A Fuzzy-Taguchi Approach for Improving Dimensional Accuracy of Fused Deposition Modelling (FDM) Built Parts

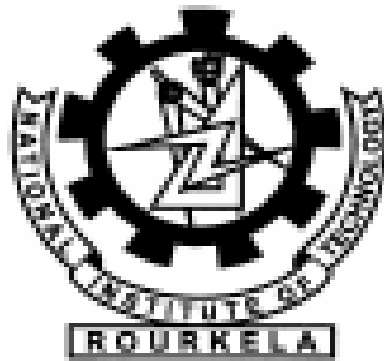**A THESIS SUBMITTING IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE IN**

Bachelor of Technology

In

Mechanical Engineering

By

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NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA

CERTIFICATE

This is to certify that the thesis entitled." A Fuzzy-Taguchi Approach for Improving Dimensional Accuracy of Fused Deposition Modelling (FDM) Built Parts "submitted by Mr. Akhil Garg in partial fulfilment of the requirements for the award of Bachelor of technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my guidance.

To the best of my knowledge the matter embodied in the thesis has not been submitted to any University /Institute for the award of any Degree or Diploma.

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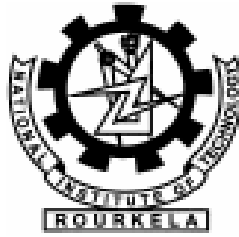
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CONTENTS

ABSTRACT

Fused deposition modeling is one of rapid prototyping system that produces prototypes from plastic materials such as ABS (acrylonitrile-butadiene-styrene) by laying the tracks of semi-molten plastic filament onto a platform in a layer-wise manner from bottom to top. The present work attempts experimental investigations to study influence of important process parameters viz., layer thickness, part orientation, raster angle, air gap and raster width along with their interactions on dimensional accuracy of Fused Deposition Modelling (FDM) processed part. The part produced from FDM machine does not match with dimension of CAD model due to presence of shrinkage. However, shrinkage is more prominent in length and width direction but a positive deviation is observed in thickness direction.

It is essential to study the effect of each parameter on responses such as percentage change in length, width, and thickness of specimen. A design of experiment (DOE) is used to study the effect of process parameters on responses. Optimum parameters setting to minimize percentage change in length, width and thickness of standard test specimen have been found out using Taguchi's parameter design. Experimental results indicate that optimal factor settings for each performance characteristic are different. There are number of techniques available for predicting responses using input parameters e.g. genetic algorithm, artificial neural network, fuzzy inference system (FIS) etc. But present work uses Fuzzy Inference System (Mamdani Fuzzy logic) to predict the dimensional accuracy in part produced by FDM machine. This method is capable of taking into account the uncertainty and impreciseness in measurements which is commonly encountered in shop floor. The model uses all input and output variables in linguistic terms enabling it convenient for practitioners. The inference engine in Mamdani type FIS uses rules which are obtained with help of design of experiment technique (DOE).

INTRODUCTION

Chapter 1

INTRODUCTION:

Reduction in product development time is vital for any industry to remain competitive in market place. RP (Rapid prototyping) Technology is used to produce functional assemblies by consolidating sub assemblies into single unit at computer aided design(CAD) stage and thus reduce the parts counts, handling time, and storage requirement and avoids mating and fit problem.FDM process is one of RP technology that is used to build ABS prototypes that are used in real practice. In general, FDM machine utilize two common steps to automatically build a part model: (a) the CAD files are sliced into a series of 2D CAD files that represent the cross section of the part and (b) these 2D slice files are simple enough to automatically generate the needed vectors to drive the 2 1/2 axis RP machine layer by layer. Each layer is built on the preceding layer by each machine's particular material fabrication technology until the 3D physical model is built [38].

Dimensional accuracy has received serious attention for many years. It is most important aspect for production of prototypes for prediction purpose since any change in dimension in prototype could lead to inaccurate results during testing and thereby producing new prototyping again, will be expensive, time consuming etc. Therefore it is very much essential to study the effect of process parameters on dimensional accuracy of specimen.

The CAD model presents the exact picture of specimen to be produced through FDM machine, but there is some shrinkage during the fabrication stage due to which the length, width and thickness of specimen alters. It is observed that shrinkage is dominant along length and width direction of built part but, positive deviation from the required value is observed in the thickness direction. Thus it leads to volume shrinkage in all respect. The analysis of process parameters used in FDM such as air gap, layer thickness, raster gap, raster width, orientation on volumetric shrinkage can be done but however by this analysis we cannot predict the actual change in length ,thickness, width of specimen . Therefore it is required to study the effect of process parameters on multiresponses such as length, width, thickness simultaneously. The quality of cost has been increased by using the DOE (Design of experiments).An effort has been made to minimize percentage change in length, width and thickness of specimen and combined responses from experimental data using Taguchi. Design of experiments (DOE) has been used to decide the significant experiment which was used in creating the rule box. For predicting the results, several techniques such as Mamdani fuzzy inference, artificial neural network, Genetic algorithm can be used but Mamdani inference method was preferred to predict the outputs of all the experiments. It considers the uncertainty which is highly essential in shop floor practice. Actually fuzzy inputs use linguistic variables (low, medium, high) which are easily comprehended by the unskilled workers on shop floor and they also minimize the chances of error. Therefore the Mamdani fuzzy inference method is used to predict dimension accuracy of specimen produced by FDM machine.

LITERATURE REVIEW
Chapter 2

LITERATURE REVIEW

Several attempts have been made to improve the part accuracy, parameters by numerous researchers. Pandey and Ragunath [1] have shown that laser power and scan length are most influencing process variables along X direction, laser power and beam speed are significant along Y direction and beam speed, hatch spacing and part build temperature are significant along Z direction while studying shrinkage phenomena in SLS part. Vasudevarao et al. [2] indicated that layer thickness and part orientation have significant effect on the roughness of parts fabricated using FDM 1650 machine. Further, they have proposed empirical equation for calculating roughness of parts. Es Said et al. [3] have shown that anisotropic behaviour on mechanical properties is caused mainly due to raster orientation when ABSP400 samples are built on FDM 1650 machine. Khan et al. [4] identified important parameters and their levels for improving the flexibility of FDM part using design of experiments approach. Lee et al. [5] performed experiments on cylindrical parts made using three RP processes FDM, 3D printer and nano composite deposition (NCDS) to study the effect of build direction on compressive strength.

Experimental results show that compressive strength is 11.6% higher for axial FDM specimen as compared to transverse FDM specimen. In 3D printing, diagonal specimen possesses maximum compressive strength in comparison to axial specimen. For NCDS, axial specimen showed compressive strength 23.6% higher than that of transverse specimen. Out of three RP technologies, parts built by NCDS are highly affected by the build direction. Anitha et al. [6] uses Taguchi method to determine the effect of layer thickness, road width and deposition speed each at three levels on the surface roughness of component produced using FDM process. The results indicate that layer thickness is the most influencing process parameter affecting surface roughness followed by road width and deposition speed. Zhou et al. [7] studied the effect of five control factors such as layer thickness, overcure, hatch spacing, blade gap, and part location on build platform and few selected interactions on the accuracy of SLS parts. It has been observed that the factor settings for maximum accuracy depend on geometrical features in the part. Campanelli et al. [8] have recommended that hatch overcure and border overcure must be set at their maximum level for improving part accuracy when layer thickness is high. If low layer thickness is desired then hatch overcure should be maintained at medium level and border overcure at maximum level. These process settings not only improve part accuracy but also eliminate the necessity for post curing the SLS part. The aforesaid discussions reveal that properties of RP parts are dependent on various process related parameters. With proper adjustment of the build parameters, quality can be significantly improved without incurring additional expenses in changing developed hardware and software. Further, literature suggests that studies on effect of process parameters in improving quality of FDM built parts, specifically, dimensional accuracy, have been devoted to a limited extent.

Optimizations of machining parameters are not only increases the utility for machining economics, but also increases the product quality to a great extent (Azouzi and Guillot,) (9) when the decision variable are restricted to only few variable and subject to the inclusion of sampling variability. In order to produce any product with desired quality by machining, cutting parameters should be selected properly. Wardany et al. (10) reported that drilling is a complex operation compared to other machining operation due to the fact that the two points of the drill wear alternately until they both have zero clearance at the margin, and become lodged within work piece. The most widely tool failure modes are flank wear, fracture, crater wear and plastic deformation as reported by Bonifacio and Dinz (11). Rao (12).,Nouari et al. (13) reported necessary information about the main factors influencing the hole quality i.e. cutting speed, temperature, feed rate, geometrical parameters as well as the influence of the cutting conditions and the temperature on the tool life in drilling. They reported that improvement of surface quality and dimensional accuracy of the holes can be achieved at large cutting speed values and a weak feed rate. To improve the EDM technology, many efforts have been directed to enhance the process stability. Introducing foreign particles into the working fluid was one of the useful approaches to improve the EDM performance. The present work laid stress on use of Fuzzy-Taguchi based approach for improving the dimensional accuracy of specimen produced by FDM. Taguchi's parameter design being simple and inexpensive is adopted for in-depth study to understand process parameters and their interaction effects on responses like accuracy of dimensions in different directions of FDM built parts with minimum experimental runs. Rule box has been created with the help of design of experiments (DOE) for implementing the Fuzzy inference system. The prediction in dimensional accuracy is made based on Mamdani inference system (Fuzzy logic).
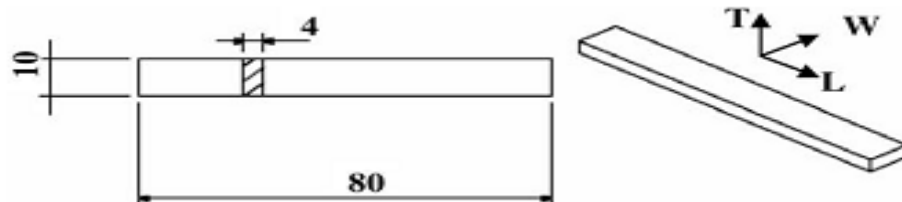
EXPERIMENTAL PLAN: [38]

FDM machines build part on a layer-by-layer basis. It uses heated thermoplastic filaments which are extruded from the tip of nozzle. FDM use separate nozzles for part material deposition and support structure material deposition [14], both work alternatively. The material used is preferably one which will melt at a pre-selected temperature and rapidly solidify upon adhering to the previous layer. Five factors viz., layer thickness (A), part build orientation (B), raster angle (C), raster width (D) and raster to raster gap (air gap) (E) each at three level, as shown in Table 2, are considered. They are briefly defined as follows.

Others factors are kept at fixed level as shown in Table 1

3D solid model of test part is modelled in CATIA V5 software and exported as STL file. STL file is imported to FDM software (Insight). Here, control factors (Table 2) are set as per experiment plan (Table 3) and other factors (Table 1) are kept at fixed level. Three parts per experiment are fabricated using FDM Vantage SE machine[35]. The material use for part fabrication is ABSP400. Three readings of length, width and thickness are taken per sample and mean is taken as representative value for each of these dimensions. Dimensions are measured using Mitutoyo vernier calliper having least count of 0.01 mm. Measured values show that there is shrinkage in length (L) and width (W) but thickness (T) is always more than the CAD model value. Percentage change in dimension is calculated using this equation (1) below

Reference taken from [38] section.

$$DX\% = ((X - X_{CAD})/X_{CAD})*100 \qquad (1)$$

Fig 1; showing the Dimensions of test specimen in mm

Experimental data based on orthogonal array L_{27} is shown in Table 3

Table1: Factors and their fixed level   :[38]

Fixed Factors		
Factors		
Part fill style	Perimeter/raster	-
Contour width	.4064	mm
Part interior style	Solid normal	-
Visible surface	Normal raster	-
XY &Z shrink factor	1.0038	-
Perimeter to raster air gap	0.0000	mm

Table 2: Process parameters to be controlled: [38]

Factors					
Layer thickness	A	.127	.178	.254	Mm
Orientation	B	0	15	30	Mm
Raster Angle	C	0	30	60	Mm
Raster width	D	0.4064	0.4564	0.5064	Mm
Air Gap	E	0	0.004	0.008	Mm

Table 3. L₂₇ Orthogonal ray with S/N ratio Data for Experimental plan: (Reference [38])

Experimental plan was carried out based on Taguchi method and results were are shown below

Factors						SN Ratio	SN Ratio	SN Ratio
Exp No	A	B	C	D	E	%change in L	%change in T	%change in w
1	1	1	1	1	1	24.8066	4.4370	-9.2977
2	1	2	1	2	2	18.4164	7.2636	-11.8583
3	1	3	1	3	3	19.4394	1.5836	-8.2436
4	1	1	2	2	2	26.3151	2.6940	-8.5194
5	1	2	2	3	3	14.3869	6.0206	-11.6715
6	1	3	2	1	1	15.0569	7.2636	-8.5194
7	1	1	3	3	3	30.9540	5.4600	-10.0120
8	1	2	3	1	1	17.2339	3.5218	-12.0412
9	1	3	3	2	2	18.5992	3.9674	-11.4806
10	2	1	1	2	3	38.0618	13.9794	-8.5194
11	2	2	1	3	1	29.5424	2.3079	-12.7364
12	2	3	1	1	2	23.0980	6.0206	-13.0643
13	2	1	2	3	1	20.2945	8.7146	-11.2854
14	2	2	2	1	2	17.0259	7.2636	-13.6849
15	2	3	2	2	3	17.5557	8.7146	-13.0643
16	2	1	3	1	2	22.4028	8.7146	-9.5424
17	2	2	3	2	3	20.7558	3.5218	-12.5678
18	2	3	3	3	1	26.4661	8.7146	-11.2854
19	3	1	1	3	2	22.8937	18.4164	-16.3689
20	3	2	1	1	3	23.9674	7.535	-19.6303
21	3	3	1	2	1	16.5266	12.3958	-19.4779
22	3	1	2	1	3	27.6042	14.8945	-18.7570
23	3	2	2	2	1	28.9143	7.9588	-20.4238
24	3	3	2	3	2	18.2966	10.4576	-16.1462
25	3	1	3	2	3	32.0412	11.0568	-16.3689
26	3	2	3	3	1	24.3172	7.9588	-18.6731
27	3	3	3	1	2	31.7564	7.9588	-17.6921

METHODOLOGY

Chapter 3

METHODOLOGY:

SN Ratio: Reference [38]

It is used to determine the influence and variation caused by each factor and interaction relative to the total variation observed in the result. S/N ratio uses a single measure, mean square deviation (MSD), which incorporates the effect of changes in mean as well as the variation (standard deviation)[15].Results behave linearly when expressed in terms of S/N ratios. Aim of experimental plan is to reduce the percentage change in length (%DL), width (%DW) and thickness (%DT), respectively. Hence, smaller the better quality characteristic is considered. S/N ratio (g) is determined

$n = -10\log_{10}(MSD)$

$MSD = t^2 + (Y_{avg} - Y_0)^2$ (2)

Where t^2(sigma square) is variance, Y_{AVG} is average value of n data points and Yo is target value (Zero in our case).

ANOVA:

Reference [38]

The purpose of the analysis of variance (ANOVA) was to investigate which parameters significantly affected the quality characteristic [16]. In this method, the total sum of squared deviations was calculated. Experiment analysis is made using Minitab R14 software. Main effect plot for S/N ratio shown in result and discussion part is used to predict the optimum factor level.

$$S_T = \sum_{i=1}^{N}(\eta_i - \bar{\eta})$$

(3)

Where ST is a total sum of square, N total number of observation and N' is the overall mean of S/N ratio.

$$SS_j = \sum_{i=1}^{l}(\eta_{ji} - \bar{\eta})^2$$

(4)

Where SSj is sum of square deviation of jth factor, l is level of jth factor

$$V_j = \frac{SS_j}{f_j}$$

$$(5)$$

Vj and fj is variance and degree of freedom respectively of jth parameter.

$$F_j = \frac{V_j}{V_e}$$

$$(6)$$

Fj, Ve is F-ratio of jth factor and Ve is variance of error. Significance of factors and interactions is determined by comparing calculated F-value with standard F-value at a particular level of confidence (95% in this study)[17]. Then finally we have to predict and verify improvements in observed values through the use of the optimal combination level of significant factors using

$$\begin{aligned}
\eta_{pre} = {} & \overline{\eta} + (\overline{A_i} - \overline{\eta}) + (\overline{B_j} - \overline{\eta}) + (\overline{C_k} - \overline{\eta}) + (\overline{D_m} - \overline{\eta}) + (\overline{E_n} - \overline{\eta}) \\
& + [(\overline{A_i B_j} - \overline{\eta}) - (\overline{A_i} - \overline{\eta}) - (\overline{B_j} - \overline{\eta})] + [(\overline{B_j C_k} - \overline{\eta}) - (\overline{B_j} \\
& - \overline{\eta}) - (\overline{C_k} - \overline{\eta})] + [(\overline{B_j D_m} - \overline{\eta}) - (\overline{B_j} - \overline{\eta}) - (\overline{D_m} - \overline{\eta})] \\
& + [(\overline{B_j E_m} - \overline{\eta}) - (\overline{B_j} - \overline{\eta}) - (\overline{E_m} - \overline{\eta})]
\end{aligned}$$

$$(7)$$

Taguchi Method:

Taguchi method is best suitable for optimization of a single performance characteristic whereas grey-based Taguchi combine the entire considered performance characteristic (objectives) into a single value that can be used as the single characteristic in optimization problems [38]. This method approaches for analysis and abstract modelling of systems for which the information is limited, incomplete and characterised by random uncertainty. Three performance measures – percentage change in length, width and thickness are considered with an aim to minimize all these simultaneously at the single factor level setting. To apply this method, input attributes (performance characteristic or objective function) need to satisfy three conditions for comparability of the different series [18]. These are, (1) the difference between the maximum and minimum input values (taken over all attributes) is less than an order of magnitude of two, (2) all attributes are of same type and (3) all attributes have the same measurement scale, and if they are quantitative, have same unit or no unit. If any of these conditions are not met standard normalization is done.

Fuzzy Inference System:

Reference [39]

This section provides an introduction to fuzzy systems. The four parts of fuzzy system are as shown below (Zadeh, 1965; Zadeh, 1976; Mendel, 1995; Cox, 1992)[19].
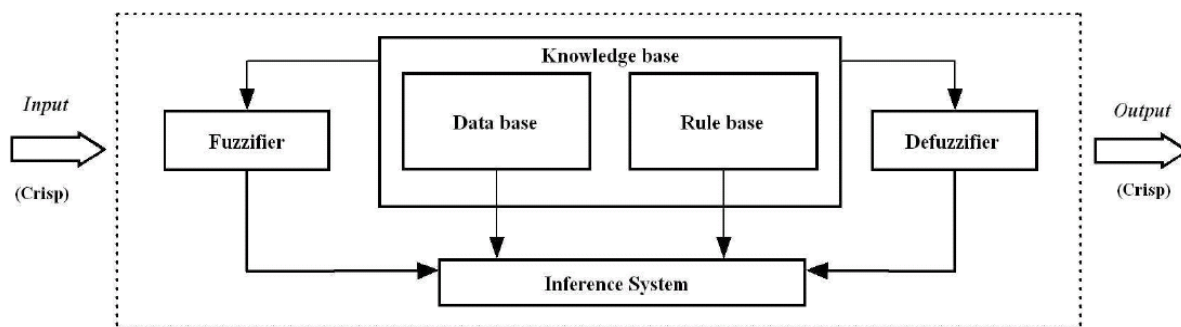

Fig: 2 Fuzzy Inference system

- **Fuzzifier:** In this method, input is called crisp input since it contains precise information about the specific information about the parameter [19] . The fuzzifier converts this precise quantity to the form of imprecise quantity like 'large', 'medium', 'high' etc. with a degree of belongingness to it. Typically, the value ranges from 0 to 1.

- **Knowledge base**: The main part of the fuzzy system is the knowledge base in which both rule base and database are jointly referred. The database defines the membership functions of the fuzzy sets used in the fuzzy rules where as the rule base contains a number of fuzzy if-then rules.

- **Inference engine**: The inference system or the decision-making unit performs the inference operations on the rules. It handles the way in which the rules are combined.

- **Defuzzifier**: The output generated by the inference block is always fuzzy in nature. A real world system will always require the output of the fuzzy system to the crisp or in the form of real world input. The job of the defuzzifier is to receive the fuzzy input and provide real world output [20]. In operation, it works opposite to the input block.

In general two most popular fuzzy inference systems are available: Mamdani fuzzy model and Sugeno fuzzy model. The selection depends on the fuzzy reasoning and formulation of fuzzy IF-THEN rules[39]. Mamdani fuzzy model is based on the collections of IF-THEN rules with both fuzzy antecedent and consequent predicts. The benefit of this model is that the rule base is generally provided by an expert and hence to a certain degree it is translucent to explanation and study. Because of its ease, Mamdani model is still most commonly used technique for solving many real world problems.

Development of Mamdani Fuzzy Model

In the present study, an attempt was made to use fuzzy system (Mamdani) to predict or estimate the erosion rate of cement by-pass dust filled hybrid composites. With availability of set of measured data input and output of the fuzzy system would be able to predict the output for any given input even if a specific input condition had not been covered in the building stage [21]. The methodology for development of fuzzy sound pressure level prediction model involved the following steps:

1. Selection of input and output variables,
2. Selection of membership function for input and output variables,
3. Formation of linguistic rule base, and
4. Defuzzification.

Selection of input and output variables

The first step in system modelling was the identification of input and output variables called the system's variables. Only those inputs that affected the output to a large extent were selected. The five important input variables were Layer thickness, Orientation, raster angle, raster width, air gap. Inclusion of more number of inputs to the system requires more number of rules and hence the complexity increases. The universe of discourse was also decided on the basis of the physical nature of the problem [22]. In the selection procedure, the above mentioned inputs and the output were taken in the form of linguistic format which displayed an important role in the application of fuzzy logic. For example, Layer thickness = {VS,S,M,L,VL}, Orientation = {VS,S,M,L,VL}, raster angle={VS,S,M,L,VL}, raster width = {VS,S,M,L,VL}, air gap = {VS,S,M,L,VL}, The output variables were similarly divided into %change in length(DL) = {T, VS, S , M , SM , ML, L , VL, H}, %change in width(%DW)=. {T, VS, S , M , SM , ML, L , VL, H}, % change in thickness(%DT)= {T, VS, S , M , SM , ML, L , VL, H}, A linguistic variable is a variable whose values are words or sentences in a natural or man-made language.

Where

T is Tiny, S is small, VS is very small, M is medium, L is large, VL is very large, ML is medium large, SM is small medium, H is high .

Selections of membership function for input and output variables

Linguistic values were expressed in the form of fuzzy sets. A fuzzy set is usually defined by its membership functions [23]. In general, triangular and trapezoidal membership functions were used to normalize the crisp inputs because of their simplicity and computational efficiency .The triangular membership function as described in equations 3 is used to convert the linguistic values in the range of 0 to 1.

$$triangle\,(x;a,b,c) = \begin{cases} 0, & x \le a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{c-x}{c-b}, & b \le x \le c \\ 0, & c \le x \end{cases}$$

$$triangle\,(x;a,b,c) = max\left(\,min\!\left(\dfrac{x-a}{b-a}, \dfrac{c-x}{c-b}\right),0\right)$$

Where a, b, c, d are the parameters of the linguistic value and x is the range of the input parameters. In this proposed model, each input have five triangular membership functions, where the output of the proposed model has nine triangular membership functions. The input variables from this array are converted to linguistic variable depending on grade of membership to the linguistic variable.[39] Similarly, the output of experimental runs is divided into nine output zones. The output is expressed in linguistic terms based on grade of membership.
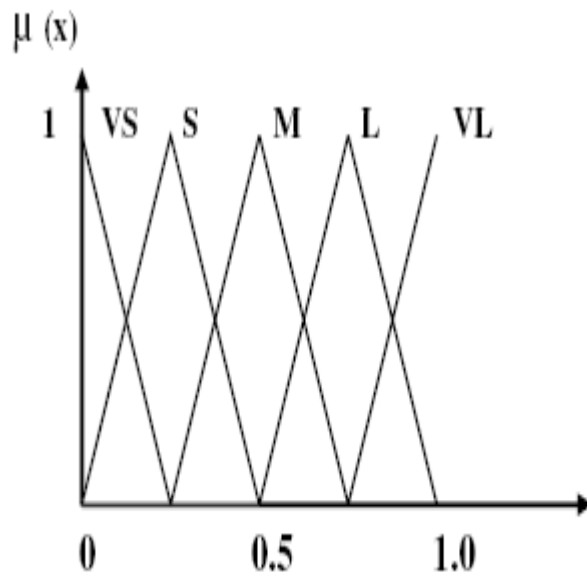
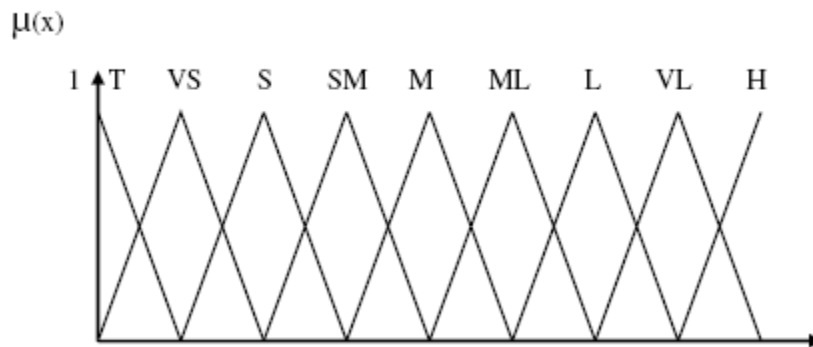**Fig 3: Input Membership function (A, B, C, D, E)**

Fig: 4   Output Membership function (%DL,%DW,%DT)

Rules for Mamdani fuzzy Mode

Rules form the basis for the fuzzy logic to obtain the fuzzy output. The rule based system is different from the expert system in the manner that the rules comprising the rule-based system originates from sources other than that of human experts and hence are different from expert systems. The rule-based form uses linguistic variables as its antecedents and consequents [24]. The antecedents express an inference or the inequality, which should be satisfied. The consequents are those, which we can infer, and is the output if the antecedent inequality is satisfied. The fuzzy rule-based system uses IF–THEN rule-based system (Mamdani and Assilia)(25), given by, IF antecedent, THEN consequent. The formation of rules is in general the canonical rule formation. For any linguistic variable,

there are three general forms in which the canonical rules can be formed. They are:

(1) Assignment statements
(2) Conditional statements
(3) Unconditional statement

The rules are formed according to problem statement and the work is carried out in Fuzzy logic toolbox in MATLAB and rules predicted are shown belo
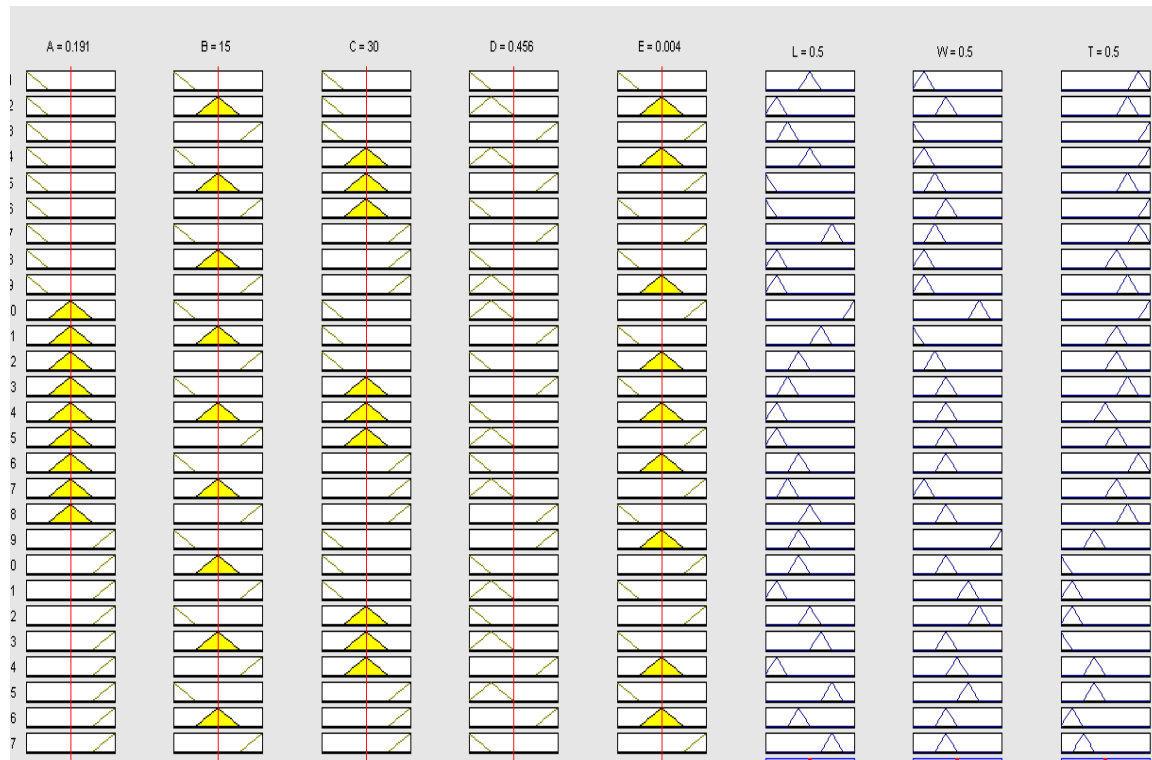

Fig: 5 Rules box determined from Fuzzy tool box in MATLAB

Defuzzification

Defuzzification means the fuzzy to crisp conversions. The fuzzy results generated cannot be used as such to the applications, hence it is necessary to convert the fuzzy quantities into crisp quantities for further processing. This can be achieved by using defuzzification process. The defuzzification has the capability to reduce a fuzzy to a crisp single-valued quantity or as a set, or converting to the form in which fuzzy quantity is present [26]. Defuzzification can also be called as "rounding off" method. Defuzzification reduces the collection of membership function values in to a single sealer quantity. In this chapter we will discuss on the various

Defuzzification Methods

Apart from the lambda cut sets and relations which convert fuzzy sets or relations into crisp sets or relations, there are other various defuzzification methods employed to convert the fuzzy quantities into crisp quantities. The output of an entire fuzzy process can be union of two or more fuzzy membership functions.

There are seven methods used for defuzzifying the fuzzy output functions.

They are:
(1) Max-membership principle,
(2) Centroid method,
(3) Weighted average method,
(4) Mean–max membership,
(5) Centre of sums,
(6) Centre of largest area, and
(7) First of maxima or last of maxima

In many instances, it is desired to come up with a single crisp output from an FIS. For example, if one was trying to classify a letter drawn by hand on a drawing tablet, ultimately the FIS would have to come up with a crisp number to tell the computer which letter was drawn [27]. This crisp number is obtained in a process known as defuzzification. There are two common techniques for defuzzifying:

1. **Center of mass.**

   This technique takes the output distribution and finds its of mass to come up with one crisp number. It is computed as shown below [(Jang et al., 2005]

   $$z = \frac{\sum_{j=1}^{q} Z_j u_c(Z_j)}{\sum_{j=1}^{q} u_c(Z_j)},$$

2. **Mean of maximum.**

   This technique takes the output distribution and finds its mean of maxima to come up with one crisp number. It is computed as shown

   $$z = \sum_{j=1}^{l} \frac{z_j}{l},$$

RESULTS AND DISCUSSIONS
Chapter 4

1) From statistical analysis ,the effect of each parameter on responses are calculated and the using the SN ratios from Table 3, the SN ratios plots are shown below for determining the optimal parameter settings.

Main effect of plot for

 a)% change in length

b) % change in width

c)% change in thickness
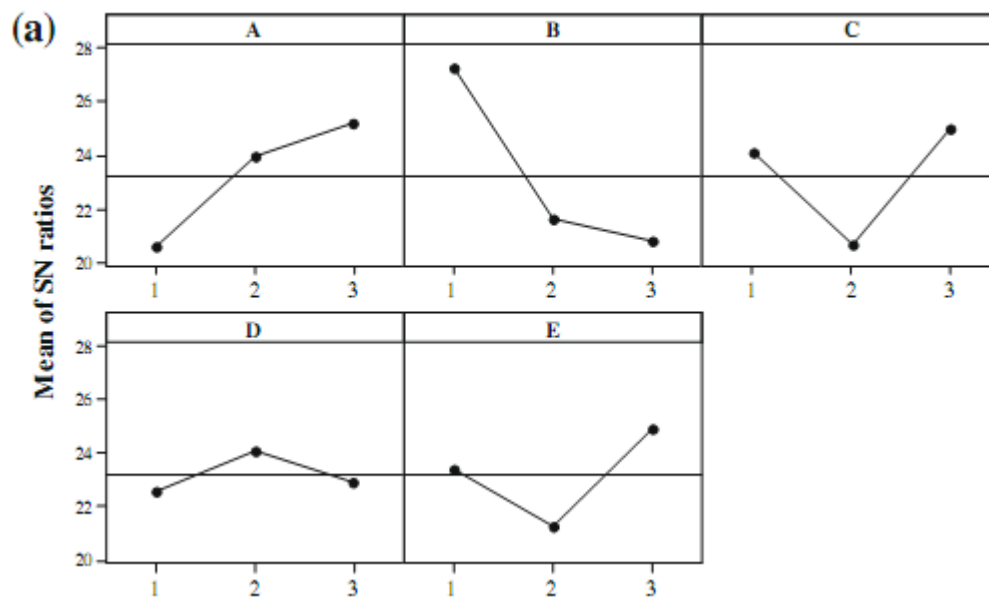
SN ratio plot for smaller the better

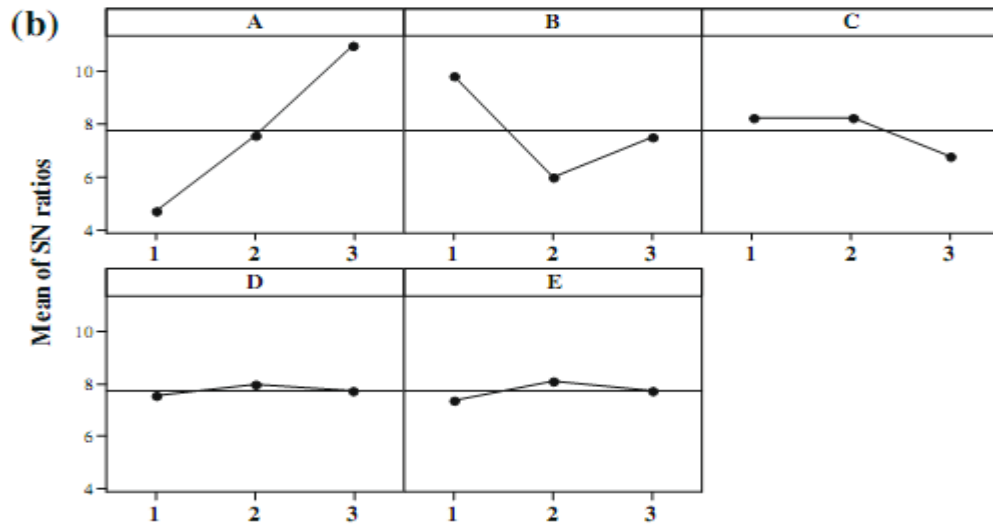**Fig: 6 SN ratio plot for % change in length (DL)**

(b)

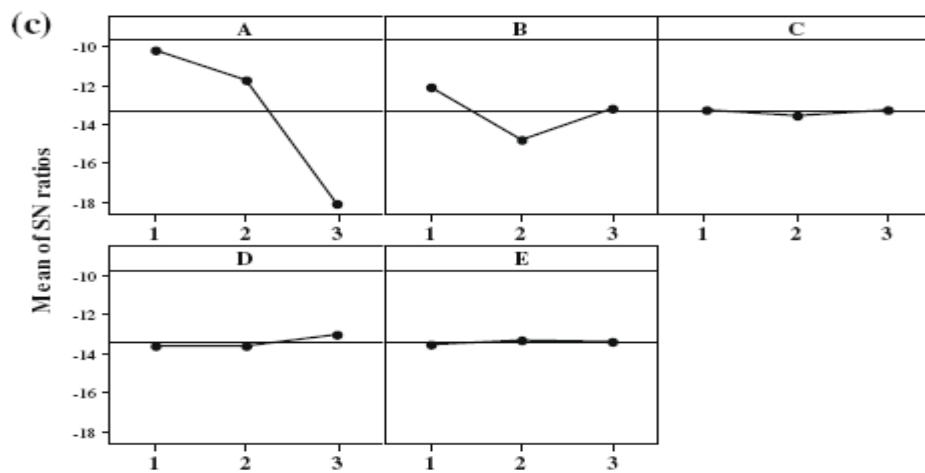Fig: 7 SN ratio plot for % change in width(DW)

(c)

Fig: 8 SN ratio plot for % change in thickness (DT)

Experimental data on percentage change in dimension is converted to S/N ratio value as shown in Table 3 using Eq. (2) for smaller the better quality characteristic. Main effect plot for S/N ratio plotted above gives the optimum factor levels (Table 7). The significant factors and interactions (Table 7) are identified using ANOVA shown in Tables 4–6 for %DL, %DW and %DT, respectively [38]

Table 4 Anova table for %change (%DL) in length [38]

Source	DOF	SS	V	F	P(%)
A	2	100.486	50.243	2.762413	10.67958
B	2	224.957	112.478	6.184159	23.90827
C	2	95.084	47.542	2.613909	10.10546
D		12.152			
E		61.578			
AXB		68.18			
BXC		76.347			
BXD	4	168.206	42.052	2.312063	17.87682
BXE	4	133.928	33.482	1.840876	14.23377
Error	12	218.257	18.18808		
Total	26	940.917			

Table 5 Anova table for %change(%DW) in width

Source	DOF	SS	V	F	P(%)
A	2	177.304	88.652	22.73795	42.87459
B	2	69.176	34.588	8.871318	16.72772
C		12.685			
D		0.864			
E		2.266			
AXB	4	65.842	16.46	4.22175	15.92152
BXC		29.816			
BXD		8.953			
BXE	4	46.636	11.659	2.990363	11.27724
Error	14	54.584			
Total	26	413.541			

Table 6:Anova table for % change(%DT) in thickness [38]

Source	DOF	SS	V	F	P(%)
A	2	322.492	161.246	291.0578	83.18617
B	2	33.962	16.981	30.65162	8.760431
C		0.529			
D		2.52			
E		0.248			
AXB	4	5.951	1.488	2.685921	1.535049
BXC	4	5.645	1.488	2.685921	1.456117
BXD	4	14.084	3.521	6.355596	3.63294

BXE		2.243			
Error	10	5.54	0.554		
Total	26	387.675			

Table 7 Optimum factor level with significant factors and interactions [38]

Factor	%DL	%DW	%DT
A	3	3	1
B	1	1	1
C	3	2	1
D	2	2	3
E	3	2	2
Significant	A,B,C,BXD,BXE	A,B,AXB,BXE	A,B,AXB,BXC,BXD

Table 8 below shows the result of confirmation experiments. Small error in the tune of 2–3% indicates the Taguchi experimental plan has proceeded in a smooth manner and proposed predictive equation (Eq. (7)) is valid.

Table 8.**Results of confirmation experiment   [38]**

Characteristic	Factor and their levels	Predicted S/N ratio	Experimental S/N ratio	Error
%DL	A3 B1 C3 D2 E3	38.5338	39.6898	2.03%
%DW	A3 B1 E2	14.9123	15.2851	2.50%
%DT	A1 B1 C1 D3	-8.69100	-8.51718	2.50%

1)The best optimal parameter settings for %change in length are A3,B1,C3,D2,E3

2)The best optimal parameter settings for %change in width are A3,B1,E2

3)The best optimal parameter settings for %change in thickness are A1,B1,C1,D3

Prediction of Dimensional Accuracy using Fuzzy Inference System

As discussed above that the Mamdani fuzzy inference is used for predicting the dimensional accuracy of test specimen[31], since this method takes uncertainity into account and is very useful in shop floor practice.It makes the use of Lingusitic variables (Low,medium,high) that could be very easily understood by the workers

Normalisation: .Experiment conducted provide data in SN ratio (smaller the better) but this data should be normalised using the formula as shown below[32]. The normalisation is carried out to give values in range of 0 to 1 for all responses ,so that rule box to be created with help of Fuzzy tool box in MATLAB2009 could be easily done ,and therefore it shall help in prediction of Dimensional accuracy in more accurate way.

$Yi= (Y – Ymin)/(Ymax – Ymin)$

Where Yi is normalised value of either %DL,%DW,%DT.

Y is corresponding value of SN ratio of either %DL,%DW,%DT from Table 3.

Ymax and Y min are the maximum and minimum values of SN ratio of 27 trials shown in Table 3 of %DL or %DW or %DT

W is Width,T is Thickness, L is length, %DL is change in length, %DT is change in thickness, %DW is change in width

Table 9: **Normalisation Data for SN ratio (Table 3)**

Experiment No	%change in L	% change in W	% change in thickness (T)
1	0.4601	0.1295	0.9134
2	0.4702	0.4774	0.5032
3	0.2134	0	1
4	0.5038	0.4659	0.4773
5	0	0.2635	0.7185
6	0.7283	0.3574	0.9773
7	0.1297	0.2302	0.8548
8	0.4702	0.1151	0.6882
9	0.4779	0.5416	0.5242
10	1	0.5364	0.4773
11	0.6401	0.0430	0.6311
12	0.3679	0.2635	0.6042
13	0.2495	0.4136	0.7502
14	0.1114	0.3574	0.5132
15	0.4638	0.4136	0.5042
16	0.3685	0.4136	0.8933
17	0.4690	0.4651	0.5149
18	0.5102	0.4136	0.7502
19	0.3593	1	0.3629

20	0.4046	0.3535	0.0361
21	0.4903	0.5123	0.4776
22	0.5382	0.7907	0.1368
23	0.5136	0.4787	0
24	0.1351	0.5171	0.3511
25	0.5256	0.5127	0.4629
26	0.4194	0.3787	0.1337
27	0.7336	0.3787	0.2442

The Value of Level for each factor A, B, C, D, E is known from Table 2. There are five factors and each factor has three level so there will be 3^5 experiments. So it also requires same amount of rules to be made in toolbox in MATLAB while using fuzzy logic [33] .This may be time consuming and expensive, therefore Design of experiments (DOE) is used to reduce the number of experiments and 27 trials will be conducted as shown in Table 3.

Results: using Fuzzy logic Tool box in MATLAB 2009

With the help of Design of experiment technique, the rule box is generated in fuzzy logic tool box in MATLAB 2009.

There were 5 inputs(A,B,C,D,E) and 3 outputs(%DL,%DW,%DT) and each input has five membership function and each output has 9 membership function. Ranges of input function are set according to value given in table 2. With use of normalised data in above table 9, range of output functions were divided and thereby membership functions were plotted.

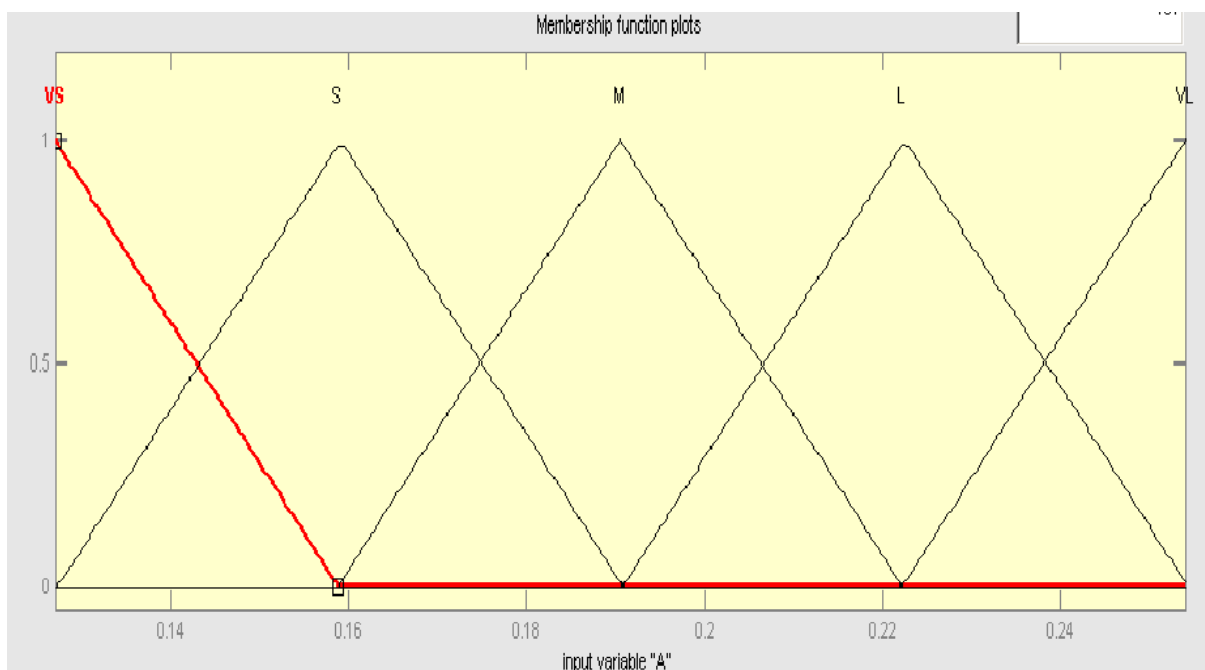The membership functions with range were determined as shown: [41]

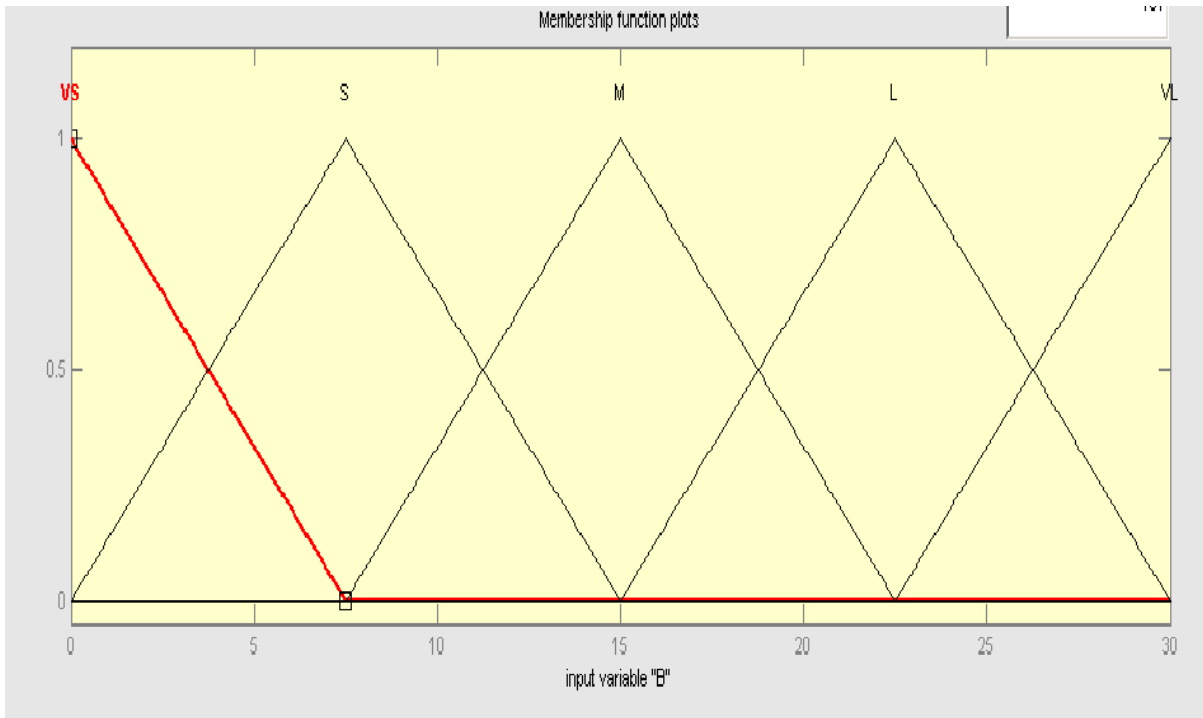**Fig: 9 INPUT "A" having 5 membership function with range 0.127 to 0.254**

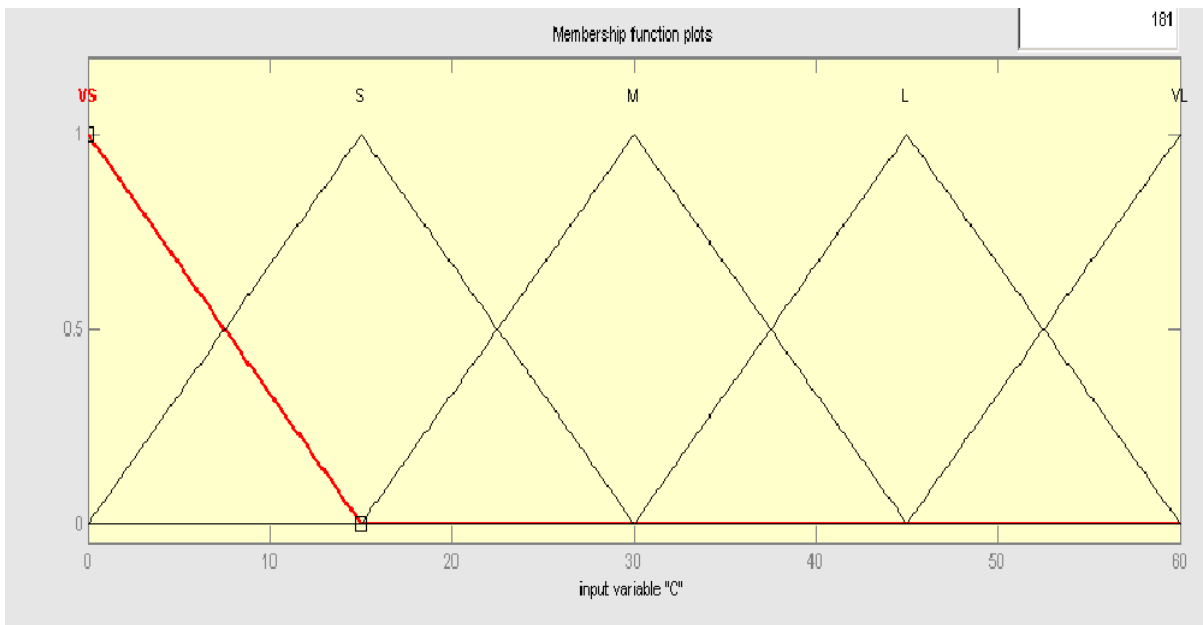**Fig: 10 INPUT "B" having 5 membership functions with range 0 to 30**

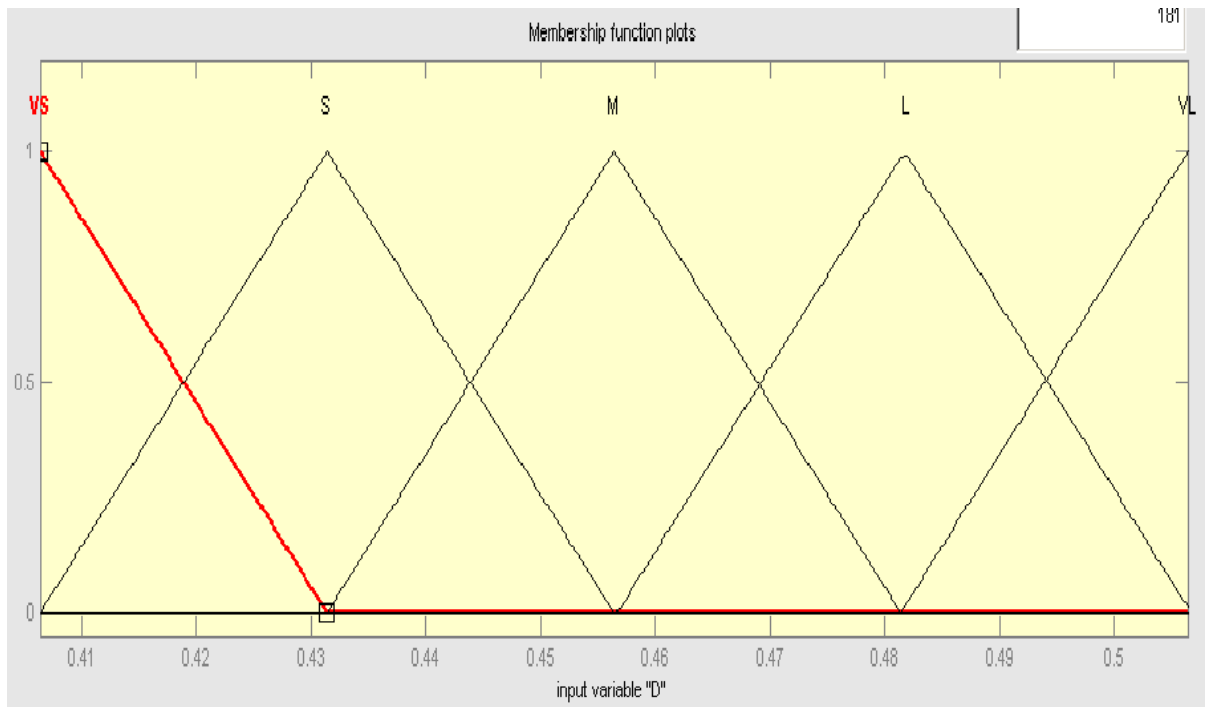**Fig: 11 INPUT "C" having 5 membership functions with range 0 to 60**

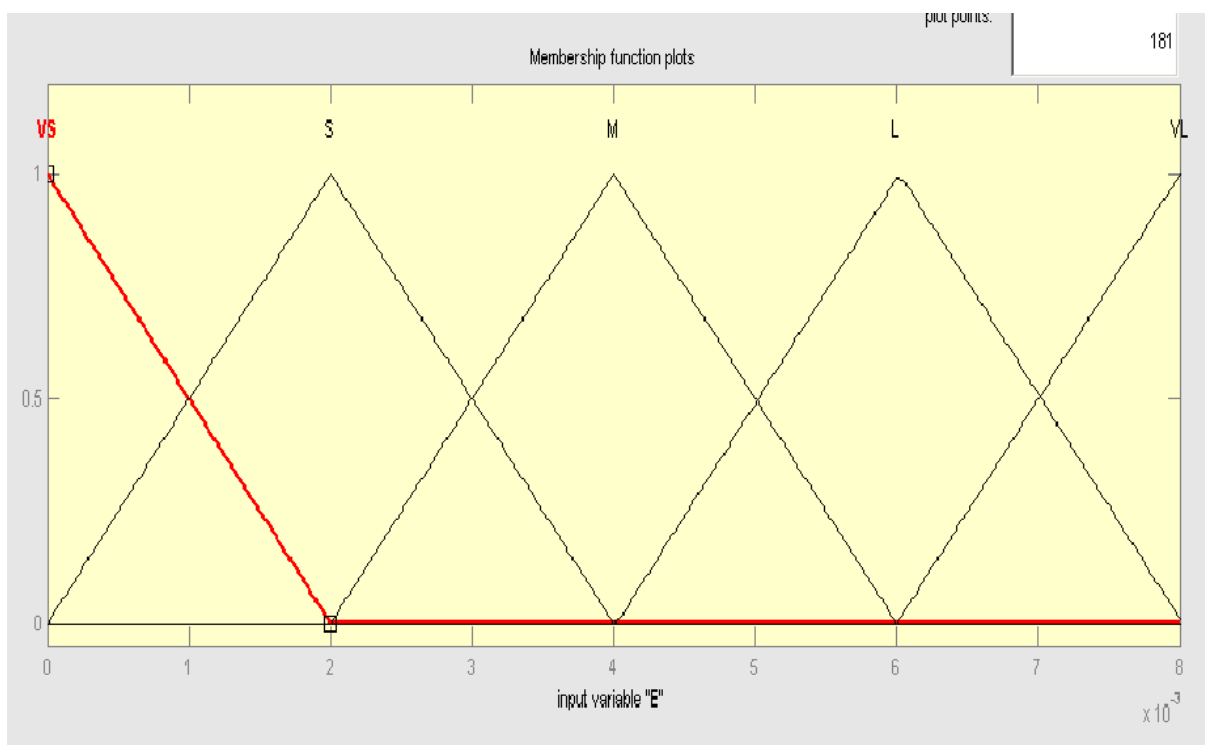**Fig: 12 INPUT "D" having 5 membership functions with range 0.4064 to 0.5064**

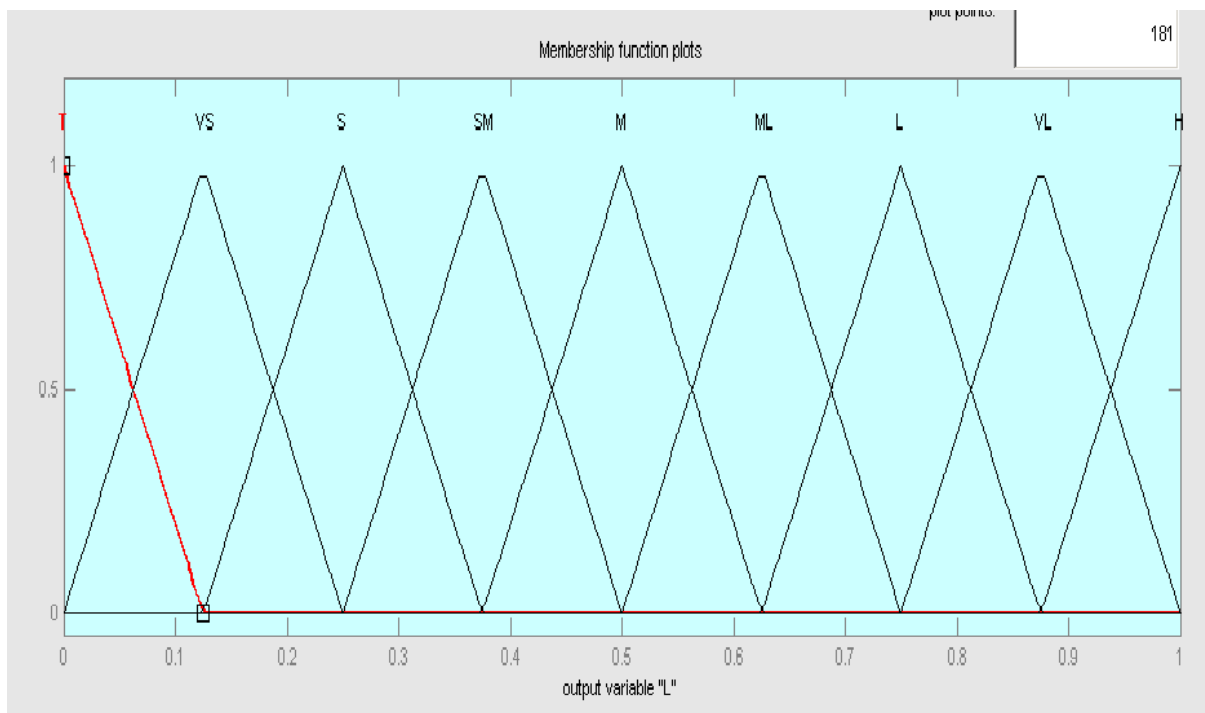**Fig: 13 INPUT "E" having 5 memberships function with range 0 to 0.008**

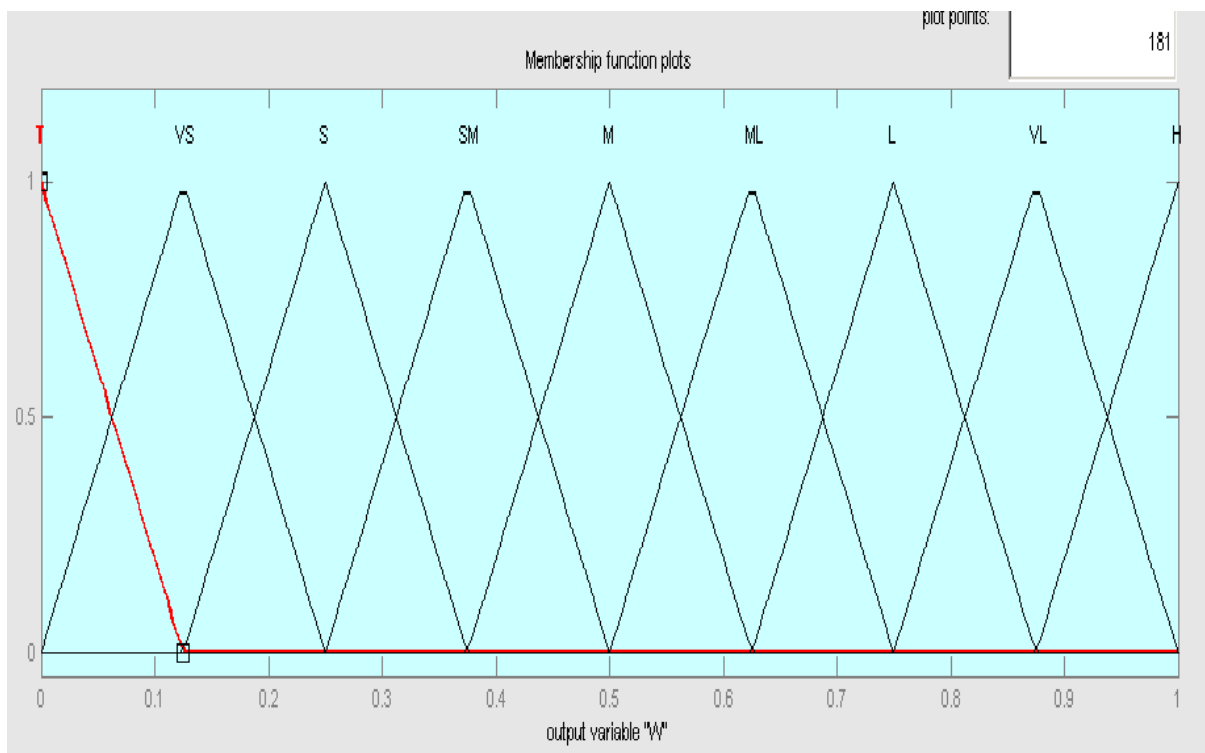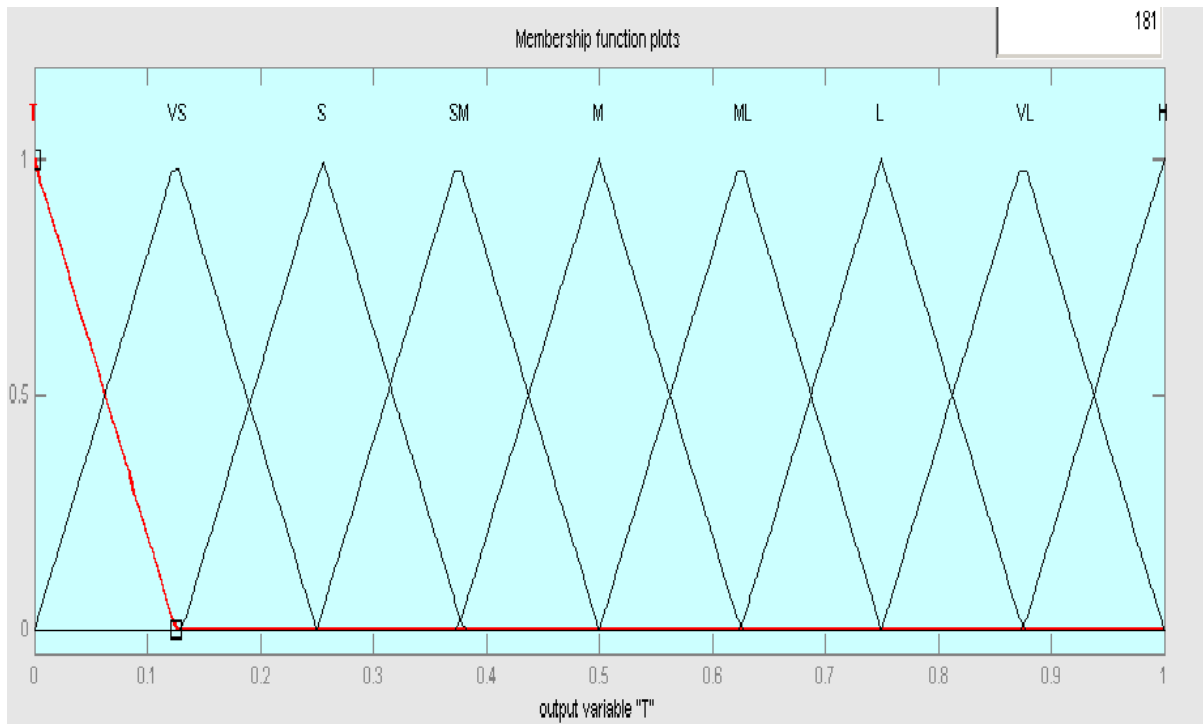**Fig: 14 Output 1(%DL) having 9 membership functions with range 0 to 1**

**Fig: 16 Output 3(%DT) having 9 membership functions with range 0 to 1**

Now with help of data given of Inputs in Table 3 and normalised data of outputs in Table 9, the influence of each input was studied on responses using membership functions plots above. Thus rule box was formed accordingly.[41]

Rule Box:

1) If (A is VS) and (B is VS) and (C is VS) and (D is VS) and (E is VS) then (L is M) (W is VS) (T is VL)
2) If (A is VS) and (B is M) and (C is VS) and (D is S) and (E is M) then (L is VS) (W is SM) (T is L)
3) If (A is VS) and (B is VL) and (C is VS) and (D is VL) and (E is VL) then (L is S) (W is T) (T is H)
4) If (A is VS) and (B is VS) and (C is M) and (D is S) and (E is M) then (L is M) (W is VS) (T is H)
5) If (A is VS) and (B is M) and (C is M) and (D is VL) and (E is VL) then (L is T) (W is S) (T is L)
6) If (A is VS) and (B is VL) and (C is M) and (D is VS) and (E is VS) then (L is T) (W is SM) (T is H)
7) If (A is VS) and (B is VS) and (C is VL) and (D is VL) and (E is VL) then (L is L) (W is S) (T is VL)
8) If (A is VS) and (B is M) and (C is VL) and (D is VS) and (E is VS) then (L is VS) (W is VS) (T is ML)

9) If (A is VS) and (B is VL) and (C is VL) and (D is S) and (E is M) then (L is VS) (W is VS) (T is L)

10) If (A is M) and (B is VS) and (C is VS) and (D is S) and (E is VL) then (L is H) (W is L) (T is H)

11) If (A is M) and (B is M) and (C is VS) and (D is VL) and (E is VS) then (L is ML) (W is T) (T is ML)

12) If (A is M) and (B is VL) and (C is VS) and (D is VS) and (E is M) then (L is SM) (W is S) (T is ML)

13) If (A is M) and (B is VS) and (C is M) and (D is VL) and (E is VS) then (L is S) (W is SM) (T is L)

14) If (A is M) and (B is M) and (C is M) and (D is VS) and (E is M) then (L is VS) (W is SM) (T is M)

15) If (A is M) and (B is VL) and (C is M) and (D is S) and (E is VL) then (L is VS) (W is SM) (T is ML)

16) If (A is M) and (B is VS) and (C is VL) and (D is VS) and (E is M) then (L is SM) (W is SM) (T is VL)

17) If (A is M) and (B is M) and (C is VL) and (D is S) and (E is VL) then (L is S) (W is VS) (T is ML)

18) If (A is M) and (B is VL) and (C is VL) and (D is VL) and (E is VS) then (L is M) (W is SM) (T is L)

19) If (A is VL) and (B is VS) and (C is VS) and (D is VL) and (E is M) then (L is SM) (W is H) (T is SM)

20) If (A is VL) and (B is M) and (C is VS) and (D is VS) and (E is VL) then (L is SM) (W is SM) (T is T)

21) If (A is VL) and (B is VL) and (C is VS) and (D is S) and (E is VS) then (L is VS) (W is ML) (T is VL)

22) If (A is VL) and (B is VS) and (C is M) and (D is VS) and (E is VL) then (L is M) (W is L) (T is VS)

23) If (A is VL) and (B is M) and (C is M) and (D is S) and (E is VS) then (L is ML) (W is SM) (T is T)

24) If (A is VL) and (B is VL) and (C is M) and (D is VL) and (E is M) then (L is VS) (W is M) (T is SM)

25) If (A is VL) and (B is VS) and (C is VL) and (D is S) and (E is VS) then (L is L) (W is ML) (T is SM)

26) If (A is VL) and (B is M) and (C is VL) and (D is VL) and (E is M) then (L is SM) (W is SM) (T is VS)

27) If (A is VL) and (B is VL) and (C is VL) and (D is VS) and (E is VL) then (L is L) (W is SM) (T is S)

Fig: 17 Rules Shown in MATLAB Fuzzy tool box for this Experiment
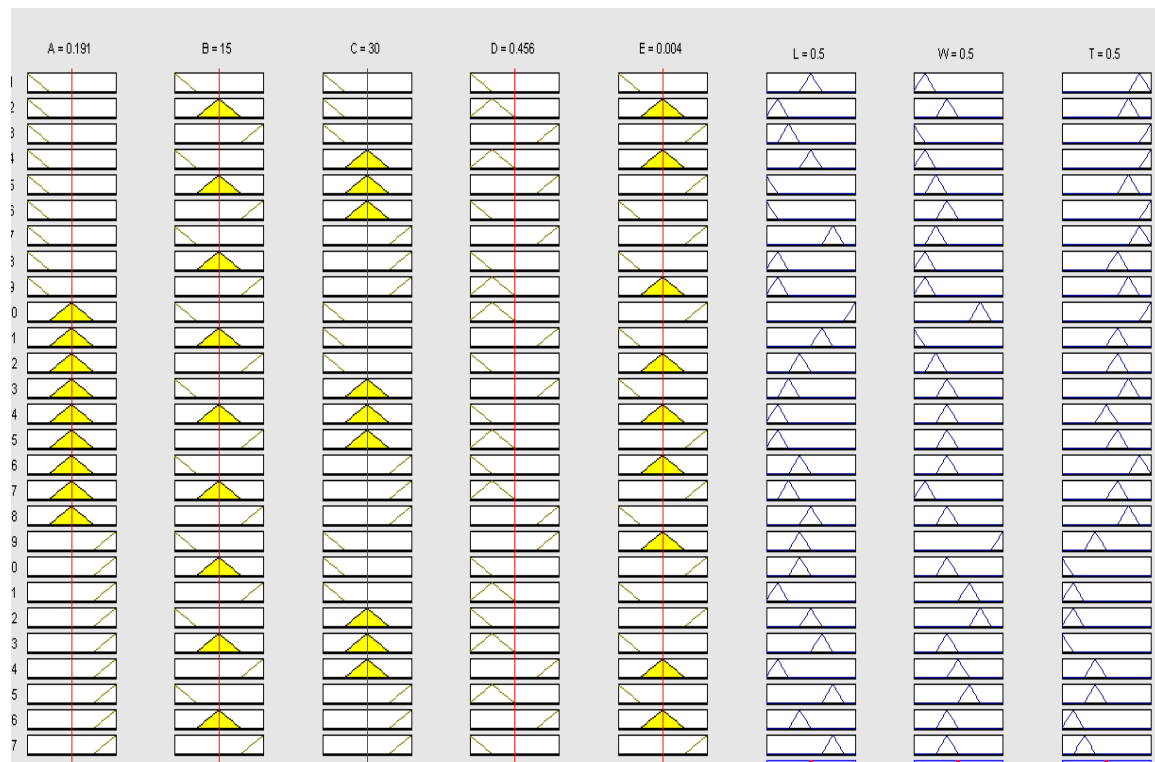
Finally the results were predicted using Fuzzy inference system (FIS) in MATLAB 2009 as shown below[41]

'Tanuja' is 'file name'

```
>> a=readfis('TANUJA');
>> evalfis([.127 0 0 .4064 0;.127 15 0 .4564 .004;.127 30 0 .5064
.008],a)

ans =

    0.5000    0.1250    0.8750
    0.5000    0.5000    0.5000
    0.2500    0.0385    0.9615

>> a=readfis('TANUJA');
>> evalfis([.127 0 30 .4564 .004;.127 15 30 .5064 .008;.127 30 30 .4064
0],a)

ans =

    0.5000    0.5000    0.5000
    0.0385    0.2500    0.7500
    0.0385    0.3750    0.9615
```

```
>> a=readfis('TANUJA');
>> evalfis([.127 0 60 .5064 .008;.127 15 60 .4064 0;.127 30 60 .4564
.004],a)

ans =

    0.7500    0.2500    0.8750
    0.1250    0.1250    0.6250
    0.5000    0.5000    0.5000

>> a=readfis('TANUJA');
>> evalfis([.178 0 0 .4564 .008;.178 15 0 .5064 0;.178 30 0 .4064
.004],a)

ans =

    0.9500    0.5000    0.5000
    0.6250    0.0438    0.6250
    0.3750    0.2500    0.6250

>> a=readfis('TANUJA');
>> evalfis([.178 0 30 .5064 0;.178 15 30 .4064 0.004;.178 30 30 .4564
.008],a)

ans =

    0.2500    0.3750    0.7500
    0.1250    0.3750    0.5000
    0.5000    0.5000    0.5000

>> a=readfis('TANUJA');
>> evalfis([.178 0 60 .4064 .004;.178 15 60 .4564 0.008;.178 30 60
.5064 0],a)

ans =

    0.3750    0.3750    0.8750
    0.5000    0.5000    0.5000
    0.5000    0.3750    0.7500

>> a=readfis('TANUJA')
>> evalfis([.254 0 0 .5064 .004;.254 15 0 .4064 0.008;.254 30 0 .4564
0],a)

ans =

    0.3750    0.9615    0.3750
    0.3750    0.3750    0.0386
    0.5000    0.5000    0.5000

>> a=readfis('TANUJA');
>> evalfis([.254 0 30 .4064 .008;.254 15 30 .4564 0;.254 30 30 .5064
.004],a)

ans =

    0.5000    0.7500    0.1251
    0.5000    0.5000    0.5000
```

```
     0.1250     0.5000     0.3750

>> a=readfis('TANUJA');
>> evalfis([.254 0 60 .4564 0;.254 15 60 .5064 .004;.254 30 60 .4064
.008],a)

ans =

     0.5000     0.5000     0.5000
     0.3750     0.3750     0.1251
     0.7500     0.3750     0.2554
```

Table 10: Prediction of results using Fuzzy logic tool box in MATLAB[41]

| Factors						SN Ratio	SN Ratio	SN Ratio
Exp No	A	B	C	D	E	%change in L	%change in W	%change in T
1	1	1	1	1	1	0.5000	0.1250	0.8750
2	1	2	1	2	2	0.5000	0.5000	0.5000
3	1	3	1	3	3	0.2500	0.0385	0.9615
4	1	1	2	2	2	0.5000	0.5000	0.5000
5	1	2	2	3	3	0.0385	0.2500	0.7500
6	1	3	2	1	1	0.7500	0.3750	0.9615
7	1	1	3	3	3	0.1250	0.2500	0.8750
8	1	2	3	1	1	0.5000	0.1250	0.6250
9	1	3	3	2	2	0.5000	0.5000	0.5000
10	2	1	1	2	3	0.9500	0.5000	0.5000
11	2	2	1	3	1	0.6250	0.0438	0.6250
12	2	3	1	1	2	0.3750	0.2500	0.6250
13	2	1	2	3	1	0.2500	0.3750	0.7500
14	2	2	2	1	2	0.1250	0.3750	0.5000
15	2	3	2	2	3	0.5000	0.5000	0.5000
16	2	1	3	1	2	0.3750	0.3750	0.8750
17	2	2	3	2	3	0.5000	0.5000	0.5000
18	2	3	3	3	1	0.5000	0.3750	0.7500
19	3	1	1	3	2	0.3750	0.9615	0.3750
20	3	2	1	1	3	0.3750	0.3750	0.0386
21	3	3	1	2	1	0.5000	0.5000	0.5000
22	3	1	2	1	3	0.5000	0.7500	0.1251
23	3	2	2	2	1	0.5000	0.5000	0.5000
24	3	3	2	3	2	0.1250	0.5000	0.3750
25	3	1	3	2	3	0.5000	0.5000	0.5000
26	3	2	3	3	1	0.3750	0.3750	0.1251
27	3	3	3	1	2	0.7500	0.3750	0.2554

Table 11: Error % calculated between Fuzzy inference systems (FIS) and the Experimental results (Exp).

Error = Modulus of [(Experimental results – Predicted results (FIS))/Experimental results]

| Factors	SN Ratio (FIS)	SN Ratio (FIS)	SN Ratio (FIS)	SN Ratio (Exp)	SN Ratio	SN ratio (Exp)	Error	Error	Error
Exp No	%change in L	%change in W	%change in T	%change in L	% change in W	% change in T	% DL	% DW	% DT
1	0.5000	0.1250	0.8750	0.4601	0.1295	0.9134	8.6	3.4	4.2
2	0.5000	0.5000	0.5000	0.4702	0.4774	0.5032	6.3	4.7	0.63
3	0.2500	0.0385	0.9615	0.2134	0	1	3.6	3.8	3.85
4	0.5000	0.5000	0.5000	0.5038	0.4659	0.4773	0.75	7.3	4.7
5	0.0385	0.2500	0.7500	0	0.2635	0.7185	3.8	5.1	4.3
6	0.7500	0.3750	0.9615	0.7283	0.3574	0.9773	2.9	4.9	1.6
7	0.1250	0.2500	0.8750	0.1297	0.2302	0.8548	3.6	8.5	2.3
8	0.5000	0.1250	0.6250	0.4702	0.1151	0.6882	6.3	8.6	9.1
9	0.5000	0.5000	0.5000	0.4779	0.5416	0.5242	4.6	7.6	4.6
10	0.9500	0.5000	0.5000	1	0.5364	0.4773	5	6.7	4.7
11	0.6250	0.0438	0.6250	0.6401	0.0430	0.6311	0.051	1.8	0.96
12	0.3750	0.2500	0.6250	0.3679	0.2635	0.6042	1.9	5.1	3.4
13	0.2500	0.3750	0.7500	0.2495	0.4136	0.7502	0.2	9.2	0.02
14	0.1250	0.3750	0.5000	0.1114	0.3574	0.5132	1.2	4.9	2.5
15	0.5000	0.5000	0.5000	0.4638	0.4136	0.5042	7.8	9.2	0.83
16	0.3750	0.3750	0.8750	0.3685	0.4136	0.8933	1.7	9.2	2.04
17	0.5000	0.5000	0.5000	0.4690	0.4651	0.5149	6.6	7.5	2.80
18	0.5000	0.3750	0.7500	0.5102	0.4136	0.7502	1.9	9.2	0.02
19	0.3750	0.9615	0.3750	0.3593	1	0.3629	4.3	3.8	3.3
20	0.3750	0.3750	0.0386	0.4046	0.3535	0.0361	7.3	6.08	6.9
21	0.5000	0.5000	0.5000	0.4903	0.5123	0.4776	1.9	2.4	4.6
22	0.5000	0.7500	0.1251	0.5382	0.7907	0.1368	7.09	5.1	8.5
23	0.5000	0.5000	0.5000	0.5136	0.4787	0	2.64	4.4	5%
24	0.1250	0.5000	0.3750	0.1351	0.5171	0.3511	7.4	3.3	6.8
25	0.5000	0.5000	0.5000	0.5256	0.5127	0.4629	4.8	2.4	8.01
26	0.3750	0.3750	0.1251	0.4194	0.3787	0.1337	9.5	0.97	6.4
27	0.7500	0.3750	0.2554	0.7336	0.3787	0.2442	2.23	0.97	4.5

Graphs: After calculating the error % the graphs were plotted between Experimental and predicted Fuzzy Inference System (FIS).

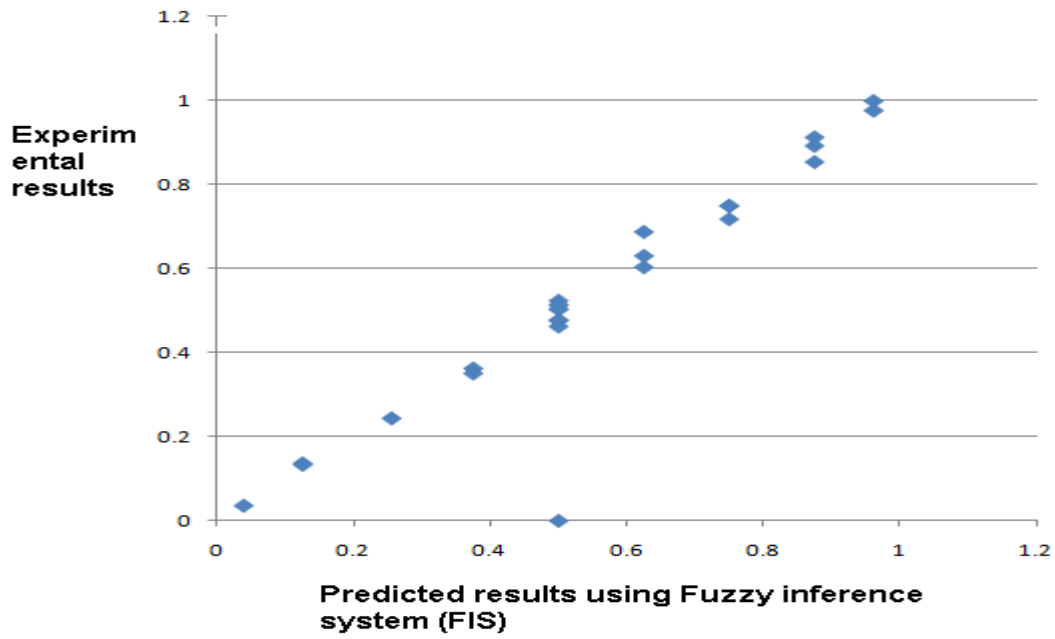1) **Experimental %DL versus Predicted % DL (FIS)**
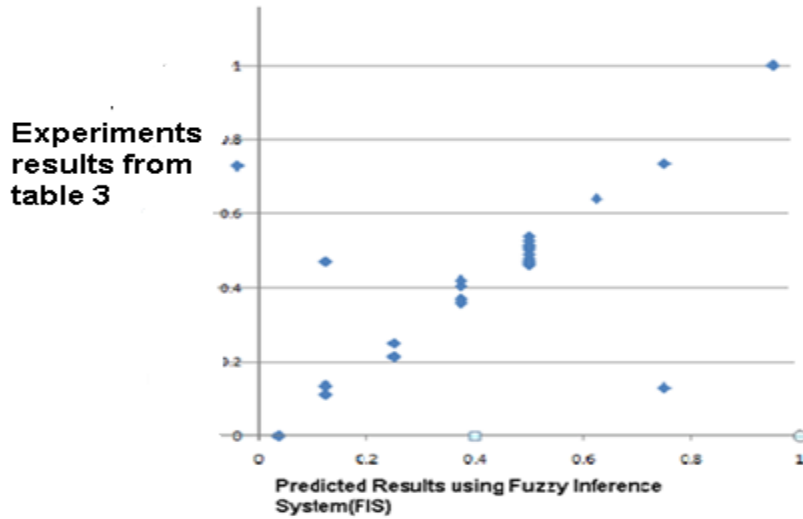
Correlation Coefficient =0.9925, which indicates strong linear relationship

2) **Experimental %DW versus Predicted %DW(FIS)**
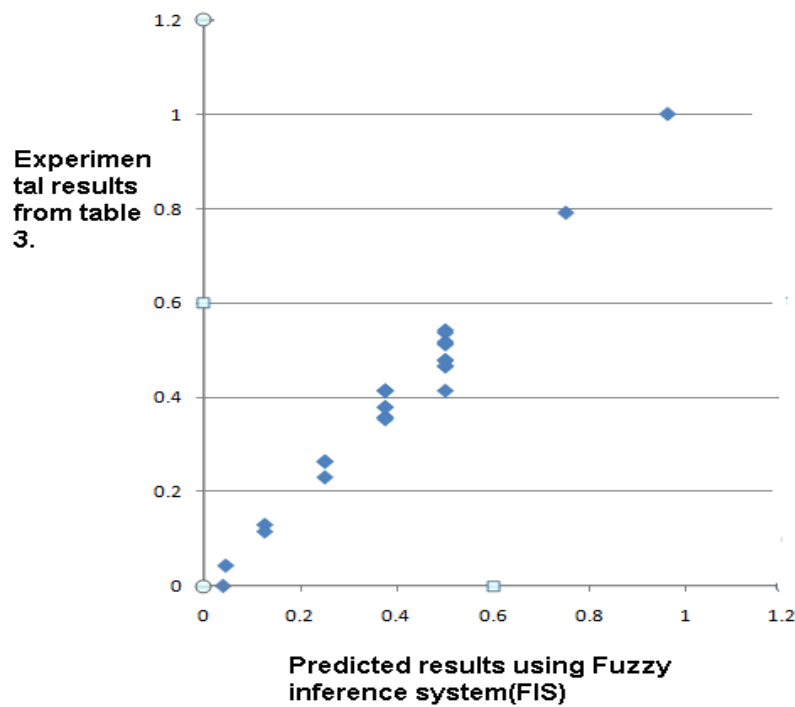
Correlation Coefficient =0.98934, which indicates strong linear relationship

3) Experimental %DT versus Predicted % DT (FIS)

Correlation Coefficient =0.9334, which indicates better linear relationship

CONCLUSION

Chapter 5

CONCLUSION:

The results predicted by Taguchi method shows that the shrinkage is dominant along the length and width of test part whereas thickness is always more than desired value . The best combination for minimisation of % change in length are higher layer thickness(level 3), orientation(level 1), maximum raster angle(level 3) , medium raster width(level 2), maximum air gap(level 3). For minimising the % change in width, it requires medium raster angle (level 2) and medium air gap (level 2) and for lower thickness it requires layer thickness (level 1) ,orientation (level 1) , raster angle (level 1), and higher value of raster width (level 3) and air gap at level 3. Study on observed results shows that there are large number of conflicting factors independently or interaction with others may influence the dimensional accuracy. The dimensional accuracy was predicted using the Fuzzy inference system (FIS) and error was calculated between the experimental results and predicted results. The graphs between experimental and predicted results were plotted for %change in length, width and thickness. Correlation coefficients were determined between experiment results and predicted results that shows the strong linear relationship between them. The low percentage error shows that the results predicted by Mamdani fuzzy logic were highly accurate and precise.

Future Scope of work:

The experimental results were calculated by considering the process parameters only ,while other parameters like temperature, humidity were kept constant .Therefore this work still require consideration of latter parameters for predicting the dimensional accuracy in more accurate way. Taguchi methods emphasize only on single quality characteristic and, in comparison, paid little attention on multiple performance characteristics (MPCs) Nevertheless; the MPCs of a product is very much acceptable in market. While optimising a process with MPCs, the best process parameters can be determined that will simultaneously optimise all the quality characteristics of interest to the designer. Using the fuzzy logic analysis, the MPCs can be easily dealt with by setting up a reasoning procedure for each performance characteristic and transform them into a single value of the multiple performance characteristic indices (MPCIs).

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