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Mamdani-Fuzzy Modeling Approach for Quality Prediction of Non-Linear Laser Lathing Process

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Abstract. Lathing is a process to fashioning stock materials into desired cylindrical shapes which usually performed by traditional lathe machine. But, the recent rapid advancements in engineering materials and precision demand gives a great challenge to the traditional method. The main drawback of conventional lathe is its mechanical contact which brings to the undesirable tool wear, heat affected zone, finishing, and dimensional accuracy especially taper quality in machining of stock with high length to diameter ratio. Therefore, a novel approach has been devised to investigate in transforming a 2D flatbed CO2 laser cutting machine into 3D laser lathing capability as an alternative solution. Three significant design parameters were selected for this experiment, namely cutting speed, spinning speed, and depth of cut. Total of 24 experiments were performed with eight (8) sequential runs where they were then replicated three (3) times. The experimental results were then used to establish Mamdani - Fuzzy predictive model where it yields the accuracy of more than 95%. Thus, the proposed Mamdani - Fuzzy modeling approach is found very much suitable and practical for quality prediction of non-linear laser lathing process for cylindrical stocks of 10mm diameter.

1. Introduction

Among others, the most commonly used lasers in industries are Carbon Dioxide (CO₂) and Neodymium-Doped Yttrium Aluminum Garnet (Nd:Y₃Al₅O₁₂). The CO₂ laser is the most versatile type and widely used in materials processing. Laser cutting, being the non-contact with very narrow heat affected zone is capable of processing most engineering materials with a high degree of precision and accuracy [1].

The ability of laser in processing intricate profiles, quick setup and low cost of production makes it most preferable in sheet metal cutting industry. Over 40% medium scale manufacturers use laser as processing process mainly in cutting industries such as producing one dimensional features turbine blade, combustion chambers and aerosol nozzles [2,3]. With great advantages of laser cutting machine, the common problem faced by conventional lathe can be overcome especially deflection on workpiece while turning cylindrical parts with high length to diameter ratio which would cause undesirable taper on end product.

Thus, in order to have a better control of the taper on a cylindrical part, laser is found to be most suitable as it processes the materials without having any mechanical contact between the laser beam (virtual tool) and the spinning work. So to understand the behavior and scientific reasoning behind the actual processing phenomenon, an expert system called Mamdani-Fuzzy is seen to be suiting best in modeling the environment to predict the response. The modeling process considering expert knowledge combined with the commercially available Artificial intelligence solution [4] & modeling is one of the scientific study which gives us a clear yet brief understanding about the research atmosphere [5]. First



attempt to establish a theoretical model for laser 'blind' cutting was conceptualized by using two intersecting beams which was then optimized successfully [6]. On the other hand, the performance of material removal rate (MRR), tool wear rate (TWR), overcut and taper of micro-hole during machining of D3 die steel was model using fuzzy logic [7]. In another experiment of laser cutting, a model of fuzzy logic was develop to minimize the kerf width and deviations at top and bottom sides of duralumin [8].

Fuzzy rule based modeling has also been implement for prediction of flank wear, surface roughness and specific cutting pressure in turning of titanium alloy where results showed that the model is very effective [9]. Besides that [19] proposed neural network approach to predict the behavior of the material removal process during laser machining. They also investigate and analyze the effect of laser power and grooving speed on groove shape using response surface methodology [20]. While in the other hand, the micro-grooving operation on Al₂TiO₅ also presents using artificial neural network (ANN) and response surface methodology (RSM) [21].

2. Experiment details

As to validate the performance of 3D laser lathe using modified 2D flat cutting machine, with a tangential insertion of laser beam and spinning workpiece has been precisely setup on the sacrificial table. The details of CO₂ laser machine specification are shown in Table 1, while the experimental setup is shown in Figure 1. Throughout these experimentations, constant and variable processing parameters were identified.

Table 1. CO₂ Laser Machine Specification

Machine	Specification
Manufacturer	LVD, Belgium
Model	Helius-2513
Brand	LVD Helius
Envelope	2500x1250 mm
Maximum speed	250 mm/s
Maximum laser power	3 kW

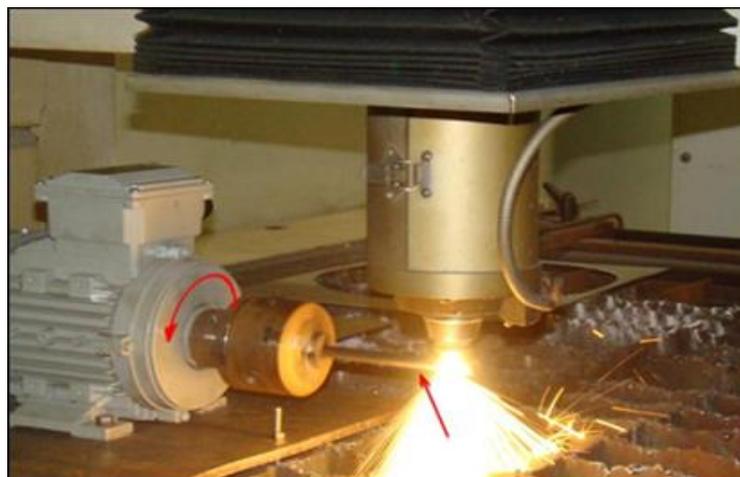


Figure 1. Laser lathing of SS400 steel

Table 2 shows the design parameters namely laser cutting speed (V), work spinning speed (N) and depth of cut (d) which were varied through-out the experiments while Table 3 presents the laser process parameters which were kept constant. Each variable was set into two levels, low and high. The observed responses are tabulated in Table 4.

Table 2. Design parameters

Factors	Levels		
	Unit	Low	High
Laser cutting Speed (V)	mm/min	510	680
Work spinning speed (N)	rpm	1000	1500
Depth of Cut (d)	mm	1	1.5

The performance of laser machining plays an important role in producing reliable quality measures. Taper is the utmost critical quality to be observed when it comes to the machining of cylindrical parts especially when it is long but small in diameter, which is often called high length to diameter ratio. The taper quality observation of every processed part was measured using CNC Formtester MMQ44.

Table 3. Laser process parameters (constant)

Laser Processing	Value
Power	1800 Watt
Frequency	1800 Hz
Duty cycle	85%
Gas pressure	0.5 bar
Laser mode	Continuous wave (CW)
Stand-off distance	1 mm
Nozzle type	Cylindrical
Beam diameter	0.5 mm
Gas jet selection	O ₂
Focus lens type	Cylindrical
Focal distance	0
Nozzle diameter	1.2 mm

2.1 Mamdani - Fuzzy modeling

Modeling helps to understand the information requirements, minimize time and eliminate cost before starting a real experiment. Further, fuzzy logic can improve such classifications and decision support models by using fuzzy sets to define overlapping class definitions [18]. In this experiment, fuzzy logic was used to model the taper condition of non-linear laser machining environment. Fuzzy logic has become popular over the last decade because it can deal with imprecise inputs, does not need an accurate mathematical model and can handle nonlinearity [10].

Table 4. Observed responses

No. Exp.	Machining Parameters			Response
	V (mm/min)	N (rpm)	d (mm)	Taper (mm)
1	510	1000	1	0.040
2			1.5	0.011
3		1500	1	0.011
4			1.5	0.006
5	680	1000	1	0.006
6			1.5	0.005
7		1500	1	0.012
8			1.5	0.005

By using commercially available Matlab package, Mamdani-Fuzzy inference system was chosen for this study because of its simplicity and non-complex algorithms often used in solving many real world problems [5]. The basic definition of Mamdani system as shown in equation (1) is the training set contains n data pairs. Each pair is made of a p – dimensional input vector x and a q – dimensional output vector y . The number of rules in the FIS rule base is r . Therefore, the expression of Mamdani rule i in this system expressed by [11] is written as follow.

$$\begin{aligned} \text{If } x_1 \text{ is } A_1^i \text{ and } x_2 \text{ is } A_2^i \dots \text{ and } x_p \text{ is } A_p^i \\ \text{Then } y_1 \text{ is } c_1^i \dots \text{ and } y_q \text{ is } c_q^i \end{aligned} \quad (1)$$

Where, A_j^i and c_j^i are fuzzy sets that define an input and output. The first step in developing fuzzy model is to determine the input and output variables. According to [17], the process of mapping from a given set of input to an output is performed by using a fuzzy inference mechanism. There are three set of inputs namely, cutting speed, spinning speed and depth of cut, where taper is the response/output. The next step is determining the range of input and output variable. The range of input and output variables are based on low and high values of variable parameters and there after is to determine the types of membership function (MF) or known as fuzzification for input and output variables. Membership function is defines as input and output space value between 0 and 1 which mapped to a membership.

As mentioned by [12], Triangular membership function is used for the input and output as it possesses simplicity and precision in determining the value of the input and output parameters, where [13] has expressed the triangular membership function as shown in equation (2).

Triangle

$$(x : a, b, c) = \begin{cases} 0 & x > a \\ (x-a)/(b-a) & a \leq x \leq b \\ (c-x)/(c-b) & b \leq x \leq c \\ 0 & x > c \end{cases} \quad (2)$$

Where, the parameters $\{a, b, c\}$ with $a < b < c$ are the parameters of the linguistic values which determine the x coordinates of the three corners of the underlying triangular membership function and x is the range of the input parameters. The membership function of cutting speed (V), spinning speed (N), depth of cut (d) and taper are shown in Figure 2. Then after, membership function is determined,

the important step is developing inference rules or fuzzy rules. This rule is based on experimental result and expertise [9].

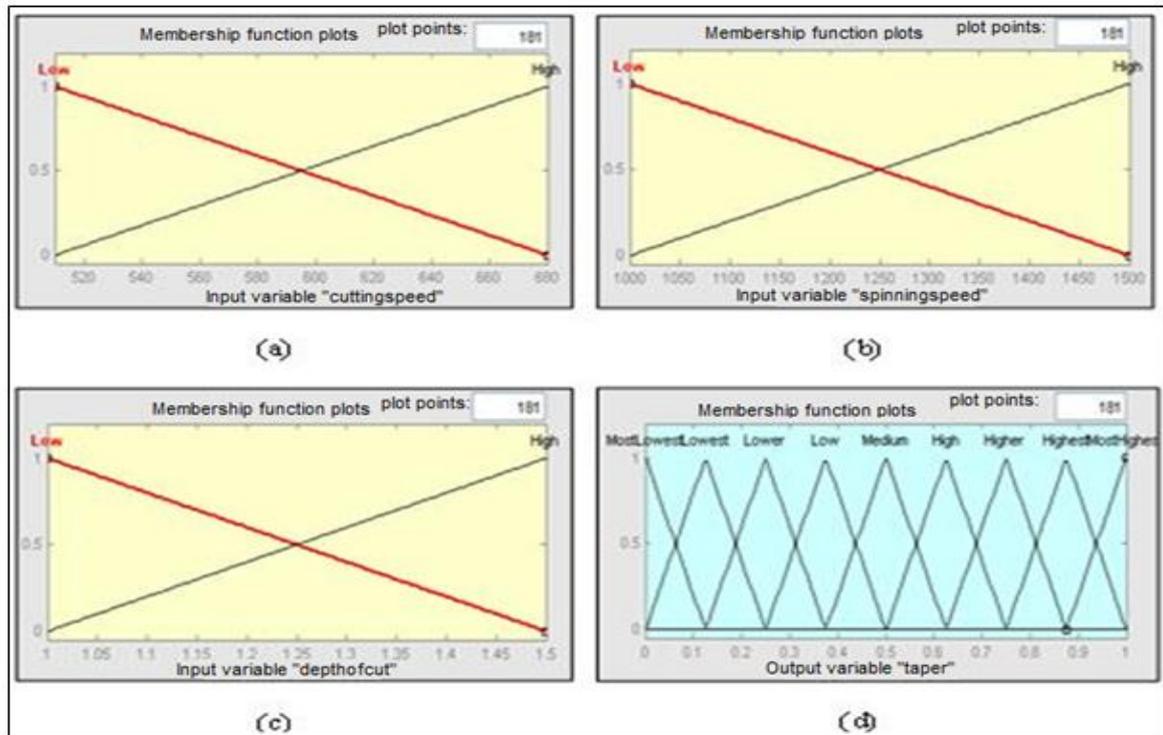


Figure 2. Input and output of fuzzification (a) Fuzzification of cutting speed, (b) Fuzzification of spinning speed, (c) Fuzzification of depth of cut, (d) Fuzzification of taper

Basically the rule is, If X is A then Y is B where, A and B are the linguistic values represented by the fuzzy sets [5]. A fuzzy logic implication statement of this form is called Fuzzy IF-THEN rules, where Fuzzy logic AND operation have been implemented in this work. As elaborated by [14] as shown in equation (3), let A_1, \dots, A_n , and B be fuzzy subsets with membership functions $\mu_{A_1}, \dots, \mu_{A_n}$, and μ_B , respectively and based on the general form fuzzy IF-THEN rule “IF a_1 is A_1 AND ... AND a_n is A_n THEN b is B .”

$$\mu_{A_1}(a_1) \wedge \dots \wedge \mu_{A_n}(a_n) \Rightarrow \mu_B(b) \tag{3}$$

Where,

$$\begin{aligned} \mu_{A_j}(a_j) \wedge \mu_{A_j}(a_j) &= \min\{\mu_{A_j}(a_j), \mu_{A_j}(a_j)\}, \\ 1 \leq i, j \leq n, \text{ and } , \text{ therefore,} \\ \mu_{A_1}(a_1) \wedge \dots \wedge \mu_{A_n}(a_n) &= \min\{\mu_{A_1}(a_1), \dots, \mu_{A_n}(a_n)\} \end{aligned}$$

The linguistic variables, low and high was used for cutting speed, spinning speed and depth of cut to represent the input numerical values. The output numerical values also represent in a similar way. Table 5 shows the fuzzy expressions of input and output parameters in numerical values. The end of developing fuzzy model, rule and surface viewer are automatically generated for analyzing.

3. Result and discussion

The rule viewer represents a roadmap of the whole fuzzy inference modeled for the non-linear laser process, where it shows crisp behavior in great detail [15]. Based on Figure 3, eight rows of rule viewer represent the rules and three columns represent the variable parameters of laser processing.

The four plots across the top represent the antecedent and consequent of the first rule. The defuzzified output represent the aggregate weighted decision for the given inference system.

Table 5. Fuzzy expression of input and output parameters

Rules	IF				THEN	
	V	Connection	N	Connection	d	Taper
1	L	and	L	and	L	ML
2	L	and	L	and	H	L
3	L	and	H	and	L	L
4	L	and	H	and	H	ML
5	H	and	L	and	L	ML
6	H	and	L	and	H	ML
7	H	and	H	and	L	L
8	H	and	H	and	H	ML

*L=Low, H=High, ML=Most Lowest, MH=Most Highest

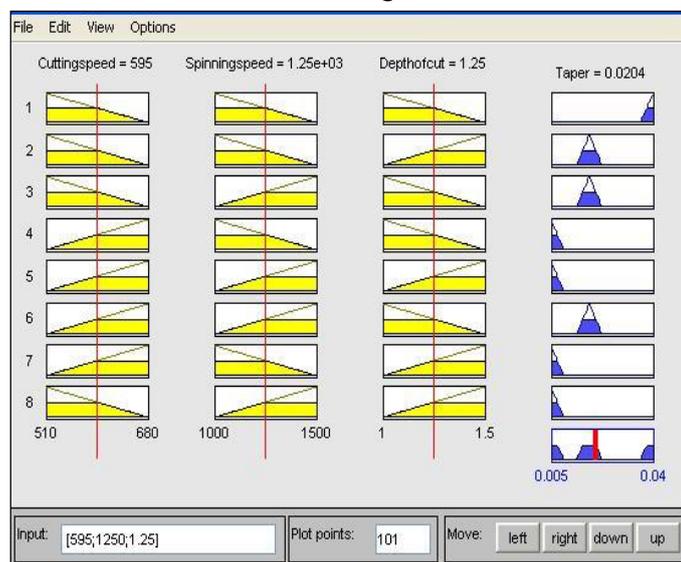


Figure 3. Rule viewer of developed fuzzy model

However the decision depends on input values for the system [12]. From the rule viewer, it was witnessed that the optimized values recommended by the Mamdani-Fuzzy are 595 mm/min for cutting speed, 1250 rpm for spinning speed, and 1.25 mm for depth of cut. On the other hand, the model's estimated response of taper was 0.0204 mm. In this model, centroid of area defuzzification method was used due to its wide acceptance and capability in giving more accurate results as compared to other

methods [16]. The relationship between prediction and experimental values is shown in Figure 4 which shows excellent correlation among experimental and predicted values with minimum error of below 3 percent. Table 6 presents the comparative values of experimental and model prediction for the entire. From the table, experiment number 4 and 8 shows zero deviation which indicate that experimental and model prediction are very close.

Table 6. Taper values of experimental vs. prediction

Expn. No.	Experimental	Prediction
1	0.04	0.039
2	0.011	0.018
3	0.011	0.018
4	0.006	0.006
5	0.005	0.006
6	0.012	0.018
7	0.005	0.006
8	0.006	0.006

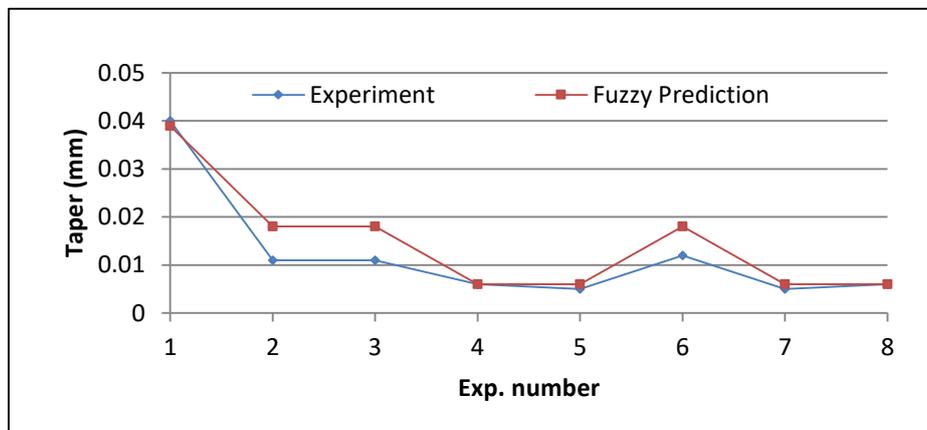


Figure 4. Comparison of prediction and experimental values

With a three-dimensional curve, the interaction between input variable and output response can be seen upon opening the surface viewer. Figure 5 shows the interaction of spinning speed and cutting speed out of taper response while Figure 6 shows the interaction between depth of cut and cutting speed. Based on surface model, the interaction between cutting speed and spinning speed shows that low cutting speed and low spinning speed will increase taper. This is because low cutting speed increase material removal rate and at the same time taper will affect. In another hand, low cutting speed and low depth of cut will also increase the taper. Again, low cutting speed increase taper which is shows that it's gives a significant effect on taper. However, moderate control of cutting speed shows taper values is quiet lower.

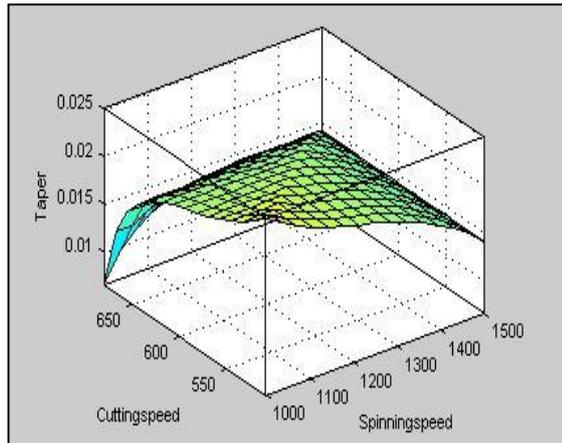


Figure 5. Interaction between cutting speed and spinning speed over taper

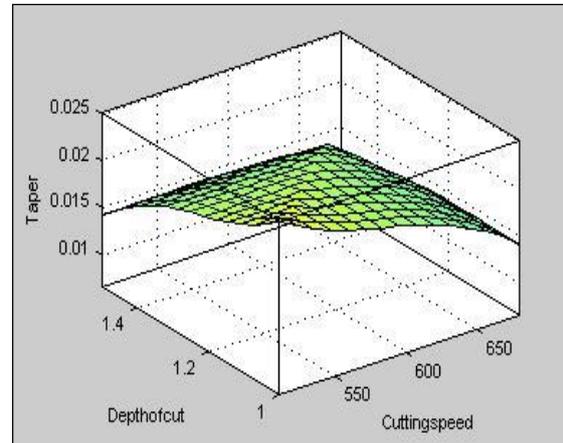


Figure 6. Interaction between cutting speed and depth of cut over taper

4. Conclusion

Prediction of taper has been done successfully and based on the model developed using Fuzzy Logic Tool Box MATLAB (R2013a), taper on the straight turning can be predicted. The results of taper prediction and experimental has been compared and it shows quite a good relationship. Therefore, fuzzy model can be used as a benchmark for selecting the input parameter before starting the real experiment.

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