International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:6, No:10, 2012

A Fuzzy Logic Based Model to Predict Surface Roughness of A Machined Surface in Glass Milling Operation Using CBN Grinding Tool

Ahmed A. D. Sarhan, M. Sayuti, and M. Hamdi

Abstract**—**Nowadays, the demand for high product quality focuses extensive attention to the quality of machined surface. The (CNC) milling machine facilities provides a wide variety of parameters set-up, making the machining process on the glass excellent in manufacturing complicated special products compared to other machining processes. However, the application of grinding process on the CNC milling machine could be an ideal solution to improve the product quality, but adopting the right machining parameters is required. In glass milling operation, several machining parameters are considered to be significant in affecting surface roughness. These parameters include the lubrication pressure, spindle speed, feed rate and depth of cut. In this research work, a fuzzy logic model is offered to predict the surface roughness of a machined surface in glass milling operation using CBN grinding tool. Four membership functions are allocated to be connected with each input of the model. The predicted results achieved via fuzzy logic model are compared to the experimental result. The result demonstrated settlement between the fuzzy model and experimental results with the 93.103% accuracy.

Keywords**—**CNC-machine, Glass milling, Grinding, Surface roughness, Cutting force, Fuzzy logic model.

I. INTRODUCTION

GLASS is generally known as a hard, brittle, solid and transparent material. The optical and physical properties of glass make it plays an essential role for many different industrial applications. Soda-lime glass is one of the most prevalent types of glass, which is widely used and can easily be found on the market. In industry, this type of glass is the most commonly produced since it is easy to make with better-cost effectiveness compared to other types of glass [1]. In addition, it also has good mechanical properties in terms of hardness, refractive index and melting temperature [2]. In silicone industry as an example, soda-lime glass has been used as a mould with a very good precision in terms of dimensional accuracy even at elevated temperatures. While using a very high precision glass mould, the shape varieties of the silicone product lead to many different complicated shapes of glass moulds to be developed [1]. However, unique properties of soda-lime glass such as, compressive hardness and brittleness make any machining of glass a very challenging process [3-9]. Glass milling would be a good process required especially in producing varieties shape of slot on glass surface. The capability of the CNC milling machine to make batch production would be a noteworthy advantage for glass machining. 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 effect on product appearance, function, and reliability [9-12]. Hence, the application of grinding process on the CNC milling machine is found to be an ideal solution in manufacturing complicated special products, making the machined surface quality on the glass mould superlative compared to other machining.

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

M. Sayuti is with the Centre of Advanced Manufacturing and Material Processing, Department of Design and Manufacturing, Engineering Faculty, University of Malaya, 50603, Kuala Lumpur, Malaysia (phone: +60379674489; fax: +60379674489; e-mail: mdsayuti@um.edu.my).

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

Surface roughness is defined as a group of irregular waves in the surface, measured in micrometers (μm). The roughness data obtained by measurement can be manipulated to determine the roughness parameter. There are many different roughness parameters in use, but R_a is the most common. Other common parameters include R_z, R_q, and R_{sk}. Surface roughness is mainly affected by different machining parameters, such as spindle speed, feed rate, depth of cut and lubrication pressure [13]. In metal machining the use of higher cutting speed and lower feed rate and depth of cut produced a better surface finish and this is mainly attributed to the high temperature generated in the interface [10, 14]. However, in glass machining, the effect of these parameters need to be investigated, but in general, with higher cutting speed and higher temperature, special rapid tooling is needed to increase abrasion resistance and hence produced good surface roughness. Cubic boron nitride (CBN) grinding tools are traditionally expected to play multiple roles; such as, reducing cutting temperatures and cutting forces and increasing abrasion resistance. The cutting temperature is a key factor, which directly affects tool quality, workpiece surface integrity and machining precision according to the relative motion between the tool and workpiece. The amount of heat generated varies with the type of workpiece material being machined and machining parameters used especially cutting speed, which had the most influence on the temperature [15]. Therefore, the design and development of control system to control the temperature is lead to better surface finish. Thus, the implementations of cutting fluid, which not only act as a lubricant but also working as a coolant, are very crucial [16-17].

The conventional method to achieve lower surface roughness and cutting forces at different machining parameters is the "trial and error" approach. However, "trial and error" approach is very time consuming due to the large number of experiments. Hence, a reliable systematic approach to predict the surface roughness at different parameters condition is thus required to cover all the parameters range in a few numbers of experiments [14-15]. 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. Fuzzy logic 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. Fuzzy logic is preferred to predicting surface roughness performance based on the input variables due to nonlinear condition in machining process [18-19]. This paper applies the fuzzy logic to develop the rule model in order to predict the surface roughness of a machined surface in glass milling operation using CBN grinding tool. The fuzzy theory is still a prominent theory although sometimes it describes uncertain and indefinite phenomena having the following structure as shown in Fig. 1:

i. Fuzzification: making something fuzzy.
ii. Fuzzy rule base: in the rule base, the if-then rules are fuzzy rules.
iii. Fuzzy inference engine: produces a map of the fuzzy set in the space entering the fuzzy set and in the space leaving the fuzzy set, according to the rules if-then.
iv. Defuzzification: making something nonfuzzy [19].

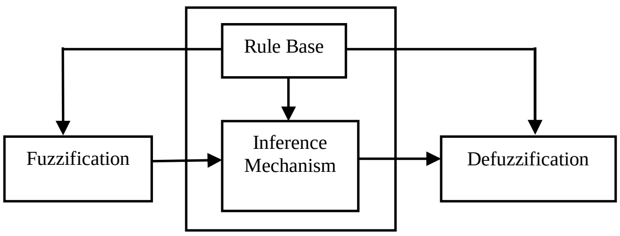


Fig. 1 The structure of a fuzzy system

Following the literature above, for predicting of the surface roughness, this study has been conducted by anticipating lubrication pressure, spindle speed, feed rate and depth of cut as machining parameters. Fuzzy rule base method is proposed to predict surface roughness of a machined surface in glass milling operation using CBN grinding tool.

II. Design of experiments

The most important stage in the designing of an experiment lies in the selection of parameters and identifying the experimental array. In this experiment with four parameters and four levels each, the factors design used is a L_{13} 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 I. The thirteen experiments with the details of combination of the experimental levels for each parameter (A-D) are shown in Table II.

TABLE I
The Machining Parameters and Experimental Condition Levels

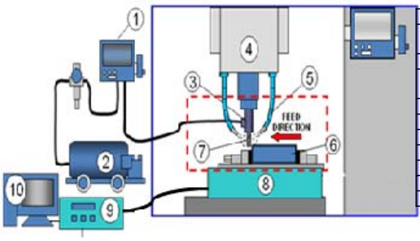
The machining parameters		The experimental condition levels			
A	Lubrication Pressure (MPa)	0.4	0.6	0.8	1.0
B	Spindle Speed (min^{-1})	5,000	10,000	15,000	20,000
C	Feed Rate (mm/min)	0.5	1	1.5	2
D	Axial Depth of Cut (mm)	0.25	0.5	0.75	1

TABLE II
The Thirteen Experiments with the Details of the Combination Levels

Exp No.	Parameters and levels			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	2	1	2	3
6	2	2	1	4
7	2	3	4	1
8	3	1	3	4
9	3	2	4	3
10	3	3	1	2
11	4	1	4	2
12	4	2	3	1
13	4	3	2	4

III. Experiment Set Up and Procedure

The second step in is to run the experiments based on the selected experimental array. The thirteen experiments were carried out in a random sequence to eliminate any other invisible factors, which might also contribute to the surface roughness. The experimental set-up is shown in Fig. 2. 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 soda lime glass 80 x 50 x 25 mm is selected as a case study. The glass chemical composition and mechanical properties are shown in Tables III and IV, respectively. And, Fig. 3 shows the workpiece and the tool paths used in the cutting tests. The tool moves in +X direction to cut 30 mm stroke with a fixed axial depth of cut. The tool type used in the glass milling operation is an internal CBN grinding tool. The tool diameter is 4.5 mm with a # 150 grit size. To investigate the surface roughness in both normal and high-speed modes, an attachable high-speed spindle (HSS) unit (Model NSK HES510 BT40) with 50,000 min^{-1} maximum rotational speed is attached to the machine spindle using a built-in rigid holder to maintain the machining accuracy. To measure the machined workpiece surface roughness R_a, a portable surface meter (Mitutoyo SJ-201P) was used with a cut off distance of 700µm. Finally, the lubricant system was used to control the cutting temperature and to reduce the friction between the tool and workpiece. The Shell Dromus BL lubricant type has been selected since it has a good lubrication quality characteristic. The properties of the lubricant used are shown in Table V.



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 III
SODA-LIME GLASS CHEMICAL COMPOSITION [1]

Chemical composition	Weight %
SiO_2	73
Na_2O	14
CaO	9
Al_2O_3	0.15
K_2O	0.03
MgO	4
TiO_2	0.02
Fe_2O_3	0.1

TABLE IV
SODA-LIME GLASS MECHANICAL PROPERTIES [1]

Properties	Value
Density at 20°C, g/cm^3	2.53
Refractive index nD at 20°C	1.52
Young's modulus at 20°C, Gpa	74
Liquidus temperature, °C	1000
Thermal Conductivity,W/m.K	0.9-1.3
Hardness (Mohs Scale)	6–7
Knoop Hardness,kg/mm^2 + 20	585

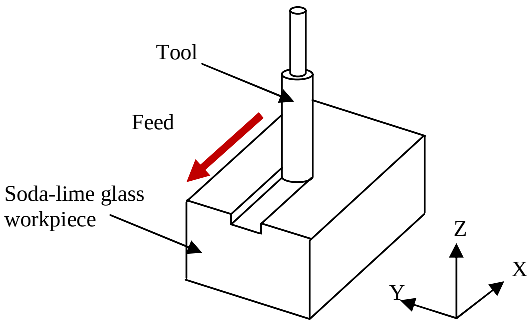


Fig. 3 The workpiece and tool paths

TABLE V
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 x 10^{-5} m^2 / s (kinematics viscosity)

IV. EXPERIMENTAL RESULT

The experimental tests are carried out using the proposed experimental set-up. The measured values of surface roughness are summarized in Table VI. Figure 4 shows an example of the measured surface roughness at 0.8 MPa lubrication pressure, 20,000 min^{-1} spindle speed, 0.25 mm/min feed rate, and 1 mm axial depth of cut.

TABLE VI
THE MEASURED SURFACE ROUGHNESS

Exp No.	Measured Surface Roughness, Ra (µm)
1	0.52
2	0.60
3	0.85
4	1.02
5	0.84
6	1.08
7	0.74
8	0.87
9	1.14
10	0.73
11	0.91
12	0.56
13	0.73

Fig. 4 An example of measured surface roughness at 0.8Mpa lubrication pressure, 20,000min^{-1} spindle speed, 0.25 mm/min feed rate and 1mm axial depth of cut

V. FUZZY LOGIC BASED MODEL TO PREDICT SURFACE ROUGHNESS

The relationship between input parameters which are the lubrication pressure, spindle speed, feed rate and depth of cut with the output parameter which is surface roughness of a machined surface in glass milling operation were referred to construct the rules. Fuzzy linguistic variables and fuzzy expression for input and output parameters are shown in Table VII. For each input variable, four membership functions were used which are Low, Medium, High, and Very High. The output variable (roughness) also used four membership functions; Best, Good, Average and Bad. The characteristics of the Inputs and Output variables are shown in Table VII.

A. Membership Functions for Input and Output Fuzzy Variables

In choosing the membership functions for fuzzification, the event and type of membership functions are mainly dependent upon the relevant event [20]. In this model, each input and output parameter has four membership functions. Gauss shape of membership function is employed to describe the fuzzy sets for input variables. In output variables fuzzy set, triangular shape of membership functions are used. Triangular membership function is generally used and possesses gradually increasing and decreasing characteristics with only one definite value [20]. The input variables have been partitioned according to the experiment parameter ranges. Membership functions for fuzzy set input variables are shown in Figs.5 a, b, c, and d respectively. Moreover, Fig.6 shows the membership functions for the output surface roughness fuzzy set.

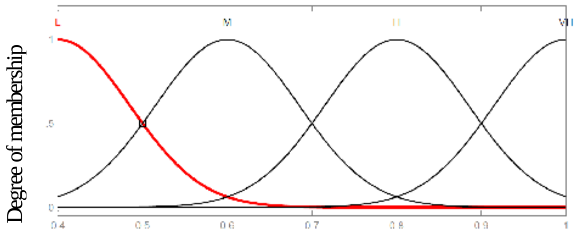
TABLE VII
FUZZY LINGUISTIC AND ABBREVIATION OF VARIABLES FOR EACH PARAMETER

Inputs		Range
Parameters	Linguistic variables	
A- Lubrication pressure(MPa)	Low (L), medium (M), high (H), very high (VH)	0.4-1.0
B- Spindle speed (min^{-1})		5,000-20,000
C- Feed rate (mm/min)		0.5-2
D- Depth of cut (mm)		0.25-1
Output		
Roughness (μm)	Best, Good, Average, Bad	0.52-1.14

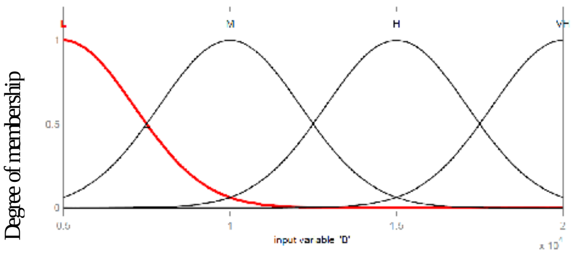
B. Structure of Fuzzy Rules

A set of 13 rules have been constructed based on the actual experimental surface roughness of a machined surface in glass milling operation using CBN grinding tool. Experimental results were simulated in the Matlab software on the basis of Mamdani Fuzzy Logic which was as follow:

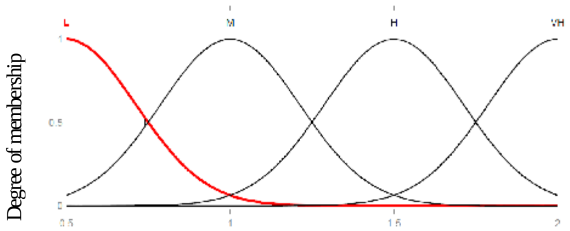
1. IF (A is L) and (B is L) and (C is L) and (D is L) then (Roughness is Best)
2. IF (A is L) and (B is M) and (C is M) and (D is M) then (Roughness is Best)
3. IF (A is L) and (B is H) and (C is H) and (D is H) then (Roughness is Average)
4. IF (A is L) and (B is VH) and (C is VH) and (D is VH) then (Roughness is Bad)
5. IF (A is M) and (B is L) and (C is M) and (D is H) then (Roughness is Average)
6. IF (A is M) and (B is M) and (C is L) and (D is VH) then (Roughness is Bad)
7. IF (A is M) and (B is H) and (C is VH) and (D is L) then (Roughness is Good)
8. IF (A is H) and (B is L) and (C is H) and (D is VH) then (Roughness is Average)
9. IF (A is H) and (B is M) and (C is VH) and (D is H) then (Roughness is Bad)
10. IF (A is H) and (B is H) and (C is L) and (D is M) then (Roughness is Good)
11. IF (A is VH) and (B is L) and (C is VH) and (D is M) then (Roughness is Average)
12. IF (A is VH) and (B is M) and (C is H) and (D is L) then (Roughness is Best)
13. IF (A is VH) and (B is H) and (C is M) and (D is VH) then (Roughness is Good)



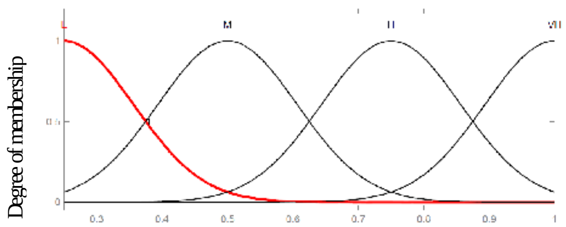
(a) Input variable "A"



(b) Input variable "B"

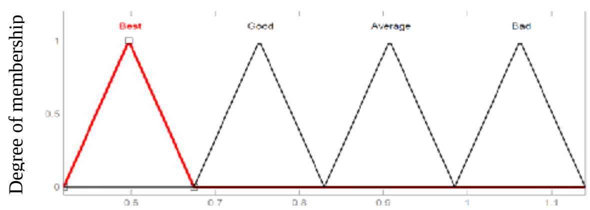


Input variable "C"



Input variable "D"

Fig. 5 Membership function for variables of inputs



Output variable "surface roughness"

Fig. 6 Membership function for the output variable of surface roughness

C. Defuzzification

Defuzzification is the conversion of a fuzzy quantity to a precise value, just as fuzzification is the conversion of a precise value to a fuzzy quantity [20]. Seven methods are available in literatures to be used by researchers for defuzzifying methods which include centroid, weight average, mean of max, center of sum, center of largest area, first (or last) of maximum method. The selection of the method is important and it greatly influences the speed and accuracy of the model. In this model, centroid of area (COA) defuzzification method is used due to its wide acceptance and capability in giving more accurate result compared to the other methods [21-22]. In this method, the resultant membership functions are developed by considering the union of the output of each rule, which means that the overlapping area of fuzzy output set is counted as one, providing more result [23-24]. Figure 7 shows the graphical representation of center of area defuzzification method. The shape refers to the remaining area of active fuzzy sets that are controlled by the related fuzzy rules.

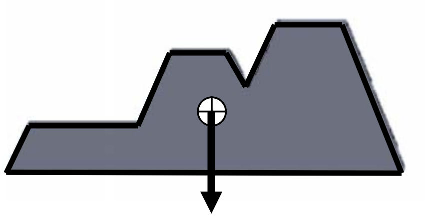
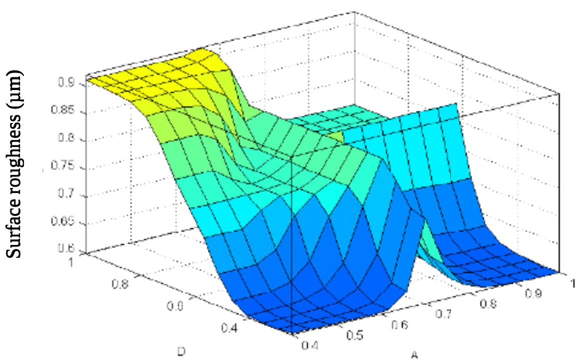
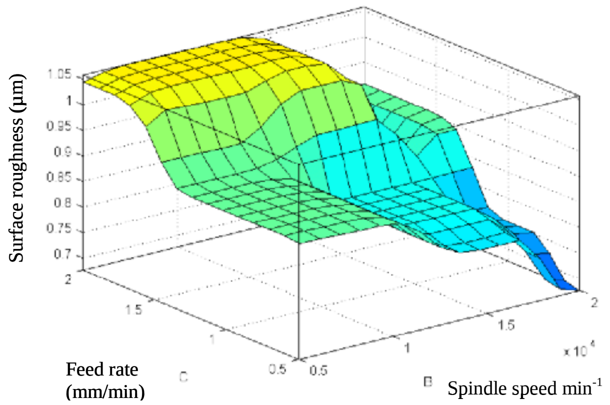


Fig. 7 Graphical of Centroid Area Method

Figure 8 (a) and (b) are examples to show the relation between input parameters change and surface roughness of a machined surface in glass milling operation predicted by fuzzy based model. As can be seen in Figs. 8 (a), the surface roughness is significantly increased with the increasing of the depth of cut while the lubricant pressure parameter change is not very significant. From the Fig. 8 (b), it is clearly seen that both of the feed rate and spindle speed parameters are very significant to change the surface roughness. The higher spindle speed and feed rate will produce the lower surface roughness.



(a) Surface roughness in relation to change of depth of cut and lubrication pressure



(b) Surface roughness in relation to change of feed rate and spindle speed

Fig. 8 The predicted surface roughness by fuzzy logic in relation to machining parameters

VI. Investigate the Fuzzy Model Accuracy and Error

Constructing the fuzzy rules, other new four experimental tests from separated experiment were carried out while the proposed fuzzy model is used to predict the surface roughness at the same conditions to investigating the fuzzy model accuracy and error as shown in Table VIII. 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].

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

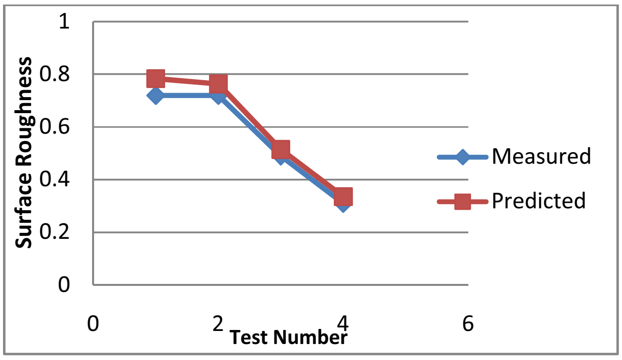
TABLE VIII
The Accuracy and Error of the Fuzzy Logic Model Prediction

No of Exp.	Parameters (Inputs)				Surface roughness (output) (µm)		Error %	Accuracy %
	A	B	C	D	Measured surface roughness	Predicted surface roughness (Fuzzy)		
1	2	4	3	2	0.72	0.783	8.75	91.25
2	3	4	2	1	0.72	0.763	5.98	94.11
3	4	4	1	3	0.49	0.514	4.89	95.11
4	4	4	1	1	0.31	0.335	8.06	91.94

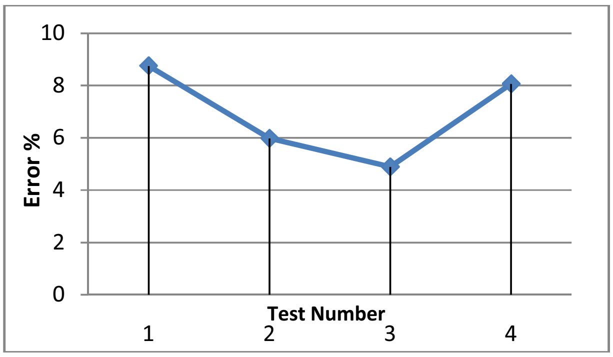
Meanwhile, accuracy is calculated to measure the closeness of the predicted value to the measured value. The model accuracy is the average of individual accuracy as shown in Equation (2) where A is the model accuracy and N is the total number of data set tested.

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

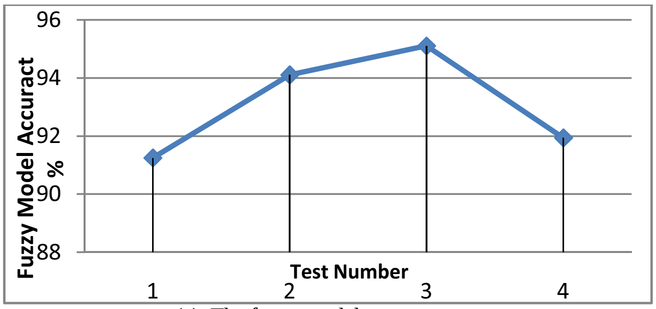
The error for dataset result was calculated and the model accuracy for fuzzy logic was determined. The experimental condition, surface roughness results, and fuzzy model predicted value are shown in Table VIII. The highest percentage of error for fuzzy model prediction is 8.75%. The low level of errors shows that the fuzzy predicted surface roughness results were very close with actual experimental surface roughness values. Table VIII also shows that the average of fuzzy model accuracy is 93.103%. The value of accuracy shows that the proposed model can predict the surface roughness of a machined surface in glass milling operation using CBN grinding tool satisfactorily as it can be seen in Fig 9 (a), (b), and (c). The close assent of surface roughness values obviously display that fuzzy logic model can be used to predict surface roughness in glass milling operation. Thus the proposed fuzzy logic model gives promising solution to predict roughness value in the specific range of parameters.



(a) Comparison of Measured and predicted results



(b) The fuzzy model error percentage



(c) The fuzzy model accuracy

Fig. 9 Comparison of the predicted and measured surface roughness of a machined surface, the fuzzy model accuracy and error percentage

VII. Discussion

In this study, a fuzzy logic based model to predict surface roughness machined surface in glass milling operation using CBN grinding tool has been implemented. The result demonstrated settlement between the fuzzy model and experimental results with the 93.103% accuracy. The close agreement of roughness values of machined surface clearly indicates that the fuzzy model can be used to predict the roughness of machined surface within the range of input parameters under consideration.

On the other hand, as can be seen in Figs. 8 (a) and (b), the axial depth of cut, feed rate and spindle speed are found to be significant parameters affecting the surface roughness, while the lubrication pressure has a less significant effect. For better surface roughness, the recommended settings are the lowest values of the depth of cut and feed rate and the highest values of the lubrication pressure and spindle speed. Furthermore, it was noted that, the interactions of the factors produce a significant impact on the surface roughness. This is because the combination of feed rate and depth of cut determines the undeformed chip section and hence influences the amount of cutting forces required to remove a specified volume of material. The greater the feed rate and depth of cut the larger the cross-sectional area of the uncut chip and the volume of the deformed workpiece. Consequently, instantaneous fracture of the glass workpiece if the cutting tool at high cutting force is severely damaged [15].

Another possible reason is given by Ghani et al. [10] that, 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. 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 glass, would significantly affect the chip formation mode, cutting forces, tool life, and surface quality.

For controlling of machining process in future, the knowledge of surface roughness as a function of machined surface quality is an essential requirement. It is not economical to conduct surface quality test for different factors combinations. The experiments consume a lot of time and may not be sufficient for online controls. A scheme can be developed that can carry out the control with online learning. The approach would be helpful for predicting process parameters in real time machining environment economically.

VIII. Conclusion

In this study, a fuzzy logic based model has been established to predict surface roughness of machined surface in glass milling operation using CBN grinding tool. This research work is contributing to the enhancement of machined surface quality of glass material particularly in mould making industries which require high accuracy of component dimension. Four membership functions are allocated to be connected with each input of the model. The predicted results achieved via fuzzy logic model are compared to the experimental result. The result demonstrated settlement between the fuzzy model and experimental results with the 93.103% accuracy.

Acknowledgement

The authors also acknowledge the financial support under the Fundamental Research Grant FRGS/2/2010/TK/UM/03/2 from the Ministry of Higher Education, Malaysia

References

[1] L, B.E., Glass: Mechanics and Technology. 2007: Wiley-VCH.
[2] R, D. and N. Y, Handbook of semiconductor manufacturing technology. 2007: CRC Press.
[3] L, Y. and H. H, Brittle materials in nano-abrasive fabrication of optical mirror-surface. Precision Engineering, 2008. 32: p. 336 - 341.
[4] W, Z.Z. and L.W. Y, Grinding of silicone and glass using a new dressing device and an improved lubrication system. Journal of Material and Manufacturing Processes, 2001. 16(4): p. 471-482.
[5] B, Z., Helical scan grinding of brittle and ductile materials. Journal of Materials Processing Technology, 1999. 91: p. 196-205.
[6] H, T.Y., C.J. C, and L.S. J, In-process surface recognition system based on neural networks in end milling cutting operations. Int. J. Mach. Tool Manuf., 1999. 39(4): p. 583-605.
[7] M, G., P. B, Coutris N, C.B. A, F. C, P. P, T.D. W, and B.K. D, A simple ballistic material model for soda-lime glass. International Journal of Impact Engineering, 2009. 36: p. 386-401.
[8] W, Z.Z., Surface finish of precision machined advanced materials. Journal of Material Processing Technology, 2002. 122: p. 173-178.
[9] Sayuti, M., Ahmed A.D. Sarhan, M. Fadzil, and M. Hamdi, Enhancement and verification of a machined surface quality for glass milling operation-using CBN grinding tool- Taguchi approach. International Journal of Advanced Manufacturing Technology, 2011.
[10] Zhang, J.Z., J.C. Chen, and E.D. Kirby, Surface roughness optimization in an end-milling operation using the Taguchi design method. Journal of Materials Processing Technology, 2007. 184(1–3): p. 233-239.
[11] Ghani, J.A., I.A. Choudhury, and H.H. Hassan, Application of Taguchi method in the optimization of end milling parameters. Journal of Materials Processing Technology, 2004. 145(1): p. 84-92.
[12] Zalnezhad, E., Ahmed A.D. Sarhan, and M. Hamdi, Optimizing the PVD TiN Thin Film Coating's parameters on Aerospace AL7075-T6 Alloy for Higher Coating Hardness and Adhesion with Better Tribological Properties of the Coating Surface. International Journal of Advanced Manufacturing Technology.
[13] Sayuti, M., Ahmed A.D. Sarhan, and M. Hamdi, Optimizing the Machining Parameters in Glass Grinding Operation on the CNC Milling Machine for Best Surface Roughness. Advance Material Research. , 2011. 154-155: p. 721-726.
[14] H, H., Machining characteristics and surface integrity of yytria stabilized tetragonal zirconia in high deep grinding. Material Science and Engineering, 2003. 345: p. 155 - 163.
[15] B, Y., S. X, and L. S, Mechanisms of edge chipping in laser-assisted milling of silicon nitride ceramics. International Journal of Machine Tools and Manufacture, 2009. 49: p. 344-350.
[16] Sarhan, A., R. Sayed, A.A. Nassr, and R.M. El-Zahry, Interrelationships between cutting force variation and tool wear in end-milling. Journal of Materials Processing Technology, 2001. 109: p. 229-235.
[17] Ahmed A.D. Sarhan, M.Sayuti, and M. Hamdi, Reduction of power and lubricant oil consumption in milling process using a new SiO2 nanolubrication system. International Journal of Advanced Manufacturing Technology, 2011 p. DOI: 10.1007/s00170-012-3940-7.
[18] Sonar, D.K., U.S. Dixit, and D.K. Ojha, The application of a radial basis function neural network for predicting the surface roughness in a turning process. The International Journal of Advanced Manufacturing Technology, 2006. 27(7): p. 661-666.
[19] 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.
[20] Jaya, A.S.M., S.Z.M. Hashim, and M.N.A. Rahman. Fuzzy logic-based for predicting roughness performance of TiAlN coating. in Intelligent Systems Design and Applications (ISDA), 2010 10th International Conference on. 2010.
[21] Leung, R.W.K., H.C.W. Lau, and C.K. Kwong, An expert system to support the optimization of ion plating process: an OLAP-based fuzzy-cum-GA approach. Expert Systems with Applications, 2003. 25(3): p. 313-330.
[22] Oktem, H., T. Erzurumlu, and F. Erzincanli, Prediction of minimum surface roughness in end milling mold parts using neural network and genetic algorithm. Materials & Design, 2006. 27(9): p. 735-744.
[23] Chandrasekaran, M., M. Muralidhar, C. Krishna, and U. Dixit, Application of soft computing techniques in machining performance prediction and optimization: a literature review. The International Journal of Advanced Manufacturing Technology, 2010. 46(5): p. 445-464.
[24] Hashmi, K., I.D. Graham, and B. Mills, Data selection for turning carbon steel using a fuzzy logic approach. Journal of Materials Processing Technology, 2003. 135(1): p. 44-58.