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Fuzzy Logic Modeling of Silicon Nitride (Si_3N_4) Laser Cutting

Pedram Parandoush, AltabHossain, NukmanYusoff, Abu Mohammed Sifullah, K M Anamul Hossain

Department of Mechanical Engineering, Faculty of Engineering, University of Malaya 50603 Kuala Lumpur, Malaysia

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ABSTRACT

This paper proposes a fuzzy logic modeling for the prediction of groove depth (GD) in silicon nitride (Si3N4) laser cutting. In any kind of laser cutting dimensional accuracy, kerf width and quality of surface finishing are the most desirable outcomes.The controllable process parameters are cutting speed, assist gas pressure and laser power. Generally, laser speed (LS) and laser power (LP) are the most important factors affecting in laser cutting especially for making deep grooves. Since, such factors act non-linearly and have mutual interactions; it is very complicated to construct a prediction model using precise mathematical models, statistical models or empirical models. Conversely, artificial neural network is trained using vast amounts of experimental data, which is also a time consuming process. On the other hand Fuzzy Logic (FL) approach is a capable modeling tool which performs in a non-linear complex field with least trial data. The results from the fuzzy logic model are compared with referenced experimental data. The prediction model was found to be valid by correlation analysis. In this research, we used laser source as continues mode (CW) which moved at a constant velocity. Silicon Nitride (Si3N4) was considered as work piece, which is a chemical compound of the elements silicon and nitrogen.It is white in color, high-melting-point solid that is relatively chemically inert and it has extensive applications for machining purposes in automotive, semi-conductor and aerospace industries for its high toughness relative to other ceramics. In this research, we employed the Fuzzy Logic prediction model has been validated by comparing and analyzing the actual experimental data of Roy & Modest, 1993 and predicted values of groove depth with respect to the laser beam velocity and power. Furthermore the developed fuzzy prediction model will be an essential operational guideline for manufacturing engineer in decision making and adjusting process parameters in laser cutting of silicon nitride.

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INTRODUCTION

Laser means light amplification by stimulated emission of radiation,which is a device works on the basis of quantum mechanics. In laser making the light amplification is achieved by stimulated emission due to the incident photons of high energy. Practically laser is formed accumulating three principle elements. Firstly lasing medium, secondly-exciting the laser medium into it's amplifying state and thirdly-optical delivery/feedback. The medium of laser may be a solid (eg. Nd:YAG or neodymium doped yttrium-aluminum-garnet), liquid (dye) of gas (e.g. CO2, He, Ne) (Majumdar and Manna, 2003)

Laser beam machining/cutting is one of Advanced Manufacturing Processes (AMP)that can machine almost all engineering materials. As laser machining works thermally and there is no direct contract with work piece so it can process the metallic alloys to non-metals as well as composites of metallic and non-metallic material. Laser Beam Machining (LBM) could overcome the difficulties in machining hard and brittle ceramics due to the thermal nature of the process.Thermal properties such as thermal conductivity and diffusivity playan important role in LBM rather than themechanical properties of the work piece as it was in conventional machining (Dubey and Yadava, 2008; Meijer, 2004; Kuar, Doloi, and Bhattacharyya,2006). Silicon nitride has extensive applications in automotive, semi-conductor and aerospace industries and has high toughness relative to other ceramics. Cams, bearings, piston rings and rocker arms can be produced by machining silicon nitride.

Modeling and simulation of the laser cutting processare indispensable for any of its applications to have a good prediction of quality characteristics. Various techniques could be implemented in order to predict the

Corresponding Author: Dr. Md. Altab Hossain, Department of Mechanical Engineering Faculty of Engineering, University of Malaya (UM)
E-mail: altab75@um.edu.my

characteristics such as: analytical and numerical methods as well as artificial intelligence (AI) methods(Samant and Dahotre, 2009).

By using Expert systems one can able to overcome the non-linearity of the laser cutting process in a simple manner at low computational costs. Fuzzylogic (FL) approach has been proven to be the most successful methodology in variousresearch investigations. To overcome the difficulties in non-linear analyzing fuzzy logicuses the mathematical tools which is conventional and is able to model indefinite parameters (Pandey and Dubey, 2013). Pandey and Dubey consideredthe theory of fuzzy logic for laser cutting. They used Duralumin sheet as a work piece and developed a model based on FL for reducing the kerf width and deviations at top and bottom sides(Pandey and Dubey, 2012). They have indicated in laser cutting gas pressure is one of the major factors. Specially during laser cutting of thermal conductive material such as Duralumin which is highly reflective. Syn, Mokhtar, Feng, and Manurung proposed separatefuzzy logic model to forecast the parameters of surface roughness and dross inclusion.They used LVD Helius-2513 CO2 laser machine for incolon alloy 800 as work piece.During the experiment they considered03 (three) input parameters: (a) laser beam power, (b) assist gas pressure and (c) cutting speed. (Syn, Mokhtar, Feng and Manurung, 2011). Pandey and Dubey developed a fuzzy expert logicto forecast the kerf widths and kerf deviation in laser cutting. They used titanium alloy sheets with pulsed laser (Pandey and Dubey,2013). Pandey and Dubey implemented grey–fuzzy methodology for simultaneous optimization of multiple performances such as cut edge, surface roughness, kerf taper and kerf width (Pandey and Dubey, 2013). Therefore, the main objective of this work is to develop a fuzzy logic model based on mamdani approach for the prediction of groove depthin laser cutting of silicon nitride with respect to the laser beam velocity and power. Moreover, this fuzzy prediction model can be a useful tool for manufacturing engineers in decision making and adjusting process parameters in laser cutting of silicon nitride.

MATERIALS AND METHODS

Methodology:

In the present study results of a validated three-dimensional Finite Element Model (FEM) developed in an ongoing research has been used for developing the fuzzy expert system able to predict groove depths achieved in the laser cutting process of silicon nitride. The considered input variables are laser power (LP) and laser speed (LS) and workpiece material is hot pressed Si_3N_4. The laser source is in continues mode (CW) which moves at a constant velocity.

Development of Fuzzy Prediction Model:

Fuzzy expert systems (FES) commonly consist of four principal components: 1) fuzzification interfaces: linguistic variables (input & outputs) are fuzzified by assigning various membership functions through various fuzzy principles, 2) knowledge base: consists ofrule base where fuzzy rule base is designed in a form of “IF and THEN” which relate input and outputs variables, 3) decision making logic, and 4) defuzzification interface.

Decision making logic:

It is a key process in a fuzzy logic model due to its ability to perform human decision making and deduce fuzzy control actions. Basically, each rule has to be evaluated through implication process and Mamdani type fuzzy model is a simple and most widely used fuzzy system (Pandey and Dubey, 2013) which consider minimum membership of fuzzy sets in the following form

$$\mu_{AB(x,y)} = min\left[\mu_{A(x)}, \mu_{B(y)}\right] \quad (1)$$

The analyze of implication results is the next step which is done through aggregation process where the output of each rule aggregate into a single fuzzy set in the following form

$$\mu_{A(x)} = \mu_{A(x1)} + \mu_{A(x2)} + \mu_{A(x3)} + ... + \mu_{A(xn)} \quad (2)$$

Defuzzification Interface: The obtained output result is in fuzzy form and requires defuzzification. Centroid method is the most popular for this purpose and can be expressed as follows:

$$y = \frac{\sum x^* \mu_{A(x)}}{\sum \mu_{A(x)}} \quad (3)$$

where y is the crisp value of the output and $x^*$is the position of the singleton in the respective universe (Passino and Yurkovich, 1998).

Application of Fuzzy Logic System:

For the implementation of fuzzy set theory into the models, fuzzy inference mechanism of the current study has been shown in Fig. 1.

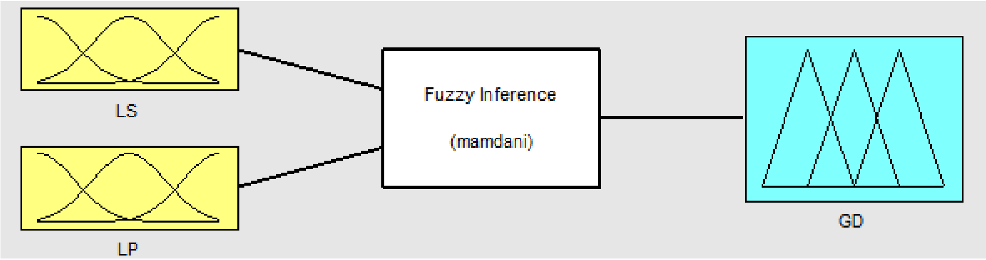

Fig. 1: Fuzzy inference mechanism.

In the present study two laser cutting parameters namely laser speed (LS), laser power (LP) were used as input variables and groove depth (GD) as output variable. The units of parameters are: LS (cm/s), LP (W), and GD (microns). For fuzzification, the input variable LP and LS were given six and four possible linguistic variables, respectively. For output variable GD, eight linguistic variables were considered. More linguistic variables in outputs are because of achieving more precision with small changes in input variables. For the input and output variables, a fuzzy associated memory was created as regulation rules based on expert knowledge, and previous experience. There is a range of membership for each linguistic word that applies to that input variable. Fuzzification of the used parameters has been made by aid of follows functions.

$$LP(i_1) = \begin{Bmatrix} i_1; & 50 \le i_1 \le 1500 \\ 0; & otherwise \end{Bmatrix} \quad (4)$$

$$LS(i_2) = \begin{Bmatrix} i_2; & 2.5 \le i_2 \le 22.5 \\ 0; & otherwise \end{Bmatrix} \quad (5)$$

$$GD(o_1) = \begin{Bmatrix} o_1; & 0 \le o_1 \le 700 \\ 0; & otherwise \end{Bmatrix} \quad (6)$$

where i_1 and i_2 are input variables, and o_1 is the output variable. Using MATLAB FUZZY Toolbox the membership values obtained from the above formula are shown in Figs. 2-3.

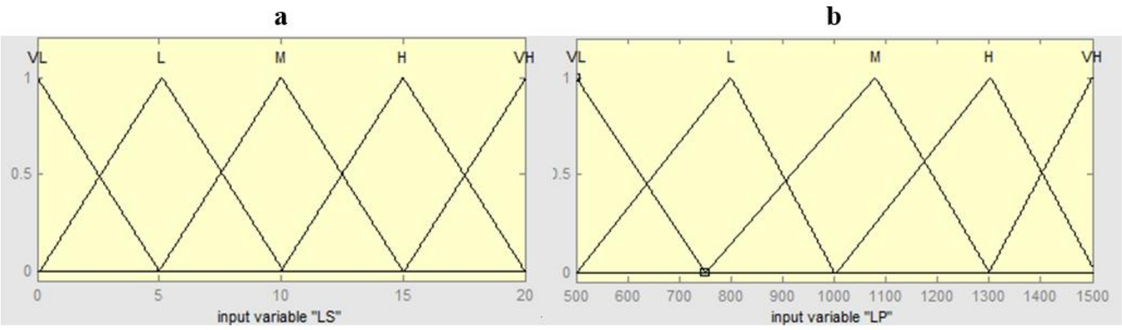

Fig. 2: Membership functions of input variables a) LS and b) LP.

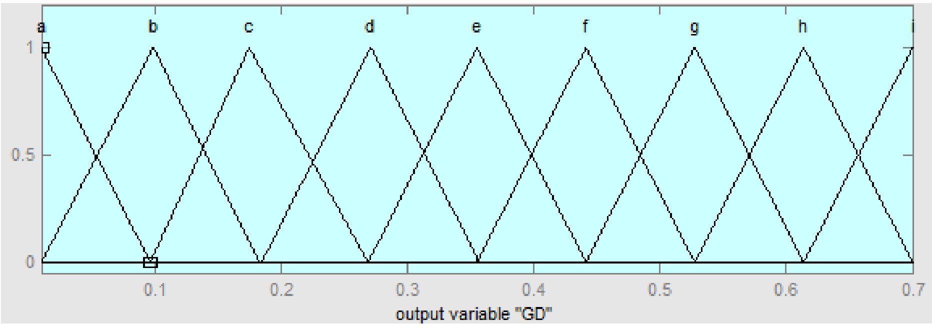

Fig. 3. Membership functions of output variable GD.

To illustrate fuzzification process, linguistic expressions and membership functions of laser power (LP) and laser speed (LS) for Medium and Low range obtained from the developed rules and above formula (Eq. 4-6) are presented as follows:

$$\mu_M(LP)=\begin{cases}\dfrac{i_1-110}{507-110}; & 110\le i_1\le 507\\ \dfrac{1100-i_1}{1100-507}; & 507\le i_1\le 1100\\ 0; & i_1\ge 1100\end{cases} \quad (7)$$

$$\mu_L(LS)=\begin{cases}\dfrac{i_2-2.5}{9-2.5}; & 2.5\le i_2\le 9\\ \dfrac{16-i_2}{16-9}; & 9\le i_2\le 16\\ 0; & i_2\ge 16\end{cases} \quad (8)$$

Statistical methods for comparison:

Mathematical andstatistical methods have been used to investigate the accuracy of the prediction ability. Relative error (ε) of formation has been established using following formula:

$$\varepsilon=\sum_{i=1}^{n}\left|\frac{y_i-\hat{y}_i}{y_i}\right|\frac{100\,\%}{n} \quad (9)$$

Goodness of fit (η) of the predicted system is calculated as follows:

$$\eta=\sqrt{1-\frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{\sum_{i=1}^{n}(y_i-\bar{y}_i)^2}} \quad (10)$$

where n is the number of observation, y_i is the actual value, $\hat{y}_i$ is the predicted value and $\bar{y}_i$ is the mean of actual value.

RESULT AND DISCUSSIONS

After calibration of numerical model for deep grooves, the results have been used to develop the fuzzy expert system in order to overcome the error caused by neglecting multiple reflections. Figure 5 shows the graphical and control surface of the developed fuzzy expert system. In the control surface, it can be seen that with lower laser speeds and higher laser powers, deeper grooves can be machined.

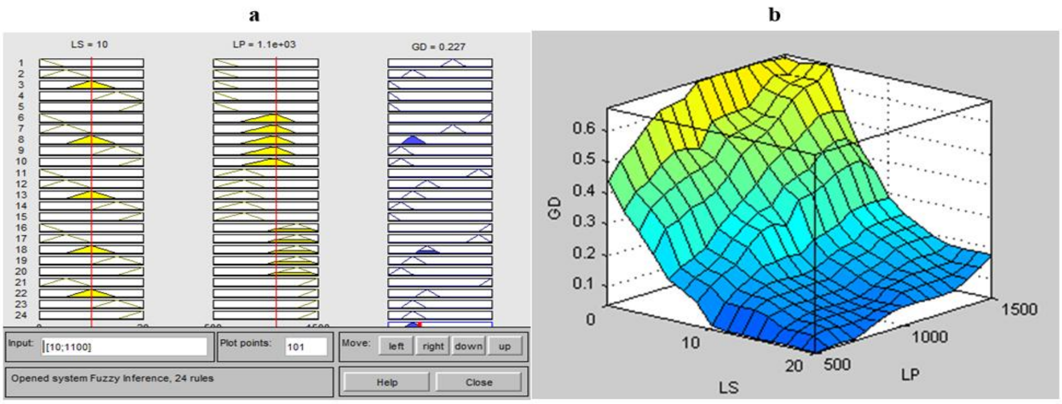

Fig. 5: a) Graphical operation of the fuzzy prediction model b) Control surfaces of the fuzzy inferring system

The Fuzzy Logic prediction model has been validated by comparing and analyzing the actual and predicted values of groove depth using experimental data of Roy & Modest (Roy and Modest, 1993). The goodness of fit was found as 0.991 (R^2 = 0.985). Thus, it can be concluded that the developed fuzzy prediction model can explain up to 98.5% of the total variability of groove depths. The mean relative error of predicted values for GD in FES model was found to be 4.714 %, which is less than the acceptable limits of 5%. The relative error gives the deviation between the predicted and experimental values and it is required to reach towards zero. The results indicate very strong prediction accuracy of the developed expert system. Consequently, the FES model can predict the groove depth with low computational cost and decreased error without considering the complex phenomena of multiple reflections in the calculation.

Conclusion:

In the presented research, a fuzzy logic approach has been proposed to solve the problem with low computational cost. In this study, according to evaluation criterions of predicted performance of the developed fuzzy logic expert system model has been found to be valid. However, the conclusions drawn from this study are as follows:

(a) The correlation coefficient was found as 0.985.

(b) The mean relative error of measured and predicted values from the FES model was found as 4.71% which is less than the acceptable limits of 10%.

(c) The goodness of fit of the prediction values from the FES model was found as 0.991 which is closed to 1.0 as expected.

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