Design and Development of a Fuzzy Logic Controller for Prediction of Inner Surface Finish of Flow Formed Component

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Abstract: Fuzzy logic controller (FLC) is well suited where there is a considerable amount of uncertainty in the process. Flow forming is an incremental forming process widely used used to reduce thickness of the tubes. Compared to machining it improves the strength. It is extensively used for manufacturing of components used for aerospace and automobile applications. The surface finish depends on stagger and the feed rate and their combined effect on the surface finish of the tube formed by flow forming process. The uncertainty arises due variation of these parameters . Hence in the present work a Fuzzy logic controller is developed to predict the surface finish with variation of stagger and feed rate and validated. The experiments are carried out on SAE 4130 Steel using L4 orthogonal array. To deal . To minimise the no. of experiments in designing data base an L-4 orthogonal array is chosen for experimentation. Flow forming is carried out and and data base with 4 rules are formulated. Triangular membership function is selected for the input and out variables and FLC is designed. The FLC is validated with 5 more experiments. Mamdani approach is used to develop the Fuzzy controller.

Key words: Orthogonal array, Fuzzy logic controller, Flow forming, Triangular function, Mamdani approach, crisp value, Membership function.

1.0 Introduction

A fuzzy logic controller is described by a set of rules of type IF (condition) THEN (action) to convert the language control strategy acquired from a human expert into a well-adapted automatic control strategy [1]. Fuzzilogic controllers are extensively used in many engineering application [2-6]
Flow forming is process in which tube fitted on the madrel is is locally deformed by the rollers to reduce its thickness. In the processes the mechanical properties of the material improve a lot . before the mid of 20th century , the thin walled components form the sheet metal such as domestic products were used to be manufactured by spinning process [7]. Due to higher skill requirement and lower repeatable more mechanised processes such as flow forming is developed [8]. More over lubrication becomes a major problem in drawing of long cylinders necciating a better process for manufacturing of thin walled cylindrical components [9] as the There is a significant work by various authors on mechanics of shear forming, shear spinning of cones, spinning of tubes. It is very difficult, if not impossible, to work to close dimensional tolerances, especially when producing large diameter articles from thin gauge material. It is equally difficult to control thickness variations in the final product to less than about 25% of the blank thickness. In contrast to hand spinning sheet metal, flow forming is based upon the principle of equal volumes. The basic shape used for practically all calculations in flow forming is cylinder. The thickness of the preforms is a function of the final length of the finished product [10]. Flow forming is a technique of elongating a thick walled preforms by reducing its wall thickness.[11]. Because of a number of merits such as lesser loads, flexibility, cheaper tooling the designs can be optimized for weight and cost specifically in automotive and aerospace [12]

Various parts that can be manufactured by flow forming are rocket motor shells, airframe and power train components, Gas bottles etc. flow forming machines are much more robust and can generate sufficiently higher forces, so are capable of processing of stronger materials such as super alloys [13].

The various parameters that need to be considered in flow forming are the speed of the mandrel, the contact geometry between the roller and the work piece, the feed, tangential force, roller angle, roller nose radius, the angle of the tilt of the roller axis with respect to the mandrel axis etc.

One of the significant feature of flow forming is its ability to take large local deformations with out failure [14]. More over pressure acting on the cylinder is not uniform. The friction force and between the cylinder tube and mandrel affects the average pressure on the roller [15]. In addition to it , the deformation area is very small compared to the work piece area there by the deformation is resisted by the material surround to the localized deformed area. Because of this the stress-strain distribution is highly complex and nonhomogeneous [16]. The localised large deformations assisted by the non uniform pressure may effect the surface quality of the formed tube So surface finish of the formed component may decided by the roller pressure, stagger, feed rate, speed etc. A plenty of parametric studies are reported in the literature on the experimental, theoretical and numerical analysis on the surface finish and forming load [17-19]. Hamid et.al [20] investigated effect of thickness reduction on the surface finish and mechanical properties of the formed tubes. Xu et.al [21] numerically studied the formation of waviness on the surface.
But there is an evidence of a limited study on the combined effect of various parameters on the surface finish of the tube formed. Hence in the present work Taguchi experimental design is used to find out the most influential parameter individually and combined on the ovality of the formed tube.A lot of studies were evident in the literature regarding the effect of various parameters on surface finish of the components

2.0 Selection of input parameters

In the current work the effect of the feed rate and roller staggering on surface finish is investigated using Taguchi method. A three level experimental design with L-9 orthogonal array is used for the design of experiments. The levels are based on the constrains of the machine and are presented in table 1. First and second column of orthogonal array is assigned with the feed rate and the stagger. The L-9 orthogonal array after assignment is shown in table 2.

Table 1: The input variables

S.No	Input Parameter	Level 1	Level 2	Level -3
1.	Feed rate(mm/min)	40	50	60
2.	Stagger (mm)	7.3	7.8	8.3

Table 2: OA after assignment

Run	1	2	3	4	5	6	7	8	9
Feed rate (mm/min)	40	40	40	50	50	50	60	60	60
Stagger (mm)	7.3	7.8	8.3	7.3	7.8	8.3	7.3	7.8	8.3

3.0 Experimentation

Flow forming machines are generally equipped with 3,4 or 6 rollers with manual setting of axial staggering. Some authors have done work on a machine with single roller to establish the dependency of the process parameters for simplicity reason [22,23] . A few have extended the work with three rollers [24]. In the present work the experiments are carried out on CNC flow forming machine with 3 rollers with a Model ST 56-90, manufactured by Leifeild ,West Germany.

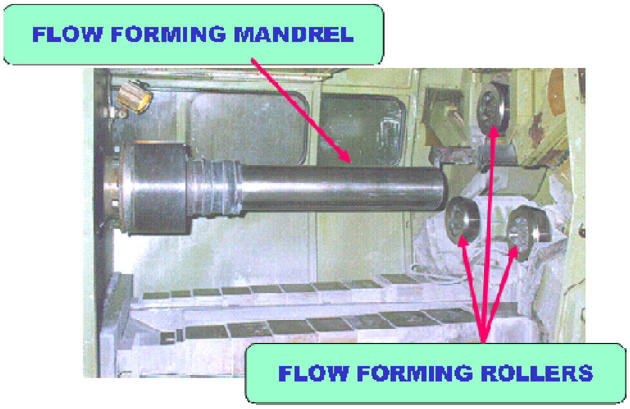


Fig 1: Flow forming machine used for the experiment

The composition of SAE 4130 used experimentation is shown in table 3

Table 3: Chemical composition of SAE 4130

Element	C	Si	Cr	Mo	Mn	S	P
% by Wt	0.28-0.33	0.15-0.3	0.8-1.1	0.15-0.25	0.4-0.6	0.01	0.015

The Mechanical Properties are provided in table 4

Table 4: Mechanical Properties of SAE 4130

S.No	Property	Value
1.	Hardness	210 to 230 BHN
2.	Ultimate Tensile Strength (UTS)	120 kg/mm2 (minimum)
3.	0.2%Proof stress	90 kg/mm2 (minimum)
4.	% Elongation	12% (minimum) of Gauge Length

The thickness is reduced in 3 passes to a value of 0.9 of initial thickness with maximum reduction of 0.5t to 0.6t, where t is the thickness before each pass.
the tubes at various stages of reductions is presented in Fig 2. The values of staggering manually set are given in table 5

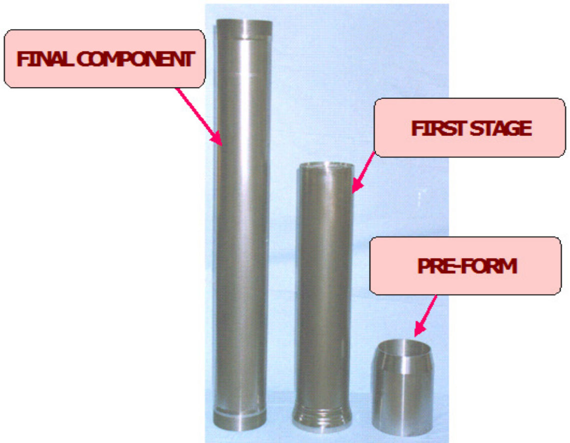
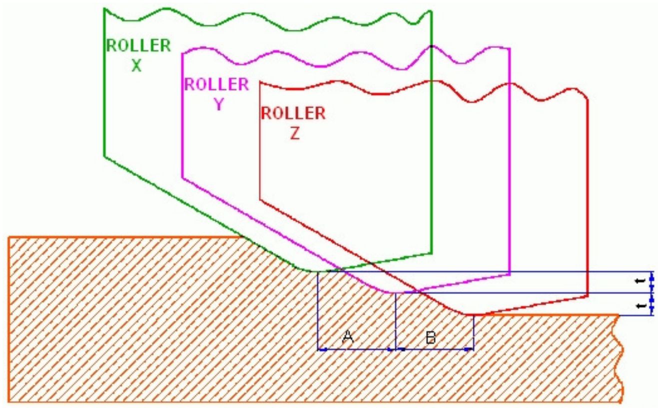


Fig:2 Tubes at various stages of reduction

The three rollers are arranged at 1200 to each other with the stagger shown in the OA. The arrangement of the roller plans are changed in each experiment the roller stagger is changed by moving X or Z rollers towards or away from the Y – roller whose arrangement is schematically shown in Fig 3. The component was flow formed ovality and thickness of all the trials are recorded. For each trail 3 parts are manufactured.



. **Fig 3: Staggering adjustment of the rollers**

The staggers at the three levels are adjusted as per the table 5.

Table 5: Adjustment for required staggering

Sl.No	Stagger(mm)		Stagger (A+B)
	A	B	
1	5.5	3	8.5
2	5.5	2.4	7.9
3	4.9	2.4	7.3

4.0 Results and Discussion

The results obtained for the 9 trials are presented in table 6. Table 6 shows the inside and outside surface finishes obtained in the 9 trial conducted as per orthogonal array

Table 6: Results of various trials

Run	1	2	3	4	5	6	7	8	9
Feed rate (mm/min)	40	40	40	50	50	50	60	60	60
Stagger (mm)	7.3	7.8	8.3	7.3	7.8	8.3	7.3	7.8	8.3
Inside surface finish (μm)	0.60	0.62	0.65	0.68	0.72	0.74	0.77	0.78	0.79

5.0 Design of Fuzzy Logic Controller

Mamdani approach is used for the design of FLC (Fuzzy logic controller). Scatter plots of inside surface finish vs feed , inside surface finish vs stagger, are presented in fig 5 and Fig 6 respectively. From Fig 5 it is noted that there exists a linear relation between feed and inside surface finish,. From fig 6it is noted that the relation between outside surface finish with stagger is almost linear. So triangular membership function is chosen. By this selection some error may occur in case of stagger and inside surface finish due to the nonlinear relationship as evident form the fig 6. As the experiments are conducted at three levels, for each input three linguistic terms are used to denote low, medium and high. Table 7 presents the linguistic terms selected for the input parameters and output parameters. The triangular membership functions of the feed rate and stagger are given in Fig 7 and Fig 8 respectively. The triangular member ship function of the output , ie. Inside surface finish is presented in Fig9 .

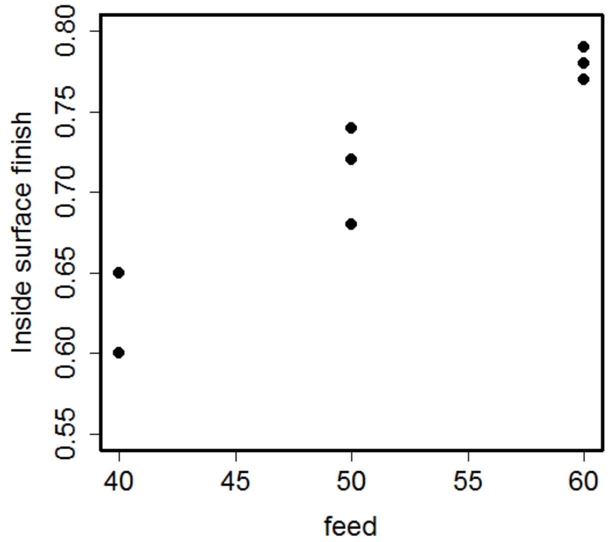


Fig 5: Scatter diagram of Inside surface finish vs feed

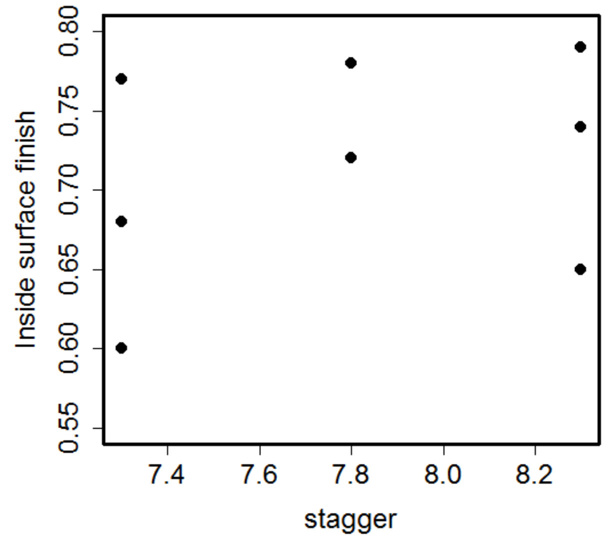


Fig 6: Scatter diagram of Inside surface finish vs stagger

Table 7: input & output variables and their linguistic terms

S.No	Input variable	Low	Medium	High
1.	Feed rate	LF	MF	HF
2.	Stagger	LS	MS	HS
3.	Inside surface finish	LI	MI	HI
4.	Out side surface finish	LO	MO	HO

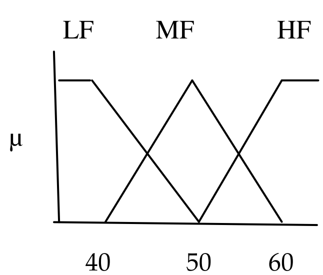


Fig :7 Feed Rate

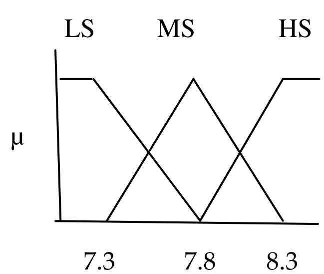


Fig 8: Stagger

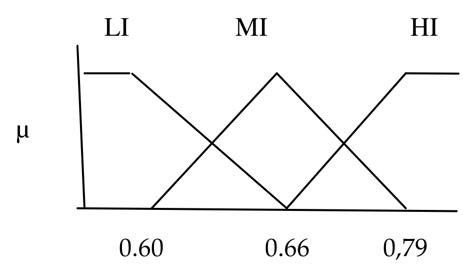


Fig 9 : Inside surface finish

From the results of the experiments shown in table 6, the rule base is designed and given in table 8. Since it is full factorical experimentation a rule base of 9 rules can be obtained. The design of FLC is validated by conducting one more set of experiments with different values. The input and output values of the experiments are presented in table 9

Table 9: Experimental results for validation

Run	Feed rate	Stagger	Inside surface finish	Outside surface finish
1	43	7.5	0.64	3.09
2	57	7.7	0.76	3.49
3	52	7.9	0.73	3.37
4	57	8.1	0.77	3.51
5	48	8.1	0.70	3.27
6	52	7.7	0.72	3.35

Table 8: Rule Base

Run	Feed Rate	Stagger	Inside surface finish	Outside surface finish
1	LF	LS	LI	LO
2	LF	MS	LI	MO
3	LF	HS	LI	MO
4	MF	LS	MI	MO
5	MF	MS	MI	MO
6	MF	HS	HI	MO
7	HF	LS	HI	HO
8	HF	MS	HI	HO
9	HF	HS	HI	HO

6.0. Validation of FLC

A sample calculation is provided here under for the first case i.e Feed 43 mm/min and stagger 7.5mm. The member ship functions for the case taken are presented in Fig 10 and Fig 11. From the Fig 10 it is noted that 43mm/min can be termed as low feed or medium feed with different membership functions. The member ship functions can be calculated by similarity of triangles and found out as μ_{LF}=0.7 and μ_{MF}=0.3. Similarly membership functions for stagger is calculated from Fig 11 as μ_{LS}=0.4 and μ_{MS}=0.6;

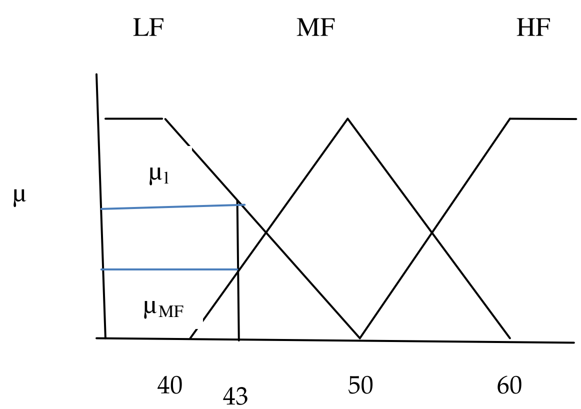


Fig :10 computation of Membership functions ofFeed Rate

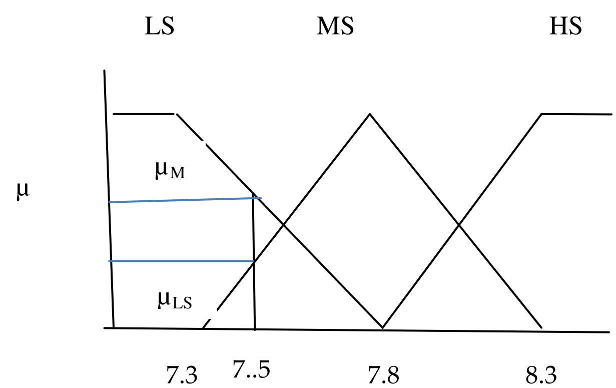


Fig 11 :computation of Membership functions ofStagger

So there 4 possible rules those can be fired and are presented in table 10.Firing strength of each rule can be found out by taking the minimum value of the member ship of functions of each rule. For example firing strength of rule 1 given in table 7 can be found out as Min (μ_{LF},μ_{LS})= min(0.7, 0.4) = 0.4

Table 10: Firing strength of the rules

Rule	1	2	3	4
Feed	LF	LF	MF	MF
Stagger	LS	MS	LS	MS
Firing strength	0.4	0.6	0.3	0.3

But the database for the sample taken consists of Fuzzified outputs as evident from table 8; Rule 1, Rule 2, Rule 4 and Rule 5. calculations are done on these Four rules rules and corresponding values obtained from experiments are compared with the calculated values.

From Fig 8 the two rules can be stated as

Rule 1: IfFeed is LF and stagger is LS then the inside surface finish is LI

Rule 2: If Feed is LF and stagger is MS then the inside surface finish is LI

Rule 4: If Feed is MF and stagger is LS then the inside surface finish is MI

Rule 5: If Feed is MF and stagger is MS then the inside surface finish is MI

The representation the above two rules on the triangular membership function are graphically presented in Fig 11, Fig 12, Fig 13 and Fig 14.

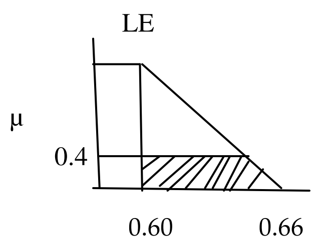


Fig 11: Rule 1

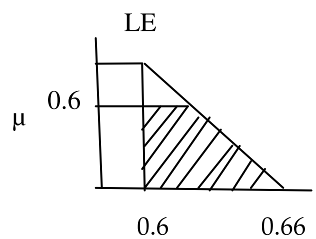


Fig 12: Rule 2

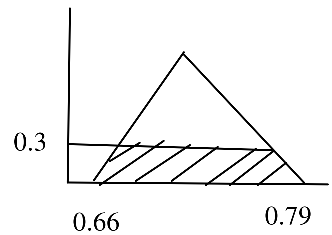


Fig 13: Rule 4

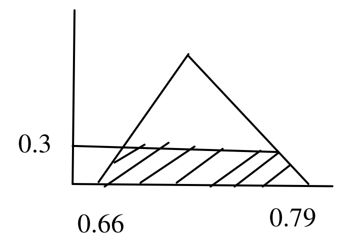


Fig 14: Rule 5

Centre of sums method is applied for defuzzificaiton. The hatched areas of the membership fucntions and the centres of areas shown in the Fig 11,Fig 12, Fig 13 and Fig 14 are computed and presented in the table10. Areas can be easily calculated by the geometry i.e Sum of area of a triangle and a rectangle for each case. Length of the rectangle and the base of the triangle can be found out by similarity of triangles. Centre of the rectangle is at half of its length and centre of the triangle is 1/3 of its length.

The centre of whole area is obtained by weighted average Centre of area = (area of rectangle X centre of rectangle+ area of the triangle and centre of the triangle)/ (area of the rectangle + Area of the triangle)

Table 10: Areas and centre of areas of the fired rules

Rule	1	2	3	4
Area	0.0192	0.0036	0.03647	0.03647
Centre	0.6199	0.6311	0.725	0.725

The Defuzzified output can be calculated by the equation (1)

$$\text{Defuzzified output} = \frac{A_1 * C_1 + A_2 * C_2 + A_4 * C_4 + A_5 * C_5}{A_1 + A_2 + A3 + A4} \ldots\ldots (1)$$

Defuzzified output for this case is computed to be 0.642

Similarly for the other four cases of validation experimentation, the values given by the FLC are calculated and compared with the experimental values. The comparison is illustrated in table 11.

Table 11. Comparison of values from FLC and experiment

Run	Feed rate	Stagger	Inside surface finish	Outside surface finish	Computed inside surface finish	Error %
1	43	7.5	0.64	3.09	0.642	-0.67
2	57	7.7	0.76	3.49	0.751	0.66
3	52	7.9	0.73	3.37	0.745	-2.68
4	57	8.1	0.77	3.51	0.759	1.85
5	48	8.1	0.70	3.27	0.688	2.11
6	52	7.7	0.72	3.35	0.734	-2.38

From table 11, it observed that the error in absolute terms ranges from 0.66% to 2.68% which may be treated to be acceptable. Hence this FLC can be used to predict inside surface finish of the tube at any given values of feed rate and stagger.

7.0 Conclusions

In the current work a Fuzzilogic controller is developed for predicting the inner surface finish of a flow formed tube of SAE 4130 using Mamdani approach. As design FLC becomes complex with the increase of number of input parameters, the concept of orthogonal array used for experimentation in the development of data base and rule base. the maximum error in the prediction is found out to be 2.68%. So development of knowledge base using Taguchi technique proved to be accurate enough to design a low cost FLC. Further investigations may be carried out to tune this controller using neural net works or genetic algorithms as the data is getting generated in due course. This off line FLC can be integrated in intelligent manufacturing systems for controlling the process in auto mode and at the same time tuning the FLC continuously to produce the synergic effect.

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