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RESEARCH

Evaluation of Surface Quality and Productivity in Conventional Milling of Copper Beryllium Using Minimum Quantity Lubrication

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ABSTRACT

Copper Beryllium (C17200) has ideal physical and mechanical properties of high fatigue strength, thermal conductivity, and hardness, making the alloy ideal for various high-reliability applications in aerospace, producing inserts and tooling for hazardous environments. However, surface quality and productivity challenges are prominent when processing the alloy due to its properties. This study evaluates the surface quality and productivity in end-milling of Copper Beryllium by analyzing the effects of feed rate, minimum quantity lubrication (MQL) flow rate, and cutting depth on surface roughness (Ra) and material removal rate (MRR). The experiment was designed using the Box-Behnken design, and the samples were machined on a CNC milling machine. The results showed that the MQL flow rate was significant to surface roughness, while the cutting depth was significant to MRR. The optimum parameters were determined as a feed rate of – 60 mm/min, an MQL flow rate of – 80 ml/hr., and a cutting depth of – 0.511 mm, which yielded a surface roughness of 0.12 μm and MRR of 10.19 g/min. The study's novelty is that it considers MQL flow using vegetable oil-based cutting fluid (CF) as an input parameter in machining, offering insight into eco-friendly and cost-effective machining practices. Finally, the significance of the study lies in investigating the machinability of Cu-Be alloy material, addressing challenges related to surface quality and productivity during milling operation.

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1. INTRODUCTION

Copper Beryllium (C17200) is a high-reliability-engineered material with high-performance applications. Alloy C17200 exhibits high thermal and electrical conductivity, high hardness and fatigue strength, resistance to wear, non-magnetic, abrasion, and excellent corrosion properties [1]. The alloy maintains a face-centered-cubic structure at a microstructure level where beryllium atoms replace the copper atom at the lattice positions. Alloy C17200 with up to 4% beryllium has a high tensile strength of 1379 MPa, shear modulus of 50 GPa, hardness of

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45 of a Rockwell C scale, thermal conductivity of 130 W m^{-1} K^{-1}, a density of 8360 kg m^{-3}, thermal expansion coefficient of 17.5 * 10 $^{-6}$ K^{-1}, and a specific heat capacity of 0.44 J Kg^{-1} K^{-1} [2,3]. As a result, alloy C17200 has been applied in various fields, including aerospace, electronics, computers, telecommunication, medical devices, and mold tooling. Essentially, the alloy is used in making relay blades, fuse chips, navigational instruments, bearing bushing, valves (stems and seats), wear plates on heavy equipment, spring connectors, non-sparking tools, washers, retaining rings, shafts, and as a mold insert forming the core and cavity of the mold tool where rapid heating and cooling, high fatigue-strength, and scratch resistance are critical [2], [4]. Therefore, machining is necessary to transform the material into complex and intricate shapes through machining.

Several methods of forming Copper Beryllium have been proposed and used in the past, including EDM, laser machining, and chemical etching; these methods present various challenges, including chemical fumes, burn marks, high energy consumption, high cost, and low productivity compared to conventional methods [5,6]. Conventional machining is easy to step up, economical, has reasonable energy consumption, and productivity and quality can be achieved. Copper Beryllium has excellent thermal conductivity, a benchmark of conventional machining [4]. On the other hand, its high tensile strength and hardness present challenges of tool wear, surface integrity, productivity, and temperature-induced ductility during machining [1,7].

Various studies have been conducted on input parameters and cooling to optimize machining output, such as MRR, surface quality, and hardness, among others, in machining Cu-Be and closely related alloys [8]. Using an RSM design, Ramesh et al. [10] studied the influence of spindle speed, axial cutting depth, and feed rate on MRR and the surface quality (Ra) during Cu-Be milling. The study concluded that MRR and surface roughness increased as the feed increased. Alagarsamy et al. [4] applied Taguchi DOE to investigate the effects of turning variables on copper-beryllium machined with a tungsten carbide tool. The study revealed that the optimum spindle speed, feed, and machining depth were 1200 rpm, 0.14 mm/rev, and 1.0 mm, respectively. Sudhakar et al. [7] considered cutting speed, machining depth, and feed under wet and dry conditions in investigating the fracture morphologies and machining characteristics of Cu-Be and concluded better mechanical properties were obtained under wet conditions than dry machining. Mehfuz & Ali [9] studied the surface quality of Cu-Be in micro-end machining. The study used a central composite design to investigate the effects of feed per tooth and cutting depth on the surface quality. The results revealed a surface roughness of 0.1 – 0.2 μm. Hung et al. [10] examined the effects of feed rate and tool input parameters on the precision grinding and facing of copper-beryllium alloy. The study revealed that surface roughness was related to the feed rate.

Pervaiz et al. [11] conducted experiments on the effects of MQL in machining hard-to-machine metals (Titanium); the study showed that high a temperature at the work-tool interface results in high tool wear, a blunt tool influences chip formation and surface integrity and increases cutting force. Ezungwu [12] established that a pressurized CF delivered directly to the work-tool interface improved chip flow and reduced cutting force and temperature. Tosun & Huseyinoglu [13] studied the effects of near-dry conditions on the surface quality of milled AA7075-T6. The MQL flow rate, feed, and spindle speeds were considered as the independent parameters. The study results revealed surface roughness decreased with an increase in MQL Flow rate. Ekinovic et al. [14] considered spindle speed, cutting depth, and feed in investigating the effect of MQL on the properties of machined aluminum bronze. MQL was supplied at 50 ml at a pressure of 2 bars. The findings indicated a 16% reduction in cutting force when operating under Minimum Quantity Lubrication (MQL) conditions. Finally, the life-cycle management cost of CFs was four times greater than the cost-cutting tools required in machining, according to Boswell et al. [15], who reviewed the management cost associated with cutting fluids (CFs) from purchase to disposal. MQL uses between 10-100ml/hr. and is a green machining concept that emphasizes sustainable means of manufacturing, i.e., minimum amounts of coolant sprayed directly at the work-tool interface in an environmentally acceptable and conscious manner [12,16]. Although specific literature was consulted in reviewing the mechanical, physical, and machinability aspects of

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Copper-Beryllium, in addition to MQL application in machining, there is a paucity of evidence on, firstly, the effects of MQL on surface quality (Ra) and productivity (MRR) and, secondly, the use and effects of an eco-friendly Cutting Fluid while milling Cu-Be.

It is now well established the MQL is an effective cooling alternative in milling operations. However, the influence of MQL on surface roughness and MRR in milling Cu-Be has remained unclear, indicating a need to understand the effects of MQL on the machining quality and productivity of Cu-Be.

2. METHODOLOGY

In this study, the Minimum quantity lubrication flow rate was considered one of the input parameters in addition to the feed and cutting depth. Furthermore, vegetable oil-based cutting fluid, an environmentally friendly CF, was used in the MQL technique. The approach combines eco-friendly cutting fluids with a sustainable delivery method, MQL. The environmental impact of the MQL technique was minimal compared to flood cooling as the demand of CF could be reduced from 25 L/hr. to approximately 10-100 ml/hr. [17]. Box-Behnken in RSM design of experiments (DOE) with the above three input variables at three levels was used to design an array of fifteen experiments. The effects and statistical significance of the independent variables to the responses were established using an ANOVA. A regression model was developed from the ANOVA results to predict the link between the input and the response. Finally, a multi-response optimization was conducted to obtain optimum machining input parameters. The study's novelty is that in additional conventional machine input parameters (feed and cutting depth), it considered the flow rate in MQL using vegetable oil-based cutting fluid as an input parameter in examining the surface quality and productivity responses in Cu-Be machining.

2.1 Material

The samples used in the study are copper-beryllium alloy C17200 rectangular, size 50 x 45 x 5 mm, supplied by Shandong Modern International Trade Co. Ltd. based in Shandong, China. Table 1 shows some physical and mechanical characteristics of Copper Beryllium.

Table 1. Notable physical and mechanical of Cu-Be (supplied by the manufacturer).

Properties	Value
Temper	TH01
Hardness (HRC)	41
Elongation (%)	5
Tensile Strength (MPa)	1290
Melting point (°C)	866
Density(g/m^3)	8.25

2.2 The design of experiment

The experiments were designed using Box-Behnken Design. The box-Behnken design in RSM was preferred since fewer points are at the extreme than the middle range. The Box-Behnken design is suited for non-extreme points in all of the inputs, where $b0$, $b1$, and so forth are the estimated parameters [18]. The study considered feed rate, MQL flow rate, and cutting depth. The input variables are shown in Table 2. A Box-Behnken Design yielded a minimum of fifteen (15) experiments. The array employed in the machining exercise is shown in Table 3. The MINITAB 19 software was utilized in DOE and analysis of response data.

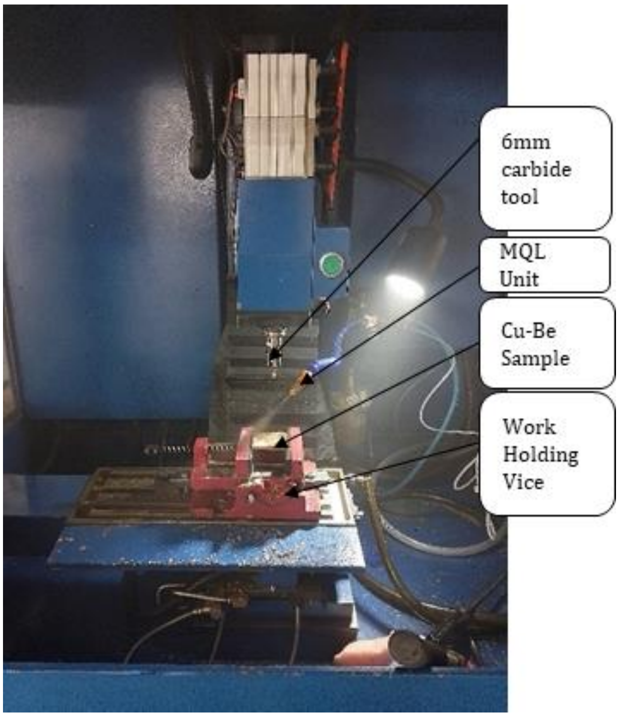

Fig. 1: The machining setup shows the work-holding device, sample position, MQL unit, and a 6mm carbide end-milling tool.

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Table 2. Milling Input Variables and Their Levels.

Input parameters.	Type and levels of Input variables		
	1	2	3
Feed rate *Fr* (mm/min)	60		80
MQL Flow Rate *Q* (ml/hr.)	20		80
Cutting depth Dc (mm)	0.2		0.9

Table 3. Box-Behnken Design Array.

Trials	Input parameters		
	Feed rate *Fr* (mm/min)	MQL Flow rate *Q* (ml/hr.)	Cutting depth *Dc* (mm)
1	70	50	0.55
2	60	50	0.20
3	70	80	0.20
4	70	20	0.90
5	80	50	0.90
6	80	50	0.20
7	60	20	0.55
8	80	20	0.55
9	60	50	0.90
10	70	50	0.55
11	70	50	0.55
12	60	80	0.55
13	80	80	0.55
14	70	20	0.20
15	70	80	0.90

2.3 Cutting fluid preparation

An oil-in-water emulsion was formulated using sunflower vegetable oil, an emulsifier, Tween 80 (a polyoxyethylene (20) sorbitan monostearate (non-ionic) surfactant) and Coco-diethanolamine (CDEA), a non-acidic anti-oxidation sulfate. The CF was formulated with fewer additives to make it eco-friendly than conventional commercial CFs. The three were mixed in the ratio 6:3:1 before diluting the concentrate with ten parts water and adding sodium Nitrite $NaNO_2$, which acted as an anti-corrosion agent [19,20]. Four characterization tests were conducted to determine the formulation's effectiveness as a cutting fluid. A pH test was conducted on the formulated oil-concentrated and the oil-in-water emulsion using an OHAUS ST series pen Meter, and the results were verified using a hydrion pH paper that turned green when testing the oil-water emulsion. An emulsion stability test was conducted on the emulsion. The emulsion was relatively stable at room temperature [20]. The volume of oil that separated from the emulsion collected at the top was examined to calculate the emulsion stability according to ASTM D 3707. A corrosion test was also carried out. Several grams of iron filings were washed in a bath of acetone to remove any oil, dust, and debris before testing. The corrosion properties of samples of cutting fluid with and without an anti-corrosion additive were tested according to the ASTM D 4627 standard. Finally, a viscosity test was carried out. The viscosity of distilled water was measured as 0.01 poise or 1cP and used as the reference for all other viscosity readings taken in the study, as the viscosity of distilled water was a known value [21].

2.4 Machining

The surface quality and the MRR were evaluated as functions of the input parameters. The samples were Machined on a 3-axis CNC machine (The Benchmill 6000); a standard vice attachment on the machine was used to hold the work during machining as the samples had a regular shape and the material could with the clamping force. A 6mm end-milling carbide tool with four flutes was used to mill the samples. A carbide tool was selected as it can withstand the heat and could produce a finer surface finish. The spindle speed was held constant at 3,235 RPM, the recommended spindle speed in the material data sheet. An MQL delivery unit operating at 7 MPa was used to distribute the atomized CF [22]. The CF demand guided the choice of the MQL unit. The surface finish was tested using the TR-200 roughness test, and the MRR was evaluated based on Equation 1.

$$\text{MRR (g/min)} = \frac{\text{Mb}-\text{Ma}}{\text{t}} \qquad (1)$$

The regression models were based on equation 2, a second-order quadratic equation indicating a point where the solution is neither maximized nor minimized.

$$y = \beta o + \beta_1 x_1 + \cdots \beta_k x_k + \cdots \beta_{11}^2 x_1^2 + \cdots \beta_{kk}^2 x_k^2 + \beta_{12} x_1 x_2 + \cdots \beta_{k-1,k} x_{k-1} x_k \ldots \qquad (2)$$

The optimum milling parameters were obtained by optimizing the responses in RSM after selecting an optimization criterion (maximization or minimization) of the output responses and an order of priority in case of conflict objectives.

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3. RESULTS AND DISCUSSION

3.1 Cutting fluid (CF) characterization

The cutting fluid was based on biodegradable vegetable oil and emulsifiers, making it an environmentally friendly option. The pH of the oil concentrate was recorded as 10.1, while that of the emulsion was recorded as 9.2. The pH of stable emulsion should fall in the range of 8.4-9.5 and 9-11 [20,23,24]. The hydrion paper verification test confirmed the emulsion was within the acceptable pH range. The emulsion stability test indicated that the oil-in-water emulsion stabilized after 48 hours at 96% stability. A corrosion test of a sample without any anti-corrosion agent resulted in between 10 and 25% of the test paper area being covered with rust spots. The reference indicated that the sample had moderately low corrosion-preventative capabilities. The sample with an anti-corrosion agent had no visible rust spots on the test paper. From the reference table, the sample with an anti-corrosion agent had excellent anti-corrosion capabilities [25]. The oil concentrate had a viscosity of 15cP. Up on dilution, the oil-in-water emulsion had a viscosity of 1.8 cP. Since the resulting cutting fluid has a relatively higher viscosity than distilled water, the cutting fluid was deemed to have a good lubricity value capable of reducing friction in the work-took interference.

3.2 The results of the milling experiments

The experimental responses of the milling test for the surface roughness Ra and the MRR are recorded in Table 4.

Table 4. Copper Beryllium milling results under MQL conditions.

Experiment Number	Input Parameters			Responses	
	Feed rate Fr (mm/min)	MQL (ml/hr.)	Cutting depth Dc (mm)	Surface roughness Ra (μm)	Material removal rate (g/min)
1.	70	50	0.55	0.168±0.06	5.633803
2.	60	50	0.20	0.173±0.07	10.30043
3.	70	80	0.20	0.191±0.06	5.607477
4.	70	20	0.90	0.511±0.14	19.71831
5.	80	50	0.0	0.553±0.25	49. 36709
6.	80	50	0.20	0.481±0.19	3.797468
7.	60	20	0.55	0.698±0.17	43.03797
8.	80	20	0.55	0.515±0.18	15.18987
9.	60	50	0.90	0.571±0.16	67.78243
10.	70	50	0.55	0.275±0.02	33.80282
11.	70	50	0.55	0.441±0.33	13.95349
12.	60	80	0.55	0.130±0.03	7.594937
13.	80	80	0.55	0.102±0.02	11.32075
14.	70	20	0.20	0.341±0.14	2.830189
15.	70	80	0.90	0.225±0.03	11.05991

3.3 Analysis of variance (ANOVA)

The adequacy of the regression models of surface roughness (Ra) and MRR were tested using the ANOVA technique on Minitab 19 software, and the regression model results fitted in the form of an ANOVA table, as shown in Tables 5 and 6, respectively. The sum of squares and the degree make up the ANOVA table. The regression model and residual error contributions were typically divided into the sum of squares. The mean square was a ratio of the sum of squares multiplied by degrees of freedom. To be adequate, the developed model's calculated F-ratio must be higher than the F-table's tabulated value for a 95% confidence level.

$$\mathrm{Ra} = 0.452 + 0.00099\,\mathrm{Fr} - 0.00590\,\mathrm{Q} + 0.214\,\mathrm{Dc} \tag{3}$$

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Table 5. Tabulated ANOVA of surface roughness (Ra).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.308551	0.102850	5.63	0.014
Linear	3	0.308551	0.102850	5.63	0.014
Fr	1	0.000780	0.000780	0.04	0.840
Q	1	0.250986	0.250986	13.73	0.003
Dc	1	0.056785	0.056785	3.11	0.106
Error	11	0.201119	0.018284		
Lack-of-Fit	9	0.163274	0.018142	0.96	0.609
Pure Error	2	0.037845	0.018922		
Total	14	0.509669			

S	R-sq	R-sq(adj)	R-sq(pred)
0.135217	60.54%	49.78%	25.24%

An ANOVA of surface roughness (Ra) shown in Table 5 was used to analyze the significance of the regression model and validate the model's ability to forecast the correlation between the independent variables and the responses considered in this study. From Table 5, the model's p-value was recorded as 0.014; hence, the model was significant and sufficient to predict the relationships between the variables. A lack-of-fit with a p-value of 0.609, above the significance threshold of 0.05, indicating the models' lack-of-fit was acceptable. The outcomes of the ANOVA further revealed that the MQL flow rate was the most infomercial input parameter to surface quality, with a p-value of 0.003. The feed and cutting depth had p-values of 0.84 and 0.106, respectively, above 0.05; hence, they were both deemed insignificant. The ANOVA showed an R^2 value of 60.54%, an R^2-adj of 49.78%, and an R^2 Predicted value of 25.24%.

$$\mathrm{MRR} = 38.7 - 0.618\ \mathrm{FR} + 44.7\ \mathrm{DC} \tag{4}$$

Table 6. Tabulated ANOVA of MRR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	2	2259.0	1129.5	4.49	0.035
Linear	2	2259.0	1129.5	4.49	0.035
Fr	1	305.1	305.1	1.21	0.292
Dc	1	1953.9	1953.9	7.76	0.016
Error	12	3020.2	251.7		
Lack-of-Fit	10	2601.3	260.1	1.24	0.526
Pure Error	2	418.9	209.5		
Total	14	5279.3			

S	R-sq	R-sq(adj)	R-sq(pred)
15.8645	42.79%	33.26%	3.04%

Table 6 shows an ANOVA table of MRR. The ANOVA included an analysis of the significance of the regression model and an examination of its validity in predicting the correlation between the independent variables and the responses. Table 6 indicated the model had a p-value of 0.035, indicating the model was significant and sufficient for prediction purposes. The lack-of-fit had a p-value of 0.526, above the significance threshold of 0.05; hence, it is acceptable. Furthermore, the p-values of the independent parameters indicated that cutting depth had a p-value of 0.016 and was the most influential variable toward MRR, while the feed rate had a p-value of 0.292, hence insignificant. The MQL flow rate had no direct link or influence on MRR; hence, it was eliminated from the ANOVA to simply the model. The regression model had an R^2 value of 42.79%, an R^2-adj of 33.26%, and an R^2 predicted value of 3.04%.

3.4 The effects of the input parameter on productivity and quality characteristics

The milled samples' main effect plot is shown in Fig. 2. It was noted that the surface quality of the milled samples increased with increasing milling depth, which was a classical trend in metal machining operations. According to Chinchanikar et al. [27] and Saravanakumar et al. [28], the load on each cutter flute increases when the cutting depth is increased, increasing milling temperature, tool wear, and vibrations. The above eventually leads to an inferior surface finish.

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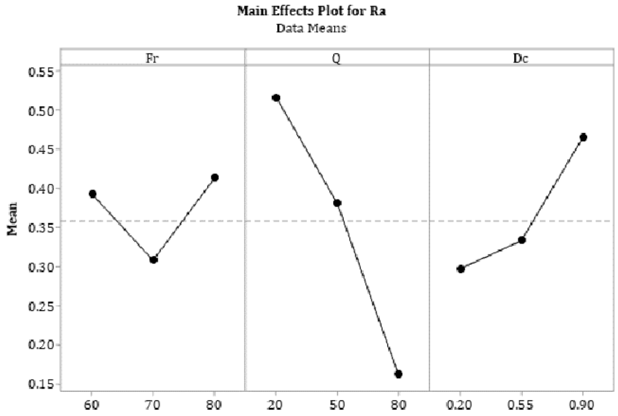

Fig. 2. Main effect plot of surface roughness Ra.

The least surface roughness value was obtained at an MQL flow rate of 80 ml/hr., a feed rate of 80 mm/min, and a cutting depth of 0.55 mm. The above input parameters were associated with lower cutting force and high penetration of the CF, hence improving lubrication and cooling effects.

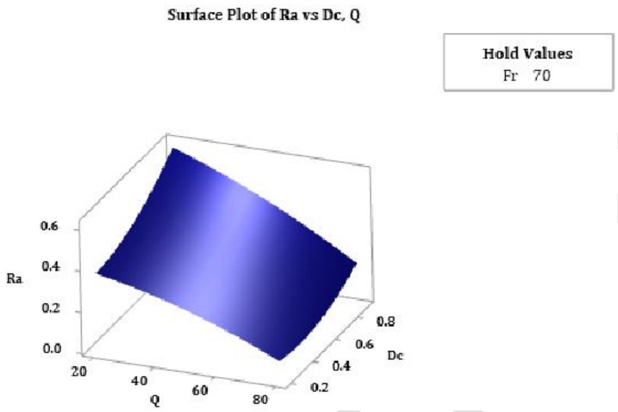

Fig. 3. Surface plot of Ra vs. Dc, Q (hold value Fr 70 mm/min).

The surface quality of the milled samples deteriorated with increased cutting depth, as observed in Fig. 3. The above observation aligns with those made in previous studies [2,29,30]. According to Kumar et al. [31], the friction between the cutter and the workpiece increases the temperature in the work-tool interface, cutting force, and tool wear as the cutting depth increases. As the tool becomes blunt, vibration occurs, leading to a poor surface finish.

Novovic et al. [32] and Sadeghi et al. [34] suggested that a machined material's surface roughness affects the component's mechanical strength when subjected to cyclic loads. A rough surface finish will likely reduce the fatigue strength of the milled part and vice versa. Raju et al. [34] showed that surface roughness affects mechanical properties, corrosion behavior, electrical and heat conductivity, wear, and light reflection.

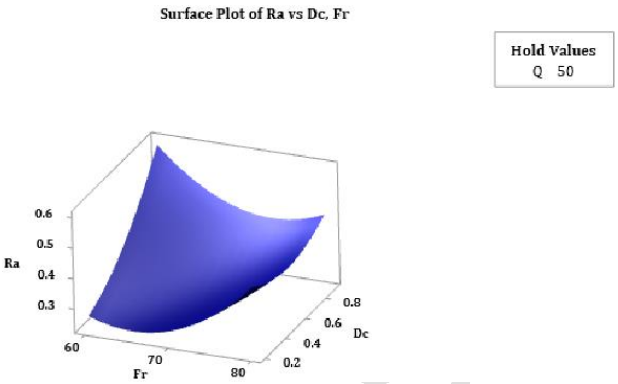

Fig. 4. Surface plot of Ra vs. Dc, Fr (hold value Q 50 ml/hr).

The surface quality decreased with increased feed up to a point and then increased with increased feed rate, as observed in Fig. 4 and Fig. 5. The contact time between the tool and workpiece is increased at a low feed rate, and a longer contact time lowers the likelihood of tool contours forming on the workpiece, improving the surface finish. Fadhel et al. [35] argued that the cutting force increased significantly with an increase in feed rate, which increased the cutting temperature, tool wear, and vibrations, all associated with a poor surface finish. Liao & Lin [36] explained that material properties change when the feed is below the optimal number as an oxide layer forms in the newly machined surface. The newly oxidized surfaces are challenging to machine, thus exacerbating tool wear and lowering surface quality. On the other hand, as the feed rate increases above the optimal value, the cutting force increases, and so does the resulting surface roughness value.

Fig 5 shows that the surface quality decreased at a higher MQL flow rate. Similar observations were made in a previous study [37]. The surface roughness of the milled samples decreased with increased MQL flow rate. The MQL technique featured a pressured cutting fluid formulated from vegetable-oil-based CF. The high pressure offered better penetration to the work-tool interface, while the CF's lubrication capacity and the cooling effect resulted in a decline in the amount of cutting force and heat at the work-tool interface [37]. It was also noted that a high surface roughness value was obtained with a higher MQL flow rate at lower feed rates, as indicated in Fig 3. According to Gaitonde et al.

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[39], thinner chips produced at lower cutting speeds created a capillary effect at a higher MQL flow rate, enabling the CF to drip closer to the cutting zone, removing excess heat more efficiently and improving the surface finish.

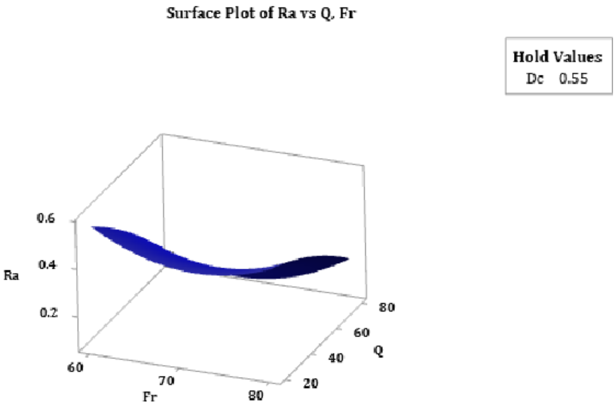

Fig. 5. Surface plot of Ra vs. Q, Fr (hold value Dc 0.55 mm).

The main effect plot of MRR is shown in Fig. 6. From the figure, it was determined that the most significant factor in MRR was the cutting depth. On the other hand, the feed rate showed no significant contribution to the material removal rate, while the MQL flow rate could not be directly linked to MRR. The main effect plot showed that increasing the cutting depth had a corresponding effect on the MRR.

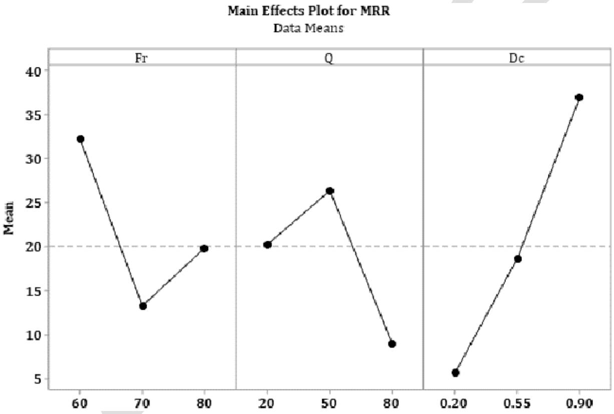

Fig. 6. Main effect of material removal rate MRR.

Fig. 7 shows a surface plot of MRR versus cutting depth (Dc) and the feed rate (Fr) while the MQL flow rate was constant at 50 ml/hr. The surface plot shows a classical behavior in MRR; increased tool engagement resulted in high productivity. The profile of the surface plot also showed that the highest MRR was obtained at a cutting depth of 0.9 mm and a feed of 60 mm/min and 80 mm/min, while the MQL flow rate was held constant at 50 ml/hr. According to Quintana et al. [40], MRR is a function of the axial cutting depth, radial cutting depth, tool radius, and feed rate. Hence, MRR was affected by the cutting depth and the feed.

Furthermore, it was determined that the MQL flow rate had no direct relationship with MRR. Soleymani Yazdi & Khorram [41] established that increasing the axial cutting depth increased the MRR. Increasing the cutting depth increased tool engagement by increasing the feed-per-tooth ratio. It was also noted that as the feed rate and cutting depth increased, the friction between the workpiece and the tool also increased, limiting tool mobility, which increased machining time and resulted in a lower MRR.

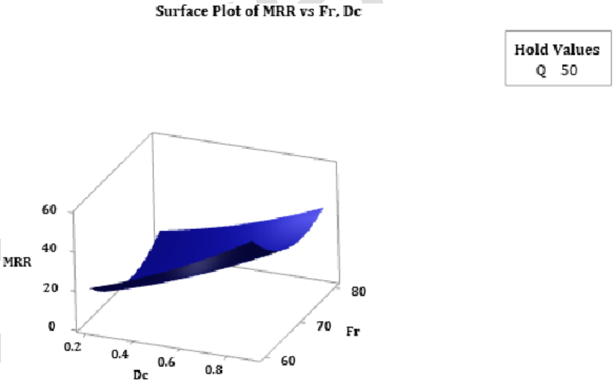

Fig. 7. Surface plot of MRR vs. Fr, Dc (hold value Q 50 ml/hr).

The MRR is a function of mass and time (Equation 1). The MQL flow rate was not directly linked to the function of MRR. It is worth noting that the maximum MRR was obtained using an MQL flow rate of 50 ml/hr.; the effects of the MQL flow rate could be attributed to higher-order interaction between the input parameters. The maximum MRR was obtained at 60 mm/min feed, an MQL flow rate of 50 ml/hr., and a cutting depth of 0.9 mm. Quintana et al. [40] and Soleymani Yazdi & Khorram [41] made similar observations: the MRR increased with increased tool engagement, thus increasing productivity. Increasing the feed rate in a milling operation reduces the milling time, thus increasing the MRR [42]. Although the feed rate did not cross the statistical threshold of dominant factors, Fig. 9 shows the MRR first reduced and then increased as the tool engagement increased. The results above seemed to agree with previous research on MRR, arguing that increasing the cutting depth and feed increased the MRR [17,31,43–45].

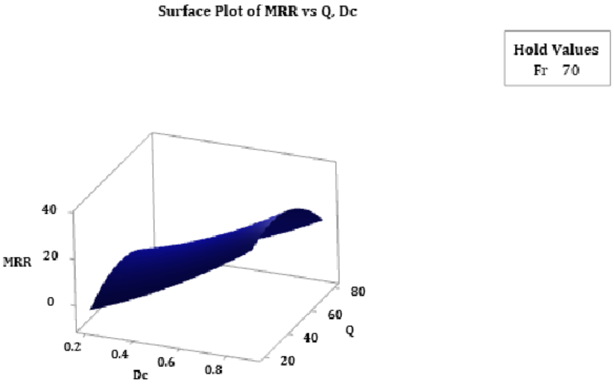

Fig. 8. Surface plot of MRR vs. Dc, Q (hold value Fr 70 mm/min).

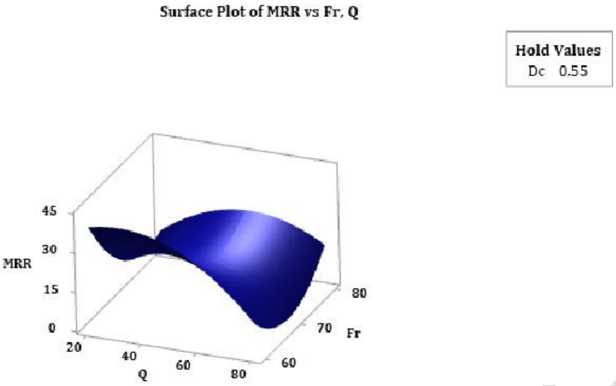

Fig. 9. Surface plot of MRR vs. Fr, Q (hold value Dc 0.55mm).

Additionally, the impact of using vegetable oil-based lubrication was assessed with respect to findings in other studies on milling Cu-Be using conventional cutting fluids. In a study report on the wear behavior of uncoated and coated tools in the milling operation of Cu-Be alloy, Sousa et al. [46] used a 5% soluble mineral oil in a 95% water emulsion in flood cooling of the cutting zone. According to the result of the study, the surface roughness of 0.2-0.125 µm was achieved using the coated and uncoated tools, respectively, at a cutting length of 48 m. Another study compared vegetable-based and conventional cutting fluids in machining copper alloys [47]; the result of the surface roughness test showed disparities, with vegetable base CF recording 0.543-0.795 µm while conventional CF recorded 0.593 – 0.841 µm. From the above result, it is clear that vegetable-based cutting fluids have comparable operational properties as conventional machining fluids, which, coupled with the non-toxic, eco-friendly, and biodegradable nature of vegetable CFs, offer immense advantages in MQL systems. The surface roughness values reported in this study were also significantly lower than those reported in the above studies where conventional CFs were used.

3.5 Process parameter optimization in machining of copper beryllium

The optimization was conducted on the MINITAB 19 RSM optimizer. The three input parameters had equal importance in the optimization criteria, but an order of priority, favoring surface roughness (Ra), was established to achieve a very high degree of surface finish for the parts to perform their intended function [48]. The optimization criteria adopted MRR maximization and surface roughness minimization with the order of priority, creating the necessary trade-off as the two responses were contradictory. The study considered uncoded variables in the design of experiments: Fr, Q, and DC centered at 0, and the levels extended to +1 and -1 from the center [18]. Hence, the inputs were rescaled in the range of +1 and -1 based on the finest preceding solution and then searched for an optimum point that the output aligned with the optimization criteria.

The optimization output, shown in Fig. 10, showed that the optimum responses were obtained at a feed of 60 mm/min, an MQL flow rate of 80 ml/hr., and a cutting depth of 0.51 mm. A multiple response prediction at a 95 % confidence interval (CI) was also carried out to obtain the optimum values. A composite desirability value of 0.7960 was obtained during optimization. The optimization plot in Figure 9 shows the condition under which optimum responses were obtained based on the selected optimization criteria.

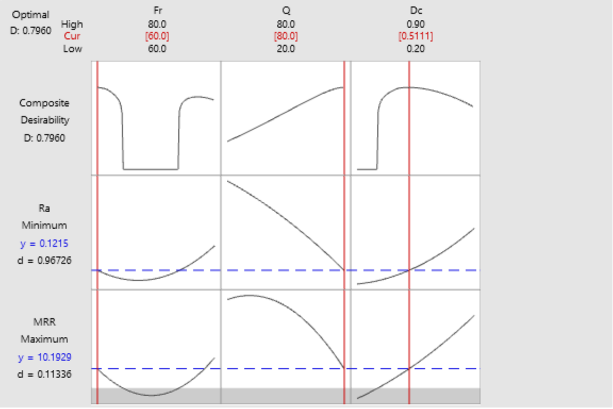

Fig. 10. Optimization plots of Ra and MRR.

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The multiple response optimization yielded a surface roughness value of 0.1215 µm and an MRR of 10.1929 g/min (1235.50 mm^3/min) as the minimum and maximum responses. The results showed significant surface roughness and MRR gains under MQL conditions using a vegetable-oil-based CF. Furthermore, the findings were comparable to previous studies. Öktem et al. [49] obtained a surface roughness value of 0.391 µm while they examined the surface roughness of samples milled for mold application. Ramesh & Elayaperumal [2] recorded a surface roughness of 0.7950 µm and an optimized MRR of 507.3378 mm^3/min while investigating optimum parameters in conventional milling of Copper Beryllium. Dhandapani et al. [18] reported the acceptable range in high-speed milling of tough materials to be 0.2 -0.8 µm. The improvements in the responses obtained in this study could be attributed to the MQL cooling technique and CF performance. The findings indicated that the CF formulation could provide the necessary lubrication and cooling effect for effect machining of the alloy. The above discussion determined that employing the RSM method with the Box-Behnken design proved effective, as optimization was achieved with minimal experiments based on the design.

4. CONCLUSIONS

This study applied the RSM DOE with a Box-Behnken design to explore how variations in process parameters (Feed rate, MQL flow rate, and cutting depth) impact the quality and productivity aspects of machining. ANOVA was applied to determine the significance of the input variables, while regression models built on the ANOVA were used to predict the correlation between the independent parameters and the output responses. A multi-parameter optimization was also conducted to find the optimal parameter settings capable of achieving superior surface quality and enhanced productivity when machining Copper Beryllium. The findings from the experiments allow for the following conclusion to be drawn.

The characterization studies of the CF yielded a pH of 10.1 for the oil concentrate and a pH of 9.2 for the emulsion; the emulsion stability was 96% after 24 hrs., a viscosity of 1.8 cp, and good corrosion resistance. The MQL flow rate was established to be the most significant input variable toward Surface roughness. The analysis showed that it was possible to get a surface roughness value high enough to reduce the need for post-processing (polishing). A high flow rate resulted in a low value of Ra. On the other hand, MQL had no direct link to MRR.

The surface quality (Ra) and MRR increased with the cutting depth. A lower surface roughness value was achieved at a lower cutting depth. The MRR was higher at higher depths of cut. The feed rate had a lower significance toward the responses than the other input parameters considered in this study. Its effects could only be established at higher-order interactions. The optimum input parameters in milling of Copper Beryllium under MQL were a feed of - 60mm/min, an MQL flow rate of - 80 ml/hr., and a cutting depth of - 0.5111 mm, of which the responses were 0.1215µm and 10.1929g/min for Ra and MRR respectively.

Although the study contributes valuable insights into milling copper beryllium, it is essential to acknowledge some limitations. The decision to consider three input variables in the study limited our ability to comprehensively explore the influences of all milling parameters on the response. Furthermore, using one vegetable oil-based CF meant a first-hand account comparative conclusion could be drawn from the result. Future studies investigating the effects of other parameters and considering the effects of various CFs are necessary for a more comprehensive conclusion on milling Copper Beryllium.

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REFERENCES

[1] Y. Yildiz, M. . Sundaram, K. . Rajurkar, and M. Nalbant, “The Effects of Cold and Cryogenic Treatments on the Machinability of Beryllium-Copper Alloy in Electro Discharge Machining,” *44th CIRP Conf. Manuf. Syst.*, pp. 1–7, 2011.

Article in Press

Article in Press

[2] B. Ramesh and A. Elayaperumal, "Determination of optimum parameter levels for multi-performance characteristics in conventional milling of beryllium copper alloy by using response surface methodology," no. June 2019, 2014.

[3] N. Nagel, "Beryllium and Copper-Beryllium Alloys," *ChemBioEng Rev.*, vol. 5, no. 1, pp. 30–33, 2018, doi:10.1002/cben.201700016

[4] S. V. Alagarsamy, M. Ravichandran, M. Meignanamoorthy, C. Chanakyan, S. D. Kumar, and S. Sakthivelu, "Influence of CNC turning variables on high strength Beryllium-Copper (C17200) alloy using tungsten carbide insert," *Mater. Today Proc.*, vol. 27, no. xxxx, pp. 925–930, 2020, doi: 10.1016/j.matpr.2020.01.260

[5] J. O. Milewski, G. K. Lewis, J. Fonseca, and R. B. Nemec, "Laser powder deposition of a near net shape injection mold core - a case study," *Mater. Manuf. Process.*, vol. 15, no. 2, pp. 247–258, 2000, doi: 10.1080/10426910008912986

[6] A. K. Dubey and V. Yadava, "Laser beam machining-A review," *Int. J. Mach. Tools Manuf.*, vol. 48, no. 6, pp. 609–628, 2008, doi: 10.1016/j.ijmachtools.2007.10.017

[7] K. V. Sudhakar, J. C. Cisneros, H. Cervantes, and C. G. Pineda, "Machining characteristics and fracture morphologies in a copper-beryllium (Cu-2Be) alloy," *J. Mater. Eng. Perform.*, vol. 15, no. 1, pp. 117–121, 2006, doi: 10.1361/105994906X83510

[8] Ä. Dias, R. Mesquita, P. Vassalo, J. C. Rebelo, and A. Mora, "An experimental study on electro-discharge machining and polishing of high strength copper-beryllium alloys," *J. Mater. Process. Technol.*, vol. 103, no. 3, pp. 389–397, 2000.

[9] R. Mehfuz and M. Y. Ali, "Surface Roughness Analysis of Beryllium-Copper Alloy in Micro End Milling," *Int. J. Mech. Eng.*, vol. 2007, no. December, pp. 1–5, 2007.

[10] N. P. Hung, Z. W. Zhong, K. K. Lee, and C. F. Chai, "Precision grinding and facing of copper-beryllium alloys," *Precis. Eng.*, vol. 23, no. 4, pp. 293–304, 1999, doi: 10.1016/S0141-6359(99)00024-0

[11] S. Pervaiz, A. Rashid, I. Deiab, and C. M. Nicolescu, "An experimental investigation on effect of minimum quantity cooling lubrication (MQCL) in machining titanium alloy (Ti6Al4V)," *Int. J. Adv. Manuf. Technol.*, vol. 87, no. 5–8, pp. 1371–1386, 2016, doi: 10.1007/s00170-016-8969-6

[12] E. O. Ezugwu, "Key improvements in the machining of difficult-to-cut aerospace superalloys," *Int. J. Mach. Tools Manuf.*, vol. 45, pp. 1353–1367, 2005, doi: 10.1016/j.ijmachtools.2005.02.003

[13] N. Tosun and M. Huseyinoglu, "Effect of MQL on surface roughness in milling of AA7075-T6," *Mater. Manuf. Process.*, vol. 25, no. 8, pp. 793–798, 2010, doi: 10.1080/10426910903496821

[14] S. Ekinovic, E. Begović, and E. Ekinovic, "Advanced Cutting Processes of Metallic Materials," *2nd Int. Conf. New Technol. NT-2015, Dev. Appl.*, no. April, 2015.

[15] B. Boswell, M. N. Islam, I. J. Davies, Y. R. Ginting, and A. K. Ong, "A review identifying the effectiveness of minimum quantity lubrication (MQL) during conventional machining," *Int. J. Adv. Manuf. Technol.*, vol. 92, no. 1–4, pp. 321–340, 2017, doi: 10.1007/s00170-017-0142-3

[16] Á. R. Machado and J. Wallbank, "The effect of extremely low lubricant volumes in machining," *Wear*, vol. 210, no. 1–2, pp. 76–82, 1997, doi: 10.1016/S0043-1648(97)00059-8

[17] J. M. Wambua, F. M. Mwema, B. Tanya, and T. C. Jen, "CNC Milling of Medical-Grade PMMA: Optimization of Material Removal Rate and Surface Roughness," *Int. J. Manuf. Mater. Mech. Eng.*, vol. 12, no. 1, pp. 1–15, 2022, doi: 10.4018/IJMMME.293226

[18] N. V. Dhandapani, V. S. Thangarasu, and G. Sureshkannan, "Investigation on Effect of Material Hardness in High Speed CNC End Milling Process," *Sci. World J.*, vol. 2015, 2015, doi: 10.1155/2015/762604

[19] J. John, M. Bhattacharya, and P. C. Raynor, "Emulsions containing vegetable oils for cutting fluid application," vol. 237, pp. 141–150, 2004, doi: 10.1016/j.colsurfa.2003.12.029

[20] S. A. Lawal, I. A. Choudhury, and Y. Nukman, "Developments in the formulation and application of vegetable oil-based metalworking fluids in turning process," pp. 1765–1776, 2013, doi: 10.1007/s00170-012-4607-0

[21] Lubrizol, "Determination of Viscosity Using A Brookfield Viscometer for Conditioning Polymers," *Lubrizol Adv. Mater.*, pp. 1–5, 2013.

[22] N. R. Dhar, M. Kamruzzaman, and M. Ahmed, "Effect of minimum quantity lubrication (MQL) on tool wear and surface roughness in turning AISI-4340 steel," *J. Mater. Process. Technol.*, vol. 172, no. 2, pp. 299–304, 2006, doi: 10.1016/j.jmatprotec.2005.09.022

[23] M. Amrita, R. R. Srikant, A. V. Sitaramaraju, M. Prasad, and P. V. Krishna, "Preparation and characterization of properties of nanographite-based cutting fluid for machining operations," *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.*, vol. 228, no. 3, pp. 243–252, 2014, doi: 10.1177/1350650113502003

[24] S. Alves and J. De Oliveira, "Vegetable based cutting fluid–an environmental alternative to grinding process," *15th CIRP Int. Conf. Life Cycle Eng.*, pp. 1–5, 2008.

[25] L. Tang *et al.*, "Biological Stability of Water-Based Cutting Fluids: Progress and Application," *Chinese J. Mech. Eng. (English Ed.*, vol. 35, no. 1, 2022, doi: 10.1186/s10033-021-00667-z

[26] A. Saravanakumar, S. Dhanabal, E. Jayanand, and P. Logeshwaran, "Analysis of Process Parameters in Surface Grinding Process," *Mater. Today Proc.*, vol. 5, no. 2, pp. 8131–8137, 2018, doi: 10.1016/j.matpr.2017.11.500

[27] S. Chinchanikar, A. V. Salve, P. Netake, A. More, S. Kendre, and R. Kumar, "Comparative Evaluations of Surface Roughness During Hard Turning under Dry and with Water-based and Vegetable Oil-based Cutting Fluids," *Procedia Mater. Sci.*, vol. 5, pp. 1966–1975, 2014, doi: 10.1016/j.mspro.2014.07.529

[28] A. K. Sharma, A. K. Tiwari, and A. R. Dixit, "Effects of Minimum Quantity Lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: A comprehensive review," *J. Clean. Prod.*, vol. 127, pp. 1–18, 2016, doi: 10.1016/j.jclepro.2016.03.146

[29] G. M. Kumar, S. P. K., and S. V. S., "Machining Parameters Optimization of Titanium Alloy using Response Surface Methodology and Particle Swarm Optimization under Minimum-Quantity Lubrication Environment," *Mater. Manuf. Process.*, vol. 31, no. 13, pp. 1671–1682, 2016, doi: 10.1080/10426914.2015.1117632

[30] B. Ramesh, R. Venkatesh, J. Abraham, S. Clement, R. B. Jahaziel, and A. Elayaperumal, "Optimization of Process Parameter Levels during Conventional Milling of Beryllium Copper Alloy Using End Mill," *Int. J. Adv. Res. Sci. Eng.*, no. January, pp. 57–63, 2011.

[31] S. Kumar, A. K. Gupta, and P. Chandna, "State of art optimization techniques for machining parameters optimization during milling," *Int. J. Eng. Adv. Technol.*, vol. 8, no. 6, pp. 5104–5114, 2019, doi: 10.35940/ijeat.F9562.088619

[32] D. Novovic, R. C. Dewes, D. K. Aspinwall, W. Voice, and P. Bowen, "The effect of machined topography and integrity on fatigue life," *Int. J. Mach. Tools Manuf.*, vol. 44, no. 2–3, pp. 125–134, 2004, doi: 10.1016/j.ijmachtools.2003.10.018

[33] M. H. Sadeghi, M. J. Haddad, T. Tawakoli, and M. Emami, "Minimal quantity lubrication-MQL in grinding of Ti-6Al-4V titanium alloy," *Int. J. Adv. Manuf. Technol.*, vol. 44, no. 5–6, pp. 487–500, 2009, doi: 10.1007/s00170-008-1857-y

[34] G. W. A. Kui, S. Islam, M. M. Reddy, N. Khandoker, and V. L. C. Chen, *Recent progress and evolution of coolant usages in conventional machining methods: a comprehensive review*, vol. 119, no. 1–2. Springer London, 2022. doi: 10.1007/s00170-021-08182-0

[35] A. Fadhel, I. Saad, K. Shather, and K. A. Khalaf, "Prediction of Cutting Forces by using Machine Parameters in End Milling Process," vol. 26, no. 11, pp. 1–4, 2008.

[36] Y. S. Liao and H. M. Lin, "Mechanism of minimum quantity lubrication in high-speed milling of hardened steel," *Int. J. Mach. Tools Manuf.*, vol. 47, no. 11, pp. 1660–1666, 2007, doi: 10.1016/j.ijmachtools.2007.01.007

[37] Z. Q. Liu, J. Xu, S. Han, and M. Chen, "A coupling method of response surfaces (CRSM) for cutting parameters optimization in machining titanium alloy under minimum quantity lubrication (MQL) condition," *Int. J. Precis. Eng. Manuf.*, vol. 14, no. 5, pp. 693–702, 2013, doi: 10.1007/s12541-013-0093-z

[38] V. N. Gaitonde, S. R. Karnik, and J. P. Davim, "Optimal mql and cutting conditions determination for desired surface roughness in turning of brass using genetic algorithms," vol. 0344, no. May 2012, doi: 10.1080/10910344.2012.673976

[39] B. Li, C. Li, Y. Zhang, Y. Wang, D. Jia, and M. Yang, "Grinding temperature and energy ratio coefficient in MQL grinding of high-temperature nickel-base alloy by using different vegetable oils as base oil," *Chinese J. Aeronaut.*, vol. 29, no. 4, pp. 1084–1095, 2016, doi: 10.1016/j.cja.2015.10.012

[40] G. Quintana, J. De Ciurana, and J. Ribatallada, "Surface roughness generation and material removal rate in ball end milling operations," *Mater. Manuf. Process.*, vol. 25, no. 6, pp. 386–398, 2010, doi: 10.1080/15394450902996601

[41] M. R. SOLEYMANI YAZDI and A. KHORRAM, "Modeling and Optimization of Milling Process by using RSM and ANN Methods," *Int. J. Eng. Technol.*, vol. 2, no. 5, pp. 474–480, 2010, doi: 10.7763/ijet.2010.v2.167

[42] K. Gandjar, M. Azmi, A. Mandala, and T. J. Ko, "The Effect of Machining Parameters to the Surface Roughness in Low Speed Machining Micro-milling Inconel 718 The Effect of Machining Parameters to the Surface Roughness in Low Speed Machining Micro-milling Inconel 718," *IOP Conf.series Mater. Sci. Eng.*, vol. 654, pp. 1–8, 2019, doi: 10.1088/1757-899X/654/1/012014

Article in Press

[43] K. Barnwal, D. Mishra, and R. S. Prasad, "Optimization of Surface Roughness: Effect of Machining Parameters on EN23," *Adv. Transdiscipl. Eng.*, vol. 27, pp. 666–671, 2022, doi: 10.3233/ATDE220811

[44] A. R. Shinge and U. A. Dabade, "The Effect of Process Parameters on Material Removal Rate and Dimensional Variation of Channel Width in Micro-milling of Aluminium Alloy 6063 T6," *Procedia Manuf.*, vol. 20, pp. 168–173, 2018, doi: 10.1016/j.promfg.2018.02.024

[45] G. Pant, S. Kaushik, D. K. Rao, and K. Negi, "Study and Analysis of Material Removal Rate on Lathe Operation with Varing Parameters from CNC Lathe Machine," *Int. J. Emerg. Technol. (Special Issue NCETST-2017)*, vol. 8, no. 1, pp. 683–689, 2017.

[46] V. F. C. Sousa, J. Castanheira, F. J. G. Silva, J. S. Fecheira, G. Pinto, and A. Baptista, "Wear behavior of uncoated and coated tools in milling operations of ampco (Cu-be) alloy," *Appl. Sci.*, vol. 11, no. 16, 2021, doi: 10.3390/app11167762

[47] M. Saikiran, G. Ravali, and P. Kumar, "Comparative study of vegetable based and conventional cutting fluids in machining of copper alloys," *Mater. Today Proc.*, vol. 19, pp. 611–614, 2019, doi: 10.1016/j.matpr.2019.08.077

[48] A. L. Kelly, L. . Mulvaney-Johnson, R. . Beechey, and P. D. Coates, "The Effect of Copper Alloy Mold Tooling on the Performance of the Injection Molding Process," *Society*, pp. 1837–1848, 2011, doi: 10.1002/pen.21975

[49] H. Öktem, T. Erzurumlu, and M. Çöl, "A study of the Taguchi optimization method for surface roughness in finish milling of mold surfaces," *Int. J. Adv. Manuf. Technol.*, vol. 28, no. 7–8, pp. 694–700, 2006, doi: 10.1007/s00170-004-2435-6

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