Fuzzy logic-based approach to investigate the novel uses of nano suspended lubrication in precise machining of aerospace AL tempered grade 6061

Ming Erh Ooi [a,1], Mohd Sayuti [a,*], Ahmed A.D. Sarhan [a,b,1,2]

[a] Centre of Advanced Manufacturing and Materials Processing, Department of Engineering Design and Manufacture, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Mechanical Engineering, Faculty of Engineering, Assiut University, Assiut 71516, Egypt

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ABSTRACT

Temper-grade aluminum alloy Al-6061-T6 is commonly used for many engineering purposes owing to its superior mechanical properties. Due to the practical importance, machining Al-6061-T6 alloy is crucial for different applications. The development of computer numerical control (CNC) of milling machines is in progress by researchers worldwide for its noteworthy advantages. The quality of machining determines the product's appearance, function and reliability. Appropriate lubrication at the machining zone improves the tribological characteristic of Al-6061-T6 alloy, leading to higher product quality. For reasons of ambiguity during machining, the soft computing technique is chosen to predict the output. In this particular research scope, a new fuzzy logic-based approach is adopted to determine the machining performance while milling Al-6061-T6 alloy using SiO_2 nanoparticles added to the lubricant. The effects of nanoparticle concentration, nozzle angle and air pressure are investigated to determine the optimum machining conditions, such as lowest cutting force, cutting temperature and surface roughness. Four membership functions are designated to connect with each input. The predicted results are computed by fuzzy logic and compared with the experimental results. The proposed fuzzy model exhibits high degree of reliability according to the experimental results. The computed results showed 96.195%, 98.27% and 91.37% accuracy with experimental results for cutting force, cutting temperature and surface roughness.

1. Introduction

Aluminum (Al) alloys are normally favored as one of the most appropriate and suitable metals for various applications. The characteristics of light weight, low cost and lucrative form are the main reasons aluminum and its alloys are so extensively used. Non-sparking and non-magnetic properties, electrical and thermal conductivity, reflectivity, and high chemical resistance are additional reasons for choosing aluminum and its alloys. Besides, ease of fabrication, non-toxicity, high strength and corrosion resistance make it popular in the construction, aircraft, marine and engineering industries.

Among all aluminum alloys, 6061 is the most commonly used due to its superior mechanical properties as well as excellent weldability. This precipitation hardened alloy contains magnesium (Mg) and silicon (Si) as major alloying elements. The mechanical properties of aluminum 6061 alloy depend on the extent of tempering (heat treatment). However, the Young's modulus of this alloy, which is approximately 69 GPa, does not depend on tempering. The elongation of this alloy is approximately 10% and the fatigue limit is 100 MPa under 5×10^8 reversed cycles. The thermal conductivity of Al-6061-T6 alloy is around 152 W/mK at 80 °C.

Aluminum alloys generally offer higher levels of machinability characteristics than other light weight metals such as titanium and magnesium alloys. However, a major problem encountered during dry machining at low cutting speed is built up edge (BUE). On the other hand, at high cutting speeds sticking is encountered. Thus, special tool geometries are required in both cases. Such machining difficulties are due to the presence of Mg and Si in Al-6061-T6 alloy.

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[*] Corresponding author. Tel.: +60 3 79674480; fax: +60 3 79677669.
E-mail address: mdsayuti@um.edu.my (M. Sayuti).
[1] Tel.: +60 3 79674480; fax: +60 3 79677669.
[2] Tel.: +20 882335572; fax: +20 882335572.

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The presence of Si also contributes to the increment of tool rake angles and hence lower speed and feed are required. Greater machining cost is consequently a reflection of the above-mentioned issues.

In manufacturing sectors, several schemes are employed to reduce machining cost in an eco-friendly manner (Fratila, 2009). During machining, lubrication plays the most important role by having effects like prolonging tool life, improving surface finish, reducing cutting temperature and cutting force, and so on (Pusavec et al., 2010). Hence, it is important to employ a proper lubrication system as it covers 7–17% of the total manufacturing cost. Disposal and health hazards are other problems with commercial lubricants (Fratila, 2010).

To overcome such problems, dry and near dry machining (NDM) of AISI D2 steel using an environmentally friendly vegetable oil as lubricant and that is meant to completely eliminate mineral and petroleum-based harmful lubricants from the turning process, have been introduced (Sharma and Sidhu, 2014). Alternatively, researchers have developed mist lubrication, which is a mixture of air and cutting fluid supplied to the cutting zone at high pressure. Normally, an atomizer is used to atomize the cutting fluid in the presence of compressed air. The cutting fluid is then conveyed to the machining zone by low air pressure (Ueda et al., 2006). As the compressed air flows through the venturi path, a partial vacuum is created around the discharge nozzle. Mist lubrication thus reduces tool wear and improves tool life (Ueda et al., 2006). Besides, the novel biocide-free metal-working fluid (MWF) based on glycerol/water rather than conventional mineral oil-based MWFs for machining processes is a new solution to some environmental issues (Wichmann et al., 2013).

For further improvement, nanolubricants are recently being used for less oil consumption and higher performance. Moreover, nanolubricants are able to provide lubricity over a wide range of temperatures (Nakamura et al., 2000). Nanometer-sized metals, oxides, carbides, nitrides or nanotubes are dispersed in the cutting fluid for the preparation of nanolubricants. Typically, carbon nanotubes (CNTs), TiO_2, Al_2O_3, MoS_2, SiO_2 and diamond nanoparticles are used in lubricants. Often in literature and several publications the most similar areas available are discussed. For example, Cu nanoparticles were studied to understand how they work in lubricant oils to improve tribological properties and it was found that Cu nanoparticles with 130-nm mean diameter were more effective in reducing the coefficient of friction in all lubrication regimes (Zin et al., 2013). Besides, the implementation of nanolubricants (oils containing MoS_2) can also reportedly reduce the specific energy, friction coefficient, frictional losses and tool wear in the machining process (Kalita et al., 2012a,b). It has also been found that MoS_2 nanolubricants can effectively reduce sliding frictional losses by a continuous supply of active lubricant additives and by forming a stable, low-friction tribofilm at the sliding interface of the tool and workpiece surfaces (Kalita and Ajay, 2010). In addition, with MoS_2 nanolubricant in the machining process, performance in terms of force ratio and specific energy has shown substantial improvement compared with ordinary lubrication systems (Kalita et al., 2012a,b).

In the machining area where the tool works in very severe conditions subject to very high temperatures and pressure to shear the workpiece material, the tool wears rapidly as the friction coefficient between the tool and chip in the cutting zone is very high; in many cases tool fracturing occurs (Rahmati et al., 2014). To overcome such problems, lubrication is essential. But in severe conditions at the cutting zone where the temperature and pressure are very high, lubrication function is reduced, which is why using nanolubrication is unavoidable.

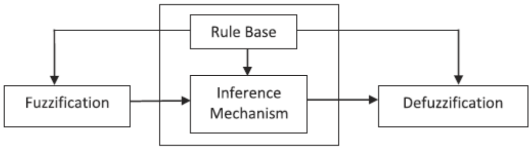


Fig. 1. The structure of a fuzzy system.

It is well documented that SiO_2 nanoparticles are most prominent compared with other nanoparticles thanks to their mechanical properties such as hardness and low cost. Moreover, reported results indicate that power and lubricant consumption is greatly reduced during the machining process in the presence of SiO_2 nanoparticles (Sarhan et al., 2011). In this research work, the performance of SiO_2 nanolubricant is investigated for precise machining of tempered-grade Al-6061-T6 alloy. Machining performance is measured as a function of nanolubricant concentration, nozzle angle and air pressure.

Handling nanoparticles without mixing them with oil is hazardous to human health because they would become airborne (Saidur et al., 2011). However, by mixing nanoparticles with lubricant oil, they are very unlikely to become airborne. Therefore, handling nanolubricant is safer compared with handling stand-alone solid lubricant (Yu and Xie., 2012). The complexity and uncertainty during machining processes are eliminated by applying fuzzy logic-based soft computing (SC) techniques (Shamshirband et al., 2010). The fuzzy logic-based model is significant in the matrix relationship containing input and output. For clarification, Fig. 1 presents the structure of a fuzzy system. Due to the nonlinear condition, fuzzy logic was selected to determine the performance based on input variables during the machining process (Sonar et al., 2006). Previous research also showed high accuracy of fuzzy logic analysis in estimating surface roughness during milling of brittle materials. In this work, fuzzy logic is applied to estimate the cutting force, cutting temperature and surface roughness values during Al-6061-T6 alloy milling using SiO_2 nanoparticles added as nanolubricant.

According to the results, the SiO_2 nanolubricant works well, especially in machining of hard materials. Ordinary lubricant oil cannot withstand high pressure and would become less effective. Therefore, when using nanolubricant, the oil acts as a carrier to introduce the nanoparticles into the cutting zone. As nanoparticles are solid, they can withstand very high pressure and temperature at the tool–workpiece interface. These act as billions of rolling elements to smoothen the machining process by reducing its coefficient of friction. Hence, surface quality improves and cutting force is reduced as well, leading to reduced power consumption and machining cost besides a more environmentally friendly process.

2. Design of experiments

Identifying the experimental array and selecting the lubrication parameters make the most important stage of this experimental

Table 1
The lubrication parameters and experimental condition levels.

Lubrication parameters		Level (*i*)			
		1	2	3	4
A	Nanoparticle concentration (wt %)	0	0.2	0.5	1.0
B	Air pressure (bar)	1	2	3	4
C	Nozzle orientation (degree°)	15	30	45	60

Table 2
The twelve experiment with the details of the combination levels.

Exp no.	Parameters combination		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	1	4	4
5	2	1	2
6	2	2	1
7	2	3	4
8	2	4	3
9	3	1	3
10	3	2	4
11	3	3	1
12	3	4	2

design. The L_{12} experimental array was used as a factor design with three parameters and four levels for the current experiment. This array was selected for its ability to verify relations among the input variables. The input parameters and levels are tabulated in Table 1. The details of the twelve experiments with the levels and parameters (A-C) are presented in Table 2.

3. Experimental setup and procedure

In the next step, the experimentally-based selected array was run. A random sequence of the twelve proposed experiments was carried out to exclude the effects of other invisible factors potentially influencing cutting force, cutting temperature and surface roughness. The setup for the proposed experiments is shown in Fig. 2. A milling machine (Cincinnati Milacron Saber TNC750 VMC) with constant spindle position was used. The maximum speed of the machine is 12 000 rpm. The cutting process of Al-6061-T6 with 80 × 50 × 25 mm^3 dimensions was chosen as a case study. The mechanical properties of Al-6061-T6 are shown in Table 3.

The selected cutting tool for this experiment is high-speed steel (HSS) with 10 mm diameter containing 2 flutes, which is the most common tool in the slot milling industry. The tool travels in the $+X$ direction to cut the workpiece at a stroke of 200 mm in length. In Fig. 3, a description of the workpiece and its tool path are shown. The cutting speed, feed rate and depth of cut used in this experiment are 5000 min^{-1}, 100 mm/min and 5 mm. These values were chosen as recommended by the tool maker. A Kistler three-axis dynamometer (type 9255B) was utilized to measure cutting forces during the experimental run. The measured cutting forces in the X, Y, and Z directions were filtered by low pass filters (10 Hz cutoff frequency). The cutting temperature was measured with a thermocouple (K-Type Testo 925), which was installed under the machining surface; its specifications are given in Table 4. Each measurement was repeated three times in order to reduce reading errors. The measured temperature reflects the amount of heat dissipation from the workpiece. The amount of dissipated heat indicates the change in friction at the tool–chip interface. For each

Table 3
Mechanical properties of Aluminum (AL6061-T6).

Ultimate tensile strength (MPa)		0.2% proof stress (MPa)		Hardness vickers, (HV) typical
Min	Typical	Min	Typical	
260	310	240	275	105

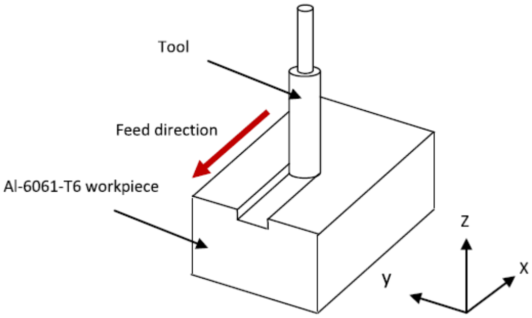


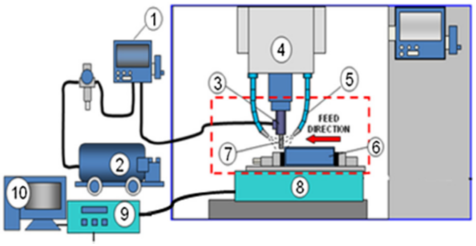
Fig. 3. The workpiece and tool paths.

Table 4
K-Type Testo 925 Thermocouple specification.

Specification	Range
Tip measuring range	−200 to +1000 °C
Accuracy	±(0.5°C + 0.3% of mv) (−40 to +900 °C) ±(0.7°C + 0.5% of mv) (remaining range)
Resolution	0.1 °C (−50 to +199.9 °C), 1 °C (remaining range)

Table 5
Mechanical properties of SiO_2.

Properties	SiO_2
Structure	Amorphous
Melting Point (°C)	Approx. 1600
Density (g/cm^3)	2.2
Refractive Index	1.46
Dielectric Constant	3.9
Dielectric Strength	10^7
Thermal conductivity at 300 K (W/cm-degK)	0.014



No	Item
1)	High Speed Spindle Controller
2)	Air Compressor
3)	High Speed Spindle(HSS)
4)	CNC Milling Centre
5)	Lubrication Nozzle
6)	Workpiece
7)	Tool
8)	Kistler Dynamometer
9)	Kistler Charge Amplifier
10)	Data acquisition system

Fig. 2. The experimental set-up.

Table 6
The properties of Shell Dromus BL lubricant oil.

Brand	Shell
Name	Dromus BL – 8 000 021 138/R 0665/DOM 06 032 006
Specification	Emulsion appearance: Milky White, Opaque pH at 5%: 8.9 Refractometer Factor: 1 Density at 15 °C kg/L: 0.889 » 889 kg/m^3 Viscosity at 40°C centistokes: 37 » 3.7×10^{-5} m^2/s (kinematics viscosity)

Table 7
The measured values of cutting force, cutting temperature and surface roughness.

Test levels	The measured values		
	Cutting force (N)	Cutting temperature (°C)	Surface roughness (μm)
1	134.16	57.20	3.14
2	197.91	71.20	0.75
3	130.78	56.10	1.42
4	184.43	48.80	1.53
5	53.81	43.50	0.74
6	150.31	53.50	1.62
7	161.99	73.10	0.88
8	157.63	69.70	1.34
9	171.81	67.80	1.07
10	107.70	61.50	0.93
11	121.92	51.30	0.80
12	188.04	65.00	1.58

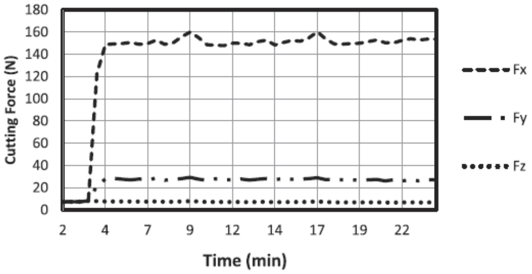


Fig. 4. An example of measured cutting forces in *X*, *Y* and *Z*-axis direction at nanoparcticle concentration: 0.2 wt%, air pressure: 1 bar, nozzle angle 30°.

machining run, the temperature was measured every two minutes. The surface roughness was measured using a surface meter (Mar-Surf PS1 Perthometer) at a cutoff distance of 700 μm.

The nanolubricant was prepared by adding SiO_2 nanoparticles (5–15 nm) with mineral oil followed by sonication (240 V, 40 kHz, 500 W) for accumulatively 48 h. The mechanical properties of SiO_2 are listed in Table 5. Shell Dromus BL lubricant oil was used as mineral oil and its properties are shown in Table 6. To deliver the lubricant to the machining zone, the MQL system was adopted. The experimentation was assisted by a thin pulsed jet nozzle with a supplementary air nozzle in order to carry the nanolubricant into the machining interface, something that reduced lubricant consumption by up to 25%. Also, the nozzle was attached with a flexible fixture mounted on the spindle of the machine. The flexibility of the system allows the injection nozzle to be positioned at a desired location without affecting the movement of the working table during experimentation. The nozzle diameter was 1 mm and the pressure for MQL oil was set at 20 MPa with 2 ml/min delivery rate.

4. Experimental results

The experimental processes were carried out using the proposed experimental setup. The cutting force, cutting temperature and surface roughness measurements are summarized in Table 7. Figs. 4 and 5 show the samples of cutting force and surface roughness at 0.8 MPa air pressure, 2×10^4 rpm spindle speed, 0.25 mm/min feed, 1 mm depth of cut with nanoparticle concentration of 0.2 wt% and nozzle angle of 30°.

5. Fuzzy logic approach

The relationships between input parameters (nanolubrication concentration, air pressure and nozzle orientation) and output parameters (cutting force, cutting temperature and surface roughness) for milling Al-6061-T6 alloy were used to develop the rules. In Table 8, the Fuzzy linguistic models for input and output parameters are presented. According to this model, four membership functions exist for each input and output parameter. For the input variables, the membership functions, such as Low, Medium, High and Very High were used to categorize it in different setup levels. The four membership functions, namely Best, Good, Average, and Bad were used for output variables (cutting force, surface roughness and cutting temperature) to categorize it in different response levels.

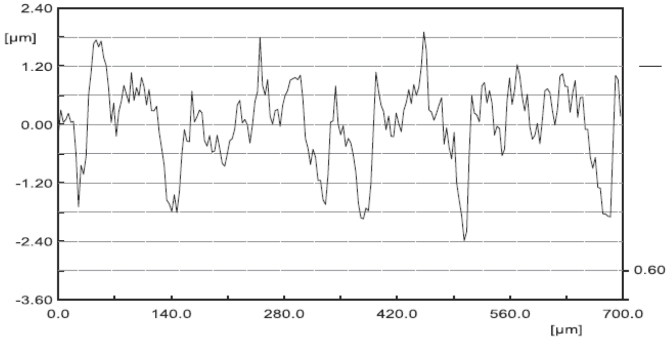


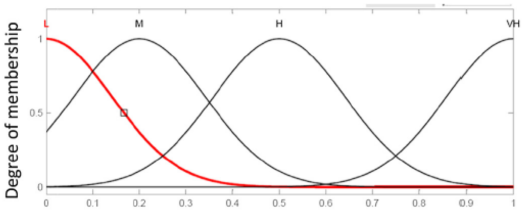
Fig. 5. An example of measured surface roughness at nanoparticle concentration: 0.2 wt%, air pressure: 1 bar, nozzle angle 30°.

Table 8
Fuzzy linguistic and abbreviation of variables for each parameter.

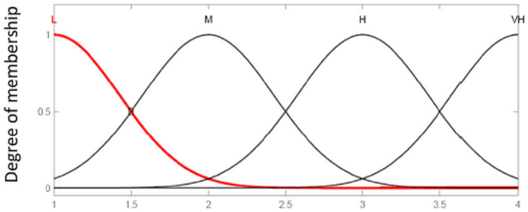
Inputs		Range
Parameters	Linguistic variables	
A – Nanoparticle concentration (wt %)	Low (L), medium (M), high (H), very high (VH)	0.0–1.0 wt%
B – Air pressure (bar)		1–4 bar
C – Nozzle orientation (degree °)		15°–30°
Output		
Cutting force (N)	Best, Good, Average, Bad	58.3–179.9
Cutting temperature (°C)		43.5–73.1
Roughness (μm)		0.34–3.14

5.1. Membership functions

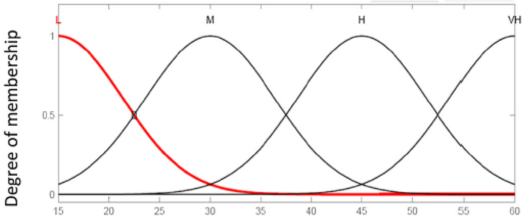
In the proposed model, it is shown that during fuzzification, the type of membership function depends on the relevant event (Jaya et al., 2010). In the present case, the input variables are partitioned according to the range of experimental parameters. The input variables for the fuzzy set of membership functions are shown in Fig. 6(a–c) while Fig. 7 represents the output variables (cutting forces, cutting temperatures and surface roughness) for the fuzzy set of membership functions.



(a) Input variable "A"

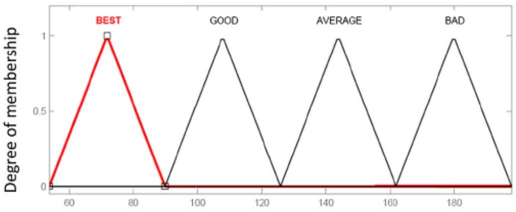


(b) Input variable "B"

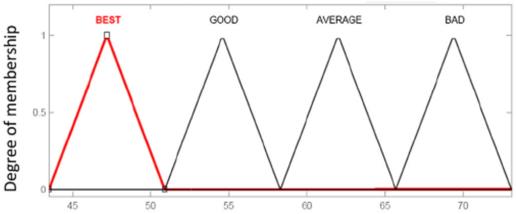


(c) Input variable "C"

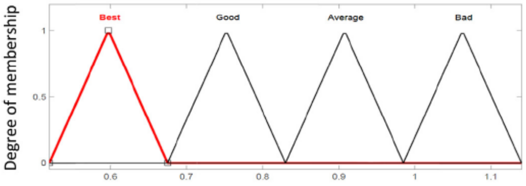
Fig. 6. Membership function for variables of inputs.



(a) Output variable "cutting force"



(b) Output variable "cutting temperature"



(c) Output variable "Surface roughness"

Fig. 7. Membership function for the output variable of cutting force, cutting temperature and surface roughness.

5.2. Structure of fuzzy rules

Based on the experimental results obtained, a set of 12 rules was constructed for cutting force, cutting temperature and surface roughness of Al-6061-T6 alloy during milling operation using SiO_2 nanosuspension lubricant (Table 9). The experimental results were then analyzed with Mamdani Fuzzy Logic (Matlab software).

5.3. Defuzzification

During defuzzification, a fuzzy quantity is converted to a constant value. Seven methods for defuzzification are reported in literature, including centroid, mean of max, weight average, center of largest area, center of sums and first of maximum method. The choice of an appropriate method greatly influences the accuracy and speed of the system. Being widely accepted for giving accurate results for centroid of area (COA), the defuzzification method was used in this work (Leung et al., 2003). The resultant membership functions are developed in the COA defuzzification method based on the output of each rule (Chandrasekaran et al., 2010). A graphical representation of the COA defuzzification method is shown in Fig. 8.

Table 9
Basis of Mamdani Fuzzy logic for cutting force, cutting temperature and surface roughness.

Cutting force	Cutting temperature	Surface roughness
1. IF (A is L) and (B is L) and (C is L) then (Cutting force is Average)	1. IF (A is L) and (B is L) and (C is L) then (Cutting temperature is Good)	1. IF (A is L) and (B is L) and (C is L) then (Surface roughness is Bad)
2. IF (A is L) and (B is M) and (C is M) then (Cutting force is bad)	2. IF (A is L) and (B is M) and (C is M) then (Cutting temperature is bad)	2. IF (A is L) and (B is M) and (C is M) then (Surface roughness is Best)
3. IF (A is L) and (B is H) and (C is H) then (Cutting force is Average)	3. IF (A is L) and (B is H) and (C is H) then (Cutting temperature is Good)	3. IF (A is L) and (B is H) and (C is H) then (Surface roughness is Good)
4. IF (A is L) and (B is VH) and (C is VH) then (Cutting force is Bad)	4. IF (A is L) and (B is VH) and (C is VH) then (Cutting temperature is Best)	4. IF (A is L) and (B is VH) and (C is VH) then (Surface roughness is Good)
5. IF (A is M) and (B is L) and (C is M) then (Cutting force is Best)	5. IF (A is M) and (B is L) and (C is M) then (Cutting temperature is Best)	5. IF (A is M) and (B is L) and (C is M) then (Surface roughness is Best)
6. IF (A is M) and (B is M) and (C is L) then (Cutting force is Average)	6. IF (A is M) and (B is M) and (C is L) then (Cutting temperature is Good)	6. IF (A is M) and (B is M) and (C is L) then (Surface roughness is Good)
7. IF (A is M) and (B is H) and (C is VH) then (Cutting force is Bad)	7. IF (A is M) and (B is H) and (C is VH) then (Cutting temperature is Bad)	7. IF (A is M) and (B is H) and (C is VH) then (Surface roughness is Best)
8. IF (A is M) and (B is VH) and (C is H) then (Cutting force is Average)	8. IF (A is M) and (B is VH) and (C is H) then (Cutting temperature is Bad)	8. IF (A is M) and (B is VH) and (C is H) then (Surface roughness is Good)
9. IF (A is H) and (B is L) and (C is H) then (Cutting force is Bad)	9. IF (A is H) and (B is L) and (C is H) then (Cutting temperature is Bad)	9. IF (A is H) and (B is L) and (C is H) then (Surface roughness is Good)
10. IF (A is H) and (B is M) and (C is VH) then (Cutting force is Good)	10. IF (A is H) and (B is M) and (C is VH) then (Cutting temperature is Average)	10. IF (A is H) and (B is M) and (C is VH) then (Surface roughness is Best)
11. IF (A is H) and (B is H) and (C is L) then (Cutting force is Good)	11. IF (A is H) and (B is H) and (C is L) then (Cutting temperature is Good)	11. IF (A is H) and (B is H) and (C is L) then (Surface roughness is Best)
12. IF (A is H) and (B is VH) and (C is M) then (Cutting force is Bad)	12. IF (A is H) and (B is VH) and (C is M) then (Cutting temperature is Average)	12. IF (A is H) and (B is VH) and (C is M) then (Surface roughness is Good)

Fig. 9 (a) and (b) demonstrate the effects of the input parameters on cutting force during Al-6061-T6 milling as investigated with fuzzy logic analysis. As seen in Fig. 9 (a), the cutting force reaches a minimum at 0.2 wt% SiO_2 concentration, after which it increases. Similarly, higher lubricant pressure increases the cutting force. From Fig. 9 (b) it is clear that nozzle angle has less significance on cutting force. Fig. 10 (a) and (b) show the effects of the input parameters on cutting temperature. It can be seen that the cutting temperature significantly increases with increasing air pressure (Fig. 10(a)). On the other hand, the cutting force reaches a maximum at 0.5 wt% SiO_2 concentration. Nozzle angle and SiO_2 concentration significantly influence the cutting temperature (Fig 10(b)). It appears that greater nozzle angle and concentration of SiO_2 nanoparticles produce higher cutting temperature. Fig. 11 (a) and (b) demonstrate the surface roughness effect of input parameters as predicted by the fuzzy-based model. The surface roughness drastically increases with increasing air pressure and concentration of SiO_2 nanoparticles (Fig. 11 (a)). From Fig. 11 (b) it is evident that minimum surface roughness is obtained at SiO_2 concentration of 0.2 wt%. In general, higher nozzle angle and greater SiO_2 concentration produce higher surface roughness.

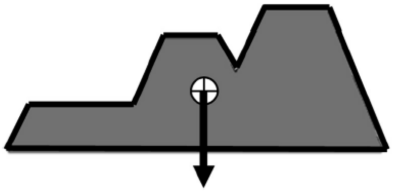


Fig. 8. Graphical of centroid Area Method.

6. Investigating the accuracy of the fuzzy model

To investigate the accuracy of the fuzzy model, four new experiments were carried out. The parameters are shown in Table 10 and the model was used to estimate the cutting force, cutting temperature and surface roughness (Ghani et al., 2014). The percentage of individual error was obtained by dividing the absolute difference of the measured and predicted values as in Equation (1), where e_i is the percentage of individual error, R_m is the measured value and R_p is the predicted value.

$$e_i = \left(\frac{|R_m - R_p|}{R_m}\right) \times 100\% \tag{1}$$

Meanwhile, the accuracy was analyzed to validate the fuzzy model. Fuzzy model accuracy (A) is defined as an average of all accuracies as per Equation (2), where N is the total number of tested data.

$$A = \frac{1}{N}\sum_{i=1}^{N}\left(1 - \frac{|R_m - R_p|}{R_m}\right) \times 100\% \tag{2}$$

Table 11 tabulates the accuracy and error of the predicted fuzzy model. The measured and predicted results for cutting force, cutting temperature and surface roughness are shown in Fig. 12 (a), (b) and (c). For cutting force, cutting temperature and surface roughness the highest errors of the fuzzy model were 8.97%, 3.5% and 9.62%. It is seen that the predicted cutting force, cutting temperature and surface roughness values were very close to the actual values. The accuracy of the proposed fuzzy model indicates that this model is capable of predicting cutting force, cutting temperature and surface roughness for Al-6061-T6 milling using SiO_2 nanolubricant.

7. Discussion

In this research project, a fuzzy logic analysis was proposed to anticipate the cutting force, cutting temperature and surface roughness during Al-6061-T6 alloy milling with using SiO_2 nanolubricant. From the results of the proposed fuzzy model is appears that the extensive dispersion of SiO_2 nanoparticles in cutting oil facilitated by high pressure stream air reduces cutting force. Tu-Chieh and Yaw-Terng showed a large interacting force between particles and workpiece that lowers the surface energy of the workpiece, something that is mainly attributed to the binding strength between the surface and sub-surface atoms in the workpiece (Tu-Chieh and Yaw-Terng, 2006). A certain amount of energy

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