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PREDICTING THE OPTIMAL PARAMETERS BY MULTI-OBJECTIVE DECISION MAKING WHILE MACHINING AN Al6061 ALLOY USING CBN INSERTS WITH DIFFERENT CUTTING-EDGE GEOMETRIES

NAPOVED OPTIMALNIH PARAMETROV MEHANSKE OBDELAVE Al6061 S CBN VLOŽKI IN RAZLIČNO GEOMETRIJO REZALNIH ROBOV S POMOČJO MODM METODE

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The present work aims to investigate the effect of cutting-tool edge geometry on cutting force and surface finish while machining an Al6061 alloy under different conditions. A series of experiments was performed with a custom-fabricated cutting insert of a chamfered edge to observe the effect of feed rate and depth of cut on the cutting forces and surface finish. The results showed that varying the cutting-edge geometry has a significant effect on controlling the cutting forces. Also, as the feed and depth of cut were reduced (at high cutting speeds), the surface roughness was observed to reduce with the geometry effect. Furthermore, in the present work validation of the experimental results were also performed based on a multi-criteria decision-making method called Grey Relational Analysis (GRA). The weighted GRA predicted the optimal combination of machining parameters for two different cutting-tool inserts. Finally, the obtained optimal results were compared with the predicted and experimental values in terms of weighted GRG. The result shows that there was no significant improvement while using the standard cutting tool, whereas a net improvement of 16.9 % was observed while using the chamfered cutting tool for machining the Al 6061 alloy.

Keywords: cutting forces, surface roughness, machining Al 6061, GRA

V članku avtorji opisujejo raziskavo vpliva geometrije posnetja robov rezalnega orodja z vložki iz kubičnega bornitrida (CBN) na sile rezanja in finiš površine med mehansko obdelavo aluminijeve zlitine vrste Al6061 pri različnih pogojih mehanske obdelave. Avtorji so izvedli vrsto preizkusov mehanske obdelave z doma izdelanimi rezalnimi vložki z različno posnetimi robovi, da bi lahko opazovali vpliv hitrosti podajanja in globino reza na rezalne hitrosti in gladkost površine. Rezultati so pokazali, da ima variranje geometrije rezalnih robov pomemben vpliv na kontroliranje rezalnih hitrosti. Zmanjšala sta se hitrost odvzema in globina reza pri večjih rezalnih hitrostih. Prav tako pa je geometrija vplivala na zmanjšanje hrapavosti površine. V članku opisujejo tudi ovrednotenje eksperimentalnih rezultatov z metodo odločitve na osnovi več objektnih kriterijev (MODC; angl.: Multi Objective Decision Criteria) na osnovi relacijske analize v »sivini« (GRA; angl.: Grey Relational Analysis). S pomočjo analize GRA so avtorji napovedali optimalno kombinacijo parametrov mehanske obdelave za dve različni vrsti rezalnih vložkov. Dobljene napovedane vrednosti optimalnih parametrov so avtorji primerjali z eksperimentalnimi glede na analize GRG (angl.: Grey Rational Grade). Rezultati so pokazali, da ni prišlo do bistvenih izboljšav, če so uporabili standardne rezalne vložke. Medtem, ko je uporaba posnetih rezalnih orodji pokazala, da je pri mehanski obdelavi aluminijeve zlitine vrste Al 6061 prišlo do 16,9 %-nega neto izboljšanja.

Ključne besede: sile rezanja, površinska hrapavost, mehanska obdelava zlitine vrste Al 6061, metoda relacijske analize v "sivini"

1 INTRODUCTION

Present industrial advancements concentrate on improving the quality of manufactured parts with minimal energy consumption, thereby minimizing the cost of manufacturing. The Al 6061 alloy is a widely used material in the manufacturing of automobile and aircraft parts due to its high machinability index, high strength-to-weight ratio, and excellent corrosion resistance. Carbon steel was used as the first cutting tool material and nowadays after a lot of discussion and studies, many researchers use carbide as a cutting material in industry[1] (M. Rasidi Ibrahim and A. Afiff Latif 2017). The quality of a manufactured part depends on surface integrity of the material but using carbide tools, excessive tool wear and poor surface finish on Al alloys was observed. Machining Al alloys has consistently created a challenge for a better quality finish. To overcome this difficulty, researchers have tried high-speed machining operations using a tool to provide suitable tool life and better surface finish for Al alloys. Zebala et al.[2] discussed the machining of sintered carbides using CBN tools with three different nose radii. The cutting forces were used to determine the equations for the growth of the components, machining time, and tool wear. The obtained equations were used to optimize the WC-Co turning process using

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CBN tools with the maximum metal-removal rate. Li and Seah[3] and Dabade et al.[4] conducted a turning operation on AA2124/SiCp composite with PCD/CBN tool. Further, Zhijin and Hongjun[5] discussed the optimum geometric parameters of the CBN tool for cutting Al-Si alloys. Bhushan et al.[6] studied the influence of cutting speed, feed rate, and depth of cut on surface roughness while machining the Al 7075 metal matrix composites using the PCD tool. Özel, T. K. Hsu et al..[7] investigated the influence of cutting-edge geometry, work-piece hardness, cutting speed, and feed rate on the resultant force and surface roughness during the hard turning of AISI H13 steel. It was found that cutting-edge geometry, work-piece hardness, cutting speed, and feed rate on the surface roughness are statistically significant.

Grey relational analysis (GRA) is used to determine the optimum conditions of various input parameters to obtain the best quality characteristics. GRA is widely used for measuring the degree of relationship between sequences by grey relational grade. In GRA to calculate the grey relational grade weighted sum of the grey relational coefficients is required. Weights are calculated using different methods like entropy, principal component analysis, etc. Padhy and Singh investigated the optimal cutting parameters during the dry hard machining of Inconel 625 with the use of the Taguchi-based Grey relational analysis method.[8]

In the metal-cutting industries, achieving better surface integrity while machining Al 6061 alloy is highly challenging owing to tool build up edge (BUE) resulting from the work-material adhesion. Tools with BUE will generate higher cutting forces and may gradually lead to catastrophic failure of the tool, effecting the total production cycle. This is of greater concern as the current manufacturing industries are moving towards the concept of sustainable manufacturing. Based on the previous research, it can be observed that many researchers had worked on machining various materials using different tools, whereas only a very few researchers have used entropy GRA for determining the optimal machining parameters. This forms the major objective of the present work to perform turning experiments and also to use the entropy GRA method to predict the optimal machining parameters while turning the Al6061 alloy using a CBN cutting tool of different cutting-edge geometry. The weighted sum of the GRA is called the Grey Rational Grade. But many methods and tools are used to improve the surface finish while machining the aluminium and still research is continuing. In the present work the effect of chamfered PCD tool on the surface finish is investigated at low feed rates. **Figure 1** shows the relation between the input and output responses while turning the Al 6061 alloy in the current study.

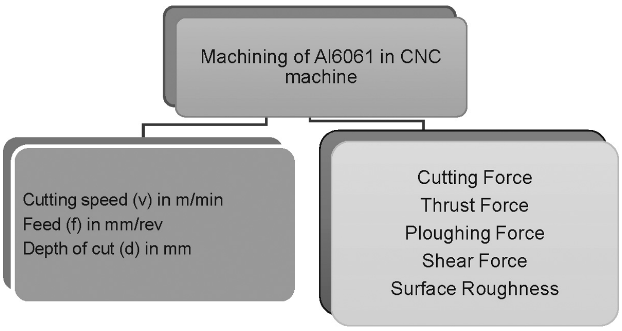

Figure 1: Schematic diagram shows the relation between the input and output responses

2 EXPERIMENTAL PART

In the current study, a turning operation on Al 6061 was performed using standard CBN tool and chamfered CBN tool. The experiments were carried out on ACE Designed W3117 CNC turning machine. The input parameters were varied during the operation and subsequently, the output parameters were determined. An entropy GRA approach was then employed to establish a correlation between the input variables and their performance characteristics. The considered input parameters and output responses are shown in **Figure 1**.

2.1 Work material

The material selected for turning operation in this investigation is the Al 6061 Alloy, and the chemical composition of the Al 6061 alloy is given in **Table 1**.

2.2 Cutting tool

A commercially available standard CBN and chamfered CBN tool were used for conducting the machining operation on the Al 6061 alloy. The tool's shape is a rhombus with an included angle of 80°, nose radius of 0.8 mm, edge length of 9 mm, inserts thickness of 4 mm, and shank cross-section of 13 mm × 3 mm. An *SCLCL 2020 K09T3* tool holder is used for holding the tool.

Table 1: Chemical composition of the Al 6061 alloy

Element	Composition (%)	Element	Composition (%)
Al	96.85	Cr	0.25
Mg	0.9	Zn	0.20
Si	0.7	Ti	0.10
Fe	0.60	Mg	0.05
Cu	0.30	Others	0.05

2.3 Experimental Design

To perform the machining operation, a limited number of experiments were designed using orthogonal experimental array design. The input parameters such as cutting speed, feed rate, and depth of cut are considered for conducting the machining operation on the Al 6061 alloy. Therefore, in the current study, an L9 orthogonal array that has 8 degrees of freedom will provide better results when selecting the machining parameters. The machining parameters are assigned in a row of the orthogonal array, and the combinations of machining parameters are nine, which is given in **Table 2**. The output variables (responses) considered for the current investigation are the cutting force, thrust force, shear force, ploughing force, and surface roughness.

Table 2: Input parameters and their levels for machining the Al 6061 alloy

Levels of factors	Input Parameters		
	Cutting speed (v) m/min	Feed rate (f) mm/rev	Depth of cut (d) mm
1	314	0.1	0.1
2	565	0.14	0.2
3	785	0.18	0.3

2.4 Experimental procedure

In the present work, the cutting speeds were maintained at different ranges of cutting speed from 314 m/min to 785 m/min, by maintaining the feed rates of 0.1 mm/rev, 0.14 mm/rev and 0.18 mm/rev and depth of cuts of 0.1 mm, 0.2 mm and 0.3 mm, respectively. There are two types of side edge chamfer CBN tools, such as 0 µm and 80 µm used for conducting the machining operation on the Al 6061 alloy. A three-component, piezo-electric dynamometer is mounted on the tool post to measure the various cutting forces: ploughing force, cutting force, shear force, and thrust force. The output of the dynamometer signal is amplified by using charge ampli?ers, which are acquired and sampled by a data-acquisition card and Kistler DynoWare software. By measuring the forces from the dynamometer, the ploughing force is determined by the equations from the referred analysis done on the slip-line method. Further, the surface roughness on the machined components was measured using a Mahr perthometer. It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. The cut-off length and sampling length for the measurements are 0.8 mm and 4.0 mm, respectively. **Figure 2** shows photographs of the piezo-electric dynamometer used for the force measurement and the Mahr perthometer used for the surface-roughness measurement, respectively.

2.5 Grey Relational Analysis (GRA)

To conduct the machining process on the Al 6061 alloy, nine different experiments were planed using orthogonal design analysis. Therefore, in GRA, the above nine different experiments can be considered as the nine subsystems. Moreover, the influence of the developed nine subsystems on the response variables, i.e., cutting force, thrust force, shear force, ploughing force, and surface roughness, is to be analyzed using the GRA technique. A grey relational analysis has been utilized to optimize the output responses in this study. The multiple

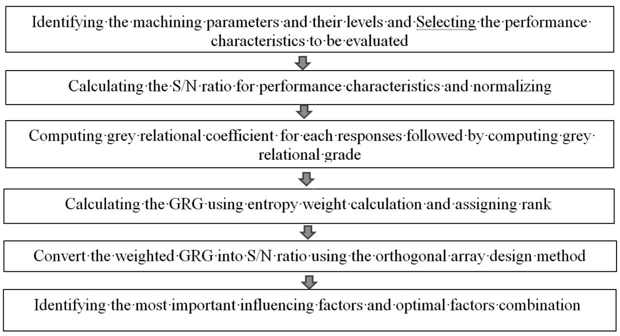

Figure 3: Flow chart showing the step-by-step procedure of GRA

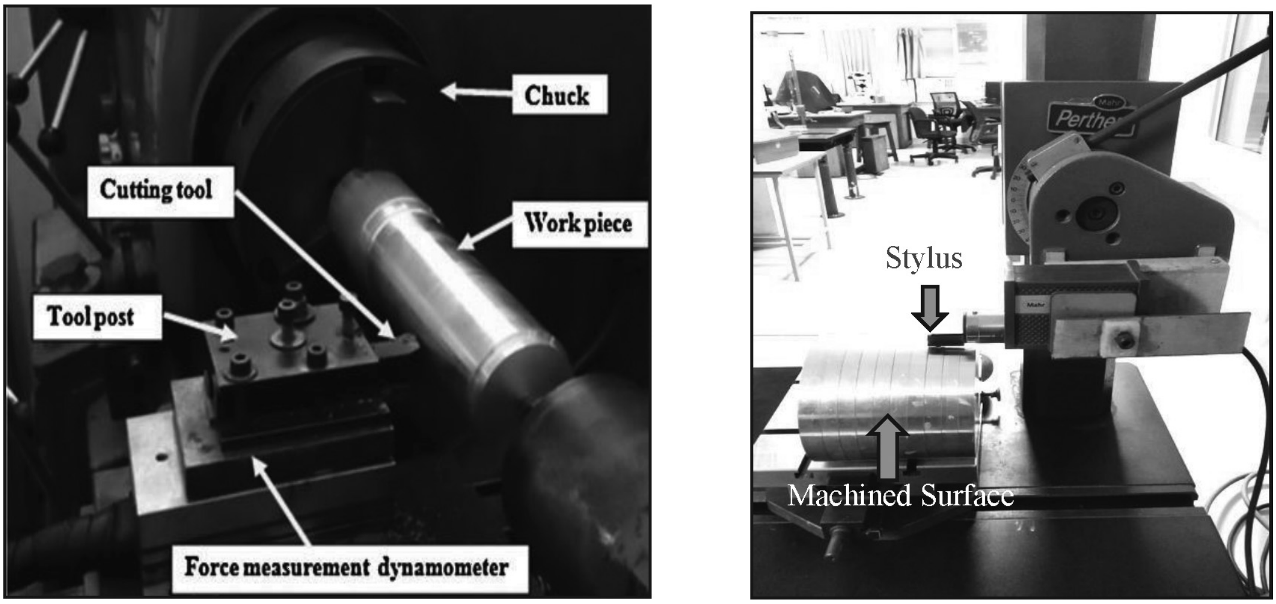

Figure 2: a) Machining unit with Force dynamometer, b) surface profile with Mahr Perthometer

Table 3a: Experiments designed using L_9 orthogonal array for Chamfered CBN cutting tool

No	*v* (m/min)	*f* (mm/rev)	*d* (mm)	F_c (N)	F_t (N)	F_s (N)	F_p (N)	*Ra* (µm)
1	314	0.1	0.1	281	255	81	299	0.446
2	314	0.14	0.2	294	286	96	313	0.434
3	314	0.18	0.3	298	329	83	361	0.532
4	565	0.1	0.1	307	221	131	285	0.514
5	565	0.14	0.2	315	286	156	290	0.486
6	565	0.18	0.3	358	294	124	138	0.458
7	785	0.1	0.1	383	294	145	338	0.581
8	785	0.14	0.2	384	307	160	331	0.479
9	785	0.18	0.3	419	288	229	280	0.517

Table 3b: Experiments designed using L_9 orthogonal array for CBN cutting tool

No	*v* (m/min)	*f* (mm/rev)	*d* (mm)	F_c (N)	F_t (N)	F_s (N)	F_p (N)	*Ra* (µm)
1	314	0.1	0.1	482	373	181	428	0.794
2	314	0.14	0.2	581	434	264	461	0.638
3	314	0.18	0.3	440	341	270	330	0.602
4	565	0.1	0.2	409	357	162	381	0.604
5	565	0.14	0.3	472	410	211	414	0.763
6	565	0.18	0.1	436	427	106	504	0.764
7	785	0.1	0.3	416	353	193	352	0.794
8	785	0.18	0.2	464	394	158	450	0.769
9	785	0.14	0.1	487	427	195	453	0.786

v – cutting speed; *f* – feed rate; *d* – depth of cut; F_c – cutting force; F_t – thrust force; F_s – shear force; F_p – ploughing force; *Ra* – surface roughness

characteristic optimizations using GRA was made based on the previous literature,[8] wherein the main steps are presented in **Figure 3**.

The corresponding highest-weighted GRG will provide the minimum values of the cutting force (CF), thrust force (TF), shear force (SF), ploughing force (PF), and surface roughness (SR) based on the systematic analysis. To minimize the five responses initially, the problem has been converted into a multi-objective optimization problem. It is stated as Minimization: *f* (CF, TF, SF, PF and SR)", the five forces considered are the function of input parameters, ranges of the independent input decision variables such as, cutting speed denoted as v (m/min); 314≤565≤785, feed rate represented as *f* (mm/rev); 0.1≤0.14≤0.18 and depth of cut indicated as *d* (mm); 0.1≤0.2≤0.3. Moreover, it can be observed that the number of output responses is high, and it is very difficult to minimize the responses. The multi-objective optimization problem has been converted into a single objective optimization problem using the GRA technique to overcome this difficulty in the present study. Further, the following subsections discussed the step-by-step procedure of the GRA optimization.[9]

3 RESULTS

The measured output responses, i.e., cutting force, thrust force, shear force, ploughing force, and surface roughness at various machining parameters using standard CBN cutting tool and chamfered CBN cutting tool,

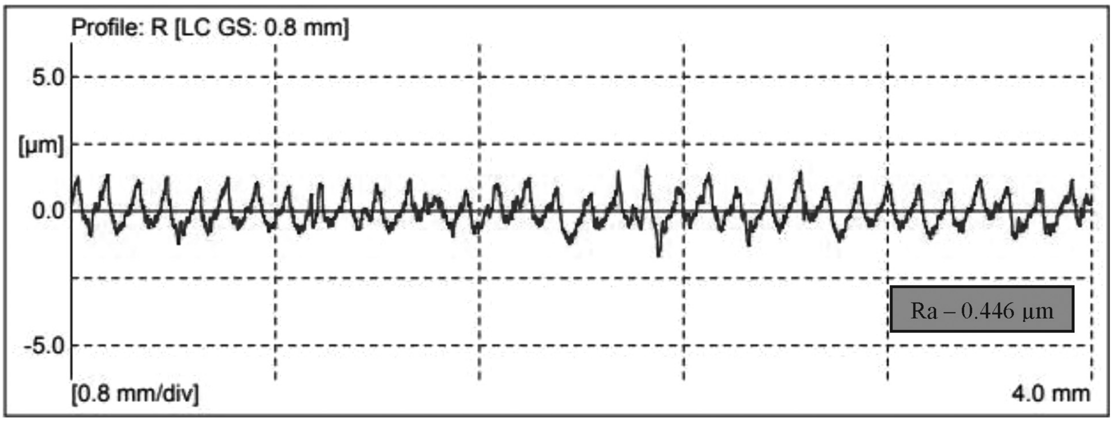

Figure 4: Surface-roughness profile obtained for the workpiece machined with standard CBN insert at 0.1 mm/rev feed rate, 314 m/min cutting speed 0.1 mm Depth of cut

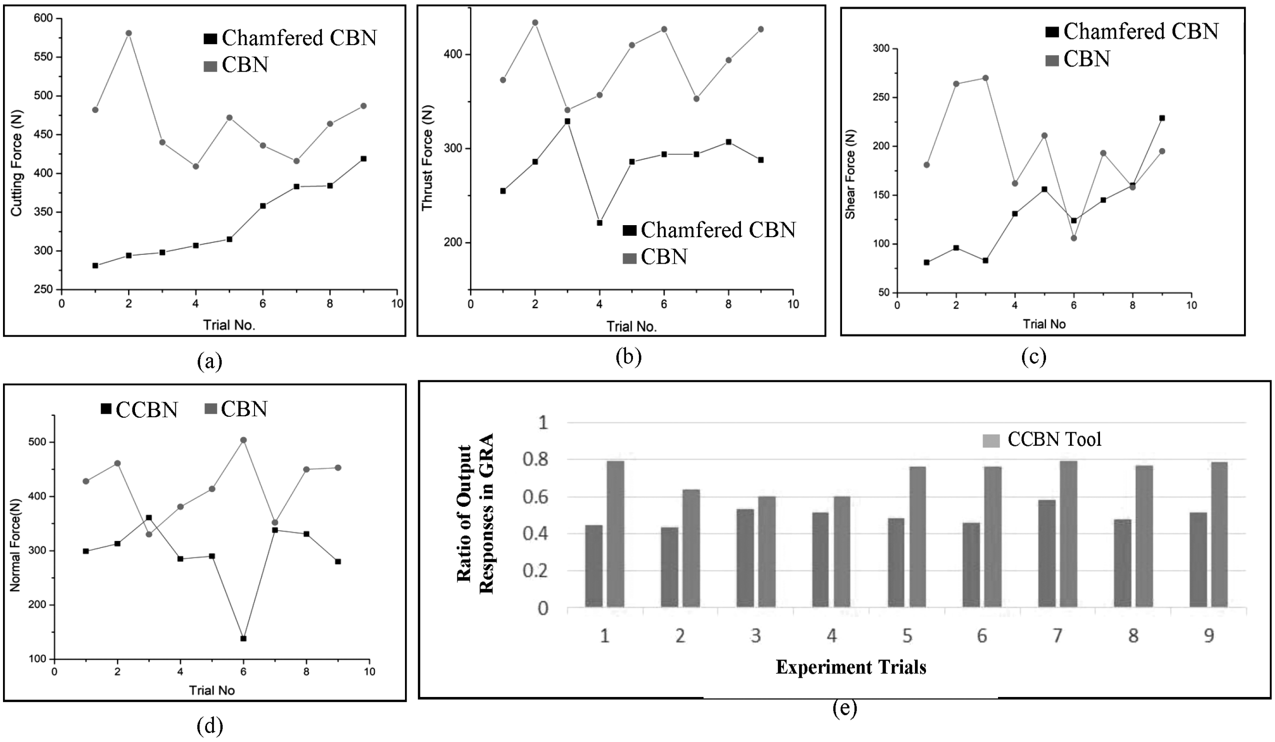

Figure 5: Variation in output responses: a) Cutting Force, b) Thrust Force, c) Shear Force, d) Ploughing Force, e) Average output responses tools vs Weighted ratios of CBN and CCBN tool.

are tabulated in **Table 3a** and **3b**, respectively. The details of the surface roughness measurement is shown in **Figure 4**.

The output responses such as cutting force, thrust force, shear force ploughing force and surface roughness with respect to each experimental trials are shown in **Figures 5a** to **5e**. It has been observed that the forces increase as the number of experiments increases in chamfered CBN cutting tool. Moreover, the surface roughness slowly increases along with the number of experiments in both and Chamfered CBN cutting tools. Further, the average of the cutting forces and surface roughness of CBN and chamfered CBN tools are shown in **Figure 6a** and **6b**. To conduct the machining operation on Al 6061 alloy using standard CBN and Chamfered CBN tools, lower cutting force, thrust force, shear force and ploughing force are performing better. Therefore, while evaluating data pre-processing in GRA, all output responses are considered as the "lower is better" (LB) and the normalized values of the output responses of the standard CBN and chamfered CBN cutting tools.

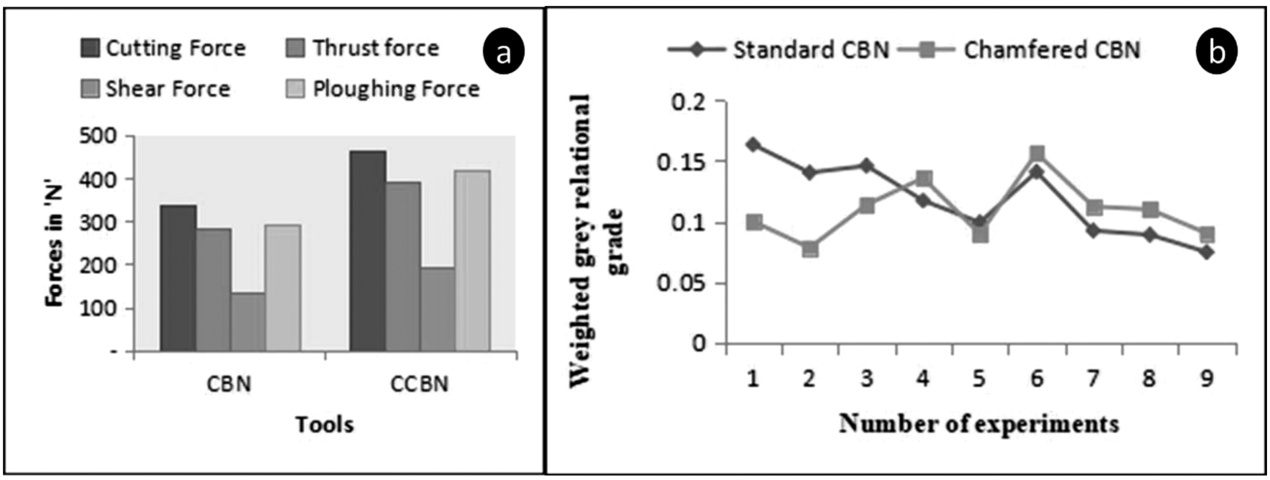

Figure 6: a) Result shows the average output responses tools vs forces, b) Weighted grey relational grade of standard and chamfered CBN tool with the number of experiments

4 DISCUSSION

Confirmation experiments were also performed three times and repeated at the optimum level of control parameters for standard CBN cutting tool (v_1-f_1-d_1) and chamfered CBN cutting tool v_2-f_3-d_1) to obtain the improvement of responses. In practice, providing numerical relative weights of different decision criteria is difficult, even for a single decision maker. It is, of course, harder to obtain parameter weights from several decision makers. Often, decision-makers are much more comfortable merely assigning ordinary ranks to the various criteria that are being considered. In such cases, relative weights of the criteria can be extracted from the ranks of criteria given by decision makers. The decision to select an appropriate weighting method is challenging to solve a decision problem with multi-criteria. It has also been found that there is no improvement between the predicted and experimental values of the standard CBN cutting tool. Because the initial machining parameter setting (v_1-f_1-d_1) and the optimal machining parameter setting (v_1-f_1-d_1) are the same. In the case of the Chamfered CBN tool, there is an improvement between the predicted and experimental values. The initial machining-parameter setting (v_1-f_1-d_1) of the weighted grey relational grade is 0.1564, and the optimal parameter setting is (v_2-f_3-d_1) of the weighted grey relational grade 0.1635.

Thus, the percentage improvement of the grey relational grade of the initial and optimal machining parameters for the standard CBN cutting tool is 0% and that for the chamfered CBN cutting tool is 15.65 %. It is found that the chamfered CBN cutting tool is performing better than the standard CBN cutting tool while obtaining the optimal machining parameters: cutting force, thrust force, shear force, ploughing force, and surface roughness using entropy GRA.

5 CONCLUSIONS

In this work, a multi-objective grey relational analysis was proposed to obtain the optimal machining parameters. The machined specimens' responses like cutting force, thrust force, shear force, ploughing force, and surface roughness were selected as quality targets. A total nine experiments are designed using the orthogonal array design of experiments. A multi-objective optimization problem has been converted to a single-objective optimization problem using GRA technique to optimize the output responses. The weights of the grey relational grade of the standard CBN and Chamfered CBN cutting tools are obtained from the entropy method. The conclusions of the present study are as follows:

- The process parameters were optimized and the optimal parameter were found to be 314 m/min of cutting speed, 0.10 mm/rev of feed and 0.1 mm of depth of cut for the standard CBN cutting tool. Whereas for the CBN chamfered tool the process parameters were noted to be 565 m/min of cutting speed, 0.18 mm/rev of feed and 0.1 mm of depth of cut.
- Optimization analysis showed an improvement in the value of predicted weighted grey relational grade from 0.1635 to 0.1812 and an increase in the value of experimental weighted grey relational grade from 0.0999 to 0.1564 for chamfered CBN tool. This confirms an improvement of 15.65 % in machining performance while using optimal parameters of chamfered CBN tools.
- Furthermore, the experimental analysis revealed a better machining performance (in terms of cutting force and surface roughness) while using the chamfered CBN cutting tool than the standard CBN cutting tool.

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