Performance Predictions of Using Novel SiO_2 Nanolubrication in End-milling of Aerospace AL 6061-T6 alloy – ANFIS Modeling Approach

M.Sayuti[1], Ahmed A. D. Sarhan[2], M. Hamdi[3]

Abstract— **Aluminum AL6061-T6 is a common alloy which is used for many purposes since it has the superior mechanical properties such as hardness and weldability. It is commonly used in aircraft, automotive and packaging food industries. Milling of Al6061-T6 would be a good process especially in producing varieties shape of products to adapt with different applications. The capability of the CNC milling machine to make batch production would be a noteworthy advantage. However, the demand for high quality focuses attention on product quality, especially the roughness of the machined surface, because of its effect on product appearance, function, and reliability. Introducing correct lubrication in the machining zone could improve the tribological characteristic of Al6061-T6 leading to higher product quality. Due to complexity and uncertainty of the machining processes, soft computing techniques are being preferred to physics-based models for predicting the performance of the machining processes and optimizing them. In this research work, a new application of ANFIS to predict the performance of machining AL-6061-T6 using SiO_2 nanolubricant is presented. The parameters of SiO_2 nanolubrication include SiO_2 concentration, nozzle angle and air carrier pressure are investigated to improve the milling of Al6061-T6 to achieve correct lubrication conditions for the lowest cutting force, cutting temperature and surface roughness. The predicted results achieved via ANFIS model are compared to the experimental result. The result demonstrated settlement between the ANFIS model and experimental results for cutting force, cutting temperature and surface roughness with 96.195%, 98.27% and 91.37% accuracy, respectively.**

Index Terms— **Al6061-T6 alloy, ANFIS modeling, Cutting force, Cutting temperature, End milling, SiO_2 nanolubrication, Surface roughness.**

I. INTRODUCTION

ALUMINUM has many benefits over other materials, including a high strength to weight ratio, corrosion resistance, formability, and price. Alloy 6061, 7075, and 2024, sometimes referred to the group of “Aerospace Alloys” for their practical applications in aviation industry. Theses alloys are engineered to be lightweight and strong, and their ease of formability allows complex shapes and drawn parts, which can then be further enhanced with heat treating. Aluminum AL6061-T6 is an alloy which contains magnesium and silicon as major alloying elements. It has been a common alloy which is used for many purposes since it has the superior mechanical properties such as hardness and good weldability [1-2]. The common applications for this material are in aircraft industry, automotive industry and packaging food industry. The capability of the CNC milling machine to make complicated special products would be a noteworthy advantage for Aluminum AL6061-T6. However, the demand for high quality focuses attention on the surface condition and the quality of the product, especially the roughness of the machined surface, because of its effects on product appearance, function and reliability [3-5].

The tribological characteristic of machining process can be improved by introducing lubrication in the machining zone [6-7]. Correct application of lubricants has been proven to greatly reduce friction in the tool chip interface, this results in improving the surface quality. Although the significance of lubrication in machining is widely recognized, the usage of conventional flooding application in machining processes has become a huge liability. Not only does the Environmental Protection Agency (EPA) regulate the disposal of such mixtures, but many countries and localities also have classified them as hazardous wastes as they contain environmentally harmful or potentially damaging chemical constituents [8-9]. Beside that economically, the costs associated with the use of lubricants is estimated to be several billion $/year. The cost related to the lubrication and cutting fluid is 17 % of total production cost which is normally higher than that of cutting tool equipments which incurs only 7.5% of total cost. Consequently, eliminating the use of lubricants, if possible, can be a significant economic incentive[10-11].

At present, many efforts are being undertaken to develop advanced machining processes using less lubrications [12]. Promising alternatives to conventional flood coolant

Manuscript received August 1, 2014; revised August 20, 2014. This work was supported by the high impact research (HIR) grant number: HIR-MOHE-16001-00-D000001 from the Ministry of Higher Education, Malaysia.

M.Sayuti is with the Center of Advanced Manufacturing and Material Processing, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, 50603, Malaysia (e-mail: mdsayuti@um.edu.my)

Ahmed. A.D. Sarhan is with the Center of Advanced Manufacturing and Material Processing, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, 50603, Malaysia (e-mail: ah_sarhan@um.edu.my).

(Corresponding author to provide phone: +60379674593; fax: +60379675330; e-mail: ah_sarhan@um.edu.my)

M. Hamdi is with the Center of Advanced Manufacturing and Material Processing, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, 50603, Malaysia (e-mail: hamdi@um.edu.my).

applications are the minimum quantity lubrication (known as MQL) [13]. Klocke and Eisennblatter (1997) [14] state that MQL is referred to the use of lubrication of only a minute amount-typically of a flow rate of 50 to 500 ml/hour which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition. This has been reported to reduce friction, cutting temperature and improve tool life due to its ability to penetrate into the chip-tool interface which improves the product surface quality. In addition, the dry chips can be recycled without incurring large cleaning expenses making the application of nanolubrication a plausible solution [9, 11, 15].

Nowadays, many nanolubricant has been identified by the advancement in modern technology which makes possible to sustain and provide lubricity over wide range of temperature [16-17]. Nanolubricant is a kind of new engineering material consisting of nanometer-sized particles dispersed in base oil. It would be an effective method to be used in reducing friction between two contact surfaces and depends on the working conditions. Lubricants are expected to withstand the high machining temperatures, non-toxic, easy to be applied and effective in term of cost [18]. The effectiveness of the lubrication depends on the morphology, crystal structure of solid lubricants, the way of particle introduced to the tool-workpiece interface and quantity [19-20].

Due to high performance of the nanoparticle based lubricants, labor and materials associated with preserving lubricant and equipment integrity soon will be minimized. Health and environmental concern need to be addressed when dealing with lubricants materials. In addition, the productivity in the machining industry could increase through cost reduction by abandonment of the cutting fluid, saving the environment and at the same time improve the machining performance. Physical analysis of nanolubricant [21] showed the nanoparticle dispersed can easily penetrate into the rubbing surfaces and have large effect of elastohydrodynamic lubrication. Under single thrust bearing tester, researchers reported that the coefficient of friction of nanolubricant is less than pure oil and the extreme pressure of nanolubricant is two times higher than that of pure oil, hence it can be concluded that nanolubricant improved the lubrication performance by preventing contact between the metal surfaces. Moreover, thermal conductivity of nanolubricant increases linearly with the concentration, which performs as hydrodynamic interaction to enhance thermal transport capability [22].

Many types of nanoparticle have been used as a lubricant by researchers in order to investigate its effects on the machining performance. It is well documented that silicon dioxide (SiO_2) nanoparticle is a hard and brittle material and cheap and available in market. This nanoparticle has very good mechanical properties especially in term of hardness (Vickers hardness - 1,000 kgf mm^{-2}) and in very small size range from 5 nm up to 100 nm. However the application of SiO_2 material with suspended in pure oil has not been well reported in improving the machining performance. Therefore, this research attempted to investigate the performance of SiO_2 as nanolubrication in end milling process of Al6061-T6 alloy.

In line with the previous research work as reviewed above, the investigation of optimum SiO_2 lubrication parameters in milling of Al6061-T6 is needed to focus on effective improvement of the machined surface quality by minimizing the cutting force and cutting temperature. These parameters include nanolubricant concentration, nozzle angle and air carrier pressure. Due to complexity and uncertainty of the machining processes, of late, soft computing techniques are being preferred to physics-based models for predicting the performance of the machining processes and optimizing them [23].

Soft computing techniques are useful when exact mathematical information is not available and these differ from conventional computing in that it is tolerant of imprecision, uncertainty, partial truth, approximation, and met heuristics. Major soft computing tools applied for this purpose are neural networks, fuzzy sets, genetic algorithms, simulated annealing, ant colony optimization, and particle swarm optimization. ANFIS is one of the soft computing techniques that play a significant role in input-output matrix relationship modeling. It is used when subjective knowledge and suggestion by the expert are significant in defining objective function and decision variables. ANFIS is preferred to predicting machining performance based on the input variables due to nonlinear condition in machining process [23]. This paper applies the ANFIS modeling to develop the rule model in order to predict the cutting force, cutting temperature and surface roughness of Al-6061-T6 milling operation while using SiO_2 nanolubricant.

Following the literature above, for predicting of the cutting force, cutting temperature and surface roughness, this study has been conducted using ANFIS modeling by anticipating nanolubrication concentration, air pressure and nozzle orientation as lubrication parameters.

II. DESIGN OF EXPERIMENTS

The most important stage in the designing of an experiment lies in the selection of lubrication parameters and identifying the experimental array. In this experiment with three parameters and four levels each, the factors design used is a L_{12} experimental array. This array is chosen due to its capability to check the interactions among parameters. The parameters and levels are assigned as in Table 1. The twelve experiments with the details of combination of the experimental levels for each parameter (A-C) are shown in Table 2.

III. EXPERIMENT SET UP AND PROCEDURE

The second step in is to run the experiments based on the selected experimental array. The twelve experiments were carried out in a random sequence to eliminate any other invisible factors, which might also contribute to the cutting force, cutting temperature and surface roughness. The experimental set-up is shown in Fig. 1. The machine used in this study is a vertical-type machining center (Cincinnati Milacron Saber TNC750 VMC); the spindle has constant position preloaded bearings with oil-air lubrication with the maximum rotational speed of 12,000 min^{-1}. The cutting process of a rectangular workpiece of Al-6061-T6 80 × 50 × 25 mm^3 is selected as a case study. The cutting tool used is high speed steel (HSS) with 2 flute and 10 mm diameter to represent the most common tool selection in milling industry suitable for slot milling process. The tool moves in +X direction to cut a stroke of 200 mm.

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.	Parameters combinations		
	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

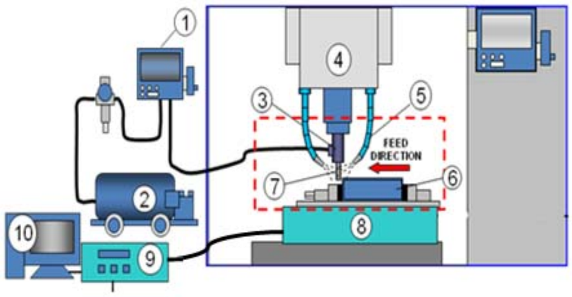


Fig. 1: The experimental set-up

The cutting speed, feed and depth of cut used are 5,000 min^{-1}, 100 mm/min and 5 mm, respectively and they are selected based on the tool manufacturer's recommendations. The cutting forces were measured using a Kistler three-axis dynamometer (type 9255B). The measured cutting force signals (X, Y, and Z directions) were captured and filtered with low path filters (10 Hz cut off frequency) while, the cutting temperature is measured by using the thermocouple (K-Type Testo 925 Thermocouple), and each test measurement was repeated three times in order to reduce abrupt readings error. The thermocouple has been installed under the machining surface and the measured temperature reflects the amount of heat dissipated in the workpiece. This amount of heat should indicate the change of the coefficient of friction between tool and chip in cutting zone. For every machining run, the temperature has been measured at every two minutes while the machined surface roughness has been measured using surface profilometer (MarSurf PS1 Perthometer) at cut off distance of 700µm.

The nanoparticle-oil is prepared by adding SiO_2 nanoparticles with an average size of 5-15 nm to the mineral oil followed by sonification (240 W, 40 kHz, 500 W) for 48 hours in order to suspend the particle homogeneously in the mixture. In this research work, the mineral oil used is Shell Dromus BL lubricant oil. To deliver the oil to the tool chip interface area, the MQL system is used. The experimentation is carried out using a thin-pulsed jet nozzle that is developed in laboratory and controlled by a variable speed control drive. The nozzle has been equipped with additional air nozzle to accelerate the lubricant into the cutting zone and to reduce the oil consumption up to 25%. The nozzle system is attached to a flexible portable fixture fixed on the machining spindle. The flexible design allows the injection nozzle to be located at any desired position without interfering with the tool or workpiece during the machining process. The diameter of the nozzle orifices is 1 mm and the MQL oil pressure is set to be 20 MPa with delivery rate of 2 ml/min.

IV. EXPERIMENTAL RESULT

The experimental tests are carried out using the proposed experimental set-up. Figures 2 and 3 show examples of the measured cutting force and surface roughness at 0.8 Mpa air pressure, 20,000 min^{-1} spindle speed, 0.25 mm/min feed rate, and 1 mm axial depth of cut, respectively.

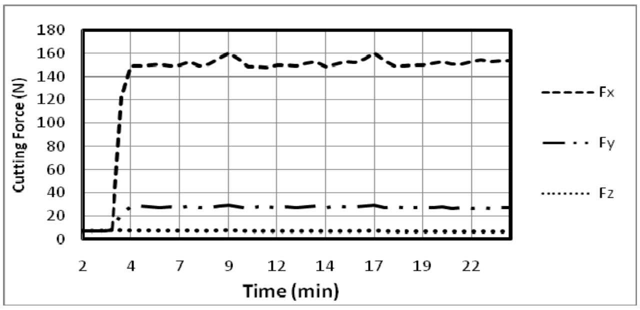


Fig.2: Measured cutting forces in X, Y and Z- directions at nanoparcticle concentration: 0.2 wt%, air pressure: 1 bar, nozzle angle 30◦

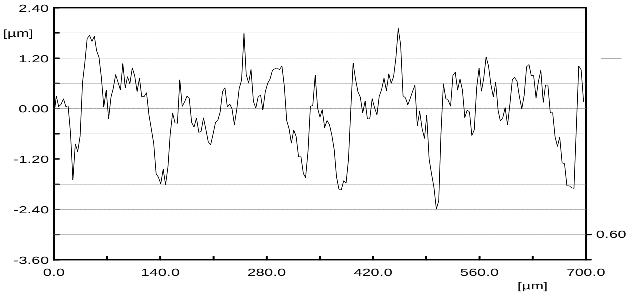


Fig.3: An example of measured surface roughness at nanoparticle concentration: 0.2wt%, air pressure: 1 bar, nozzle angle 30º

V. ANFIS MODELING

The measured cutting forces, surface roughness and cutting temperature were used as the training data set to build the ANFIS model. Five network layers were used by ANFIS to perform the following fuzzy inference steps as shown in Fig. 4: Layer 1 - input fuzzification, Layer 2 - fuzzy set database construction, Layer 3 - fuzzy rule base construction, Layer 4 - decision making, and Layer 5 - output de-fuzzification [24].

To explain this model simply, two rules and two linguistic values for each input variable are suggested.

Layer 1 the output of the node is the degree to which the given input satisfies the linguistic label associated to this node. Usually, bell-shaped membership functions are chosen to represent the linguistic terms.

First parameter membership functions

$$A_i(x) = exp[-0.5((x-a_{i1})/b_{i1})^2] \quad (1)$$

Second parameter membership functions

$$B_i(y) = exp[-0.5((y-a_{i2})/b_{i2})^2] \quad (2)$$

Where a_{i1}, a_{i2}, b_{i1}, b_{i2} are the parameter set.

As the values of these parameters change, the bell-shaped functions vary accordingly thus exhibiting various forms of membership functions on linguistic labels A_i and B_i. The parameters in this layer are referred to as principle parameters.

Layer 2 each node computes the firing strength of the associated rule. The nodes of this layer are called rule nodes. The outputs of the top and bottom neurons are as follows:

Top neuron $\alpha_1 = A_1(x) \times B_1(y)$ (3)

Bottom neuron $\alpha_2 = A_2(x) \times B_2(y)$ (4)

Layer 3 every node in this layer is labeled by N to indicate the normalization of the firing levels. The output of the top and bottom neurons is normalized as follows:

Top neuron $\beta_1=\alpha_1/(\alpha_1+\alpha_2)$ (5)

Bottom neuron $\beta_2=\alpha_2/(\alpha_1+\alpha_2)$ (6)

Layer 4 the output of the top and bottom neurons is the product of the normalized firing level and the individual rule output of the first rule and second rule respectively.

Top neuron $\beta_1 z_1 = \beta_1 (a_1 x + b_1 y)$ (7)

Bottom neuron $\beta_2 z_2 = \beta_2 (a_2 x + b_2 y)$ (8)

Layer 5 the single node in this layer computes the overall system output as the sum of all incoming signals, i.e.

$$z = \beta_1 z_1 + \beta_2 z_2 \quad (9)$$

If a crisp training set $((x^k, y^k), k = 1, \ldots ,k)$ is given, then the parameters of the hybrid neural net (which determine the shape of the membership functions of the premises) can be learned by descent-type methods. The error function for pattern k can be given by:

$$E_k = (y^k - o^k)^2 \quad (10)$$

where y^k is the desired output and o^k is the computed output by the hybrid neural net [24].

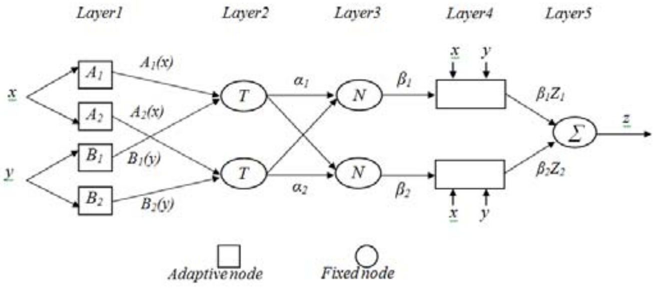


Fig.4 ANFIS architecture for Sugeno fuzzy model.

VI. ANFIS PREDICTION MODEL RESULTS AND DISCUSSION

Figure 5 (a) and (b) are examples to show the relation between input parameters change and cutting force of a machined surface in Al-6061-T6 milling operation predicted by ANFIS model. As can be seen in Fig. 5 (a), the cutting force is minimum at 0.2%wt of SiO_2 concentration, the cutting forces significantly increases with the increasing of the SiO_2 concentration. In addition, the air pressure parameter change is also significant; the higher air pressure the higher cutting force can be obtained. From Fig. 5 (b), it is clearly seen that nozzle angle is less significant to change the cutting force.

Figure 6 (a) and (b) shows the predicted cutting temperature by ANFIS model in relation to lubrication parameters in machining of Al-6061-T6. As can be seen in Figs. 6 (a), the temperature is significantly increased with the increasing of both, the air pressure and SiO_2 concentration parameters. However, the lowest cutting force value can be obtained at the lowest value of air pressure (1 bar) and lowest value of SiO_2 concentration parameters (0 %wt, pure oil).

From the Fig. 6 (b), it is clearly seen that both of the nozzle angle and SiO_2 concentration parameters are very significant to change the cutting temperature. It appears that the lowest nozzle angle (15 degree) and lowest SiO_2 concentration (0 %wt, pure oil) will produce the lowest cutting temperature.

Figure 7 (a) and (b) shows the predicted surface roughness by ANFIS model in relation to lubrication parameters in machining of Al-6061-T6. As can be seen in Figs. 7 (a), the surface roughness is significantly decreased with the increase of the both air pressure and SiO_2 concentration parameter. The best surface quality can be obtained at (3 bar) air pressure value and (1 %wt) SiO_2 concentration. However, From the Fig. 7 (b), it is clearly seen that the best surface quality can be obtained at (30 degree) nozzle angle.

VII. INVESTIGATE THE ANFIS MODEL ACCURACY AND ERROR

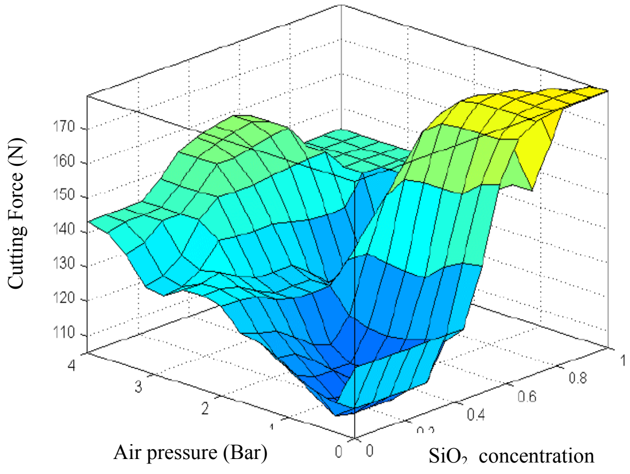
To investigate the ANFIS model accuracy and error, other new four experimental tests from separated experiment were carried out while the proposed ANFIS model is used to predict the cutting force, cutting temperature and surface roughness at the same conditions. Table 3 is presenting the parameters input for accuracy and error of the ANFIS model prediction. The individual error percentage is obtained by dividing the absolute difference of the predicted and measured values by the measured value as shown in Equation (1) where (e_i) is individual error; (R_m) is measured value and (R_p) is predicted value [13].

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

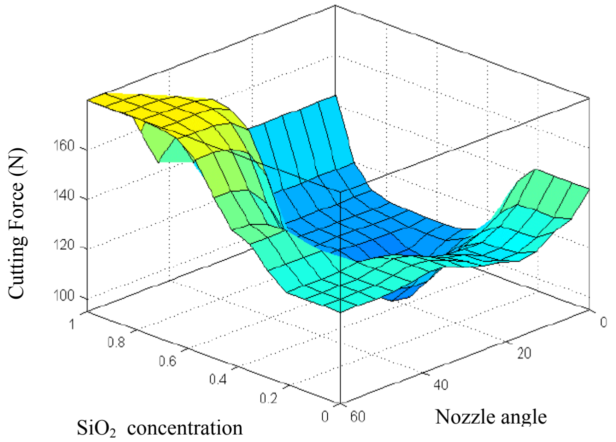
Meanwhile, accuracy is calculated to measure the closeness of the predicted value to the measured value. The model accuracy is the average of individual accuracy as shown in Equation (2) where A is the model accuracy and N is the total number of data set tested.

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

The error for data set result was calculated and the model accuracy for ANFIS model was determined. The measured and predicted results of cutting force, cutting temperature and surface roughness are shown in Figs. 8 (a), (b) and (c), respectively.

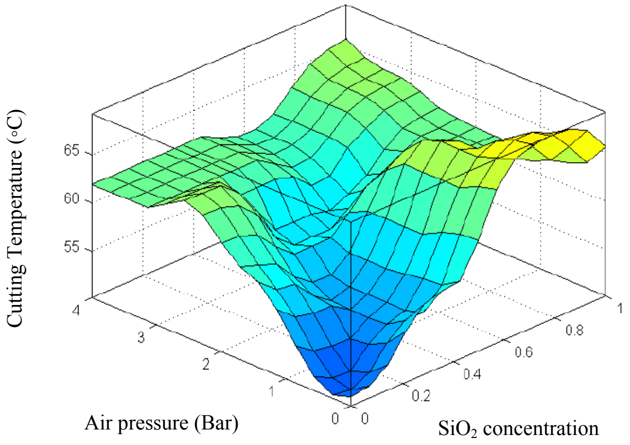


a) Cutting force in relation to change of air pressure and SiO_2 concentration

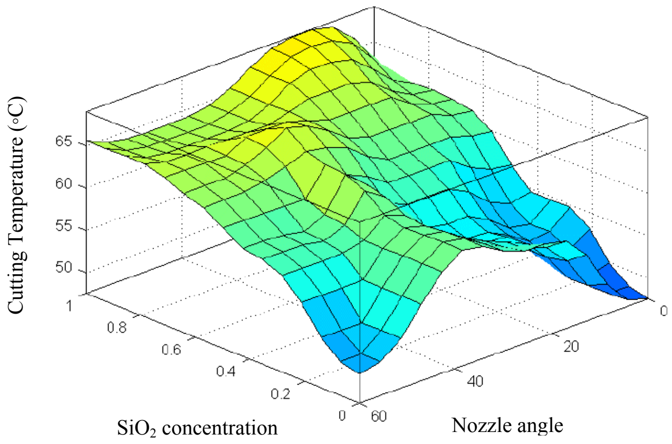


b) Cutting force in relation to change of SiO_2 concentration and nozzle angle

Fig. 5: The predicted cutting force by ANFIS in relation to lubrication parameters

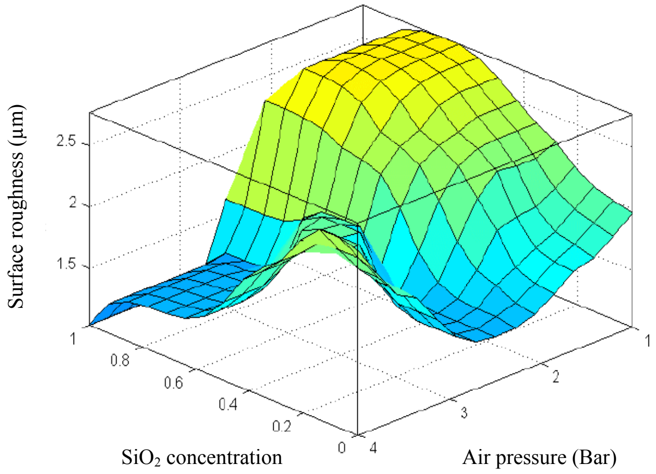


(a) Cutting temperature in relation to change of air pressure and SiO_2 concentration

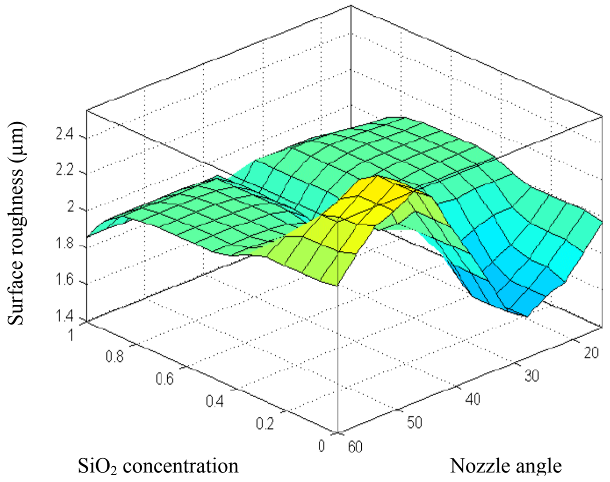


(b) Cutting temperature in relation to change of SiO_2 concentration and nozzle angle

Fig. 6: The predicted cutting temperature by ANFIS model in relation to lubrication parameters



(a) Surface roughness in relation to change SiO_2 concentration and air pressure



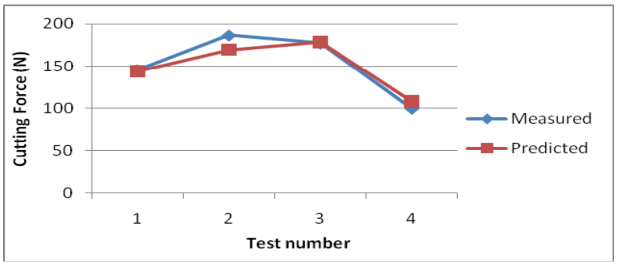
(b) Surface roughness in relation to change of SiO_2 concentration and nozzle angle

Fig. 7: The predicted surface roughness by ANFIS model in relation to lubrication parameters

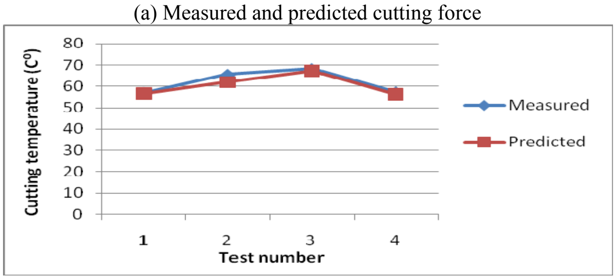
ISBN: 978-988-19253-7-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

TABLE 3: THE PARAMETERS INPUT FOR ACCURACY AND ERROR OF THE ANFIS MODEL PREDICTION

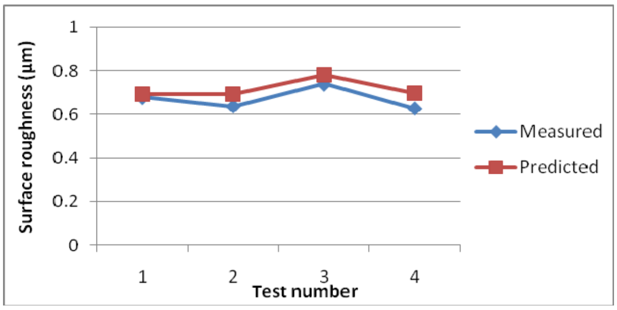
No of Exp.	Parameters (Inputs)		
	A	B	C
1	4	3	2
2	3	4	1
3	4	4	1
4	4	2	3



(a) Measured and predicted cutting force



(b) Measured and predicted cutting temperature



(c) Measured and predicted surface roughness

Figure 8: Comparison of the predicted and measured cutting force, cutting temperature and surface roughness in machining Al-6061-T6

For the cutting force, cutting temperature and surface roughness the highest percentage of error for ANFIS model prediction are 8.97%, 3.5% and 16.42%, respectively. The low level of errors shows that the ANFIS predicted model results were very close with actual experimental values. The value of accuracy shows that the proposed model can predict the cutting force, cutting temperature and surface roughness in machining Al-6061-T6 using SiO_2 nanolubricant satisfactorily.

VIII. DISCUSSION

In this study, ANFIS model is proposed to predict cutting force, cutting temperature and surface roughness of Al-6061-T6 milling operation using SiO_2 nanolubricant. The result demonstrated settlement between ANFIS model and experimental results with the cutting force, cutting temperature and surface roughness.

As can be observed from the ANFIS modele results, extensive dispersed of SiO_2 nanoparticles in cutting oil facilitated by high pressure stream air in cutting zone shows a good performance in reducing cutting force. Tu-Chieh and Yaw-Terng [25] found large interacting force between particle and workpiece would reduce the surface energy of workpiece which is the binding strength between the surface and sub-surface atoms of workpiece. The breaking process required certain amount of energy to break the weekend asperities of work surface and generate newly surface with lower roughness. The making process of nanoparticle transfers the potential energy from tool, then it is converted into kinetic energy of surface atoms and dissipated as heat [25]. So, with the increasing of nano-oil concentration, more and more nanoparticles will transfer more kinetic energy to the workpiece surface and increasing the dissipation of heat. The low friction behavior in nature of nanoparticle, effectively in minimize the frictional effects at tool-workpiece interface and thus reduces cutting. For large amount of nanoparticles presence in cutting oil, it will collide with and impede by the asperities on work surface and generate higher cutting force. Another possible reason is, when the spindle speed is increased accordingly, cutting energy input to the machine tools and generated machining compressive stresses grows correspondingly higher and lead to increased chip-tool interface temperatures. The generated heat in the machining zone helps to soften workpiece material, reducing cutting forces required to cut the material leading to better surface quality [10]. However, it is believed that the spindle speed should be controlled at an optimum value, as the influence of temperature, especially for low thermal conductive materials such as Al-6061-T6, would significantly affect the chip formation mode, cutting forces, tool life, and surface quality.

For cutting temperature, ANFIS model results show that, the values is almost similar to the experimental results. In conjunction, in high speed machining operation nozzle orientation may be an important factor, but very less literature has ever made detail study of the most appropriate nozzle orientation. It may be because of many conditions which need to be considered such as nozzle specification, cutting operation and desire cutting performance in order to really determine the optimum nozzle orientation. For cutting temperature wise, 15° nozzle angle shows the optimum, since the measurement of temperature is in workpiece which majority contribution of cutting temperature is from tertiary deformation zone, therefore 15° nozzle orientation successfully withdraw heat from the tertiary zone. However, 30° nozzle angle shows optimum for best surface roughness and chip thickness ratio. It may be related to its orientation is much better in accelerating the cutting oil in the cutting zone and assisting in machining to obtain better surface quality. Again, as mentioned before, the cutting oil in tool-chip interface has negligible on the cutting force and stress in cutting edge, therefore 60° nozzle angle may not be the optimum for chip thickness ratio as cutting force shows optimum in 60° nozzle angle. During the cutting process, the consumed energy changes into heat in deformation zones. The heat generated increases the cutting temperature with an increase of nano-oil concentration, and it may reach the melting temperature of the work material. The another reason of drastically increase of temperature may due to the formation of thin film which refrain temperature disperse away from the machined surface. It could be supposed that temperature rise softens the material aiding grain boundary dislocation, and hence ease the cutting operation, thus it will also lower the cutting force [26]. Hence, it causes the temperature of some thin layers on the back face of the chip adjacent to rake face of the tool becomes close to melting temperature. Associate with the higher temperature, strain energy effects and the present of extreme pressure additive in cutting oil, chemical reaction films are further formed on the machined surface [27].

As per illustrated from ANFIS modeling, the surface roughness are possible to be predicted using soft computing techniques. The surface roughness result illustrated that surface roughness decrease initially and drastically increase when air pressure beyond 2 bar. This may due to the reason which the higher air pressure will lead to formation of welded surface. This welded surface could act as peeler which may pull away some workpiece material mechanically. While when the increase of lower air pressure, it helps in accelerate the nano-oil into deep cutting zone and assisted in polishing the machined surface, but cutting temperature generated is not high enough, therefore lead to intensive formation of protective film and thus reduce its roughness.

IX. CONCLUSION

In this study, ANFIS model has been established to predict the cutting force, cutting temperature and surface roughness of machined surface in Al-6061-T6 milling operation using SiO_2 nanolubricant. The result demonstrated settlement between the ANFIS model and experimental results for cutting force, cutting temperature and surface roughness are 96.195%, 98.27% and 91.37% accuracy, respectively. The close agreement of experimental values of machined surface clearly indicates that the ANFIS model can be used to predict the cutting force, cutting temperature and surface roughness within the range of input parameters under consideration.

ACKNOWLEDGMENT

This work was supported by the high impact research (HIR) grant number: HIR-MOHE-16001-00-D000001 from the Ministry of Higher Education, Malaysia.

REFERENCES

[1] Lakshminarayanan, A., V. Balasubramanian, and K. Elangovan, Effect of welding processes on tensile properties of AA6061 aluminium alloy joints. The International Journal of Advanced Manufacturing Technology, 2009. 40(3): p. 286-296.

[2] Shankar, M.R., S. Chandrasekar, W.D. Compton, and A.H. King, Characteristics of aluminum 6061-T6 deformed to large plastic strains by machining. Materials Science and Engineering: A, 2005. 410-411: p. 364-368.

[3] Li, Y. and S.Y. Liang, Cutting Force Analysis in Transient State Milling Processes. The International Journal of Advanced Manufacturing Technology, 1999. 15(11): p. 785-790.

[4] Reddy, N.S.K. and P.V. Rao, A genetic algorithmic approach for optimization of surface roughness prediction model in dry milling. An international Journal of Machining Science and Technology, 2005. 9(1): p. 63-84.

[5] Guo, Y.B., W. Li, and I.S. Jawahir, Surface Integrity Characterization And Prediction in Machining of Hardened and Difficult-To-Machine Alloys: A State-Of-Art Research Review and Analysis. Machining Science and Technology, 2009. 13(4): p. 437-470.

[6] Lee, J., S. Cho, Y. Hwang, H.-J. Cho, C. Lee, Y. Choi, B.-C. Ku, H. Lee, B. Lee, D. Kim, and S.H. Kim, Application of fullerene-added nano-oil for lubrication enhancement in friction surfaces. Tribology International, 2009. 42: p. 440-447.

[6] X.Tao, Z.Jiazheng, and X. Kang, The ball-bearing effect of diamond nanoparticles as an oil additive. J.Phys. D Appl. Phys., 1996. 29: p. 2932-2937.

[8] Lathkar, G.S. and U.S.K. Bas, Clean metal cutting process using solid lubricants,, in proceeding of the 19th AIMTDR Conference. 2000, Narosa Publishing House IIT Madras. p. 15-31.

[9] Reddy, N.S.K., M. Nouari, and M. Yang, Development of electrostatic solid lubrication system for improvement in machining process performance. International Journal of Machine Tools & Manufacture, 2010. 50: p. 789-797.

[10] E. O. Ezugwu & J. Bonney, “Finish Machining of Nickel-Base Inconel 718 Alloy with Coated Carbide Tool under Conventional and High-Pressure Coolant Supplies, ” Tribology Transactions, Volume 48, Issue 1, 2005, pp 76-81

[11] Sharma, V.S., M. Dogra, and N.M. Suri, Cooling techniques for improved productivity in turning. International Journal of Machine Tools and Manufacture, 2009. 49(6): p. 435-453.

[12] Sreejith, P.S. and B.K.A. Ngoi, Dry machining: Machining of the future. Journal of Materials Processing Technology, 2000. 101(1-3): p. 287-291

[13] Masabumi Masuko, Saiko Aoki & Akihito Suzuki, “Influence of Lubricant Additive and Surface Texture on the Sliding Friction Characteristics of Steel under Varying Speeds Ranging from Ultralow to Moderate, ” Tribology Transactions, Volume 48, Issue 3, 2005, pp 289-298

[14] Klocke, F. and G. Eisenblätter, Dry Cutting. CIRP Annals - Manufacturing Technology, 1997. 46(2): p. 519-526.

[15] HE, S., Solid lubrication materials for high temperature a review. Tribology International 1982. 15: p. 303-314.

[16] Miaosun, S., Solid lubrication materials. 2000, Beijing: China Chemistry Press, Beijing.

[17] Nakamura, T., S. Tanaka, K. Hayakawa, and Y. Fukai, A study of the lubrication behavior of solid lubricants in the upsetting process. Journal Tribology 2000. 122: p. 803-808.

[18] Deshmukh, S.D. and S.K. Basu, Significance of solid lubricants in metal cutting, in 22nd AIMTDR. 2006.

[19] Alberts, M., K. Kalaitzidou, and S. Melkote, An investigation of graphite nanoplatelets as lubricant in grinding. International Journal of Machine Tools & Manufacture, 2009. 49: p. 966-970.

[20] Masabumi Masuko, Saiko Aoki & Akihito Suzuki, “Influence of Lubricant Additive and Surface Texture on the Sliding Friction Characteristics of Steel under Varying Speeds Ranging from Ultralow to Moderate” Tribology Transactions, Volume 48, Issue 3, January 2005, pages 289-298

[21] Peng, D.X., Y. Kang, R.M. Hwang, S.S. Shyr, and Y.P. Chang, Tribological properties of diamond and SiO_2 nanoparticles added in paraffin. Tribology International, 2009. 42: p. 911-917.

[22] Keblinski, P., S.R. Phillpot, S.U.S. Choi, and J.A. Eastman, Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids). International Journal of Heat and Mass Transfer, 2002. 45: p. 855-863.

[23] Shamshirband, S., S. Kalantari, and Z. Bakhshandeh, Designing a smart multi-agent system based on fuzzy logic to improve the gas consumption pattern. Scientific Research and Essays 2010. Vol. 5(6): p. 592-605.

[24] Kasabov NK (1997) Foundations of neural networks, fuzzy systems, and knowledge engineering, vol 33. Computers & Mathematics with Applications, vol 7. MIT Press, Cambridge, MA. doi:http://dx.doi.org/10.1016/S0898-1221(97)84600-7

[25] Hung Tu-Chieh, S.Y.-T., A method for reducing tool wear in a polishing process. International Journal of Machine Tools & Manufacture. 46(2006): p. 413-423.

[26] Reza Yousefi, Y.I., A study on ultra - high-speed cutting of aluminium alloy: Formation of welded metal on the secondary cutting edge of the tool and its effects on the quality of finished surface. Journal of the International Societies for precision Engineering and Nanotechnology. 24(2000): p. 371-376.

[27] Y.C. Lin, H.S., Limitations on use of ZDDP as an antiwear additive in boundary lubrication. Tribology International. 37(2004): p. 25-33.