TOOL LIFE IN TURNING OF HYBRID COMPOSITES: TAGUCHI ANALYSIS

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Abstract

The study reveals that the hybrid metal matrix composite material's hardness is higher than that of Al6061 grade aluminum material, and its density is slightly lower. PVD coated carbide tools perform better than uncoated ones, and the feed rate has a more significant impact on tool life than cutting speed according to ANOVA analysis. The researchers also identified that the type of work material affects tool life by 21.8%, while feed per revolution affects tool life by 14.6%. In conclusion, the study's findings contribute to optimizing the turning process for hybrid metal matrix composite material, leading to more efficient and cost-effective manufacturing processes. The Taguchi L-16 orthogonal array was used for the experimental runs, and each parameter was selected within the acceptable range. The researchers turned a silicon carbide and red mud- enhanced hybrid metal matrix composite made of aluminum using a JOBBAR XL CNC lathe. Overall, this study provides valuable insights into improving productivity in the manufacturing of machine parts.

Keywords: Hybrid metal matrix composite material, Taguchi method, K20 grade, ANOVA analysis, Al6061 grade aluminum material, Taguchi L-16 orthogonal array, ISO3685.

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1. INTRODUCTION

Hybrid metal matrix composites (HMMCs) have gained increasing attention in recent years due to theirsuperior mechanical properties, including high strength, stiffness, and wear resistance. However, their machining is challenging due to the presence of multiple phases and abrasive particles in the matrix. Tool wear is a critical issue in the machining of HMMCs, which can result in high costs and decreased product quality. Therefore, optimizing tool life is crucial to minimize tool replacement frequency, reduce machining costs, and increase productivity. The Taguchi method is a statistical approach that has been widely used for process optimization in manufacturing. It allows for the determination of the optimal combination of machining parameters to achieve a desired performance measure while minimizing the effect of noise factors. In this experimental study, we aim to investigate the effects of machining parameters, such as cutting speed, feed rate, and depth of cut, on tool life in turning HMMCs using the Taguchi method. By using this method, we can identify the optimal machining parameters to achieve maximum tool life and minimize tool wear. The results of this study can provide insights into the machining of HMMCs and help manufacturers to improve their machining processes.

2. MATERIAL AND METHODS:

a. Work Materials

The study employed red mud and silicon carbide particles as reinforcement materials, and an Al6061 aluminium alloy as the matrix material. The specific chemical compositions of the reinforcements and the matrix material are presented in Tables 1, 2, and 3.

Table 1: Details of the chemical analysis of the aluminium alloy Al6061

Chemical composition	Mg	Si	Fe	Cu	Cr	Al
% wt	0.98	0.66	0.31	0.22	0.11	Rest

Table 2: Details of Redmud's chemical analysis

Chemical composition	Fe2O3	Al2O3	TiO2	SiO2	CaO
% wt	56.0	22.6	16.5	3.4	1.5

Table 3: Silicon Carbide Chemical Analysis Details

Chemical composition	Si	C	Al	Fe	Ca
% wt	62.0	26.5	2.5	0.56	0.60

2.2 Work material hardness measurement:

The hardness of both the matrix material and its composites was measured using a Brinell hardness testing machine. A steel ball indenter with a diameter of 10 mm and a standard load of 500 Kgf was used for the measurements.

2.3 Density Measurement of work materials

The density of the aluminium alloy and its composites was determined using the Archimedes immersion technique. As the presence of reinforcements can alter the properties of the work material, it was essential to monitor the density continuously during the casting process of the hybrid metal matrix composite material.

2.4 SEM - Microstructural analysis

Microphotographs of both the Al6061 aluminium alloy and its composite material containing 3% Redmud and 6% silicon carbide reinforcements were analyzed. SEM pictures of the hybrid metal matrix composite material revealed the presence of Redmud and silicon carbide particles.

2.5. Machine tool

The turning experiments were performed using the ACE Designs JOBBER XL CNC lathe as shown in Figure 1. An alternate pass approach was utilized to shape the newly developed hybrid metal matrix composite material. In order to eliminate experimental errors, the cutting tool wear was closely monitored and adjusted after each pass. Detailed information about the CNC lathe used in the experiments can be found in Table 4. The hybrid metal matrix composite material used in the tests had a diameter of 120 millimeters and a length of 300 millimetres.

Table 4: CNC Lathe specifications

A 270 mm maximum diameter can be machined.
A maximum length of 400 mm can be machined
Hydraulic job clamping system

Range of spindle speeds: 50 to 4000 RPM
CNC lathe dimensions in mm: 2200X1750X1750

Figure 1: JOBBER XL CNC Latheused for the experiment

2.6. Cutting Tools Used For The Experiment

The experiment involved the use of a standard Kennametal positive rake angle throwaway type turning tool holder, with tungsten carbide grade K20 throw-away type CCGT120404-AL inserts, both coated and uncoated, being employed in the trials. Coated tungsten carbide inserts are preferred for cutting tools due to their enhanced durability and consistency. Physical vapour deposition or chemical vapour deposition can be used to apply wear-resistant coatings such as titanium carbide, titanium nitrate, aluminium oxide, aluminium nitrate, and zirconium carbo nitride to cutting tools. To evaluate the coating's effectiveness, various techniques were employed, including exposing the cutting tool to a rotating ball to create a spherical depression on its surface. The diameter of the resulting dent was then used to determine the coating's thickness on the cutting tool. Figure 2 provides a visual representation of the experimental cavity produced on the coated insert. The experimental results revealed that the coating thickness of the TiN coated insert used for the experiment was measured 4.16microns.

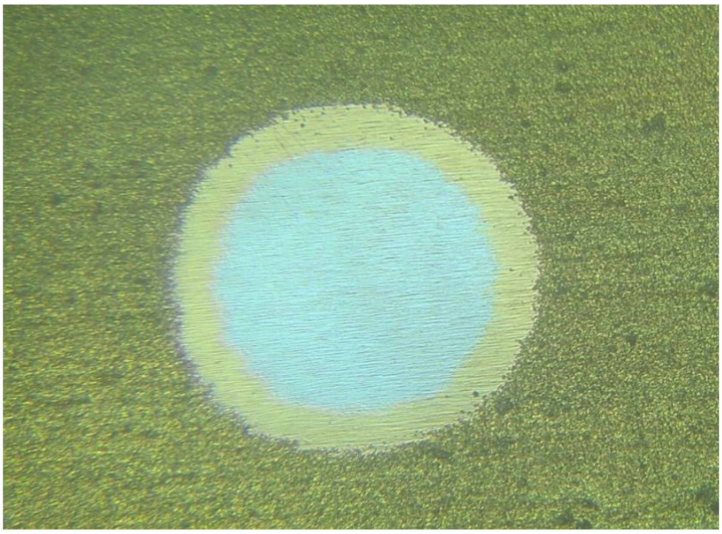


Figure 2: Cavity formed on the coated insert used for experiments

2.7 Tool Life Analysis Using Design of Experiments

For the tool life test of the composites, identical-style coated and uncoated inserts were utilized. To analyze the impact of individual components and their interactions, the researchers employed the Design of Experiments (DoE) methodology. This methodology enables researchers to systematically design experiments, collect data, and analyze the results to identify the most significant factors that affect the response variable. By using the DoE methodology, the researchers were able to determine the effects of the coating on tool life and other key performance indicators, as well as the interaction between the coating and other factors.

Table 5: Selection of factors and levels

FACTORS		LEVELS			UNIT	DoF
A	Work material	Al6061	Hmmcs			1

B	Cutting speed	300	400	500	m/min	2
C	Feed per rev.	0.06	0.12	0.18	mm/rev.	2
D	Cutting tool	Uncoated, K10	Coated, CK10			1
INTERACTION						
AD						1
BD						2
CD						2

During the experiment, the researchers varied the machining parameters, specifically the cutting speed and feed, while keeping the depth of cut constant. Additionally, the cutting tool overhang remained consistent throughout the trial. Table 5 presents the selected factors and their interactions, while Table 6 provides a list of the constant parameters employed in the experiment.

Table 6: Constant parameters

Tool holder over hang	30 mm
Depth of cut	1.5 mm
Type of machining	Dry machining

2.8 Design of the experiment:
To account for the 11 degrees of freedom in the experiment, a minimum of 12 experiments were required. The closest orthogonal array was found to be L16. Figure 2 displays the required linear graph for the experiment. As the experiment involved three-level components, an idle column method was added to support the two-level array. Figure 5 displays the updated linear graph, which was derived after comparing the required linear graph in Figure 3 with the standard linear graph shown in Figure 4.

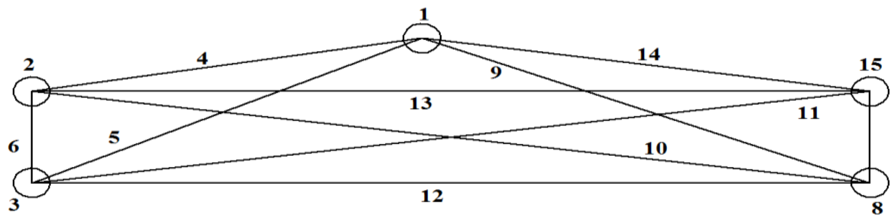


Figure 3: Needed Linear Graph

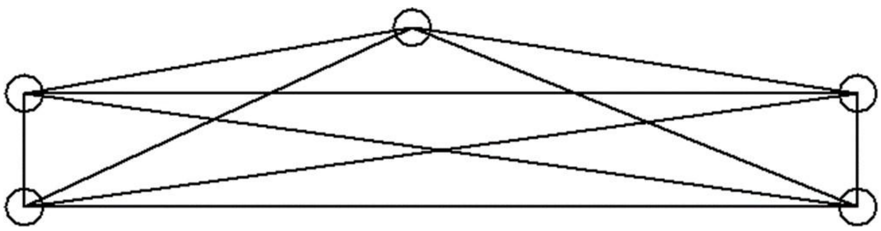


Figure 4: Standard Linear Graph

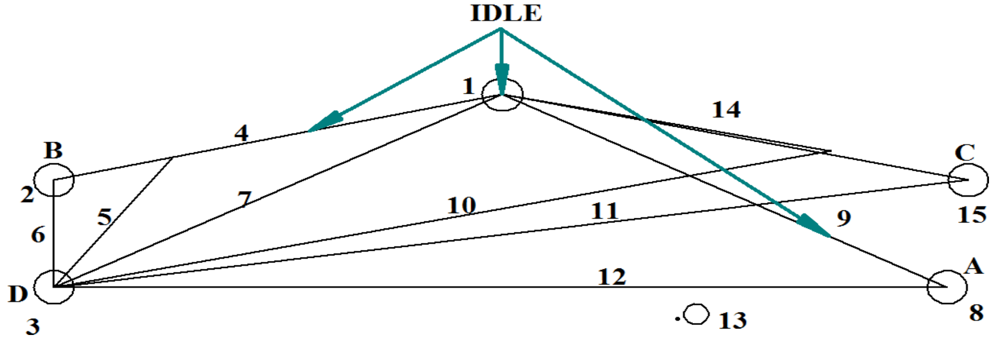


Figure5: Updated Linear Graph

In the updated linear graph shown in Figure 5, certain columns have been left empty, indicating that no factor was assigned to them. This was done because some amount of the major influence of the three-level factors could potentially be confused with factors 1, 4, and 9. Therefore, to avoid any confusion, these columns were left empty in the linear graph.

3. Results And Discussion

In this section, the results of the experiments conducted were summarised and discussed. Specifically, the hardness of both the matrix and composite material was examined at various locations on the specimen to determine the uniformity of the hardness. The findings showed that the composite material had a higher hardness than the alloy, and that its hardness was relatively homogeneous throughout. Figure 6 illustrates the correlation between the hardness of the matrix material and the hybrid metal matrix composite materials.

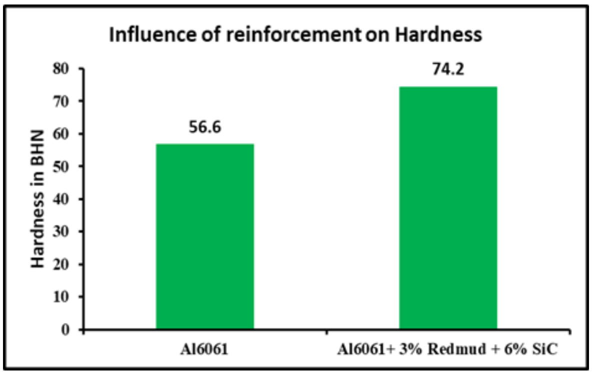


Figure 6: Influence of Reinforcement on the work material's hardness

a. Results of Density Measurement

The findings of the density measurement showed that the density of hybrid metal matrix composite was found to be marginally higher. This may be because silicon carbide particles are present, since the density of silicon carbide particles is more than that of aluminium alloy. Figure 7 illustrates how the addition of reinforcement affects the overall density of the material.

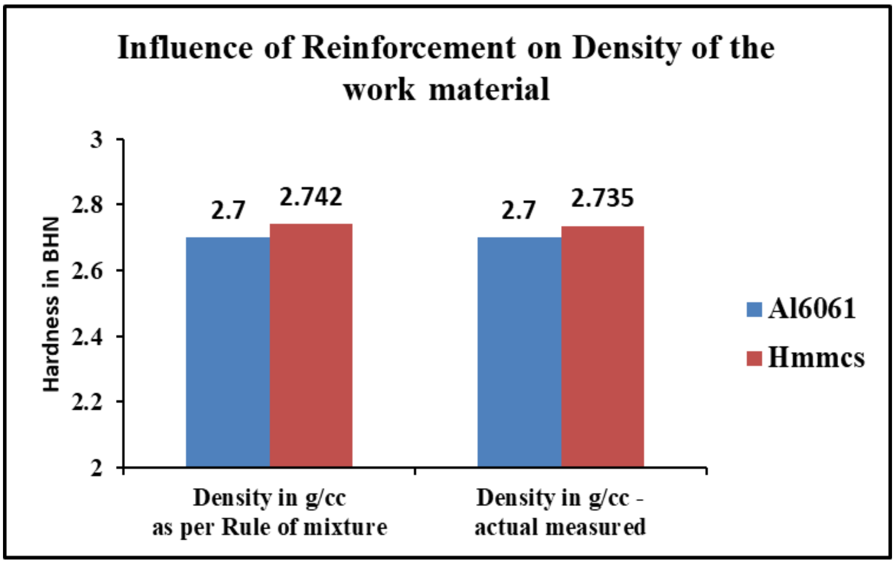


Figure 7: The effect of reinforcement on the material's density

3.2 Results of SEM analysis

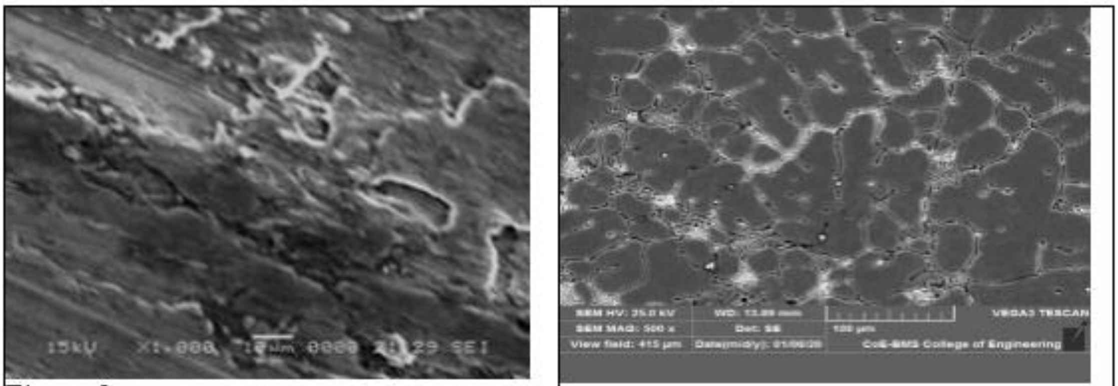


Figure 8a Figure 8b

Figure 8(a)-8(b): shows SEM pictures of an aluminium alloy of the Al6061 grade and hybrid composite made of 3% Redmud and 6% silicon carbide particles.

Figures 8a and 8b depict scanning electron micrographs of the Al6061-grade aluminium alloy and hybrid composite made up of 3% Redmud and 6% silicon carbide particles. The SEM examination of the Redmud and silicon carbide particles-reinforced composite was carried out using a TESCON-VEGA 3 LMU scanning electron microscope. The SEM analysis of the machined parts showed that the redmud and silicon carbide particles were evenly dispersed throughout the composites, with minimal void space. Specifically, the particles of redmud and silicon carbide were uniformly dispersed, leading to an even distribution of these particles within the hybrid composite material.

4. Findings of the experiments on tool life:

The experiments conducted involved varying parameters according to the physical layout, and the results are presented in Table 7. The statistical analysis of these experiments is shown in Table 8. It was observed that when turning Al6061 grade aluminium alloy with a cutting speed of 400 m/min and a feed rate of 0.06 mm/revolution, the coated carbide inserts exhibited a tool life of 36.27 minutes. On the other hand, when turning the hybrid metal matrix composite material at a cutting speed of 300 m/min and a feed rate of 0.06 mm/revolution, the longest tool life of 11.63 minutes was achieved with coated carbide inserts. When turning the hybrid metal matrix composite material with uncoated carbide inserts at a cutting speed of 500 m/min and a feed rate of 0.18 mm/rev, the tool life was just 2.88 minutes. It is noteworthy that when the tool fails during continuous turning due to any kind of damage exceeding 0.3 mm such as flank wear, cutting edge spalling, notch wear, nose deformation, or crater wear, the turning operation must be stopped.

Table7: Experimental results of various parameters in accordance with the physical arrangement

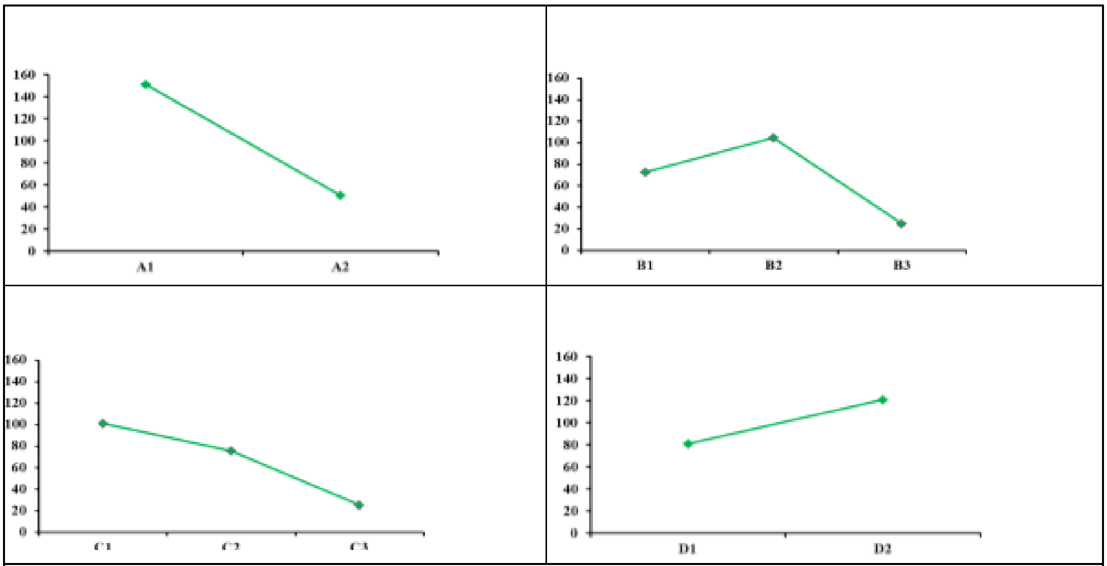
Expt. No.	**Work material**	**Cutting tool**	**Cutting speed in m/minutes**	**Feed per rev. in mm**	**Tool life in minutes**
1	Al6061	Uncoated	300	0.06	**24.22**
2	Hmmcs	Uncoated	300	0.12	**8.48**
3	Al6061	Coated	300	0.12	**28.11**
4	Hmmcs	Coated	300	0.06	**11.63**
5	Al6061	Uncoated	400	0.12	**14.08**
6	Hmmcs	Uncoated	400	0.06	**7.24**
7	Al6061	Coated	400	0.06	**36.27**
8	Hmmcs	Coated	400	0.12	**6.02**
9	Al6061	Coated	400	0.12	**21.62**
10	Hmmcs	Coated	400	0.18	**4.86**
11	Al6061	Uncoated	400	0.18	**10.14**
12	Hmmcs	Uncoated	400	0.12	**4.29**
13	Al6061	Coated	500	0.18	**7.23**
14	Hmmcs	Coated	500	0.12	**5.11**
15	Al6061	Uncoated	500	0.12	**8.36**

16	Hmmcs	Uncoated	500	0.18	**2.88**

Table 8: ANOVA analysis

Source	**DoF**	**SS**	**MS**	**F Ratio**	**ɩ%**
A	1	632.94	632.94	17.35	23.80
B	2	288.40	144.20	3.95	9.90
C	2	471.20	235.60	6.45	16.60
D	1	100.25	100.25	2.74	4.30
AD	1	19.60	19.60	0.53	2.00
BD	2	396.72	198.36	5.43	13.33
CD	2	355.37	177.68	4.87	12.35
Error	--	36.48	36.48		
Idle 1	--	314	314		
Idle 4	--	24.33	24.33		
Idle 9	--	87.61	87.61		
TSS = 2726.9					

Design of experiments was utilised to analyse the effect of filler material in Hmmcs on the tool life of disposable type inserts in continuous turning operations. Figure no. 9 depicts the optimal interplay of these variables.



A1B2C1D2 is the optimum combination

Figure 9: optimum combination of parameters

The study identified A1B2C1D2 as the best feasible combination. However, the primary objective of the study is to explore the effectiveness of Hmmcs in the industrial setting and identify the optimal machining parameters that can enhance productivity and reduce machining time. Therefore, verification tests were conducted on both Al6061 and Hmmcs, using both uncoated and coated carbide inserts with C1D2 combination. The results of these verification tests are presented in Table 9 and Figure 10.

Table 9 : Verification test

Insert type	**Al6061**				**Hmmcs**			
	Trial 1	Trial 2	Trial 3	**Avg.**	Trial 1	Trial 2	Trial 3	**Avg.**
Uncoated	19.57	18.84	19.55	**19.32**	7.44	6.91	7.38	**7.24**
Coated	37.43	35.12	36.31	**36.28**	10.45	10.98	10.62	**10.68**

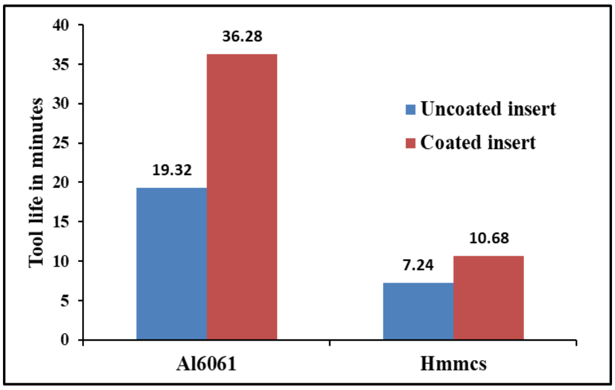


Figure 10 : Effect of insert type on tool life

The graph in Figure 10 shows that the coated carbide inserts had a longer tool life than the uncoated carbide inserts for both Al6061 and Hmmcs, when cutting at a cutting speed of 400 m/min and a feed rate of 0.06 mm/rev. The difference in tool life between the coated and uncoated inserts was more pronounced for the Hmmcs material, indicating that the coating provided better wear resistance when machining the composite material.

4. Conclusions

After performing research to investigate the machinability of Al6061 grade aluminium alloy and its composites reinforced with redmud and silicon carbide particles using PVD coated carbide and uncoated carbide inserts, the following conclusions were drawn:

- It was discovered that the hardness of the hybrid metal matrix composite material is significantly higher than that of the Al6061 grade of aluminium material.
- The density of the Al6061 grade aluminium material was slightly lower than that of the hybrid metal matrix composite material, which had a little higher density.
- An investigation performed with a scanning electron microscope demonstrates that the reinforcing particles are distributed evenly throughout the hybrid metal matrix composite material.
- After conducting the experiments and conducting the analysis of variance, it was shown that the type of insert had the most significant effect on the tool's longevity.
- The evaluation was carried out using uncoated and PVD-coated carbide tools that were utilised in the experiment respectively. After comparing the results, it was discovered that PVD coated carbide tools performed better than uncoated carbide tools when it came to the overall performance of the tools.
- The results of the experiments and the analysis of variance indicated, among other things, that the feed rate has the most significant influence on tool life, and that cutting speed is the next cutting parameter that adds to the overall equation. According to test results, $A_1B_2C_1D_2$ is the best possible combination, which gives highest tool life.
- According to ANOVA analysis, the type of work material affects tool life by 21.8%, while feed per revolution affects tool life by 14.6%.
- Confirmation tests were also run, and the outcomes were compared to the projected values derived by combining the best possible parameters from the Taguchi analysis.

Declarations:

➢ **Availability of data and material**

Access to underlying research materials is available upon request.

➢ **Competing Interests**

The authors declare that they have no competing interests.

➢ **Funding**

No funding was obtained for this study.

➢ **Authors' contributions**

All authors have read and approved the manuscript and contributed equally.

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