FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 8 No. 5, October, 2024, pp 143 - 151
DOI: https://doi.org/10.33003/fjs-2024-0805-2781

COMPARATIVE STUDY OF DIFFERENT CUTTING FLUIDS ON TOOL-WORK INTERFACE TEMPERATURE DURING TURNING OPERATION ON 6061 ALUMINUM ALLOY

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ABSTRACT

This study investigated the impact of tool-work interface temperature during the turning process of a cylindrical workpiece made of 6061 aluminum alloy. The experiment utilized four different cutting fluids: palm oil-based cutting fluid (POBCF), neem seed oil-based cutting fluid (NOBCF), orange seed oil-based cutting fluid (OSOBCF), and mineral oil-based cutting fluid (MOBCF) using uncoated carbide cutting tool of grade H13A. Various machining parameters were considered, including spindle speed (180, 250, 355, 500 rpm), feed rate (0.105, 0.116, 1.4, 1.6 mm/rev), and depth of cut (0.5, 1.0, 1.5, 2.0 mm). The experimental design followed the Taguchi specified L16 (4^3) orthogonal array and was conducted on a Lathe Machine XL 400. To measure the tool-work interface temperature, an infrared thermometer (KM 690) was employed during the aluminum alloy machining process. Subsequently, a mathematical model for the tool-work interface temperature values was developed through regression analysis using Minitab 16. The significance of the chosen machining parameters and their respective levels on the tool-work interface temperature was determined using analysis of variance (ANOVA) and F-test. The findings indicated that machining under orange seed oil-based cutting fluid (OSOBCF) conditions resulted in a 9.02%, 16.4%, and 21.7% lower temperature at the tool-work interface compared to palm oil-based cutting fluid (POBCF), neem seed oil-based cutting fluid (NOBCF), and conventional oil-based cutting fluid (MOBCF), respectively. This suggests a potential for producing higher-quality products under orange seed oil cutting fluid conditions compared to other wet conditions.

Keywords: 6061 Aluminum alloy, Tool-work interface temperature, Cutting fluid, ANOVA

INTRODUCTION

In metal cutting machining operations, the effective use of lubricants is crucial for maintaining optimal manufacturing conditions (Walker, 2023). These conditions, characterized by specific process parameters, contribute to the production of high-quality machine components (Selvam and Senthil, 2016; Ruibin and Wu, 2016). Over 95% of the total energy supplied to the machine tool is transformed into heat as a result of the relative motion between the cutting tool and the workpiece (Leppert, 2011; Sharma *et al.*, 2016). This heat energy is generally considered waste, and its production in this manner leads to reduced product surface quality and increased tool wear (Walker, 2015).

Although the need for rapid machining is clear to improve productivity, the increased wear on tools, caused by the relative motion between the cutting tool and workpiece, limits the achievable cutting speed. Consequently, effective control of the intense heat generated from friction becomes crucial to ensure superior product quality and extended tool life. This heat at the tool-work interface not only affects product quality but also induces microstructural distortion in machined components (Matuszak *et al.*, 2023). The degree of friction between the tool and workpiece significantly influences the quality of machined components (Kumar, 2021). Addressing this concern is possible by employing cutting fluids at the tool-work interface (Sharma *et al.*, 2016; Kurgin *et al.*, 2012). The primary purposes of using cutting fluids are: (i) mitigating heat generation at the tool-work interface (Matuszak *et al.*, 2023; Elmunafi *et al.*, 2015), (ii) reducing friction during machining operations (Chae *et al.*, 2021), and (iii) removing metal chips generated during machining (Anwar *et al.*, 2023). Lubricants and coolants effectively wash away metal chips, maintaining a clean tool-work interface and facilitating smooth material removal from the workpiece Lawal *et al.*, 2013). These properties make lubricants and coolants widely useful in a range of metal cutting processes, such as turning, milling, grinding, and drilling (Moradpour *et al.*, 2024). In metal cutting, the choice of cooling method has a direct impact on the deformation mechanism (Islam *et al.*, 2013).

However, convectional cutting fluids, including additives like biocides, surfactants, detergents, and anti-corrosive agents, pose environmental and health hazards. Their increased usage contributes to environmental degradation, including issues like soil pollution, water contamination, disposal challenges, and health hazards leading to potential health problems, including cancer (Nicol and Hurrell, 2008). Additionally, the high cost of recycling waste cutting fluid necessitates a separate waste disposal and management system. Mineral-based cutting fluids, being non-biodegradable, further exacerbate environmental concerns. In contrast, biodegradable and non-toxic vegetable oils have been successfully tested in machining operations, making them a viable and environmentally friendly alternative to conventional cutting fluids (Boubekri *et al.*, 2010; Abdalla *et al.*, 2007).

Therefore, this paper focuses on comparative analysis of different formulated cutting fluids (palm oil, orange seed oil, neem seed oil and mineral based oil) on tool-work interface temperature.

MATERIALS AND METHODS

Workpiece

For this investigation, a cylindrical workpiece composed of 6061 aluminum alloy with 45 mm diameter and 350 mm length was chosen. The 6061 aluminum alloy serves as a prominent manufacturing material in the automotive industry and finds application in the construction of motorcycles, truck bodies, aircraft structures, rail coaches, ship buildings, pylons and towers, as well as motorboats (ASM Handbook Volume 2, 1993), The chemical composition of the 6061 aluminum alloy is provided in Table 1.

Table 1: Chemical composition of 6061 aluminum alloy

Element	Al	Mg	Cu	Cr	Mn	Si
Percentage	97.9	1.00	0.28	0.20	0.15	0.60

Cutting tool

Uncoated carbide inserts grade SNMG 120408-QM H13A (ISO designation) were used in turning of 6061 aluminum alloy under different cutting fluids (orange seed oil, OSOBCF; neem seed oil, NOBCF; palm oil, POBCF and Mineral oil, MOBCF).

Cutting Fluids

The properties of the formulated cutting fluids used in the machining are given in Table 2.

Table 2: Characteristics of Vegetable cutting fluids

S/N	Property	Value			
		OSOBCF	**NOBCF**	**POBCF**	**MOBCF**
1	pH value	9.67	9.07	9.56	7.4
2	Viscosity (cSt)	33.57	12.00	11.25	10.71
3	Stability	Stable	Stable	Stable	Stable
4	Corrosion level test	Corrosion resistant	Corrosion resistant	Corrosion resistant	Corrosion resistant
5	Colour	Milky	Milky	Orange	Milky

Experimental Conditions

- **Machine tool** Lathe Machine XL 400, 4kw, 2000 rpm
- **Workpiece material** 6061 Aluminum Alloy
- **Size** 45 mm in diameter and 350 mm length
- **Cutting tool, Specification** Uncoated carbide insert, SNMG 120408-QM H13A (ISO designation)
- **Tool holder** DBSNR 2020K 12 (ISO designation)
- **Environment** Orange seed oil based cutting fluid, Neem seed oil based cutting fluid, palm oil based cutting fluid, Mineral oil

The experiments were planned based on a Taguchi specified L16 (4^3) orthogonal array with four levels and three factors using Minitab 21 software. The experiments examined the effect of machining parameters such as spindle speed, feed rate, and depth of cut on the response output.

Experimental Procedure

The turning experiments used a specially formulated cutting fluid, specifically an orange seed oil-based fluid with cooling properties. Details of these custom cutting fluids are provided in Table 2. The experiments were carried out at the Chemistry Departmental Laboratory of the Nigerian Defence Academy in Kaduna, using an XL 400 lathe machine with a maximum spindle speed of 1000 to 2000 rpm and a maximum spindle power of 2.2 kW. The chosen cutting parameter ranges were based on the tool manufacturer's specifications.

The research focused on examining three factors and analyzing their levels using uncoated carbide inserts SNMG 120408-QM H13A (ISO designation) on a DBSNR 2020K 12 (ISO designation) tool holder. The study also included experimental machining of 6061 aluminum alloy, incorporating various cutting parameters such as spindle speed, feed rate, and depth of cut. Temperature readings were taken at the tool tip and workpiece interface after each pass using an infrared thermometer (KM 690), with tool tip temperatures measured three times to obtain average values.

Table 3: Machining parameters and their levels

Level Number	Spindle Speed (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)
1	180	0.105	0.5
2	250	0.116	1.0
3	355	0.14	1.5
4	500	0.16	2.0

RESULTS AND DISCUSSION

Experimental results for 6061 Aluminum alloy machining with different cutting fluids

The results for cutting temperature obtained using four distinct types of cutting fluids, namely POBCF, NOBCF, OSOBCF, and MOBCF, are presented in Table 4. To facilitate a more comprehensive comparison of the lubricant oils, the data has been transformed into charts, as illustrated in Figure 1. It is evident that the cutting temperature falls within the respective ranges of 4757°C, 4056°C, 3351°C, and 4661°C for POBCF, NOBCF, OSOBCF, and MOBCF. In general, the cutting temperatures are 743°C, 809°C, 676°C, and 863°C for POBCF, NOBCF, OSOBCF, and MOBCF, respectively.

Table 4: Experimental conditions and results

S/N	Machining Parameters			Tool-Work Interface Temperature (ºC)			
	Spindle speed (rpm)	**Feed rate (mm/rev)**	**Depth of cut (mm)**	**POBCF**	**NOBCF**	**OSOBCF**	**MOBCF**
1.	180	0.105	0.5	40	45	33	46
2.	180	0.116	1.0	42	48	39	49
3.	180	0.14	1.5	46	51	44	50
4.	180	0.16	2.0	48	52	46	54
5.	250	0.105	1.0	45	49	37	51
6.	250	0.116	0.5	43	47	34	48
7.	250	0.14	2.0	50	56	39	56
8.	250	0.16	1.5	47	52	42	52
9.	355	0.105	1.5	46	48	45	57
10.	355	0.116	2.0	49	55	51	59
11.	355	0.14	0.5	44	48	44	53
12.	355	0.16	1.0	46	50	46	55
13.	500	0.105	2.0	56	57	49	61
14.	500	0.116	1.5	49	53	46	59
15.	500	0.14	1.0	47	51	42	58
16.	500	0.16	0.5	45	47	39	55
		Average		**46.44**	**50.56**	**42.25**	**53.94**

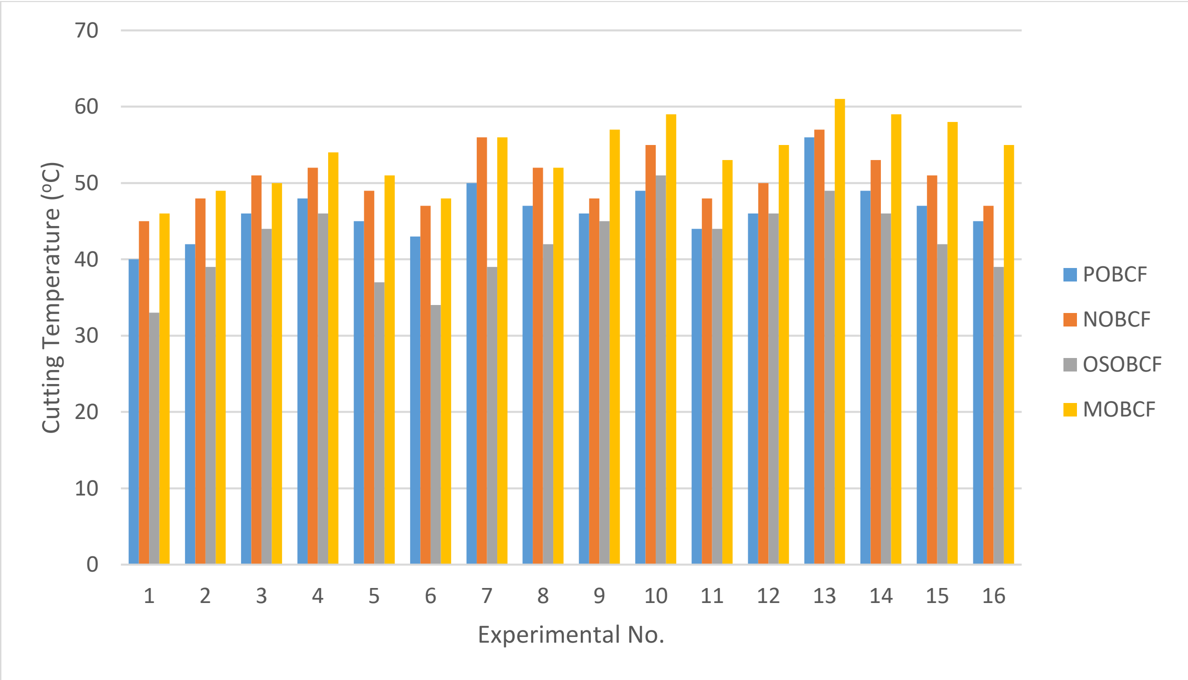

Figure 1: Effect of cutting fluid on cutting temperature of 6061 Aluminum alloy

In terms of cutting temperature, OSOBCF demonstrated superior performance compared to NOBCF, POBCF, and MOBCF. The behavior of OSOBCF cutting fluid with respect to cutting temperature can be elucidated by examining its fatty acid characteristics. This finding aligns with the observations of (Alves and Oliveira, 2006), who noted that mineral oil-based cutting fluids exhibit reduced efficiency at higher cutting speeds.

The utilization of cutting fluid, specifically OSOBCF, is thought to lower the coefficient of friction at the tool-workpiece interfaces, leading to a considerable reduction in cutting temperature (Obi *et al.*, 2013). The triglyceride molecules in vegetable oil, such as those in OSOBCF, are renowned for their outstanding lubricity. These molecules stick to the metal surface, forming a monolayer film with nonpolar fatty acid chains that allow for smooth sliding at the contact surface. This finding is consistent with the results observed by (Alaba, *et al*., 2023).

The study indicates that as spindle speed and depth of cut increase, chip-tool interface temperature rises under four lubrication conditions, attributed to elevated energy input and the influence of varying cutting parameters. In comparison to MOBCF, the experiment results for the four cutting fluids studied reveal a reduction in cutting temperature of approximately 22%, 14%, and 6% for OSOBCF, POBCF, and NOBCF, respectively.

Effect of process parameters on Cutting Temperature

Graphs depicting the effects of different levels of each cutting parameter for POBCF, NOBCF, OSOBCF, and MOBCF are presented in Figures 2, 3, 4, and 5, respectively.

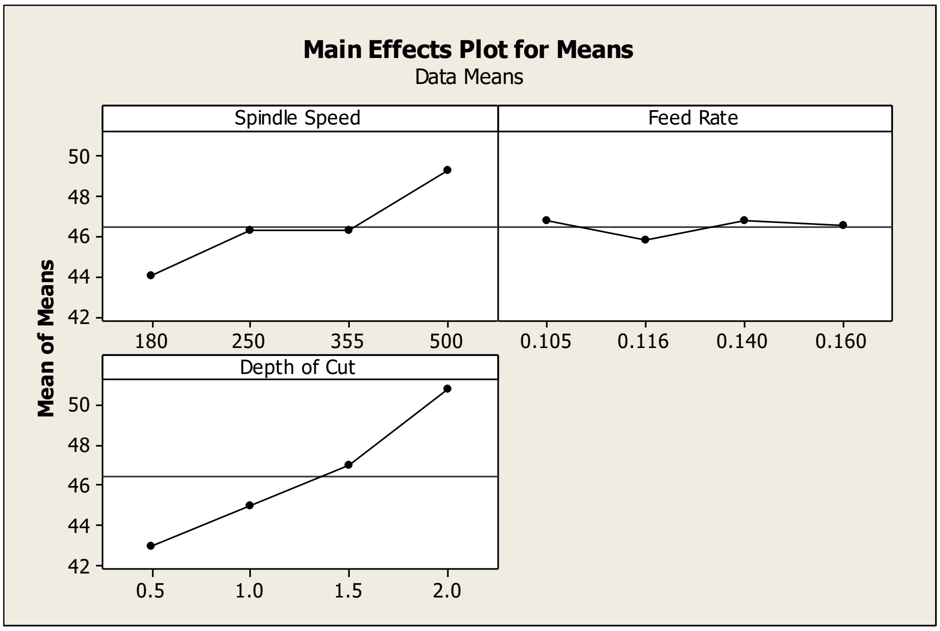

Figure 2: Main Effects Plot for Cutting Temperature with POBCF

Figure 2 reveals that the optimal specifications for achieving the best temperature levels with POBCF lubricant are a spindle speed of 180 rev/min (level 1), a feed rate of 0.116 mm/rev (level 2), and a depth of cut of 0.5 mm (level 1).

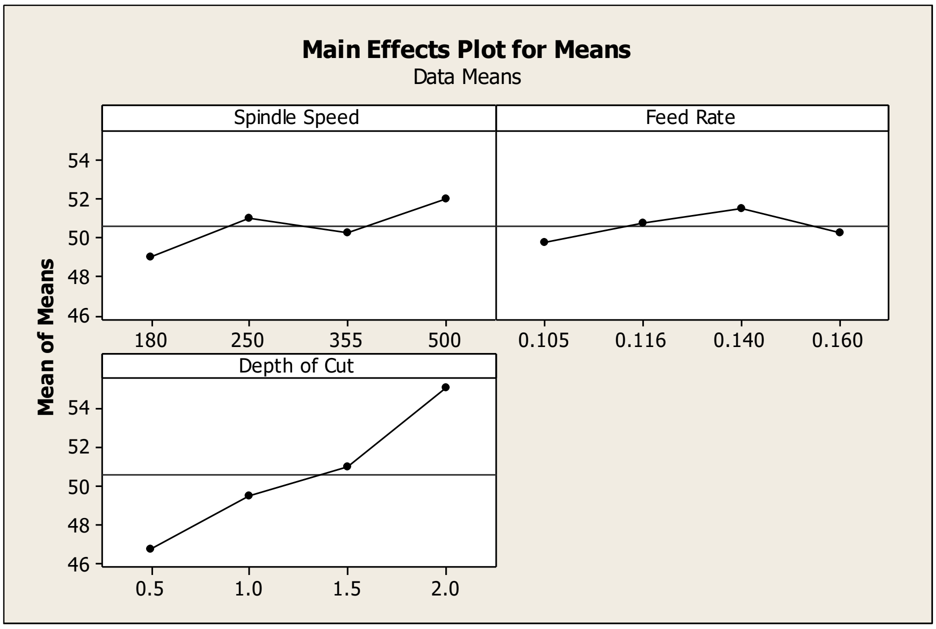

Figure 3: Main Effects Plot for Cutting Temperature with NOBCF

As illustrated in Figure 3, the optimal specifications for the NOBCF lubricant correspond to specific parameter levels: a spindle speed of 180 rev/min (level 1), a feed rate of 0.105 mm/rev (level 1), and a depth of cut of 0.5 mm (level 1).

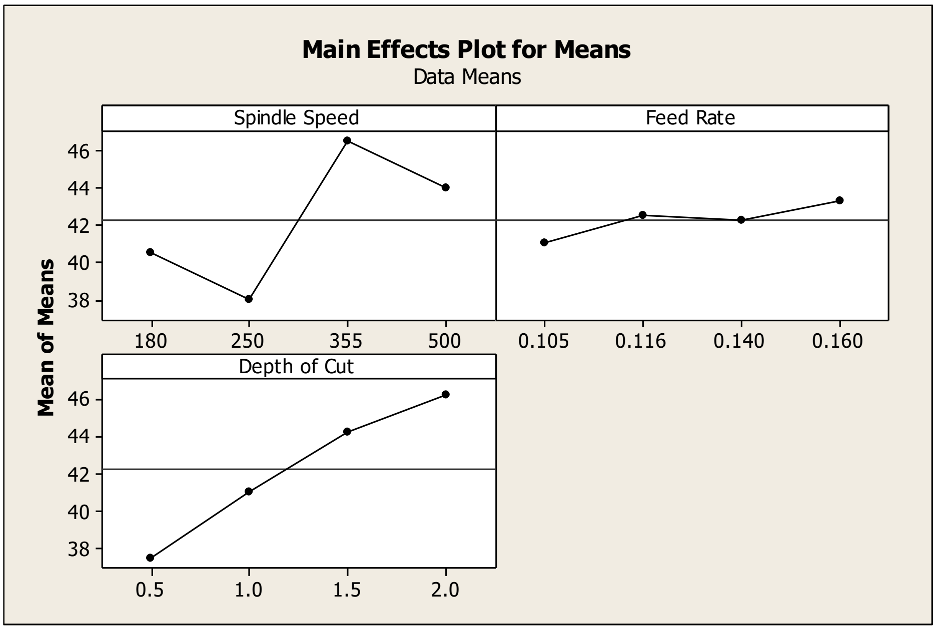

Figure 4: Main Effects Plot for Cutting Temperature with OSOBCF

In Figure 4, the influence of process parameters on cutting temperature for OSOBCF is depicted. The optimal conditions for the machined sample were observed to be a spindle speed of 250 rpm, a feed rate of 0.105 mm/rev, and a depth of cut of 0.5 mm.

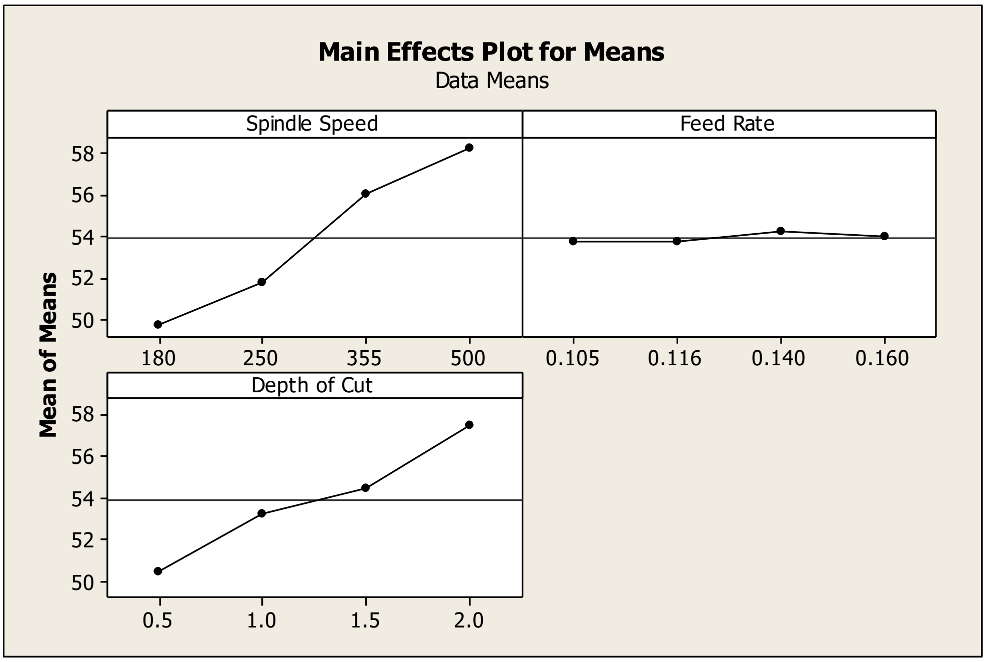

Figure 5: Main Effects Plot for cutting temperature with MOBCF

Figure 5 displays the main effects plots for surface roughness using MOBCF fluid. Achieving the optimum surface roughness is possible by employing a spindle speed of 180 rpm, a feed rate of 0.105 mm/rev, and a depth of cut of 0.5 mm.

The mean analysis of turning parameters for cutting temperature indicates values of 5.25 rpm for spindle speed, 1.00 mm/rev for feed rate, and 7.75 mm for depth of cut (See Table 5).

Table 5: Main effects on mean cutting temperature for POBCF

parameter	Level 1	Level 2	Level 3	Level 4	Max-Min	Rank
Spindle speed (rpm)	44.00	46.25	46.25	49.25	5.25	2
Feed rate (mm/rev)	46.75	45.75	46.75	46.59	1.00	3
Depth of cut (mm)	43.00	45.00	47.00	50.00	7.75	1

The findings suggest that, in turning operations with POBCF, depth of cut has the most significant impact compared to spindle speed and feed rate. The optimal sequence for process factors affecting cutting temperature is Depth of cut > Feed rate > Spindle speed.

Table 6: Main effects on mean cutting temperature for NOBCF

parameter	Level 1	Level 2	Level 3	Level 4	Max-Min	Rank
Spindle speed (rpm)	49.00	51.00	50.25	52.00	3.00	2
Feed rate (mm/rev)	49.75	50.75	51.25	50.25	1.75	3
Depth of cut (mm)	46.75	49.50	51.00	55.00	8.25	1

The responses for NOBCF are presented in Table 6, revealing that the optimal values for cutting temperature are observed at spindle speed 180 rpm, feed rate 0.105 mm/rev, and depth of cut 0.5 mm. Notably, depth of cut is identified as the most influential parameter among these three, followed by spindle speed and then feed rate.

Table 7: Main effects on mean cutting temperature for OSOBCF

parameter	Level 1	Level 2	Level 3	Level 4	Max-Min	Rank
Spindle speed (rpm)	40.50	38.00	46.50	44.00	8.50	2
Feed rate (mm/rev)	41.00	42.50	42.25	43.25	2.25	3
Depth of cut (mm)	37.50	4.00	44.25	46.25	8.75	1

Table 7 indicates that among the parameters considered, depth of cut has the most significant impact on the process. This is evident from its highest max-min value of 8.75 for cutting temperature, establishing it as the most influential factor.

Table 8: Main effects on mean cutting temperature for MOBCF

parameter	Level 1	Level 2	Level 3	Level 4	Max-Min	Rank
Spindle speed (rpm)	49.75	51.75	56.00	58.25	8.50	1
Feed rate (mm/rev)	53.75	53.75	54.25	54.00	0.50	3
Depth of cut (mm)	50.50	53.25	54.50	57.50	7.00	2

As per the findings presented in Table 7, spindle speed exerts a more substantial influence on the response in turning operations with MOBCF, as indicated by its higher max-min value of 8.50 compared to the depth of cut and feed rate.

Evaluation of ANOVA

ANOVA was used to determine the specific interactions of each control factor on the experiment's results. It helped identify the significant machining parameters, with analysis conducted at a 5% significance level and a 95% confidence level. The importance of the control factors is indicated by the F values, and the second to the last column in Tables 9, 10, 11, and 12 presents the percentage contribution of each parameter.

Table 9: Results of ANOVA on cutting temperature for POBCF

Source	Degree of freedom (DOF)	Sum of squares (SS)	Mean of squares (MS)	F-value	P – value	% Contribution	Remark
Spindle speed (rpm)	3	55.688	18.562	7.75	0.017	27.31	Significant
Feed rate (mm/rev)	3	2.687	0.896	0.37	0.775	1.32	Insignificant
Depth of cut (mm)	3	131.187	43.729	18.25	0.002	64.33	Significant
Error	6	14.375	2.396			7.05	
Total	15	203.937				100	

The impact level of the control factors on the results is depicted in this column. As indicated in Table 9, the response values were influenced by spindle speed, feed rate, and depth of cut, with corresponding effects of 27.31%, 1.32%, and 64.33%, based on the results obtained with POBCF.

Table 10: Results of ANOVA on cutting temperature for NOBCF

Source	Degree of freedom (DOF)	Sum of squares (SS)	Mean of squares (MS)	F- value	P – value	% Contribution	Remark
Spindle speed (rpm)	3	19.188	6.396	3.23	0.103	10.66	Insignificant
Feed rate (mm/rev)	3	6.686	2.229	1.13	0.410	3.72	Insignificant
Depth of cut (mm)	3	142.188	47.396	23.95	0.001	79.02	Significant
Error	6	11.875	1.979			6.60	
Total	15	179.938				100	

Table 10 illustrates the case of NOBCF, where an ANOVA analysis indicated that the response values were influenced by spindle speed, feed rate, and depth of cut, with respective effects of 10.66%, 3.72%, and 79.02%.

Table 11: Results of ANOVA on cutting temperature for OSOBCF.

Source	Degree of freedom (DOF)	Sum of squares (SS)	Mean of squares (MS)	F- value	P – value	% Contribution	Remark
Spindle speed (rpm)	3	169.00	56.333	9.66	0.010	43.22	Significant
Feed rate (mm/rev)	3	10.500	3.500	0.60	0.638	2.69	Insignificant
Depth of cut (mm)	3	176.500	58.833	10.09	0.009	45.14	Significant
Error	6	35.000	5.833			8.95	
Total	15	391.000				100	

In Table 11, the influence of each input parameter on cutting temperature is presented: spindle speed (43.22%), feed rate (2.69%), and depth of cut (45.14%), respectively. The findings indicate that depth of cut holds the highest significance for cutting temperature, followed by spindle speed. Consequently, depth of cut has the most substantial impact on the response values for POBCF, NOBCF, and OSOBCF.

Table 12: Results of ANOVA on cutting temperature for MOBCF.

Source	Degree of freedom (DOF)	Sum of squares (SS)	Mean of squares (MS)	F- value	P – value	% Contribution	Remark
Spindle speed (rpm)	3	180.688	60.229	152.16	0.000	63.41	Significant
Feed rate (mm/rev)	3	0.688	0.229	0.58	0.650	0.24	Insignificant
Depth of cut (mm)	3	101.187	33.729	85.21	0.000	35.51	Significant
Error	6	2.375	0.396			0.84	
Total	15	284.937				100	

Meanwhile, according to Table 8, spindle speed holds the highest significant contribution at 63.41% to the cutting temperature, followed by depth of cut with a percentage contribution of 35.51%, and feed rate has the least contribution at 0.24%. An interesting finding from the ANOVA tables is that the P-values for the depth of cut are consistently below 0.05. This indicates that depth of cut significantly affects the response values with 95% reliability across all cutting fluids

Mathematical model

The parameters spindle speed (v), feed rate (f), and depth of cut (d) were employed to formulate a regression model, R^2, with a 95 percent confidence level for the response variable, specifically cutting temperature (CT). The determination coefficients of the model (R^2) were computed to evaluate its appropriateness. Eqs (1) (4) in line with the experimental findings, represent first-order mathematical models with R^2 for cutting temperature corresponding to POBCF, NOBCF, OSOBCF, and MOBCF.

Regression Equation for POBCF

$$CT\ (^oC) = 34.9 + 0.0147v + 3.7f + 5.05d \quad (1)$$

Model Summary

R^2 = 87.19%

Regression Equation for NOBCF

$$CT\ (^oC) = 40.325 + 0.0075v + 9.7144f + 5.25d \quad (2)$$

Model Summary

R^2 = 84.24%

Regression Equation for OSOBCF

$$CT\ (^oC) = 25.1817 + 0.017314v + 31.718f + 5.9d \quad (3)$$

Model Summary

R^2 = 64.21%

Regression Equation for MOBCF

$$CT\ (^oC) = 38.7176 + 0.0273v + 6.7623f + 4.45d \quad (4)$$

Model Summary

R^2 = 95.76%

Specifically, in the case of cutting temperature, the R^2 values are 87.19%, 84.24%, 64.21%, and 95.76% for POBCF, NOBCF, OSOBCF, and MOBCF, respectively, indicating high values close to 1. These results are deemed statistically significant and acceptable, signifying an excellent fit for the model. Consequently, the developed model implies robust relationships between the experimental and predicted outcomes. This comparative observation affirms the model's reliability in safely predicting anticipated outcomes before conducting experiments in the context of turning 6061 Aluminum Alloy with cutting fluids.

By examining the chart displaying the average tool-work interface temperatures for the four machining conditions, it becomes apparent that machining performance is enhanced under the OSOBCF condition. Figure 6 illustrates a comparative chart of the tool-work interface temperatures for the four types of cutting fluid.

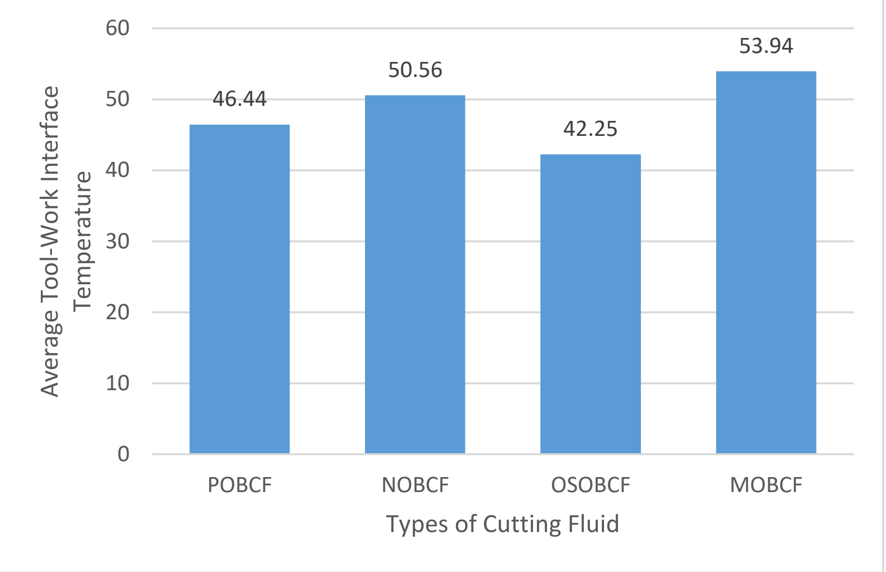

Figure 6: Comparison chart of tool-work interface temperature

The comparative chart of the machining performance at tool-tip cutting temperature under orange seed oil-based cutting fluid (OSOBCF) conditions resulted in a 9.02%, 16.4%, and 21.7% lower cutting temperature compared to palm oil-based cutting fluid (POBCF), neem seed oil-based cutting fluid (NOBCF), and conventional oil-based cutting fluid (MOBCF), respectively.

CONCLUSION

Every machining operation aims to achieve a favorable surface finish, enhancing the overall quality of the product. Inherent to machining processes is the utilization of lubricants, intended to enhance tool and work properties, and ultimately contribute to the superior quality of the end product. Drawing insights from the tool-work interface temperature test conducted on 6061 aluminum alloy during turning operations with uncoated carbide inserts under formulated cutting fluids (POBCF, NOBCF, OSOBCF, and MOBCF), this research work concludes that based on the experimentation conducted under POBCF, NOBCF, OSOBCF, and MOBCF machining conditions, it can be deduced that the depth of cut exerts the most significant influence on the tool-work interface temperature. This is followed by the spindle speed and feed rate, as substantiated by the results of the ANOVA and F-test. The optimal specifications for cutting temperature under NOBCF and MOBCF conditions are a spindle speed of 180 rpm, feed rate of 0.105 mm/rev, and a depth of cut of 0.5 mm. For POBCF, the recommended parameters are a spindle speed of 180 rpm, a feed rate of 0.116 mm/rev, and a depth of cut of 0.5 mm. On the other hand, OSOBCF calls for a spindle speed of 250 rpm, a feed rate of 0.105 mm/rev, and a depth of cut of 0.5 mm to achieve optimal cutting temperature.

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