWR	Ra			
1	0.1709	0.0653	0.0854	0.0327	0.5896	0.5445	0.5567	-5.087	1
2	0.1602	0.0683	0.0801	0.0341	0.5842	0.5344	0.5480	-5.224	2
3	0.1602	0.0642	0.0801	0.0321	0.5616	0.5237	0.5348	-5.436	3
4	0.1816	0.0912	0.0908	0.0456	0.5540	0.5115	0.5241	-5.612	4
5	0.1816	0.0864	0.0908	0.0432	0.5318	0.5010	0.5111	-5.829	5
6	0.1922	0.0879	0.0961	0.0440	0.5292	0.4908	0.5035	-5.959	6
7	0.2456	0.1829	0.1228	0.0914	0.5280	0.4798	0.4960	-6.090	14
8	0.2456	0.1847	0.1228	0.0924	0.5356	0.4786	0.4977	-6.060	12
9	0.2563	0.1834	0.1282	0.0917	0.5437	0.4775	0.4997	-6.025	9
10	0.1602	0.1634	0.0801	0.0817	0.5546	0.4762	0.5024	-5.978	8
11	0.1602	0.1612	0.0801	0.0806	0.5486	0.4723	0.4980	-6.056	11
12	0.1709	0.1625	0.0854	0.0813	0.5424	0.4679	0.4930	-6.143	16
13	0.2029	0.2602	0.1015	0.1301	0.5375	0.4633	0.4884	-6.224	18
14	0.1922	0.2473	0.0961	0.1236	0.5383	0.4713	0.4941	-6.123	15
15	0.1922	0.2456	0.0961	0.1228	0.5370	0.4782	0.4984	-6.048	10
16	0.2243	0.0487	0.1121	0.0243	0.5357	0.4856	0.5030	-5.969	7
17	0.2243	0.0474	0.1121	0.0237	0.5409	0.4617	0.4898	-6.200	17
18	0.2349	0.0466	0.1175	0.0233	0.5465	0.4322	0.4737	-6.491	23
19	0.1602	0.3287	0.0801	0.1644	0.5550	0.3937	0.4541	-6.857	27
20	0.1709	0.3304	0.0854	0.1652	0.5474	0.4141	0.4650	-6.650	25
21	0.1602	0.3282	0.0801	0.1641	0.5415	0.4393	0.4795	-6.385	21
22	0.1602	0.1653	0.0801	0.0826	0.5330	0.4710	0.4961	-6.088	13
23	0.1495	0.1642	0.0748	0.0821	0.5238	0.4608	0.4867	-6.255	19
24	0.1495	0.1634	0.0748	0.0817	0.5111	0.4480	0.4743	-6.479	22
25	0.2029	0.2452	0.1015	0.1226	0.4971	0.4316	0.4594	-6.757	26
26	0.2136	0.2464	0.1068	0.1232	0.4970	0.4478	0.4693	-6.572	24
27	0.2029	0.2458	0.1015	0.1229	0.5000	0.4697	0.4834	-6.314	20

Fig. 9 Means of S/N ratio (TC-TOPSIS)

Table 11 S/N ratio means (closeness coefficient)

Factors	Closeness coefficient				Rank
	Level-1	Level-2	Level-3	Delta	
CV	-5.705	-6.139	-6.488	0.783	1
FR	-5.982	-6.071	-6.278	0.296	3
DOC	-5.918	-6.138	-6.276	0.358	2

Table 12 Validation of TOPSIS optimum condition

	Input machining conditions	Optimized process parameters using TOPSIS	
		Predicted	Experiment
Levels	CV ₁ -FR ₂ -DOC ₂	CV ₁ -FR ₁ -DOC ₁	CV ₁ -FR ₁ -DOC ₁
TWR (mg/min)	1.8		1.4
Ra (μm)	0.475		0.373
Closeness Coefficient	0.5035	0.5384	0.5098
The improvement in closeness coefficient = 0.0063			
The percentage improvement in closeness coefficient = 1.2%			

The high level of FR reduces the contact time of the tool with the workpiece material. Meanwhile, the higher DOC creates more vibration on the tool, which prompts the chattering of the tool. This activity makes the waviness on the surface of the workpiece. Whereas for the TC-TOPSIS

method, the optimized cutting condition is predicted as CV₁-FR₁-DOC₁. The lower level of process parameters (CV, FR, and DOC) will enhance the tool life with an acceptable level of Ra. Product life is estimated depending on the surface quality of the part and the manufacturing cost is estimated depending on the tool life. The observations resulted in the TWR and Ra recorded for optimal cutting conditions through the TC-TOPSIS approach is better. From the above discussions, it might be summed up that the dry turning machining characteristics on the CT tungsten carbide insert have improved during the machining of the Al6063 material by using Taguchi's coupled TOPSIS technique.

4 Conclusions

The turning studies on cryogenic treated insert on machining Al6063 alloys at different turning parametric conditions for TWR and Ra as a response are measured using TC-GRA and TC-TOPSIS strategy. The CT enhances the micro-hardness up to 5.7% with the newly formed uniform eta (η) carbide particles dispersion in the voids. The maximum reduction in TWR and Ra is observed for deeply cryo treated insert and the percentage of reduction vary between 8.3 to 32.1%, and 2.6 to 21.4%, respectively. The effect of the machining parameters on TWR will be in the order of FR followed by DOC and CV. Ra is highly influenced by the DOC and CV where the FR effect is found to be low. The optimum cutting conditions were assessed through the TC-GRA as CV₃-FR₃-DOC₃ and for TC-TOPSIS as CV₁-FR₁-DOC₁. The decrease in TWR and increase in Ra is recorded for TC-GRA and their rates are 11.11%, and 274%, respectively whereas, for the TC-TOPSIS approach, the TWR and Ra were decreased at a rate of 22.2%, and 21.4%, individually. Subsequently, the TC-TOPSIS technique is reported to be a suitable method for solving multi-response problems within a given scope of process variables under dry turning conditions. For the Metal cutting industries, the TC-TOPSIS technique is recommended while performing dry turning on Al6063 alloy. The mathematical complexity in the Taguchi incorporated TOPSIS method is very minimum and it will no way affect solving

Table 13 Comparison of validated results of GRA and TOPSIS

Responses	Initial cutting condition	Optimal cutting conditions		Percentage change in optimal results over results from the initial condition	
		GRA	TOPSIS	GRA	TOPSIS
	CV ₁ -FR ₂ -DOC ₂	CV ₃ -FR ₃ -DOC ₃	CV ₁ -FR ₁ -DOC ₁	CV ₃ -FR ₃ -DOC ₃ (%)	CV ₁ -FR ₁ -DOC ₁ (%)
TWR (mg/min)	1.8	1.6	1.4	11.1 reduction	22.2 reduction
Ra (μm)	0.475	1.778	0.373	274 increment	21.4 reduction

the multi-response optimization problems. The effect of temperature cannot be neglected at dry machining conditions which has a direct influence on TWR and Ra. Through non-contact mode, the effect of machining temperature has to be reported in later studies.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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