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Fuzzy logic method to investigate grinding of alumina ceramic using minimum quantity lubrication

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Abstract

The use of nanofluid in lubrication during machining of advanced engineering ceramics has been found to be highly efficient and eco-friendly. This work involves experimental investigation of grinding Alumina (Al_2O_3) ceramic to determine the effect of the grinding variables. The grinding variables considered include depth of cut, feed rate, type of diamond wheel, and lubrication type. Moreover, the response parameters considered include grinding power, coefficient of friction, and surface quality. The responses obtained during the experiments were used to develop a fuzzy logic prediction model. The findings from this work can be concluded as follows: (a) The depth of cut and feed rate have direct proportional relationship with the grinding power and coefficient of friction. (b) The metallic bonded diamond wheel was found to have higher machining efficiency than the resinoid bonded one. (c) Higher number of diamond grits produces lower frictional coefficient. (d) The carbon nanotube based nanofluid when used in the minimum quantity lubrication (MQL) process proffers better lubrication capability than conventional flood cooling system. (e) The developed fuzzy logic models were found to have high prediction accuracies of 97.22%, 98.60%, and 96.8%, respectively, for grinding power, grinding force ratio, and surface roughness.

KEYWORDS
grinding, alumina, nanoparticles, carbon nanotube, fuzzy logic, alumina

1 | INTRODUCTION

Advanced engineering ceramics such as alumina, zirconia, silicon nitride etc have gained high popularity in biomedical and aerospace applications,[1] due to their excellent hardness, high wear and thermal resistances, biocompatibility, and aesthetics.[2]

Among the conventional machining techniques used to machine advanced ceramics, surface grinding using diamond wheels is still the most efficient method utilized when processing the brittle materials.[3] Studies have shown that machining takes up a bunch of the cost of producing advanced ceramic components.[4] Due to their excessive hardness, there are many setbacks encountered during the machining of these kind of materials.[5] Studies have shown that the difficulty encountered during the machining results about a great limitation to their extensive usage in various engineering fields.[3] In addition, there is high rate formation of residual deformations such as macro and micro-cracks, during machining of the brittle materials. These unwanted deformations have been found to deteriorate the quality of the manufactured components.[6] As such, there is need to improve on the machining of these materials, especially improving the efficiency and achieving defect-free components at lower costs.[7,8]

Previous works have shown that the utilization of brazed diamond wheels in grinding operations could be used to improve machining efficiencies and part quality. Moreover, there are various factors which affect the performance of the diamond wheels in grinding operations which includes bond strength, grain projections, and grain sizes.[9] According to the findings Chen, Huang,[10] the energy expended per unit material removed during grinding operations arise mainly due to the sliding and ploughing actions around the grinding region. Hence, by appropriately controlling the sliding and ploughing ability of the wheel, there would be better utilization of the energy expended in the grinding process.

Previous studies have shown that the lubrication cost constitutes a huge part of the machining costs for automotive components.[11] Figure 1 shows the chart for the total costs of using lubrication fluids in machining in the automotive industry. A significant finding from the previous research is that the cost of lubrication exceeds the cost of tool and grinding wheels.[12] Further studies have shown that the type of lubrication employed during grinding operations significantly affects the performance of the grinding process.[13] Moreover, researchers have also shown that the lubrication employed during grinding operations are vital to improving the grinding of advanced materials,[14] because they affect the grinding forces and efficiency of the process[15]

Xie and Huang[16] reported that dry grinding is characterized by surface burns on the work piece surface with high rate of tool wear, whereas flood cooling helps reduce these unwanted conditions. The flood cooling was found to provide continuous chips whose surface profiles were sharp and smoother than the surface profile of the dry ground components. However, recent findings have shown that the conventional flood cooling lubrication system is being replaced by MQL systems (mist lubrication). The MQL system has thus far shown to be a promising alternative to the conventional flood coolants, which are mostly mineral oil-based, and non-biodegradable. Not only does the Environmental Protection Agency regulate the disposal of the flood coolants, but many states and localities also have classified them as hazardous wastes.[17] Thus, the use of the mineral oil based non-biodegradable coolants during machining is highly discouraged.

The MQL system works by atomizing fluids with compressed air, which are transported via a nozzle at specific ejection pressures into the grinding region. Nowadays, the MQL nanofluids are being introduced into the grinding process to enhance the process' efficiency. Nanoparticles are increasingly being utilised as additives in lubrication systems due to the positive contribution they proffer such as increased thermochemical characteristics, rheology and lubricity of the lubricants. In nano MQL system, some amount of nanoparticles are mixed with a suitable fluid (oil or water), and then stirred thoroughly to achieve a homogenous mixture.[18] Many researchers have shown that the MQL nano lubrication process offers higher lubrication activity in machining operations, and significantly reduces the surface roughness, grinding forces. The efficiency of machining processes has also been reported to be improved by the nanofluid MQL technique.[19] The nanofluids compared to the conventional lubricants also have higher thermo-physical characteristics such as higher heat conduction capacity, viscosity and better heat evacuation ability.[20]

Several nanoparticles have been effectively used to produce the nanofluids used in the MQL grinding operations. They include TiO_2, Al_2O_3,SiO_2, Carbon nanotube (CNT), MoS2, graphene, graphene-oxide, and diamond.[21] Previous works have shown that the nanofluids have higher bearing and load carrying capability compared to the pure base oils.[22] Among the various types of nanoparticles, the CNT since its discovery in the early 1990's has fascinated researchers with its outstanding properties, such as high thermal conductivity, hardness, and bending strength.[23] Cornelio, Cuervo[24] studied the Tribological performance of CNTs when used as additive in oil and water. They found that the presence of CNT in the fluid results in decrease of the coefficient of friction and wear. Moreover, the tribology of the oil-based CNT nanofluid was found to be better than the water based CNT nanofluids. In addition, it is recommended to use of Multi-walled carbon nanotubes

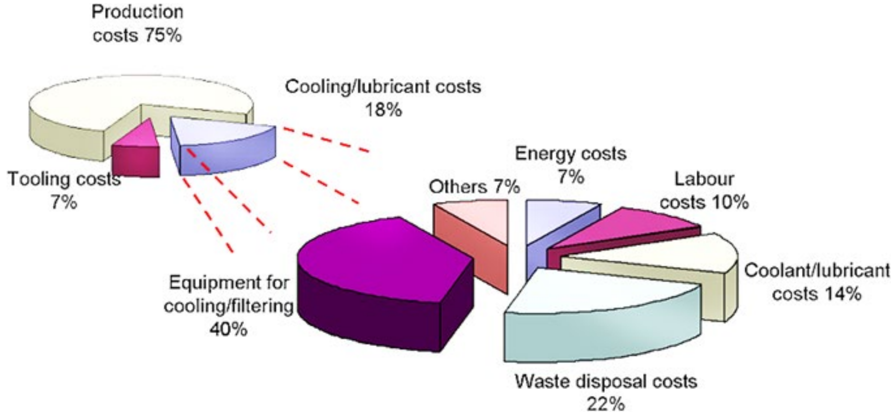

FIGURE 1 Distribution of cooling/lubricant costs in machining operations in the automotive industry (Sanchez et al[12]) [Colour figure can be viewed at wileyonlinelibrary.com]

(MWCNTs) for industrial/manufacturing applications due to its relatively lower price compared to the single or double-walled CNT's, and diamond nanoparticle.[25]

Recently, there has been increase in the trend of modelling manufacturing processes using artificial intelligence (AI) methods because of their superior computing and prediction capacity. Several studies have been done using numerous artificial intelligent methods. Basic AI techniques used for prediction in manufacturing processes include artificial neural network (ANN), fuzzy logic, Adaptive neuro-fuzzy inference system (ANFIS).[19] Among the AI techniques, the fuzzy logic modelling has the capability of comprehending the knowledge pattern using flexible linguistic terms in form of IF-THEN rules.[26] The complex and uncertain nature of the manufacturing processes could be analyzed by the application of fuzzy logic-based computational methods.[27]

In this work, experimental investigation of conventional surface grinding was conducted in other to analyse the effects of using MQL nano fluids during grinding of Alumina ceramic. The effects of different process parameters on the grinding power, friction coefficient, and surface integrity were investigated. The performance of the MQL nano fluid (carbon nanotubes based) was compared with that of the water based coolants. Finally, Fuzzy logic model was used to predict and study the effect of the grinding parameters on the response parameters.

2 | EXPERIMENTATION

In grinding, the material removal process is characterized by high speed and smaller material removal as compared to other conventional machining methods. Figure 2 illustrates the concept of surface grinding process. The linear speed of the grinding wheel is obtained from the rotational speed using the mathematical relation given in Equation 1;

$$v = \pi DN \tag{1}$$

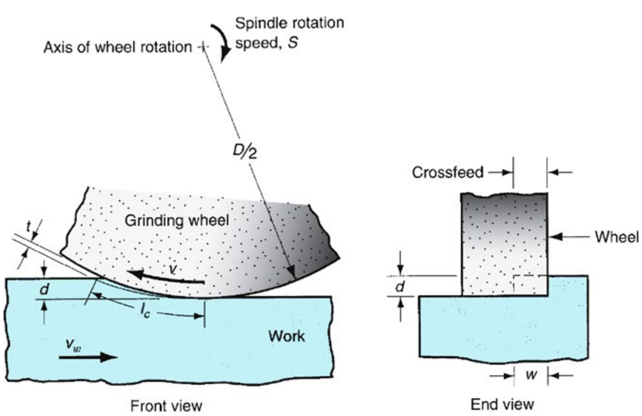

FIGURE 2 Geometry of surface grinding[43] [Colour figure can be viewed at wileyonlinelibrary.com]

where v = wheel's linear speed; lc = chip length; t = chip thickness, d = depth of cut, Vw = Feed rate; N = spindle speed; and D = wheel diameter.

Analysis of the performance of the flood coolant and the carbon nanotube-based MQL nanofluid was done by performing surface grinding operations on highly pure ceramic work material, that is, Al_2O_3 (99.5%). The Al_2O_3 specimen (which has a dimension of $100 \times 100 \times 10$ mm) was produced by Goodfellow Corporation. The mechanical properties of the Al_2O_3 material are given in Table 1.

Figure 3 shows the experimental set-up used in this research work. The experiments were conducted on the Naga-Ichi horizontal grinding machine with model no. NI 450AV2 shown in Figure 3B. Four different diamond wheels, respectively, with fine and coarse grain concentrations were utilized in conducting the grinding experiments, two were metallic bonded and the other two were made of resin bond. The two wheels contain different grain sizes, that is, coarse-25 and fine-125. The diamond wheels were dressed properly prior to each experimental run, using the Norton 38A150-I8VBE alumina stick dresser. Two types of lubricants, that is, conventional flood cooling using conventional coolant and MQL nano lubricant were used to conduct the experiments. Additionally, the nano lubricant used in this work was produced by adding 2% w/w of carbon nanotube particles (elemental composition shown in Figure 4A and energy-dispersive X-ray spectroscopy (EDX) shown in Figure 4B) into 500 mL vegetable oil. The mixture was then sonicated for an hour using ultrasonic sonicator with settings of (240 V, 40 kHz, 500 W).

The parameters and the range of values used in this experiment are summarized in Table 2. The design of experiment array L-16 ($4^3 \times 2^1$) was obtained using the Minitab-17 software. The process factors and their corresponding levels used in each experimental run based on L-16 design are given in Table 3. The diameter, thickness and hole-diameter of grinding wheel are 200, 5 and 31.75 mm, respectively.

TABLE 1 Properties of alumina material

Material type	Alumina
Purity	99.5%
Compressive strength (MPa)	2500
Density (g/cm^3)	3.9
Dielectric constant	10.1
Coefficient of thermal expansion at 20-1000°C ($\times 10^{-6}$/K)	8.0
Specific heat at 25°C (J/K/kg)	900
Thermal conductivity at 20°C (W/m/K)	35
Hardness-Vickers (kgf/mm^2)	1600
Shear strength (MPa)	330
Tensile modulus (GPa)	300-400

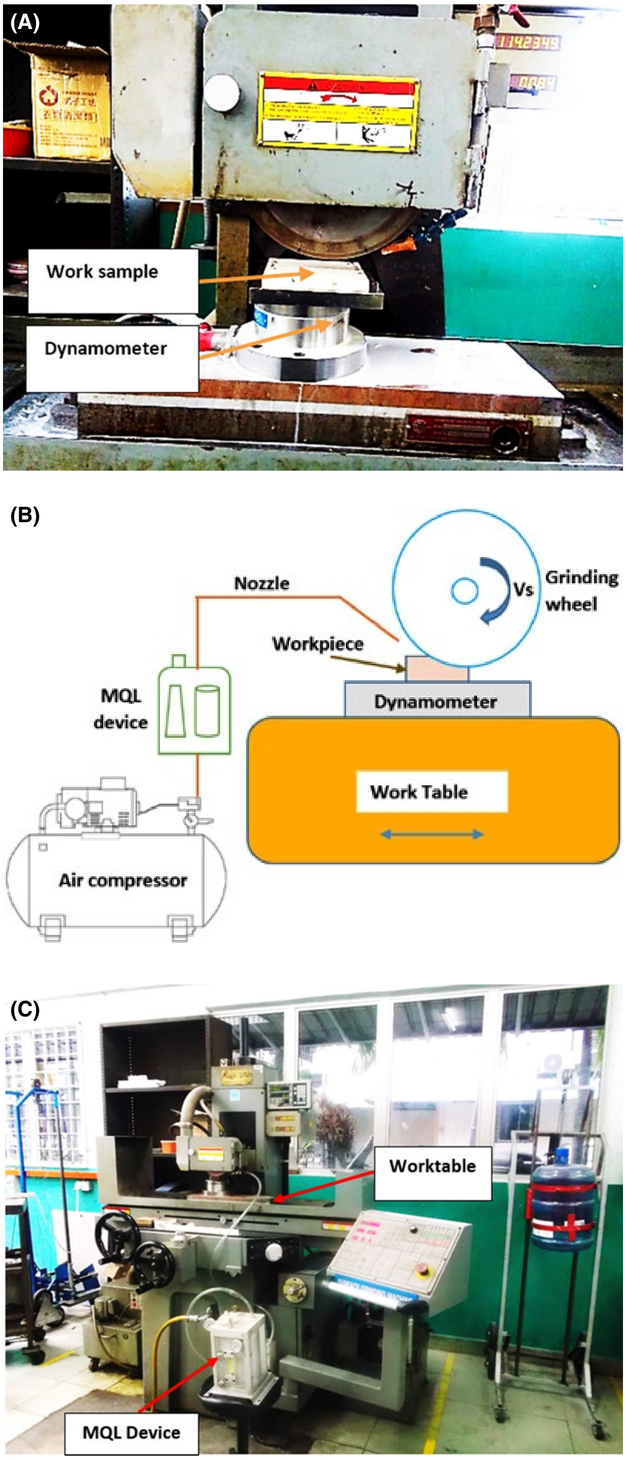

FIGURE 3 Experimental set up (A) grinding zone (B) Schematic of MQL set-up (C) set up of grinding machine [Colour figure can be viewed at wileyonlinelibrary.com]

An industrial-based MQL lubrication system (WINMIST WT-01) was utilized to deliver the nano lubricant. Some of the MQL parameters were kept constant in accordance with the studies of[27] The air pressure and lubricant flow rate were kept constant at 20 MPa and 2 mL/min, respectively. The nano-lubricant was effectively atomized through a nozzle (air atomizer) of 1 mm diameter, and micro droplets of the mixed lubricant was streamlined into the grinding zone. The average grinding forces from each experimental run was obtained using the Kistler type- 9272 dynamometer (see Figure 3A). The obtained signals after 10 grinding pass were amplified using Kistler 5019 charge amplifier, and the force data were obtained using a oscilloscope (Tektronix TBS-1022). The surface integrity of each experimental run was obtained by taking roughness measurements along the axis of the wheel path. The surface roughness of the components was obtained with a Mitutoyo SJ-210 profilometer.

3 | EXPERIMENTAL RESULTS

Malkin and Hwang[28] explained that there are two types of grinding forces generated during grinding operations, that is, due to sliding and cutting. Grinding forces are generally classified as either tangential force (*Ft*) or normal force (*Fn*). Both forces are examined in terms of the sliding or cutting components. The Tangential and normal grinding forces are respectively expressed in Equations 2 and 3.

$$Ft = Ft_c + Ft_{sl} \tag{2}$$

$$Fn = Fn_c + Fn_{sl} \tag{3}$$

where Ft_c = tangential cutting force; Ft_{sl} = tangential sliding force; Fn_c = normal cutting force; Fn_{sl} normal sliding force in this work, it is assumed that he cutting forces ft_c and fn_c are constant throughout each experimental run.

Based on the hypothesis that abrasive grains are normally distributed on the grinding wheel surface, Zhang, Ge[29] explained using a statistical probability that abrasive grains in the grinding area under fixed conditions, then the forces could be determined by the number of active cutting grains per unit area of the wheel. Kalita, Malshe[2] also explained that the coefficient of friction (given in Equation 4) which is the ratio of tangential force to the normal forces in each grinding experiment represents the degree of a material's brittleness. Typical values of coefficient of friction ranges between 0.2 and 0.7. However, under certain special conditions, the coefficient of friction can be greater than 1 or even negative as reported by authors'.[30] When the value of the coefficient of friction is near zero, it illustrates high degree of lubrication activity (frictionless). However, a value of coefficient of friction close to one indicates that there is higher amount of frictional activity and deeper grain penetration.

$$\text{Grinding force ratio } \mu \text{ (coefficient of friction)} = \frac{F_t}{F_n} \tag{4}$$

The grinding power refers to the total power used during the machining process, and it is affected by both the

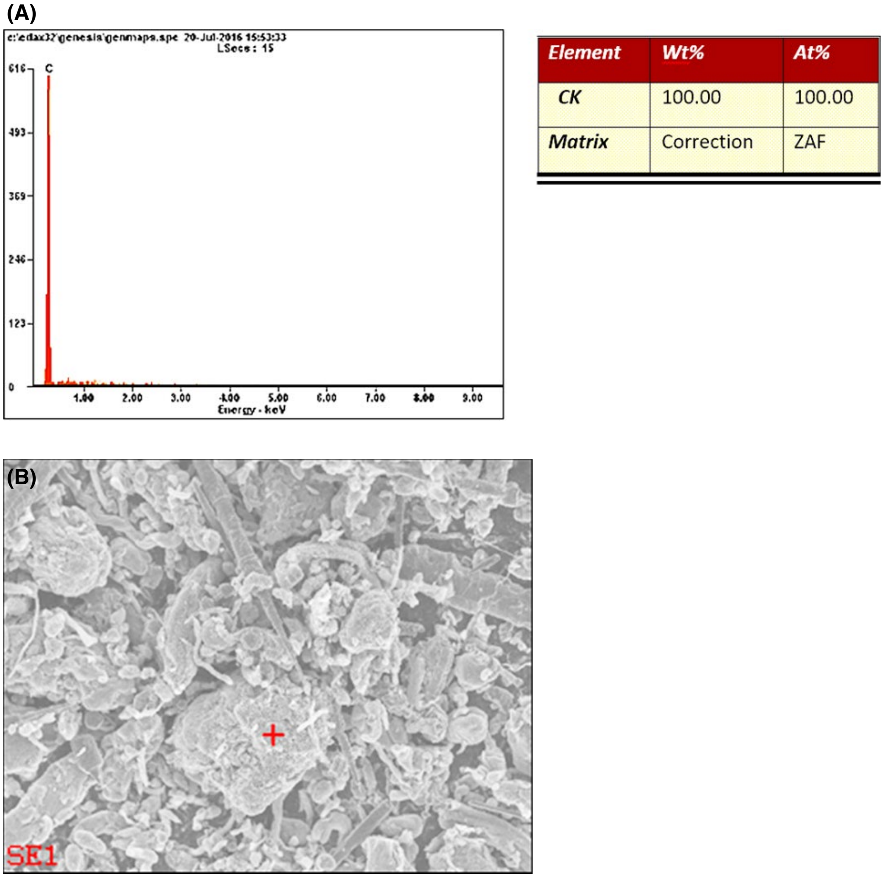

FIGURE 4 EDX of carbon nanotubes powder (A) EDS and elemental composition (B) SEM image [Colour figure can be viewed at wileyonlinelibrary.com]

tangential force and spindle speed as given in Equation 5. The efficiency of the grinding operation could be improved by significantly lowering the net grinding power.[31] Furthermore, a lower amount of power consumed during the machining process often indicates higher efficiency, especially when it occurs simultaneously with higher material removal rate. The result of the grinding power obtained after each experimental run is given in Table 4.

$$\text{Grinding power P} = \text{Tangential force (Ft)} \times \textit{textSpindlespeed}\ \text{(Vs)} \tag{5}$$

In the oscilloscope, the channels 1 and 2 were used for recording the values of the tangential and normal grinding forces respectively. The numerical values of the normal and tangential forces recorded in each experimental run are shown in Table 5.

The topography of the machined parts was also found to differ according to the parametric settings utilised in the machining process. The surface integrity, which is a measure of the surface roughness, is obtained in form of the arithmetic average absolute value (Ra). From the topographic illustration of the roughness contour shown in Figure 5A, the surface roughness can be presented as Equations 6 & 7. In addition, an example of the surface profile obtained from the experimental run 5 is shown in Figure 5B.

$$R(a) = \frac{1}{L}\int_0^L |y|dx = \frac{1}{L}\left(\sum S_{uj} + S_{vj}\right) = \frac{S}{L} \tag{6}$$

$$R_a = R_t\left(S_u + S_v\right) \tag{7}$$

TABLE 2 Experimental parameters (factors and levels)

			Levels			
S/N	**Parameters**	**Symbol**	**1**	**2**	**3**	**4**
1	Depth of cut ap (μm)	A	5	10	15	20
2	Feed rate (m/min)	B	10	15	18	23
3	Wheel type	C	SD25M100M	SD125M100M	SD25M100B	SD125M100B
4	Lubrication type	D	Flood	CNT+MQL		

TABLE 3 Experiment array for 16 experimental conditions

Experiment number	A	B	C	D
1	1	1	1	1
2	1	2	2	1
3	1	3	3	2
4	1	4	4	2
5	2	1	2	2
6	2	2	1	2
7	2	3	4	1
8	2	4	3	1
9	3	1	3	1
10	3	2	4	1
11	3	3	1	2
12	3	4	2	2
13	4	1	4	2
14	4	2	3	2
15	4	3	2	1
16	4	4	1	1

TABLE 4 Measured forces and surface roughness

Exp. run no.	Normal grinding Force (N)	Tangential grinding Force (N)	Surface roughness (μm)
1	54.4	63	0.227
2	59.2	67	0.319
3	41.6	59	0.105333
4	44.8	61.5	0.133
5	51.2	67	0.116
6	52.8	69	0.142
7	66.88	71	0.38333
8	71.36	73	0.453667
9	90.56	101	0.2433
10	93.44	103	0.352
11	67.2	87	0.233
12	72	88	0.278
13	83.2	101	0.226
14	85.6	102	0.264
15	108.8	111	0.549
16	118.4	119	0.56333

In addition, the enhanced film forming effect illustrated in Figure 6 which was explained by Ding, Lin[32] indicates that during the grinding operation, the nanofluid combines with the debris of ceramic material and worn-out wheel to form a homogeneous protective thin film along the contact region. This protective tribological film could proffer improved lubrication actions, thereby reducing friction and wear. During the shearing friction process, the carbon nanotube particles help to smoothen the abrasion process.

TABLE 5 Calculated grinding power, coefficient of friction, and surface roughness

Exp. run no.	Grinding power-P (kW)	Grinding force Ratio-μ	Surface roughness-Ra (μm)
1	1.2784	0.863492	0.227
2	1.3912	0.883582	0.319
3	0.9776	0.602899	0.105333
4	1.0528	0.613699	0.133
5	1.2032	0.764179	0.116
6	1.2408	0.765217	0.142
7	1.57168	0.868571	0.38333
8	1.67696	0.892	0.453667
9	2.12816	0.896634	0.2433
10	2.19584	0.898462	0.352
11	1.5792	0.908108	0.233
12	1.692	0.923077	0.278
13	1.9552	0.823762	0.226
14	2.068	0.838095	0.264
15	2.5568	0.98018	0.549
16	2.7824	0.994958	0.56333

4 | FUZZY LOGIC

Fuzzy logic technique has many benefits, which are useful in mathematical analysis of uncertain systems. The fuzzy logic is a spontaneous method of relating complicated and uncertain engineering problems. Moreover, fuzzy logic is also a powerful, conservative and effective method used for plotting the relationships between input and output variables of non-linear systems. The fuzzy logic system comprises of four main parts (see Figure 7).

The components of a fuzzy system includes the input fuzzification region, knowledge/data base, fuzzy inference system and output defuzzification region.[33] The functions of each layer is explained as follows;

1. Input Fuzzification layer: This layer involve input variables into the inference system.
2. Knowledge base layer: This layer composes of the information base and the rules of the fuzzy expert system. It contains a quantification of the linguistic variables in other to obtain a suitable range for mapping purposes.
3. Fuzzy Inference layer: This layer is the region where the execution of commands are conducted based on the given fuzzy rules and data supplied into the input fuzzification layer. The Fuzzy inference system (FIS) utilises the

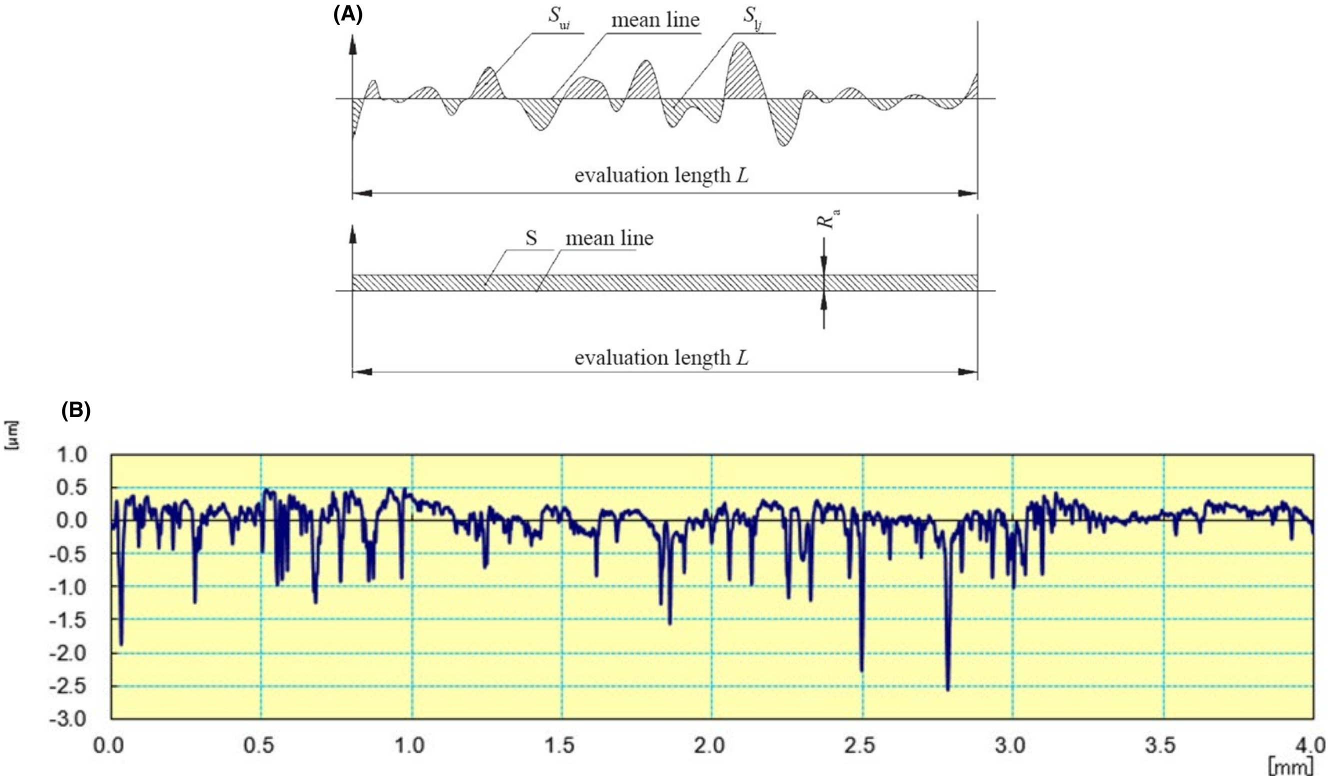

FIGURE 5 Topography of surface roughness-Ra (A) Topographic structure of the surface profile[44] (B) Measured Ra of experiment no. 5 [Colour figure can be viewed at wileyonlinelibrary.com]

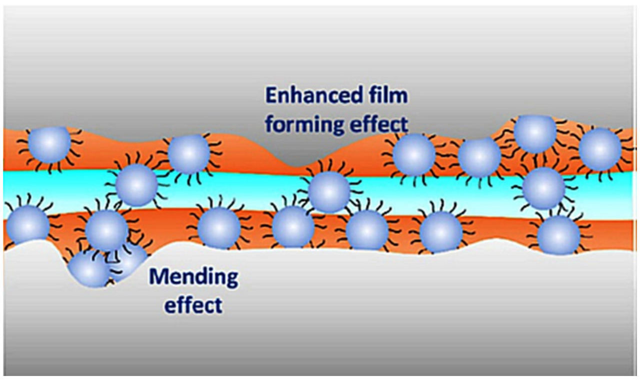

FIGURE 6 Schematic diagram of lubrication mechanism during grinding of ceramic using water-based nanofluid (Ding et al[32]) [Colour figure can be viewed at wileyonlinelibrary.com]

fuzzified membership functions to make decisions. The fuzzy rule base contains the predefined set of logic statements relating the linguistic variables (in form of membership functions) that are used for arithmetic executions in the fuzzy logic expert system. Typical example of the rule based multi input/output fuzzy inference system consist of if–then statements as shown below:

Rule 1: if A_1 is a_1 and B_1 is b_1 and C_1 is c_1 and D_1 is d_1, then X is x_1 and Y is y_1 and Z is z_1.

Else

Rule 2: if A_2 is a_2 and B_2 is b_2 and C_2 is c_2 and D_2 is d_2, then X is x_2 and Y is y_2 and Z is z_2.

Else

...

Rule n: if A_n is a $_n$ and B_n is b_n and C_n is c_n and D_n is d_n, then X is x_n and Y is y_n and Z is z_n.

4. Defuzzification layer: This layer contains the actual value of the output which is calculated by converting the fuzzified results into an accurate mathematical value (ie crisp value).

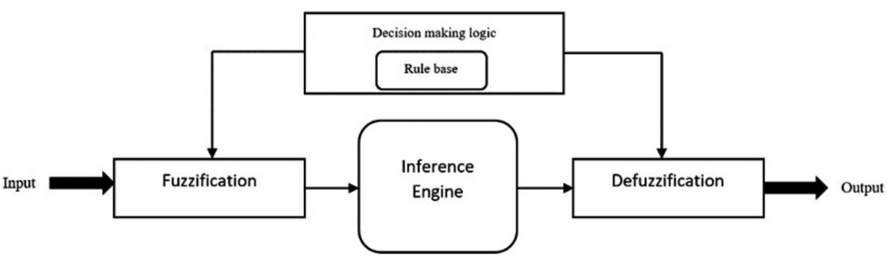

FIGURE 7 Structure of fuzzy expert system

Where a_i, b_i, c_i, and d_i are the fuzzy variables.

In this work, the mapping of input-output relation in the grinding experiment was done using the fuzzy logic toolbox of MATLAB R2015 software. Four input parameters were used as the input variables to develop the fuzzy logic for predicting the experimental outcomes. The architecture of the Mamdani fuzzy inference system is shown in Figure 8A. The input variables used include; grinding depth (a_p), Feed rate (V_w), type of diamond wheel and lubrication method. The membership function used for the input variables is the generalised bell membership function. This is because the generalised bell has been found from previous studies to have minimum epoch error compared to the Gaussian and triangular membership functions. The membership functions of the input variables was selected according to the factor level of the each input variable (see Figure 8B-E). The grinding power, force ratio and surface roughness were used as output of the fuzzy logic system.

The triangular membership function was chosen for the membership function of the output variables. The membership functions of the output variables are shown in Figure 9A-C. The rules of the fuzzy inference system were developed using 16 pair of rules according to the Taguchi L-16 (43×21) design. The steps followed to develop the multiple input/output fuzzy prediction model are similar to those done by.[27]

4.1 | Verification of fuzzy mode

In other to verify the accuracies of the developed Fuzzy logic model, additional four experiments were carried out using alternate settings of the input parameters (see Table 6). In addition, the accuracy of the Fuzzy logic model was calculated using equation 8. The accuracy of the Fuzzy logic model for grinding power, grinding force ratio and surface roughness was calculated as 97.22%, 98.60%, and 96.8%, respectively.

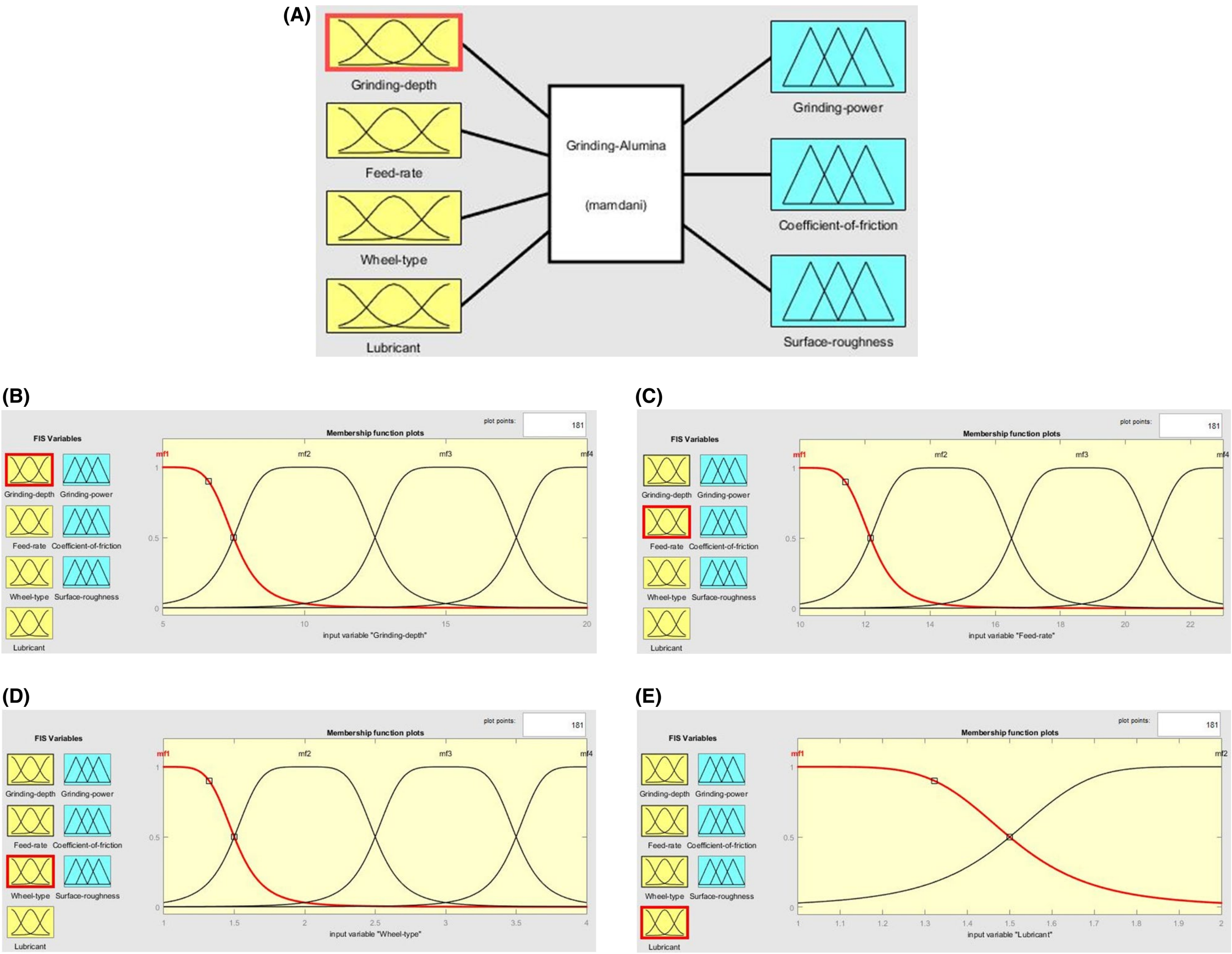

FIGURE 8 Input membership functions [Colour figure can be viewed at wileyonlinelibrary.com]

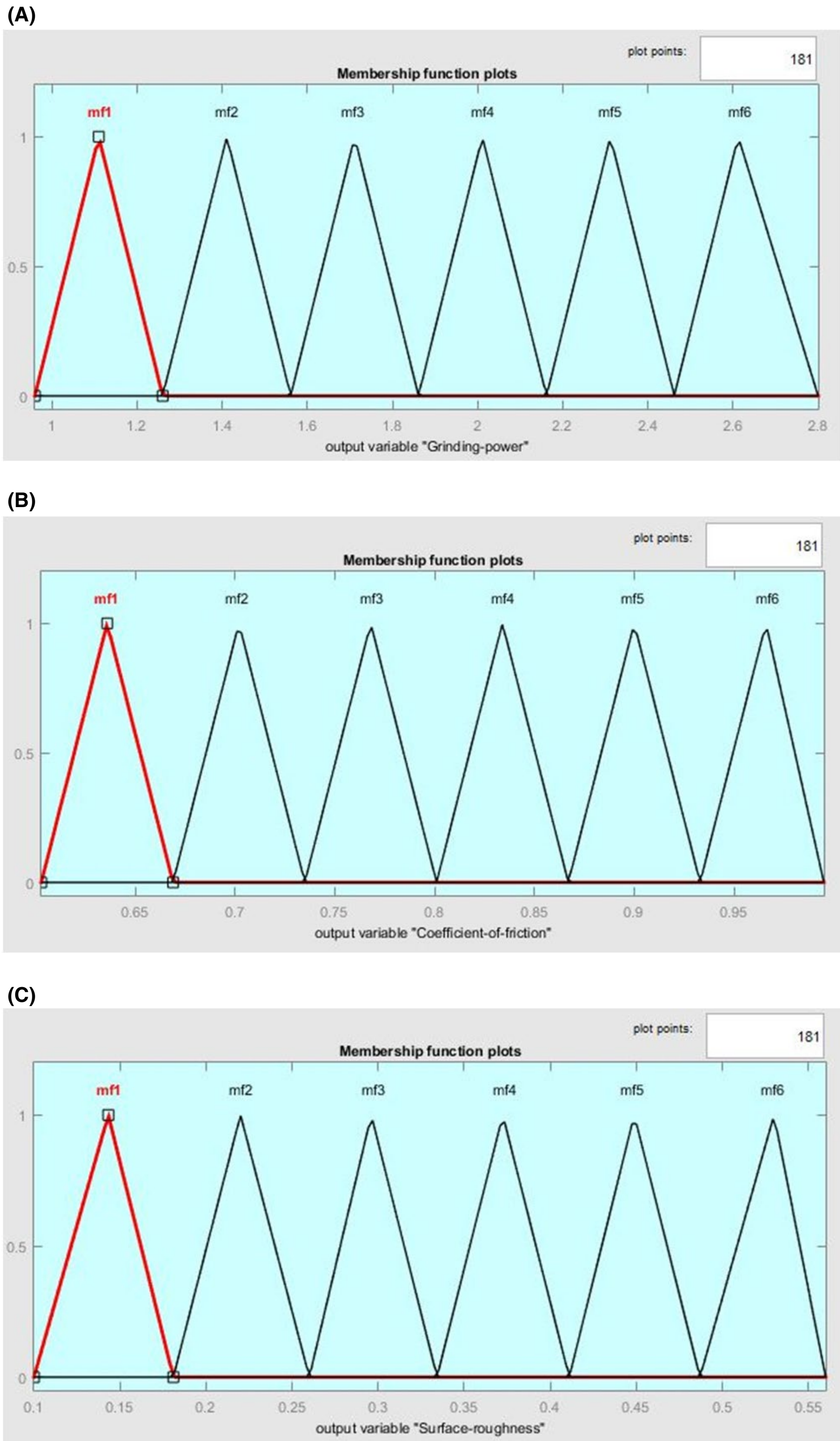

FIGURE 9 Output membership functions [Colour figure can be viewed at wileyonlinelibrary.com]

$$\text{Accuracy } A = \frac{1}{N}\sum_{i=1}^{N}\left(1 - \frac{V_{\text{measured}} - V_{\text{predicted}}}{V_{\text{measured}}}\right) \times 100\% \tag{8}$$

$$\text{Where error} = \frac{\text{V}_{\text{measured}} - \text{V}_{\text{predicted}}}{\text{V}_{\text{measured}}} \times 100\%,$$

N is the total number of experimental runs and V is measured response.

The high prediction accuracy of the fuzzy logic model indicates that the grinding power, coefficient of friction, and surface roughness can be accurately predicted prior to conducting the machining operations. In addition, the model would help in proper selection of the machining variables,

TABLE 6 Parametric settings and results for validation experiments

S/N	Process parameters A	B	C	D	Force (N) (Ft)	(Fn)	Power (kW) Pred.	Power (kW) Meas.	Force-ratio μ Pred.	Force-ratio μ Meas.	Ra (μm) Pred.	Ra (μm) Meas.
1	5	15	1	2	34.7	71.4	1.29	1.309	0.785	0.778	0.188	0.192
2	5	10	3	2	35.5	74.6	1.3	1.334	0.771	0.764	0.185	0.181
3	15	23	3	2	81.6	89.2	1.94	1.92	0.895	0.915	0.405	0.416
4	15	10	2	1	67	83.6	1.6	1.58	0.792	0.802	0.248	0.255
5	20	23	4	1	89.6	99.6	2.00	2.11	0.883	0.9	0.394	0.422
6	20	15	2	2	91.2	103.4	2.03	2.14	0.871	0.882	0.367	0.356

thereby improving efficiency and eliminating material wastage.

5 | DISCUSSION

This research deals with application of artificial intelligent technique (ie fuzzy logic expert system) to predict the grinding power, frictional coefficient, and surface roughness in surface grinding of Alumina ceramic materials. The effect of different grinding process parameters ie grinding depth, type of wheel, feed rate and lubrications system have been studied. The Taguchi design of experiment was used because it presents a systematic technique of designing experiments using the minimum number of combinatorial test runs. The performance of carbon nanotubes suspended in vegetable oil was also investigated. Canola vegetable oil was selected because it is environmentally friendly and has a high viscosity at room temperature (which allows effective suspension of the nanoparticles). In addition to being cheap, the canola oil has the ability of retaining its viscosity at high temperatures.[34]

5.1 | Grinding power

Literatures have shown that the type of lubrication utilised in grinding operations often has significant effect on the tangential grinding force. The tangential force as shown in equation 5 is the main variable component associated with the grinding power and the material removal mechanism. Results obtained from previous research works have shown that fluid MQL process could be used to significantly reduce the tangential grinding forces.[19] Studies have also shown that by effectively reducing the tangential forces, there would be significant reduction to the grinding power, thereby improving the efficiency of the grinding process.[35]

From the surface viewer of the fuzzy inference system shown in Figure 10A, it could be deliberated that the power expended during the grinding operations with MQL nanoparticle is significantly lower than when the flood coolant was utilised. This relation could be ascribed to the effective lubrication capacity of the nanofluid MQL. Moreover, it could be seen from Figure 10A that there is a directly proportional relationship between the grinding power and the depth of cut. This shows that the power required to remove a unit amount of material at lower grinding depths is much lower than at higher depths of cut. As such in other to avoid excessive energy loss, it is advisable to perform the grinding experiments using machine

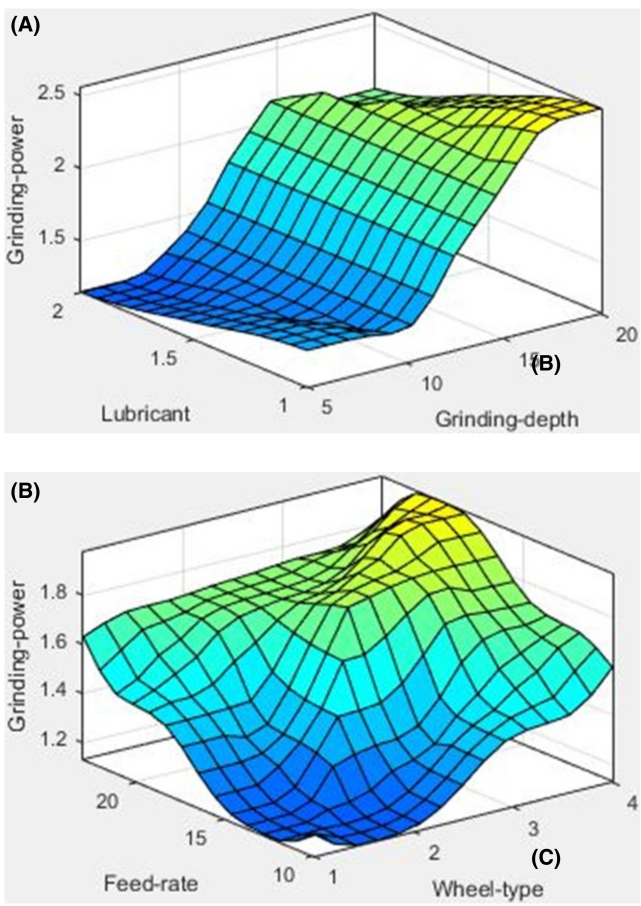

FIGURE 10 Grinding power vs (A) Depth of cut and type of lubricant (B) Wheel type and feed rate [Colour figure can be viewed at wileyonlinelibrary.com]

settings with smaller grinding depths. Furthermore, the feed rate was also found to exhibit a linear relation with the grinding power. As shown from the surface viewer in Figure 10B, an increase in the feed rates from 10 to 23 m/min, results in steady increase of the grinding power. This show that there is higher energy used for material removal at higher feed rates, a finding which corroborates with the explanations of authors.[35]

In addition, it was also found that the grain concentration has significant effects on the grinding power. As can be seen in Figure 10B, the type of bond on the wheel more effect on the grinding power than the grit concentration. The metallic bond was found to have a higher efficiency (lower grinding power) than the resin bonded diamond wheels, especially at lower feed rate and depth of cut. This phenomenon could be explained using the hertz law of contact mechanics. Its occurrence could be attributed to the superior stiffness of the metallic bonded wheels compared to the resin bonded ones. The low stiffness of the resin bonded wheels makes them to lose their sharpness and become dull with increasing grinding depth and number of grinding passes. Besides, the area of contact between the resinoid wheels and the alumina ceramic increases during each grinding pass, as a result of the wheels ability to deform with increased pressure. This phenomenon leads to increased frictional forces due to increased rubbing actions, thereby resulting to energy loss due to higher amount heat generated.

5.2 | Coefficient of friction

The ratio of tangential to normal grinding forces in the grinding process is referred to as the coefficient of friction.Studies have shown that during the grinding operations, utilization of biodegradable vegetable oils can offer significant improvement to lubricity. The coefficient of friction (viscosity) is also referred to as the degree oiliness of the lubricant. Previous research work have indicated that a higher viscosity results in production of stronger oil film. Studies have also shown that a higher viscosity results in improved lubrication performance of the base oils during machining.[36] However, the lubrication performance of the base oils has been found to decline upon achieving a given numerical value. Thus, in other to maintain the viscosity and achieve improved tribology, researchers propose the addition of solid nanoparticles into the base oils, thereby producing nanofluids.

Previous research works have shown that during grinding operations, the use of nanofluids in MQL process often results to improvement in the lubrication, which in turn lead to substantial extension of the wheel life and higher surface integrity. Moreover, the increase in the lubrication activity also lead to significant reductions of the grinding force ratio.[18] Investigations by Molaie, Akbari[37] revealed that the use of 6% weight concentration of molybdenum disulphide (MoS_2) in paraffin as lubricant during grinding operations results in about 25% reduction of the normal force and more than 50% reduction of the tangential force. Similarly, Kalita, Malshe[2] presented that the nano-particle MQL grinding produces significant reduction of the tangential grinding force and frictional coefficients.[4] This highly desired reduction of the grinding forces has been attributed to the creation of a thin tribo-film by pulping of the nanoparticles along the grinding path,[37] thereby resulting to better lubrication performance. The thin tribo-film was found to be created as a result of pulverization of the nanoparticles, which produces facilitates smoother sliding actions between the diamond grains and the work material.

In Figure 11A, it could be seen that the coefficient of friction increases with increase with increase in the grinding depths of cut. There was about 10% increase in coefficient of friction when the depth of cut was increased from 5 to 20 μm. In addition, it was found that at lower grinding depths, the coefficient of friction during the conventional flood grinding operations was about 4% higher than that of the MQL nano lubrication. However, at higher depth of cuts, it was observed that there was no significantly effect by the type of lubrication

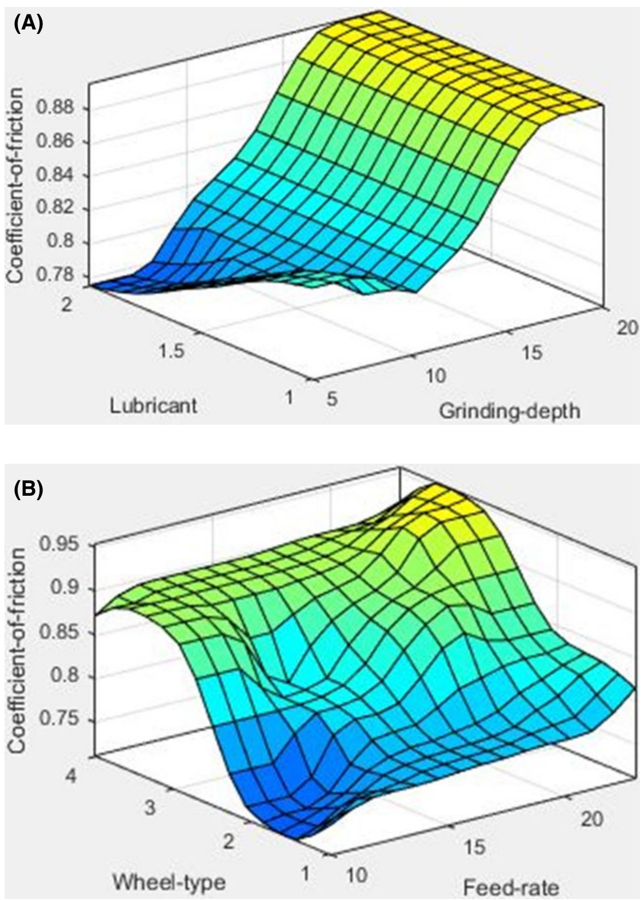

FIGURE 11 Effect of process parameters on grinding force ratio (coefficient of friction) (A) Type of Lubricant vs depth of cut (B) Wheel-type vs feed rate [Colour figure can be viewed at wileyonlinelibrary.com]

on the coefficient of friction. Figure 11B shows the variation of the coefficient of friction with the feed rate and wheel type. The results from this work indicates that the type of bonding on the grinding wheel significantly affects the coefficient of friction. The resinoid bonded wheel could be observed to be unable to withstand the high centrifugal forces and high temperatures during the MQL grinding process. This led to smashing of the grinding wheel due to shocks generated at high grinding depths. The results also show that the resin bonded grinding wheel was unable to hold onto the abrasive grits rigidly to perform the needed effective material removal. A high rate of wheel wear, wear flats and grain pull out was observed in the resin bonded wheels (See Figure 12A,B) compared to the metallic bonded wheels (see Figure 12C,D). Similarly, the coefficient of friction was found to depend on the grain concentration on the grinding wheel. When the grain concentration was low, it was found that the frictional coefficient was smaller. This indicates that the wheels with higher grain concentration encounter lower amount friction forces during the material removal process. Furthermore, in Figure 11B, the fuzzy logic model illustrates that the grinding force ratio has a direct proportional relationship with the feed rate. An increase table speed was increased, it was observed that the increase in the coefficient of friction was gradual rather a steep one.

5.3 | Surface quality

Previous literatures have shown that different kinds of lubrication techniques significantly affects the surface quality of ground components.

Studies have shown that the surface quality of mechanical components affects their reliability and performances.Studies have also shown that the use of MQL nano lubrication improves the surface quality of the work piece.[19,37,38] The performance of the 2% percent weight of carbon nanotubes as nanofluid on the surface quality during grinding of alumina ceramic was compared with mineral oil-based conventional coolant.

Figure 13 shows the surface viewer for surface roughness as obtained from the Fuzzy logic model. In Figure 13A, it is seen that both the lubricant type and the grinding depth has significant effect on the surface roughness. It was observed that the MQL nanofluid produces lower surface roughness at smaller depths of cut. Moreover, during nanofluid MQL grinding, as the depth of cut is increased, the surface roughness was found to increase from about 0.1 μm at 5 μm, to about 0.4 μm at depth of 20 μm. For the flood cooling experiments, the values of surface roughness was found to be about 0.2 μm at 5 μm depth of cut and approximately 0.5 μm at 20 μm depth. Generally, the value of

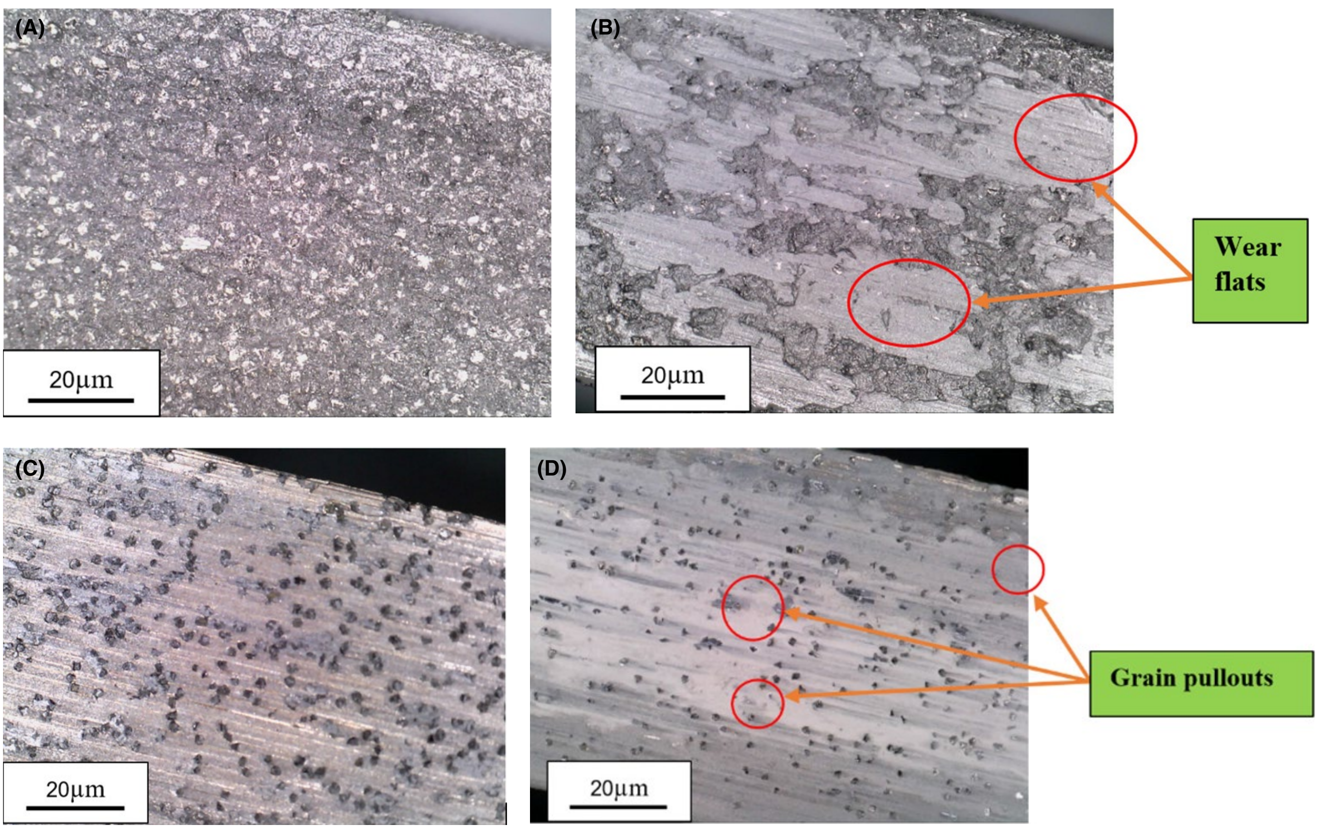

FIGURE 12 Grinding wheel (A) Resinoid bond wheel before grinding (B) Resinoid bond wheel after 10 grinding passes (C) Metallic bond wheel before grinding (D) Metallic bond wheel after 10 grinding passes [Colour figure can be viewed at wileyonlinelibrary.com]

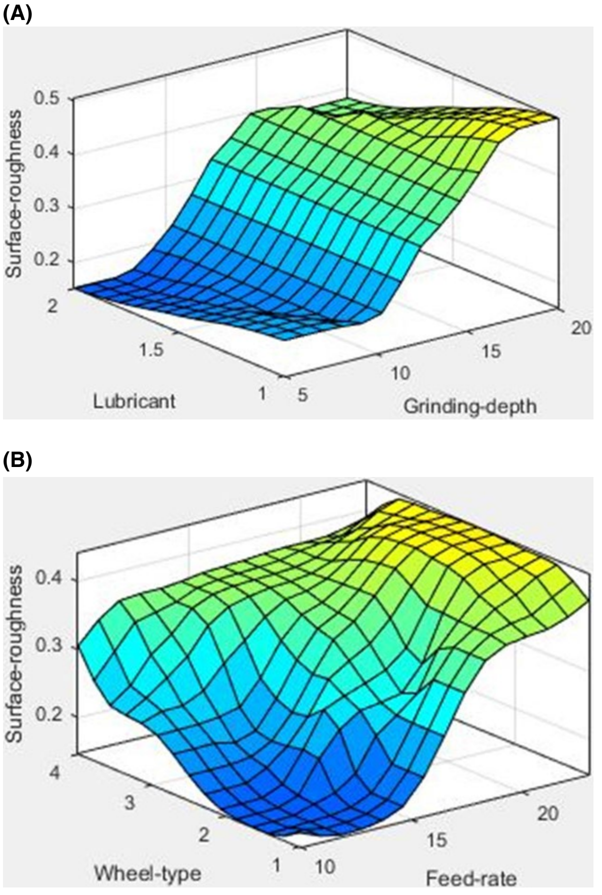

FIGURE 13 Effect of process parameters on surface roughness (A) Type of lubricant vs Depth of cut (B) Wheel type vs feed rate [Colour figure can be viewed at wileyonlinelibrary.com]

surface roughness was found to be higher when the flood coolant was used. This indicates that the MQL nano fluid proffers significant reduction to the surface roughness of the machined work piece especially at lower grinding depths.

The feed rate was also found to exhibit a directly proportional relation with the surface roughness as illustrated in Figure 13B. The surface roughness was found to increase linearly as the feed rates was increased from 10 to 23 m/min. This shows that higher table feed rate causes severe deterioration to the surface quality of the ground Alumina material. As such, when a high surface quality is desired, the slower feed rate should be used to perform the grinding operations. Although, this would be at expense of the speed of machining and material removal rates. In addition, the Fuzzy logic model shows that at lower feed rates, the metallic bonded wheels produces better surface roughness than the resin bond wheels. However, at high feed rates above (18 m/min), the surface quality deteriorates significantly irrespective of the type of wheel used (see Figure 12B). However, the resinoid bonded wheels were seen to inflict less damages onto the alumina material at higher feed rates. This is could be attributed to the inability of the resinoid wheel to withstand the high grinding forces at higher feed rates. In addition, as result of the high impact forces during grinding with higher feed rates, the resinoid wheel was observed to have increased wear that leads to self-sharpening of the wheel, thereby exposing newer diamond grains.

Lastly, the surface integrity of the alumina ceramic was analysed after the grinding operations. The microscopic images obtained showed intense macro cracks on the specimens machined with flood cooling. although it was machined using small depth of cut, the specimen from experiment 7 was observed to have a surface profile which is poor, and characterized by intense micro/macro cracks, furrows and large pores as shown cycled in Figure 14A. Experiment 5 & 7 have the same depths of cut and grit concentrations, but the image analysis show that the amount of macro fractures and cracks in experiment 7 was much higher than in experiment 5 (see image in Figure 14B). The improved surface quality achieved in experiment 5 compared to experimental run 7, could be attributed to the positive effects provided metallic bonding of the wheel, coupled with lower feed rate and better lubrication performance proffered by the nanofluid MQL system. Similarly, Figure 14C & D, respectively, shows the microscopic images of the surface profiles in experiments 10 & 6. Although both experiments 6 & 10 have similar feed rates, the surface quality from experimental run 6 was found to be better than that of experimental run 10. This could be attributed to the superior lubrication performance of the MQL technique in experiment 6. Also, the higher gridning depth in experiment also leads to higher surface deformation and deterioration as compared to experimental run 6. Moreover, in Figure 14C, it could be seen that there is discontinuity in the wheel path and intense macro-fracture on the surface of the ground Alumina material. This unwanted phenomenon found in the sample from experimental run 10 resulted from the increased wheel vibrations occurring at higher depths (with visible chatter lines), and also the poor lubrication capacity of the conventional flood coolants.

Further analysis shows that at higher depth of cuts, the surface quality is mostly poor irrespective of the feed rate and type of wheel used. The microscopic images of experiments 13 and 16 (respectively shown in Figure 14E,F). Figure 14F shows the poor surface profile obtained in the specimen of experimental run 16. The profiles shows the presence of non-uniform material removal mode, with severe disruptions and intense macro breakages occurring along the path of the wheel. This shows that there is poor lubrication when higher table speed and depth of cut are used. However, in experimental run 13, even with a very high grinding depth, the surface quality was relatively better than that of experimental run 16. This could be attributed to the combined positive

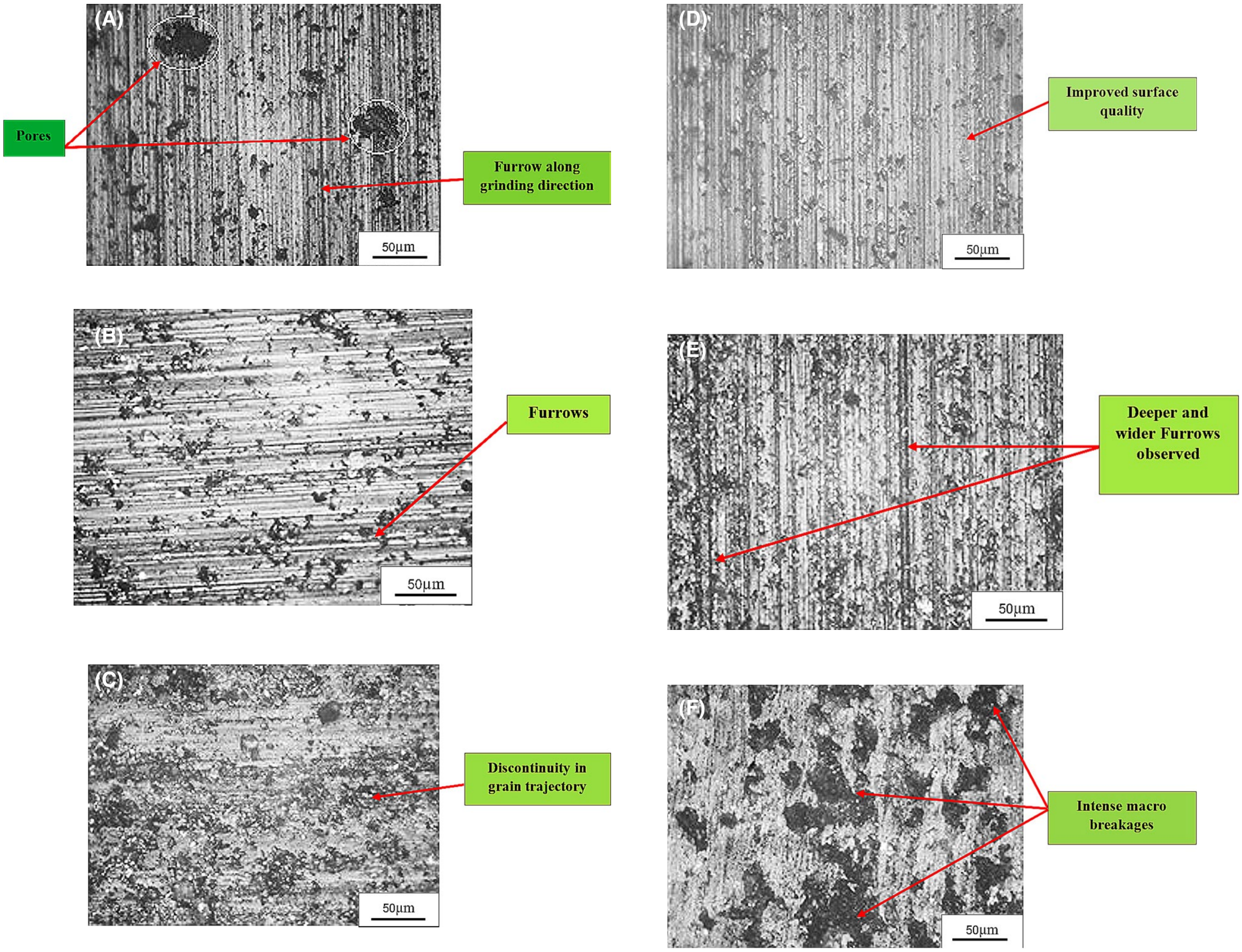

FIGURE 14 Microscopic image of the ground surface profile for experiment no. (A) 7 (B) 5 (C) 10 (D) 6 (E) 13 (F) 16 [Colour figure can be viewed at wileyonlinelibrary.com]

effect provided by the lower feed rate and nanofluid MQL used in experimental run 13.

6 | CONCLUSIONS

In this work, we have made analysis of the effects of grinding process parameters during grinding of 99.5% pure Alumina ceramic using both flood cooling and nano fluid MQL process. The nanofluid MQL was produced by suspending pellets of carbon nanotube in canola vegetable oil. The grinding parameters considered are depth of cut, feed rate, type of diamond wheel and the kind of lubrication. The effects of these parameters on the machining power, coefficient of friction and surface quality were analysed using fuzzy logic modelling technique. The samples machined using flood cooling lubricant were found to be characterised with various kinds of surface and subsurface damages. In addition, the energy expended per unit material removed was found to be higher during flood cooling compared to the nanofluid MQL process. This finding corroborates the results of authors.[2,39] Hence, it could be concluded based on their performances that the nanofluid MQL technique has better efficiency than the flood cooling process. Similarly, the use of canola oil as the fluid in the nanofluid MQL process makes the process more efficient during machining, due to its relative cheapness, availability and environmental friendliness. This finding agrees with the research works of.[19,40] Generally, the MQL nano lubrication system was observed to have optimum grinding performance by having the lowest values of grinding power, coefficient of friction and surface roughness. Finally, the Fuzzy logic model developed for predicting the grinding power, grinding force ratio and surface roughness was found to have an average accuracy of 97.22%, 98.60%, and 96.8%, respectively. This high accuracy exhibited by the fuzzy logic modelling indicates that it can be used to predict the outcome of the experiments even prior to conducting the machining, thereby reducing material wastages and unnecessary trials. This finding agrees with previous research works by authors.[41,42]

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