Intelligent Modeling of Laser Cutting of Thin Sheet

Arun Kumar Pandey and Avanish Kumar Dubey

***Abstract*—Laser cutting being a complex cutting process needs a reliable model for prediction of the process performance. This research work presents a modeling study of laser cutting process. A hybrid approach of Artificial Neural Network (ANN) and Fuzzy Logic (FL), Adaptive Neuro Fuzzy Inference System (ANFIS) has been used for developing the Kerf width and Material removal rate (MRR) models. The developed ANFIS based models of Kerf width and Material removal rate have also been compared with Response Surface Methodology (RSM) based models and it has been found that the values of Kerf width and Material removal rate predicted by the ANFIS based models are more closer to the experimental values.**

***Index Terms*—ANFIS model, Kerf width, Material removal rate, RSM model.**

I. INTRODUCTION

Advanced machining processes are characterized by their advanced machining features such as ability to machine difficult to cut materials and generation of complex shapes and intricate profiles with stringent design requirements. These processes can be classified into three broad categories based on the types of energy utilized such as mechanical, chemical and thermal. Laser beam machining is a thermal energy based advanced machining process in which material is removed by focusing the laser beam on the work surface at a constant distance to melt and vaporize the unwanted work material. The molten material is ejected by the supply of suitable assist gas jet [1].

The most widely used Laser Beam Machining process is laser cutting process. It is used for the cutting of those materials which exhibit favorable thermal and optical properties of the materials. It is best suited for cutting sheetmetals of different materials at optimum cutting speed and cut quality. The schematic of laser cutting is shown in Fig.1. Laser cutting is a non contact type, thermal energy based advanced beam machining process. In laser cutting, a high intensity laser beam is focused at a spot and material gets melted at that spot. A high pressure assist gas (either reactive or inert gas) is supplied with the nozzle to remove the molten metal from the melting pool. The effectiveness of the laser cutting process depends upon the thermal properties and to some extent optical properties, rather than mechanical properties of the material to be cut. Therefore, materials which exhibit a high degree of brittleness or hardness and have favorable thermal properties such as low thermal diffusivity and conductivity are well suited for laser cutting.

In the market a large variety of lasers are available such as solid lasers, liquid lasers and gas lasers. Among all lasers Nd-YAG (solid laser) and CO_2 laser (Gas Laser) are used for most of industrial applications, due to their high powers. Nd-YAG laser cutting becomes an excellent cutting process because of high laser beam intensity, low mean beam power, good focusing characteristics and narrow heat affected zone (HAZ) [2]. Laser cutting system can operate into two modes i.e. continuous mode and pulsed mode. There has been growing interest in recent years in the use of pulsed Nd-YAG lasers for precision cutting of thin sheetmetals.

Since its introduction laser cutting has always been the major area of research for improving the quality of the cut. A number of researchers have performed experimental as well as theoretical investigations to improve different quality characteristics such as Kerf width, Surface roughness, HAZ and Recast layer thickness [2]-[3] .The different quality characteristics of interest in laser cutting are shown in Fig. 2.

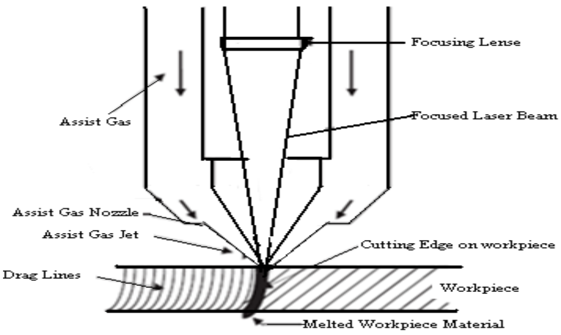

Figure 1. Schematic of LASER CUTTING

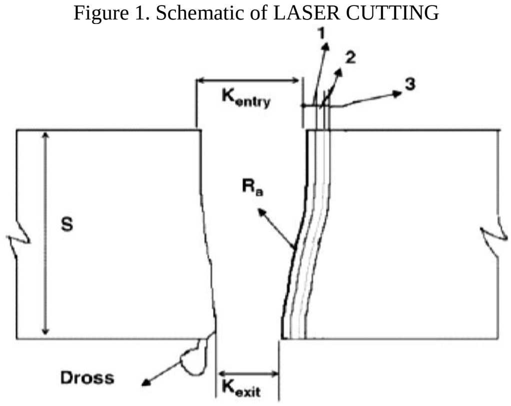

Figure 2.Various QUALITY CHARACTERISTICS in Laser cutting [3].

Kentry: kerf width at entry side, Kexit: kerf width at exit side, Ra: surface roughness, S: thickness of the work piece, 1: oxidized layer, 2: recast layer, and 3: heat affected zone (HAZ).

The researchers have varied one factor (input parameter) at a time to analyze the effect of input process parameters on

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output quality characteristics in most of the experimental study [4]-[8]. Only few researchers have applied Design of Experiments (DOE) and Modeling techniques for performing optimization and laser cutting process modeling and found that quality characteristics have improved considerably [9]-[12].In most of the laser cutting process modeling, the researchers have applied regression analysis technique [13]-[15] and found the relative effect of different input process parameters on the output parameters.

The nonlinear behaviors of the laser-material interactions play a significant role in creation of the final surface profile and the resultant geometry of the laser cut features. The need to precisely control a large number of parameters often with random components makes the task of improving the process performance very difficult. Moreover, modeling all these factors using conventional, analytical and numerical methods poses a substantial challenge. In practice, the operator has to perform number of experiments to set the appropriate process control parameters related to the laser apparatus, motion control system and workpiece material. This trial and-error approach is costly and time consuming. To overcome this problem, soft computing techniques based on Artificial Intelligence (AI), such as artificial neural network (ANN), fuzzy logic (FL) and genetic algorithm (GA) can be efficiently used for modeling and optimization in laser cutting process [16].

The AI methods are extensively used for modeling and optimization of advanced machining processes [17]. T. Erzurumlu and H. Oktem have used ANN for modeling and optimization of laser cutting process and found that model developed by the ANN is more suitable for the predicting the surface roughness in laser cutting [18].

The two AI tools such as ANN and FL can be combined together to utilize the advantages of both the tools and to overcome the drawback, if any due to the use of a single technique. Adaptive Neuro fuzzy inference system (ANFIS) is such a hybrid tool obtained by integration of ANN and FL. Pradhan and Biswas have applied ANFIS for the modeling of MRR in Electrical discharge machining of tool steel and found that ANFIS based model predicted values of MRR are more closer to the experimental values[19]. Sivarao etal. have used ANFIS modeling for laser cutting in order to analyze the effect of input process parameters such as stand off distance, focal distance, gas pressure, laser power, cutting speed, frequency and duty cycle on the output parameters kerf width and surface roughness and they found that the ANFIS model developed is suitable for predicting the surface roughness and kerf width [20].

In the present paper, ANFIS based models have been developed to predict the kerf width and Material removal rate in laser cutting of thin steel sheets by experimental data. The training data set is used to obtain fuzzy rules using the mountain clustering technique and rules are fine tuned using the back propagation algorithm. These ANFIS models are developed by using "ANFIS EDIT" tool box of MATLAB. The data predicted by ANFIS models have been compared with the data obtained from RSM based models.

II. ANFIS Methodology

ANFIS methodology is a type of AI based soft computing technique of modeling. The concept of soft computing is proposed by Prof. Loft Zadeh according to which "soft computing is an emerging approach of computing which parallels the remarkable ability of human mind to reason and learn in an environment of uncertainity and imprecision. Soft computing has three main constituents such as FL (based on human perception), ANN (based on human brain) and GA (based on natural science) [21].

In FL modeling, the concept of Fuzzy set theory is used. Fuzzy set theory is a perfect mean for modeling uncertainty and imprecision arising from mental phenomena. These are neither random nor stochastic. In the field of AI there are various ways to represent knowledge. Perhaps the most common way to represent human knowledge is to form it into natural language expressions of the type: "IF antecedent, THEN consequence". The form in expression is commonly referred to as the "IF-THEN rule-based form". This form generally is referred to as deductive form. It typically expresses an inference such that if we know a fact (premise, hypothesis, antecedent), then we can infer another fact called a conclusion. The fallowing steps are used in FL modeling [22].

1. Identify the different crisp variables (inputs and outputs) of the system.
2. Define a set of membership function (MF) for each variable.
3. Define / form the fuzzy rules, that relate the MF of each variable through a series of "IF and THEN" rules.
4. Evaluate each rule through a process, known as fuzzy implication.
5. Analyze and combine the results obtained by each rule, by a process known as fuzzy aggregation.
6. Convert the fuzzy output into crisp output by a process known as defuzzification.

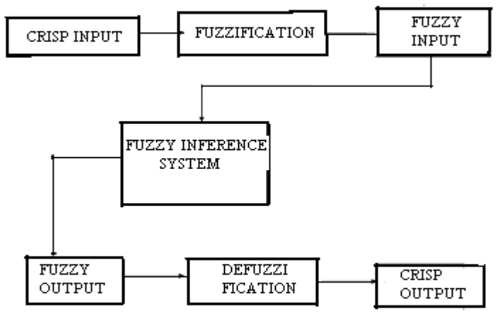


Figure 3. Block diagram of FL Modeling

The block diagram of FL modeling is shown in the Fig.3.

An ANN is an information processing paradigm that is inspired by the way of biological nervous systems, such as the brain process information. It is composed of a large number of highly interconnected processing elements (neurons) working in network to solve specific problems. ANN, like people, learns by examples. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurons. ANN, with their remarkable ability to derive meaning from complicated or imprecise data, can be used to extract patterns and detect trends that are too complex to be noticed by either humans or other computer techniques. A trained neural network can be thought of as an "expert" in the category of information it has been given to analyze. This expert can then be used to provide projections given new situations of interest and answer "what if" questions. Other benefits of ANN include, Adaptive learning, Self-Organization, Real Time Operation, Fault Tolerance via Redundant Information Coding [23].

Fuzzy systems and ANNs have their own advantages and drawbacks. Fuzzy systems have the ability to represent comprehensive linguistic knowledge which is usually given by an expert. However, fuzzy systems do not provide a mechanism to automatically acquire and tune those rules. On the other hand ANNs are adaptive systems that can be trained and tuned from a set of samples. Once they are trained, ANNs can deal with new input data by generalizing the acquired knowledge. Nevertheless, it is very difficult to extract and understand that knowledge. In other words, fuzzy systems and ANNs are complementary paradigms. ANFIS has been recently proposed to combine the advantages of fuzzy systems and ANNs. ANFIS are fuzzy systems which use theory of ANNs in order to determine their properties through processing of data samples. ANFIS harness the power of the FL and ANNs through utilizing the mathematical properties of ANNs in tuning rule-based fuzzy systems that approximate the way human's process information.

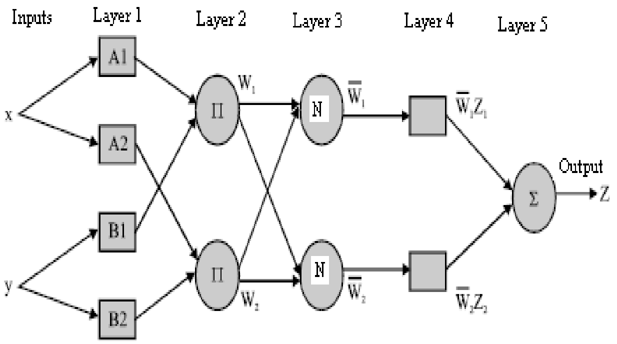


Figure 4. ANFIS architecture

An ANFIS aims at systematically generating unknown fuzzy rules from a given input/output data set. A typical structure of ANFIS architecture is shown in Fig.4. Every node in layer 1 is an adaptive node with a node function that may be a Gaussian membership function or any membership functions. Every node in layer 2 is a fixed node labeled Π, representing the firing strength of each rule. Every node in layer 3 is a fixed node labeled N, representing the normalized firing strength of each rule. Every node in Layer 4 is an adaptive node with a node function. The single node in layer 5 is a fixed node labeled Σ, indicating the overall output (Z) as the summation of all incoming signals [21].

There are two types of fuzzy inference systems (FIS), which are used in ANFIS modeling. 1. Mamdani FIS, 2. Sugeno FIS. But due to fallowing advantages Sugeno FIS is used.

1) There are algorithms which can be used to automatically optimize the Sugeno FIS. One of the tools that can calibrate the weights of the Sugeno FIS output is MATLAB's ANFIS.
2) Better processing time since the weighted average replace the time consuming defuzzification process.
3) Computational efficiency and accuracy.
4) Adequate for functional analysis because of the continuous structure of output function (same inputs do not originate substantially different outputs.
5) Rules' consequents can have as many parameters per rule as input values allowing more degrees of freedom and more flexibility in the design.

III. MODELING OF LASER CUTTING FOR KERF WIDTH

During laser cutting of thin sheets, a KW model has been developed. In the development of this model, four input process parameters such as pulse frequency, pulse width, cutting speed and assist gas pressure are considered. For developing the model, the experimental data have been taken from author's previous research work [3].The block diagram of ANFIS Model (Sugeno Type) developed is shown in Fig.5. Four input parameters have been shown in the left part of the diagram as shown in figure 5.

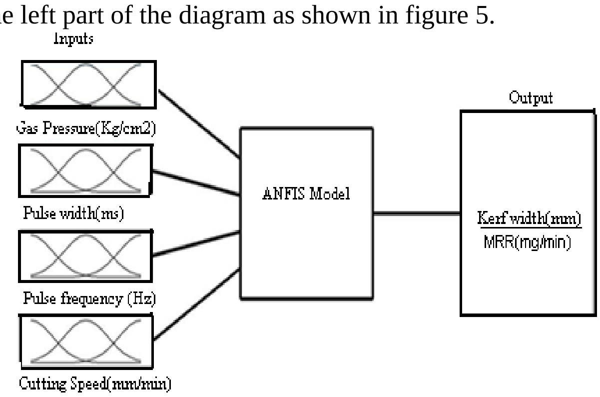
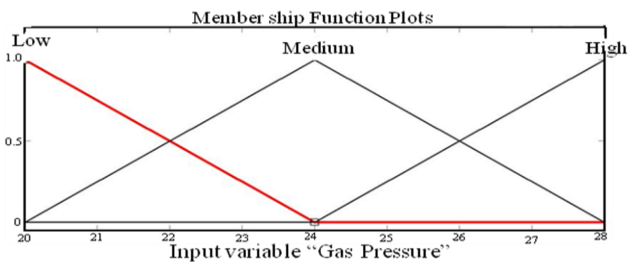
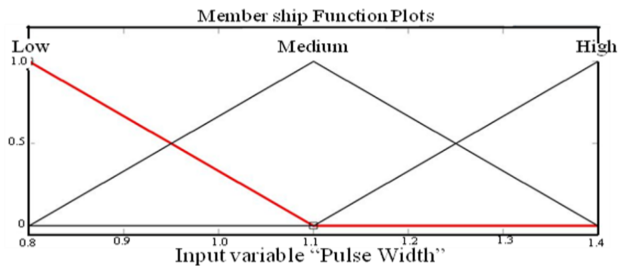
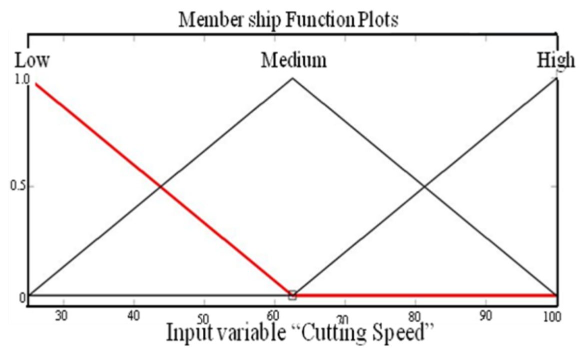


Figure 5. Block Diagram of ANFIS MODEL FOR KERF WIDTH







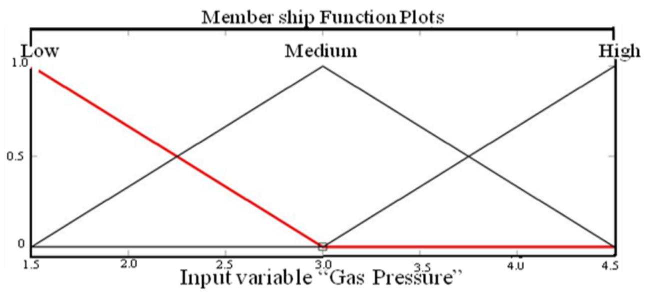


Figure 6. MEMBERSHIP FUNCTION PLOTS of Inputs for Kerf Width

Right part of the diagram shows the output kerf width and middle part shows the Sugeno type ANFIS model engine. The membership for each input variable is shown in the Fig. 6. The degree of membership for each input process parameters is taken as low, medium and high as shown in the Fig.6.

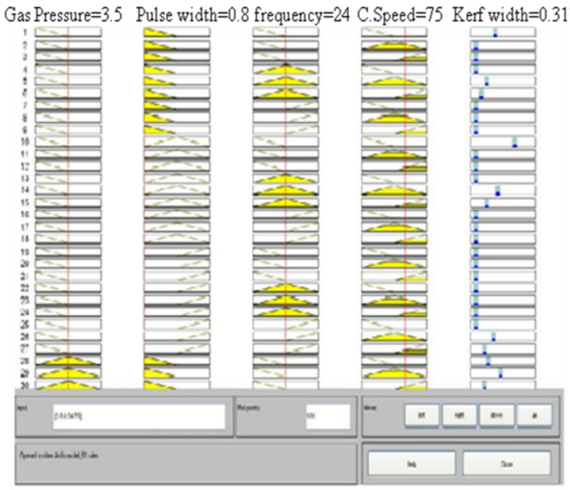


Figure 7. RULE VIEWER for Kerf Width

As, there are four inputs each having three membership function, the total number of fuzzy rules formed will be 81(3x3x3x3).All the rules are analyzed by using weighted average method to get final output as shown in Fig.7. In this figure; the last column shows value of the output and all other columns show the value of different input process parameters. Each horizontal row Shows different fuzzy rules formed. This Neuro fuzzy model can be trained by using certain experimental data sets. For the training 20 data sets [Ex.no.1-10, 12-15, 17-20, 23-24] are used. Further for testing 5 subsequent data sets [Ex. No. 25-29] are used. For the error minimization of the equivalent neural network 100 epochs are used.

IV. MODELING OF LASER CUTTING FOR MRR

An ANFIS Based MRR model during Laser Cutting of thin sheets has been developed. For the development of this model, four input process parameters such as pulse frequency, pulse width, cutting speed and assist gas pressure are considered. For developing the model, the experimental data have been taken from author's previous research work [3].The block diagram of ANFIS Model (Sugeno Type) developed is shown in Fig.5. Four input parameters have been shown in the left part of the diagram. Right part of the diagram shows the output kerf width and middle part shows the Sugeno type ANFIS model engine. The membership for each input variable is shown in the Fig. 8. The degree of membership for each input process parameters is taken as low, medium and high as shown in the Fig.8. The ranges of these low, medium and high may be adjusted automatically with the software.

As, there are four inputs each having three membership function, the total number of fuzzy rules formed will be 81(3x3x3x3).All the rules are analyzed by using weighted average method to get final output as shown in Fig.9.

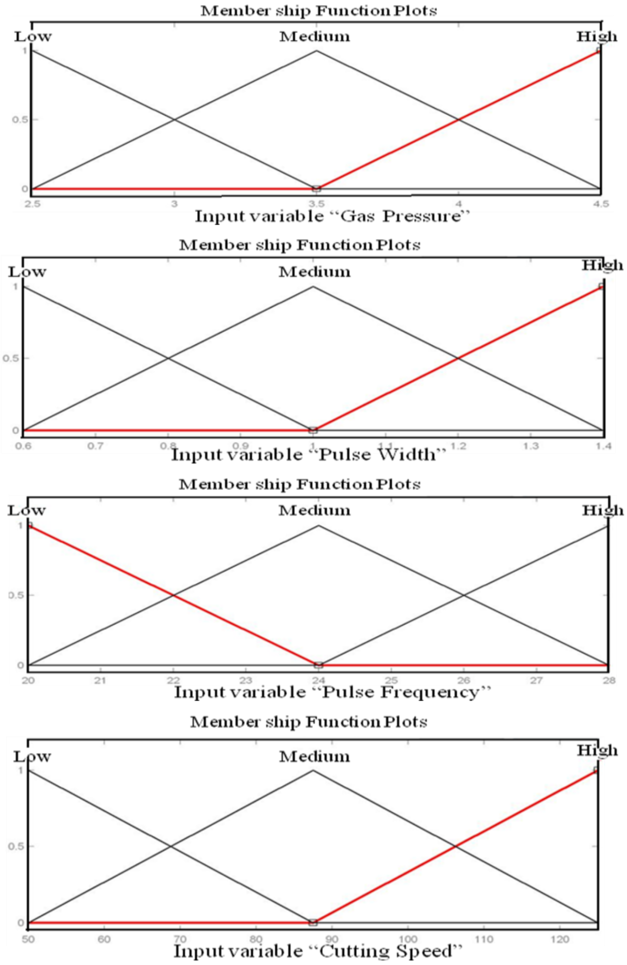


Figure 8 MEMBERSHIP FUNCTION PLOTS of Inputs for MRR

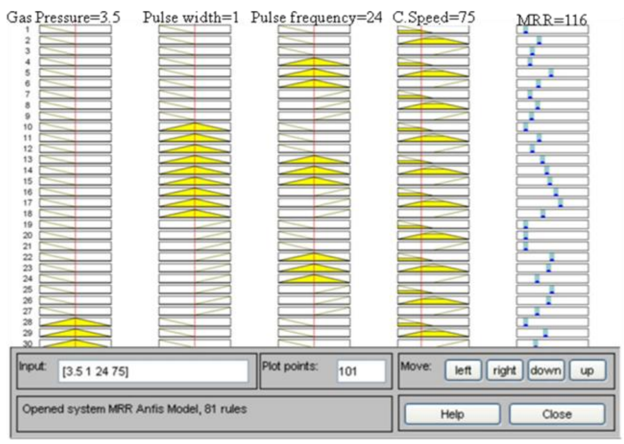


Figure 9.RULE VIEWER for MRR

In this figure; the last column shows value of the output MRR and all other columns show the value of different input process parameters. Each horizontal row shows different fuzzy rules formed. This ANFIS model can be trained by using certain experimental data sets. For the training 20 data sets [Ex.no.1,5,7-15,17,19,22-25, 27,28,30] are used. Further for testing 10 subsequent data sets [2-4,16,18,20,21,26,29,31] are used. For the error minimization of the equivalent neural network 100 epochs are used. This phase is also known as optimization phase and in this process weights are updated by using different network algorithm such as back propagation algorithm.

V. Validation of Model

The values of KW and MRR predicted by developed ANFIS based models are quite close to that of values obtained from the experiments as shown in Fig.10&11 respectively. The developed models have also been compared with the RSM based models for KW and MRR, developed by the author [3]. For the comparison of the models, the KW and MRR are calculated by using KW and MRR equations obtained from RSM based models for different sets of input process parameters. For the same input process parameters, the KW and MRR are found with the help of ANFIS models. The values of KW and MRR obtained from both of these models are shown in the Table1&2 respectively. The standard deviation for ANFIS models of KW and MRR is 0.0458 and 27.89 respectively. Standard deviation for RSM based models of KW and MRR is 0.0584 and 29.35 respectively. For ANFIS models of KW and MRR, the root mean square error (RMSE) is 0.0137 & 4.19 where as for RSM models 0.08576 & 4.46 respectively.

TABLE 1. Comparison Between Experimental Value and Predicted Value of KW

S.No.	*Experimental Value of KW(mm)*	*ANFIS Model based predicted Value of KW(mm)*	*RSM based Model predicted Value of KW(mm)*
1.	0.3148	0.311	0.5442
2.	0.3808	0.3930	0.4930
3.	0.3498	0.3500	0.4764
4.	0.4088	0.419	0.4276
5.	0.3988	0.412	0.4314
6.	0.4312	0.427	0.4562
7.	0.3701	0.368	0.5982
8.	0.4511	0.452	0.4962
9.	0.3972	0.403	0.4412
10.	0.3012	0.311	0.3262
11.	0.3411	0.299	0.3712
12	0.4351	0.432	0.4812
13.	0.4551	0.446	0.4981
14.	0.412	0.384	0.4012
15.	0.3805	0.373	0.3995
16.	0.3885	0.395	0.3985
17.	0.3611	0.375	0.3815
18.	0.3012	0.311	0.3312
19.	0.3658	0.372	0.3788
20.	0.3855	0.375	0.4012
	Std. deviation	0.0458	0.0584
	Mean average % error (MAPE)	0.9955	5.6245
	Root mean square error (RMSE)	0.0137	0.08576

For ANFIS models of KW and MRR, the mean average percentage error (MAPE) is 0.9955 & 2.49 where as for RSM models 5.6245 & 6.92 respectively. It is found that the data predicted by ANFIS based models are more acceptable or closer to the experimental values of KW and MRR.

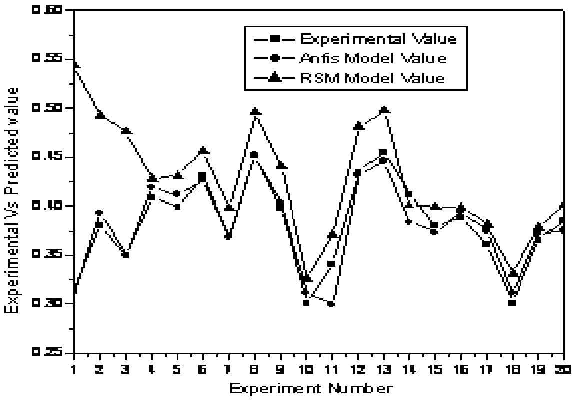


Figure 10. Plot of EXPERIMENTAL VS. PREDICTED KERF WIDTH.

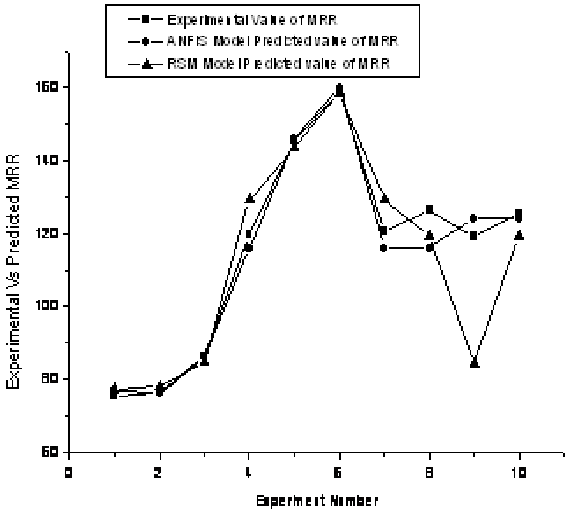


Figure 11. Plot of EXPERIMENTAL VS. PREDICTED MRR

TABLE 2. Comparison Between Experimental Value and Predicted Value of MRR

S.No.	*Experimental Value of KW(mm)*	*ANFIS Model based predicted Value of KW(mm)*	*RSM based Model predicted Value of KW(mm)*
1	75.16	76.80	77.179
2	76.17	75.80	78.03
3	86.17	85.80	84.60
4	119.75	116.00	129.15
5	145.67	146.20	143.77
6	158.33	160.00	158.43
7	120.50	116.00	129.15
8	126.50	116.00	119.15
9	119.15	124.00	84.06
10	125.50	124.00	119.15
1	75.16	76.80	77.179
2	76.17	75.80	78.03
3	86.17	85.80	84.60
4	119.75	116.00	129.15
5	145.67	146.20	143.77
6	158.33	160.00	158.43
7	120.50	116.00	129.15
8	126.50	116.00	119.15
9	119.15	124.00	84.06
10	125.50	124.00	119.15
	Std. deviation	27.89	29.35
	Mean average % error (MAPE)	2.49	6.92
	Root mean square error (RMSE)	4.19	4.46

The comparison results of ANFIS based models and RSM based models for KW and MRR have also been represented graphically in Figure 10&11 respectively.

VI. CONCLUSIONS

ANFIS based models for predicting the Kerf width (KW) and Material removal rate (MRR) in Laser cutting process have been developed by using, a hybrid approach of Fuzzy Logic and Neural Network. The results obtained by developed ANFIS based models are very close to the experimental values of KW and MRR. The comparison of these models with RSM based models show that kerf width and material removal rate values predicted by ANFIS based models are more reliable as compared to RSM based models. And the developed ANFIS based models are more adequate as seen from the statistical analysis. These models may be used satisfactorily for the prediction of Kerf width and Material removal rate in laser cutting of thin steel sheet.

REFRENCES

[1] G. Chryssolouris, "Laser machining—theory and practice" (Mechanical Engineering series), *Springer, New York*: 1991.

[2] A. K. Dubey and V.Yadava, "Laser beam machining—A review," *International Journal of Machine Tools & Manufacture 48 (2008) 609–628.*

[3] A K. Dubey and V. Yadava, "Multi-objective optimization of laser beam cutting process," *Optics & Laser Technology 40 (2008) 562–570.*

[4] J. Hu, Z. Zhang, J. Luo, X. Sheng, "Simulation and experiment on standoff distance affecting gas flow in laser cutting", *Applied Mathematical Modelling 35 (2011) 895–902*.

[5] D.G. Ahn, K.W. Byun and M.C. Kang, "Thermal Characteristics in the Cutting of Inconel 718 Superalloy Using CW Nd:YAG Laser", *J. Mater. Sci. Technol., 2010, 26(4), 362-366.*

[6] H. Golnabi , M.Bahar, "Investigation of optimum condition in oxygen gas-assisted laser cutting", *Optics & Laser Technology 41 (2009) 454–460.*

[7] G.F .Zhang, B. Zhang(2), Z.H. Deng, and J.F. Chen, "An Experimental Study on Laser Cutting Mechanisms of Polycrystalline Diamond Compacts", *Annals of the CIRP* Vol. 56/1/2007.

[8] C. Karatas, O. Keles, I. Uslan, Y. Usta, "Laser cutting of steel sheets: Influence of workpiece thickness and beam waist position on kerf size and stria formation", *Journal of Materials Processing Technology 172 (2006) 22–29.*

[9] K.Huehnlein, K. Tschirpke, R. Hellmann, "Optimization of laser cutting processes using design of experiments", *Physics Procedia 5 (2010) 243–252.*

[10] A. Sharma, V.Yadava, R. Rao, "Optimization of Kerf quality characteristics during Nd: YAG laser cutting of nickel based superalloy sheet for straight and curved cut profiles", *Optics and Lasers in Engineering 48 (2010) 915–925.*

[11] R.Rao, V. Yadava, "Multi-objective optimization of Nd: YAG laser cutting of thin superalloy sheet using grey relational analysis with entropy measurement", *Optics & Laser Technology 41 (2009) 922–930.*

[12] A. Stournaras, P. Stavropoulos, K. Salonitis, G. Chryssolouris, "An investigation of quality in CO2 laser cutting of aluminum", *CIRP Journal of Manufacturing Science and Technology 2 (2009) 61–69.*

[13] Sivarao, Shukor, T.J.S.Anand and Ammar, "DOE Based Statistical Approaches in Modeling of Laser Processing,*" International Journal of Engineering & Technology 04(2010)*.

[14] M. Kurt, Y. Kaynak, E. Bagci and H. Demirer, "Dimensional analyses and surface quality of the laser cutting process for engineering plastics," *International Journal of Advanced Manufacturing Technology 41 (2009) 259–267.*

[15] Sivarao, T.J.S.Anand, Ammar and Shukor, "RSM Based Modeling for Surface Roughness Prediction in Laser Machining," *International Journal of Engineering & Technology 04 (2010)*.

[16] F.Basem, Y. George and K. Knopf, "Neural network modeling and analysis of the material removal process during laser machining," *International Journal Advanced Manufacturing Technology 22 (2003) 41–53.*

[17] U. Caydas, A.Hascalık and S.Ekici, "An adaptive neuro-fuzzy inference system (ANFIS) model for wire-EDM," *Expert Systems with Applications 36 (2009) 6135–6139.*

[18] M. K. Pradhan and C. K. Biswas, " Neuro-fuzzy model and Regression model a comparison study of MRR in Electrical discharge machining," *International Journal of Mathematical, Physical and Engineering Sciences 3:1(2009)*.

[19] T. Erzurumlu and H. Oktem, "Comparison of response surface model with neural network in determining the surface quality," *Materials and Design 28 (2007) 459–465.*

[20] Sivarao, P. Brevern, N.S.M. El-Tayeb and V.C. Vengkatesh, "ANFIS Modeling of Laser Machining Responses by Specially Developed Graphical User Interface" *International Journal of Mechanical & Mechatronics Engineering 09 (2009)*.

[21] J.S.R.Jung, C.T.Sun and E. Mizutani, "Neuro Fuzzy and Soft Computing" (a computational approach to learning and machine intelligence), *Prentice Hall of India; 2004*.

[22] G.J.Klir and B.Yuan, "Fuzzy sets and Fuzzy Logic" (Theory and applications), *Prentice Hall of India; 2005.*

[23] S.Haykin,"Neural Networks" (A Comprehensive Foundation), *Pearson Education Asia; 2001.*

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Dr. Avanish Kumar Dubey is life time member of Institution of Engineers (India). His area of interest is Laser Material processing, Non conventional machining processes, Design of experiment applications in manufacturing processes and applications of Artificial Intelligence in advanced machining processes. Dr. Avanish Kumar Dubey is a member of editorial boards of some refereed international journals and also reviewer of many refereed international journals of repute.