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EXPERIMENTAL AND MATHEMATICAL APPROACH OF EVALUATING SUSTAINABILITY INDICATORS IN END MILLING OF ALUMINIUM 7011H UNDER DIFFERENT ECO-FRIENDLY NANO HYBRID COOLING STRATEGIES USING RESPONSE SURFACE METHODOLOGY APPROACH

Suresh Kumar Mandru[1], P. Ramamurthy Raju[2] & Ch. Ratnam[3]

[1] Scholar, Department of Mechanical Engineering, A. U College of Engineering, Andhra University, Andhra Pradesh, India

[2]Professor, Department of Mechanical Engineering, S. R. K. R Engineering College, Andhra Pradesh, India

[3]Professor, Department of Mechanical Engineering, A. U College of Engineering, Andhra University, Andhra Pradesh, India

Abstract

The increasing depletion of resources and rising cost of raw materials have made sustainability in the industrial sector imperative. One of the more recent and developing methods that opens the door to sustainability in machining is green machining. Cut fluid use should be minimised. Other environmentally friendly and sustainable methods that are in vogue are using different coolants in place of traditional cutting fluids that contain chemicals. The comparative analysis of carbonaceous and tri-hybridized nano metal-oxide based cutting fluids in the end milling of 7011H aluminium alloy is presented in this research. The Response Surface Methodology (RSM) approach was used to conduct the experiments, and the feed rate, speed, and kind of nanofluids were taken into account as input variables. Surface roughness was used as a metric to measure the output responses. Based on the acquired results, it was found that the cutting fluids that were carbonaceous and hybridised nano metal oxide based produced extremely similar levels of output efficiency. Additionally, the surface of the machined surface was examined, and it was discovered that this green machining technique produced a superior surface finish.

Keywords: End milling, MQL, Metal-oxide nanofluids, Carbonaceous nanofluids, Tri-hybridization, Green and Sustainable machining

1 Introduction

Recent years have seen a considerable shift in study focus to the green and sustainable environment of machining. In order to achieve green machining, machinists frequently research the effects of coolant, lubrication, and lubricant application technique [1]. Traditional coolants need to be changed since they deplete raw materials and endanger the environment. Furthermore, research is being done on substitute techniques for the flood coolant approach, which is already in use and has been linked to issues like excessive coolant consumption, ineffective heat absorption, and higher production costs. One such effective method is Minimum Quantity Lubrication (MQL), which involves mixing coolant with air mist and nuzzling the resulting aerosol towards the machining region [2]. When compared to traditional petroleum-based coolants, edible and biodegradable vegetable oils are proven to be just as effective at removing heat as coolants used in environmentally friendly and green machining concepts. Because of their superior heat conductivity, low fat to weight ratio oils like coconut oil are particularly popular among researchers [3]. Nanoparticles were favoured because they

increased thermal conductivity and introduced the duality of solid particles with liquid coolants. In order to produce a uniform mixture, the nanoparticles were weighed in percentage, added to the base fluid, and sonicated for around two hours. Anuj Sharma et al.'s work [4] on turning operations with MWCNT nanofluids and alumina produced more effective outcomes. When graphite and carbon-based nanoparticles were used as lubricants in grinding, Alberts M. et al. [5] saw a notable improvement in surface finish. Researchers have recently turned their attention to combining two nanoparticles of similar kind to create hybrid nanofluids, which have been shown to be more successful than mono-type nanofluids [6]. While a small number of researchers were investigating the potential of carbon-based nano cutting fluids such as graphene and multi-walled carbon nanotubes, few were studying metal-oxide based nano cutting fluids such as TiO_2, Al_2O_3, MOS_2. [7]. This inspired me to concentrate my research efforts on investigating the potential of tri-hybridized nano cutting fluids. The technique known as Response Surface Methodology (RSM) is employed to effectively establish a statistical correlation between the factors under consideration. Previous studies have studied the varied levels of parameters undertaken using the optimal design level. [8]. The current study compares carbonaceous nano cutting fluid with trihybridized nano cutting fluid based on metal oxide. Furthermore, a comparison and presentation of the surface morphology of each is required.
The ultimate aim of this research work is to minimize the usage of conventional coolant thereby reducing the cost of production and green machining environment.

2 Experiment

2.1 Material7011H Square bar of 50 mm X 50 mm X 50 mm was taken as workpiece in this study. The presence of chemical in the material is shown in Table 1.

Table 1 Composition of 7011H alloy taken in this study

Composition metal	Al	Zn	Mg	Fe	Si	Ti	Mn	Cr
%	90.2	5.6	2.5	0.5	0.4	0.2	0.3	0.3

The end milling tool used here is Taparia make with diameter of 8 mm. This ceramic carbide tool whose hardness is 54HRC provides better cutting for the gummy material. The experiments were performed on S3-Axis LMW(Lakshmi machine works Ltd)JV 55 T12 vertical milling machine and KENCO make MQL system. The connected system for performing experiments is shown in Figure 1.

Figure 1 Experimental Setup

2.2 Properties of Nano Coolant Used

Two families comprise the nano coolant employed in this investigation. (i) Carbonaceous; (ii) Metaloxide based. The metal-oxide family comprises TiO_2, Al_2O_3, and MOS_2 as the selected nanoparticles. Similarly, graphene and h-BN were selected under the carbonaceous family MW-CNT. In terms of density and thermal conductivity, they are comparable [9]. The idea of employing nanofluids in hybridization conditions has shown to be successful, as numerous researchers have demonstrated in earlier studies of a similar nature. By combining the nanopowders at a weight percentage of 1% with canola oil, two types of hybridised cutting fluids were created: tri-hybridized metal-oxide (TMO) and tri-hybridized carbonaceous (TC) [10]. Table 1 displays the measured values for thermal conductivity, kinematic viscosity, and density for base fluid, metal-oxide nanoparticles, and carbonaceous nanofluids at 50°C (working temperature).

Table 1 Rheological Properties of Nano Cutting Fluids

Parameter	Base fluid (Canola oil)	Tri-hybridized Metal-oxide nano cutting fluids	Tri-hybridized Carbonaceous nano cutting fluids
Density (g/cc)	0.901	0.903	1.012
Kinematic Viscosity (c.St)	22.8	21.8	23.25
Thermal Conductivity (W/(m-K))	0.161	0.232	0.286

The values found are far closer and have good agreement with earlier studies [10–11]. At the operating temperature, enhanced flowability and spread ability are provided by higher values of these rheological parameters. Because of their physical characteristics and carbon content, carbonaceous nano cutting fluids had higher values.

2.3 Parameters and their Levels Considered for the Study

End milling usually depends on the parameters such as speed, feed rate and type of fluid. Based on the machine and tool standards the levels were fixed. The selected levels are shown in Table 3.

Table 3 Conditions with Their Levels Taken for Study

Conditions	Units	Levels	
		Low	High
Speed (N)	rpm	5000	7000
Feed (f)	mm/rev	0.075	0.150
Nano cutting fluids	-	TMO	TC

2.4 Experimental Design

The experimental design is performed with three variables. The experiments are based on RSM optimal design. Design-Expert 11 was used as an aid to generate the experimental runs and presented in Table 4.

Table 4 Experimental runs

S.No.	Speed N (rpm)	Feed f (mm/rev)	Nano cutting fluids
1	5000	0.150	TMO
2	5345	0.091	TMO
3	6500	0.075	TMO
4	6177	0.134	TMO
5	5345	0.091	TMO
6	6470	0.098	TMO
7	5487	0.148	TMO
8	6425	0.138	TMO
9	5135	0.082	TMO
10	5735	0.150	TMO
11	6500	0.076	TC
12	5000	0.115	TC
13	5765	0.075	TC
14	6500	0.113	TC
15	5322	0.133	TC
16	6177	0.091	TC
17	5322	0.133	TC
18	6177	0.091	TC
19	6500	0.150	TC
20	5000	0.075	TC

3 Results and Discussion

The experimentation data obtained for both tri-hybridized metal-oxide and tri-hybridized carbonaceous nano fluids is presented and discussed.

3.1 Surface Roughness

Surface integrity is measured by surface roughness, and the main goal of machining processes is to minimise surface roughness. High temperatures and rapid occurrence of BUE are common for gummy materials such as 7011. This study investigates the performance of coolants under high speed and feed settings. The tool used to quantify the surface roughness (Ra) was the SURFCOM 1400G from Accretech in Japan. Ra was measured in accordance with ISO 1302 guidelines. A minimum count of one micron, a cut-off length of 0.3 mm, and a sample length of 4 mm were maintained. After taking three readings, the average Ra was taken into account.

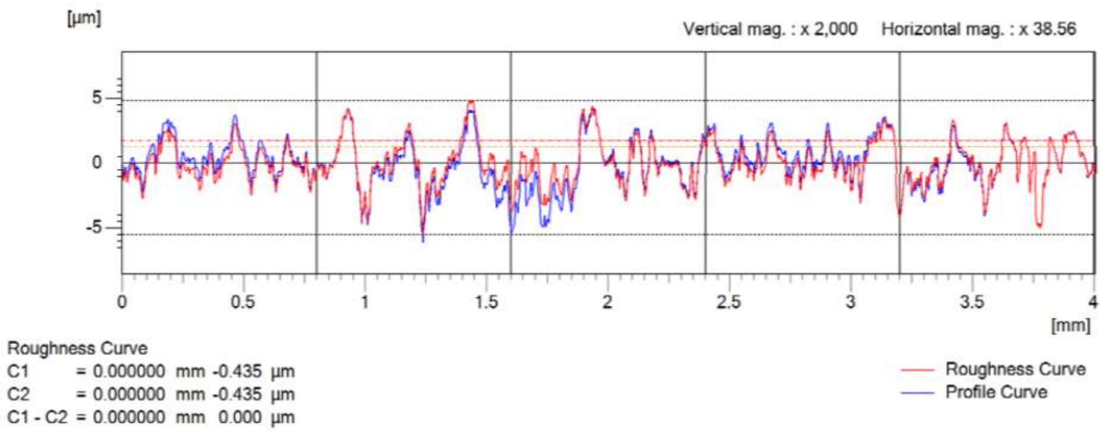

Figure 2 Surface Roughness Plot Measured using SURFCOM

Table 5 The Run Order and Output Response Parameters

S.No.	Speed N (rpm)	Feed f (mm/rev)	Nano cutting fluids	Ra (µm)
1	5000	0.150	TMO	0.44
2	5345	0.091	TMO	0.54
3	6500	0.075	TMO	0.32
4	6177	0.134	TMO	0.28
5	5345	0.091	TMO	0.45
6	6470	0.098	TMO	0.14
7	5487	0.148	TMO	0.44
8	6425	0.138	TMO	0.26
9	5135	0.082	TMO	0.33
10	5735	0.150	TMO	0.46
11	6500	0.076	TC	0.26
12	5000	0.115	TC	0.23
13	5765	0.075	TC	0.60
14	6500	0.113	TC	0.34
15	5322	0.133	TC	0.35
16	6177	0.091	TC	0.26

17	5322	0.133	TC	0.18
18	6177	0.091	TC	0.41
19	6500	0.150	TC	0.27
20	5000	0.075	TC	0.23

Table 5 presents the measured surface roughness measured for 20 runs. The combined effect of speed and feed rate on Ra is presented and analyzed.

Figure 2 displays the surface roughness peak plot, where the lowest crest and trough indicate that the Ra has decreased after the use of nano cutting fluids in the machining process. The investigated values also show that the lowest surface roughness is produced by a medium speed and medium feed rate. On the other hand, a greater feed rate at a slower speed resulted in a rougher surface. Thus, it is predictable that the parameters under consideration would be optimised. Surface roughness has been improved with the application of RSM.

3.2 The Interaction Effects of Ra and Mathematical Modelling

Using interaction analysis and RSM, the unique impact of process factors on the output is examined. Figure 3(a-b) illustrates the interaction impact between the surface roughness and the process parameters. The relationship between feed rate and speed on the output character Ra when machined with TC and TMO, respectively, is depicted in Figures 3a and 3b. It can be seen in both figures that surface roughness tends to diminish with increasing feed rates and speed. A linear steepness is observed throughout the plot in Fig. 3a. Increased feed rate and speed are proven to lower the Ra. The tri-hybrid nano fluids' rheology has performed well in its attempt to lower the Ra during high-speed machining. Roughness has decreased as a result of the selected nanoparticles' healing properties and the rolling action between surfaces.

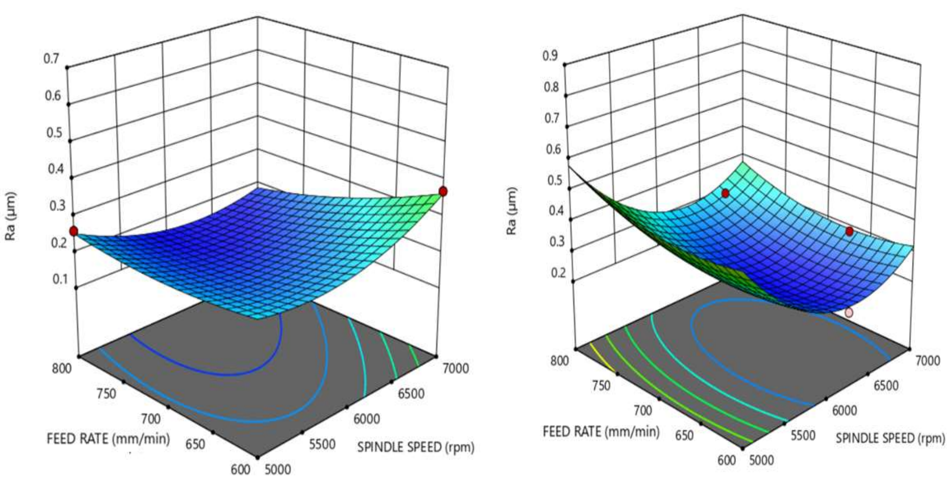

Figure 3a Interaction surface plot for TMO Figure 3b Interaction surface plot forTC

The interaction map for tri-hybridized carbonaceous nanofluids is displayed in Figure 3b. When compared to greater speeds and lesser feed rates, the Ra is observed to be on a higher note at higher speeds. The foregoing result may be explained by the fact that the heat generated between the tool and workpiece at greater speeds has been lowered by the temperature absorption and thermal conductivity of carbon-based nano fluids. Throughout the investigation, a linear slope is found, indicating a rectilinear relationship between the components. At high feed rates, a peak point is observed in the surface roughness due to the decreased permeability of TC nano fluids. When compared to TC, TMO's superior rheological behaviour has produced a higher surface quality. This complements the first one nicely. research works [11]. Table 6 and Table 7 presents the values for ANOVA and model summary analysis respectively.

Table 6 ANOVA for Ra

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Level Significance
Model	8	0.200742	0.025093	13.09	0.001	Yes
Linear	3	0.022845	0.007615	3.97	0.038	Yes
N	1	0.003821	0.003821	1.99	0.186	Yes
f	1	0.000176	0.000176	0.09	0.768	Yes
Type of fluid	1	0.017788	0.017788	9.28	0.011	Yes
Square	2	0.023193	0.011596	6.05	0.017	Yes
N*N	1	0.022401	0.022401	11.68	0.006	Yes
f*f	1	0.000048	0.000048	21.82	0.002	Yes
2-Way Interaction	3	0.125477	0.041826	21.82	0.002	Yes
N*f	1	0.002238	0.002238	1.17	0.303	Yes
N*Type of fluid	1	0.115901	0.115901	60.45	0.002	Yes
f*Type of fluid	1	0.115901	0.115901	6.53	0.027	Yes
Error	11	0.021089	0.001917	-	-	Yes
Lack of fit	8	0.013799	0.001725	0.71	0.690	
Pure	3	0.007290	0.002430	-	-	-
Total	19	0.221831	0.025093	-	-	-

Table 7 Model Summary

S	R-Sq	R-sq(adj)	Rsq(pred)
0.0137857	90.49%	83.58%	84.30%

Regression Equation in Uncoded Units For TMO

$Ra(\mu m) = 4.99 - 0.001773\, N + 1.97\, f + 0.000656 N*N + 3.4\, f*f - 0.000669\, N*f$ --- Eqn. (1)

For TC

$Ra(\mu m) = 6.41 - 0.002047\, N + 3.99\, f + 0.000741\, N*N + 3.4\, f*f - 0.000669\, N*f$ --- Eqn. (2)

Table 8 Validation of Predicted and Confirmation Runs

Parameters	Type of Nano Fluid	Predicted Ra (µm)	Confirmation run Ra (µm)	Desirability value
N = 6500 rpm f = 0.15 mm/rev	TMO	0.331	0.378	0.721
	TC	0.451	0.487	0.620

Depth of cut = 1.5 mm				

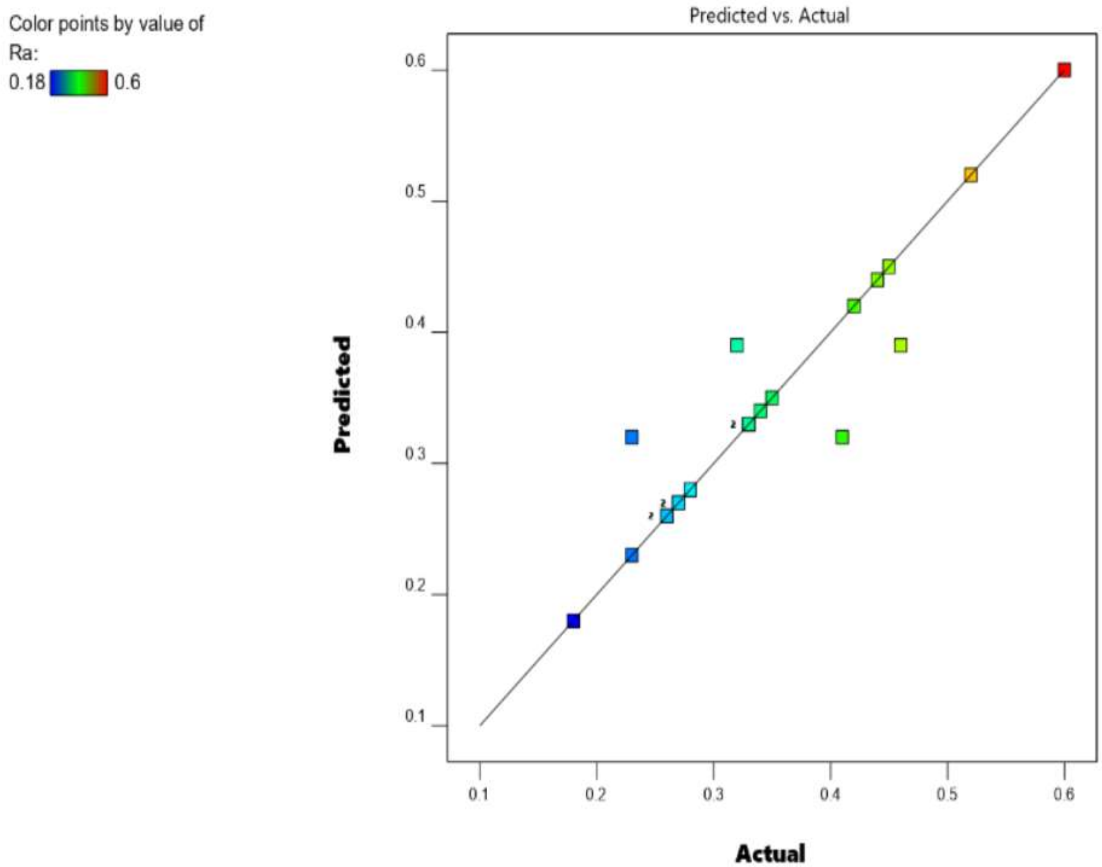

Figure 4 Predicted vs Actual plot for Ra

The second order polynomial model coefficient was found via statistical analysis, and the resulting relationship is displayed in equations (1 & 2). The parameter has a 95% confidence level and is significant. ANOVA yields a p-value of less than 1, indicating that the parameters under consideration are well within the scope of the study and consistent with prior research [12]. The adjusted and anticipated RSquare values are above 80%, confirming the significance of the levels under consideration. Additionally, the study was expanded to optimise the parameters after examining how the parameters interacted.

The optimised conditions are predicted and validated in Table 8. Figure 4 displays the expected vs. Actual values plot values. The proximity to the real spots demonstrates that the study's parameters are within the goal functions and achieve the surface roughness minimization goal. This is consistent with earlier studies of a similar nature [13]. According to confirmation testing, the solid nanoparticles gave the tool a good margin of error and some small cushioning over the surface during machining, which helped to achieve the lowest possible surface roughness. Both TMO and TC have shown good performance in high-speed machining; however, TMO has somewhat improved as a result of metal-metal surface interaction. Furthermore, Figure 5(a&b) displays the SEM pictures of the machined specimen for optimised parameters that were captured with a 1500x resolution Carl Zeiss microscope. According to the surface morphology analysis, TMO and TC nanofluids both fared better under the previously mentioned high-speed circumstances. When TC nanofluids were compared to TMC nano cutting fluids, a tiny adhesion of chip was discovered along with modest BUE generation. The rheological characteristic and decreased lubricity behaviour of carbonaceous nano cutting fluids at elevated temperatures could be the cause of this [14–15]. It made sense to use both tri-hybridized nano cutting fluids to minimise the output response.

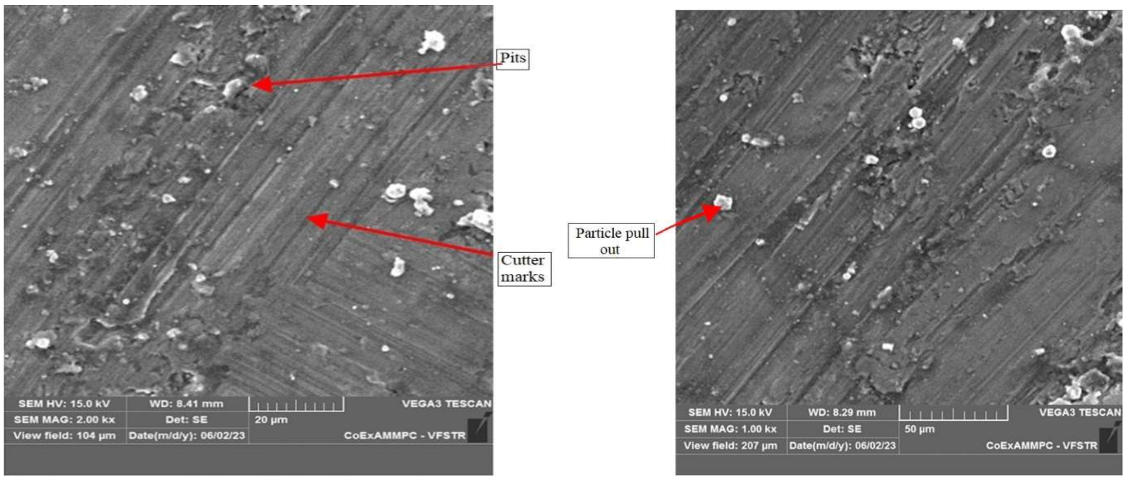

Figure 5 SEM Images of Machined Specimen (A) TMO, (B) TC

4 Conclusions

The investigations and analysis are reported here to evaluate the effects of tri-hybridized metal-oxide and carbonaceous nano cutting fluids on surface integrity in end milling of 7011 aluminium alloy.

(i). Feed rate followed by speed are the most significant parameters in the minimizing the output response Ra.

(ii).The addition of metal-oxide and carbonaceous nano cutting fluids has improved the thermal conductivity and rheology of the base fluid

(iii). Minimum surface roughness was observed in TMO nano fluids when compared to TC nano fluids. Around 60 % improvement is found in TMO when compared to TC due to metal-metal interaction and good thermal conductivity.

(iv). Both nano cutting fluids provide better surface integrity with TMO being on the upper hand in better flowability and has seized BUE formation.

(v). Overall, the reduction of cutting fluid was successfully performed without compromising the quality. This paves the way for Green and Sustainable machining

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