IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 13, Issue 6 Ver. VI (Nov. - Dec. 2016), PP 09-16
www.iosrjournals.org

Development of a Mathematical Model to study the fluidity in Thixoforming using Fuzzy Logic Approach

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Abstract: *Semisolid metal processing is carried out at temperatures ranging between its liquidus and solidus temperatures of the metal. This process is also known as thixoforming or thixocasting depending on the initial condition of the billet and process adopted. Fluidity is an important process parameter which determines the quality of the end product. Simulation studies are carried out to determine the fluidity parameter using Taguchi's design of experiments. An attempt is made to develop a mathematical model using fuzzy logic approach to predict the fluidity parameter. Some of the process conditions that are used to study the process are billet temperature ram speed and die temperature. The model was validated by experimental study.*
Keywords*: Aluminum alloy, Deform 3D, Fluidity, Fuzzy logic, Thixoforming*

I. Introduction

Semisolid metal processing (SSMP) is a technology employed for production of near net shaped components. This process is carried out at a temperature range between its liquidus and solidus temperature [1]. The origin of SSMP can be traced to the experiments conducted by David Spencer at MIT in 1971 as part of his doctoral thesis under the supervision of Martin Flemings [2]. The process combines a number of advantages of casting and forging. Compared to casting, SSMP provides a more stable filling front places lower thermal loads on the metal dies and less shrinkage.

Semisolid metal processing (SSMP) is also known as thixoforming or thixocasting depending on the initial condition of the billet and process adopted [3]. Some of the alloys which are suitable for carrying out the semisolid metal processing are alloys of aluminum, copper and magnesium. Aluminum alloy A356.0 and 356.0 are a 7% Si, 0.3% Mg alloy with 0.2 Fe (max) and 0.10 Zn. The alloys have very good casting and machining characteristics. They are used in the heat-treated condition. The schematic view of thixocasting and thixoforging processes is shown in Fig.1. The three important steps in this process are billet production, reheating to semi-solid condition and forming operation [4]. Typical composition of A356 alloy is given in Table 1. Alloy composition influences the properties and microstructure of the cast product. The fluidity and filling characteristics are largely influenced by the alloy composition.

Table 1: Chemical composition of A356 alloy (%wt)

Component	Si	Cu	Mg	Ti	Fe	Mn	Zn	Al
Wt %	6.5-7.5	Max. 0.2	0.25-0.45	Max 0.2	Max. 0.2	Max. 0.1	Max. 0.1	93

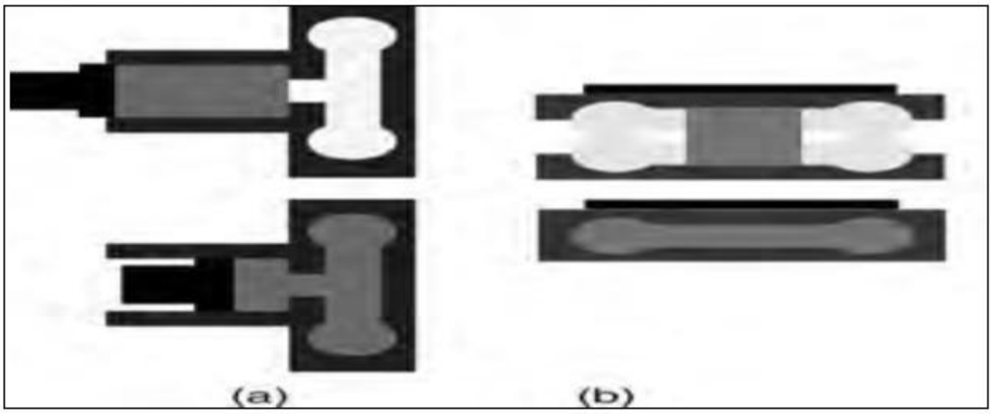


Figure1 Schematic representation of (a) thixocasting and (b) thixoforging processes

II. Fluidity

Fluidity is the ability of the material to flow before it completely solidifies [5]. The present study comprises of evaluating an important parameter known as mold filling ability – a measure for fluidity. Simulation studies were carried out to optimize the process parameters such as temperature, billet size and ram speed. Experiments were carried out to determine the mould filling ability and validate the simulation results.

The term fluidity is normally used in foundry to designate the casting materials ability to fill the mould cavity. The properties of casting materials which affect the fluidity to a great extent are viscosity and heat content of the melt, freezing range, specific weight and surface tension of the liquid metal [5]. The lower the coefficient of viscosity of molten metal, the higher would be the fluidity. In general, the alloys, which have a narrow freezing range, have a higher fluidity compared to the wide freezing range ones. The mould properties that affect the fluidity are thermal characteristics, permeability and the mould cavity surface.

2.1 Mould Filling Ability

Mould filling ability is influencing considerably the heat transfer and solidification of the metal. Mould filling is a critical parameter in the production of quality castings, especially in the case of complex shaped castings where section thickness varies considerably [6]. The die used for the present study was modeled based on Engler and Ellerbrok design [7].

2.2 Methodology adopted for calculating mould filling ability

The hot metal poured into the die fills the curved cavity between the two cylindrical cores having a line contact at the center, but solidifies before filling up the complete casting. The inverse of the diameter of curvature of the edge tip of the fin gives the value of the mould filling ability. The diameter at the tip of the fin gives the meniscus diameter of the liquid metal at the time of solidification as represented in the Fig. 2. It is difficult to measure the diameter of the tip of the edge and hence an indirect way of calculation has been used which is presented below.

From Figure 2

$R^2 + (r+x)^2 = (r+R)^2$ ……………………Equation (1)

By solving Equation (1) we get,

$1 / 2r = (R-x) / x^2$ (since $2r = d$)

So, $1 / d = (R-x) / x^2$ ………………… Equation (2)

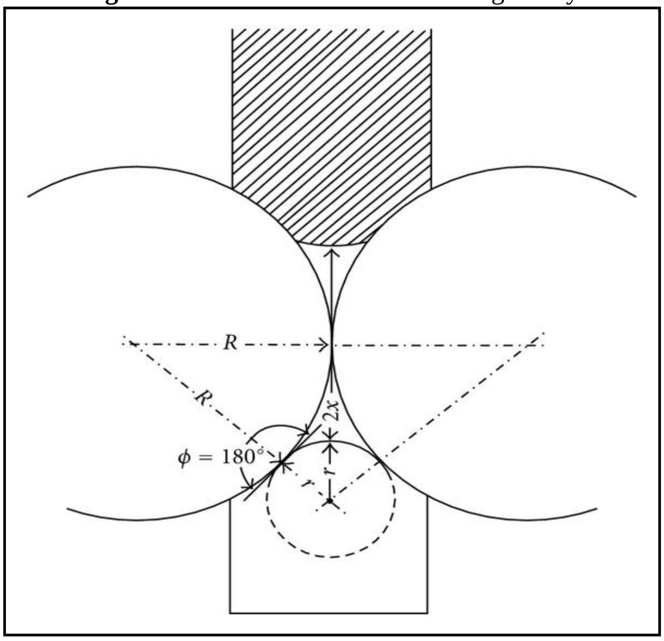
Where R = Radius of the sand core in mm,

r = Radius of the meniscus ($2r = d$) in mm,

2x = Distance between edges in mm,

1 / d = Mould filling ability, 1 / mm or mm^{-1}

Figure 2 Measurement of mould filling ability



III. Experimental Plan

Design of experiments is an efficient approach for understanding about the influence of process parameters and also their individual or combined effect of these parameters [8]. When the number of process parameters or experiments is large then systematic data can be obtained by planning a well-designed set of experiments.

For the present simulation studies the process parameters considered are Billet temperature, Ram speed and Die temperature. Minitab software has been used for experimental design of experiments. An orthogonal array would provide a balanced design considering each factor or combination of factors if there is an interaction among them. Table 2 shows the details of the factors and their levels for the present study. Orthogonal array L27 (3**3) is used with three factors and three levels as shown in Table 4.3.

Table 2: Factors and their levels for shrinkage simulation studies

	Factor 1	Factor 2	Factor 3
	Billet temperature ^{0}C	Ram Speed mm/sec	Die temperature ^{0}C
Level 1	580	10	30
Level 2	600	15	125
Level 3	620	20	250

IV. Numerical Simulation

The mould filling ability during casting was investigated for A356 alloy by carrying out the simulations using finite element software Deform 3D. The L 27 orthogonal array simulations were carried and the fluidity parameter was found out using equation 2. The size of the billet was taken as 92 X 32 X 45 mm. The above considered process parameters, billet size and positioning of billet on the die was arrived at after conducting several trial runs based on the shape of the final component and under fill at the end of simulation.

The bottom die, top die and billet were modeled in Solid Works and exported into the Deform 3D software in stl format. The die is a hollow rectangular cavity with two cylindrical cores. Fig. 3(a) shows the schematic representation of the die used for simulation. The billet was placed in the die and the process was simulated for different values of factors based on the L27 orthogonal array. Fig. 3(b) represents the component shape at the end of simulation. The average distance 2x between the two edges was measured. The mould filling ability value of 1/d was calculated using (2) and the results are tabulated in Table 4.

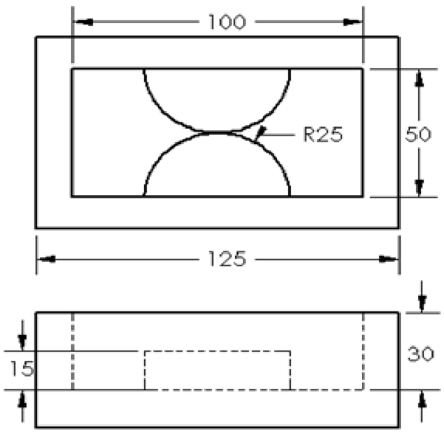


Figure 3(a) Schematic representation of die

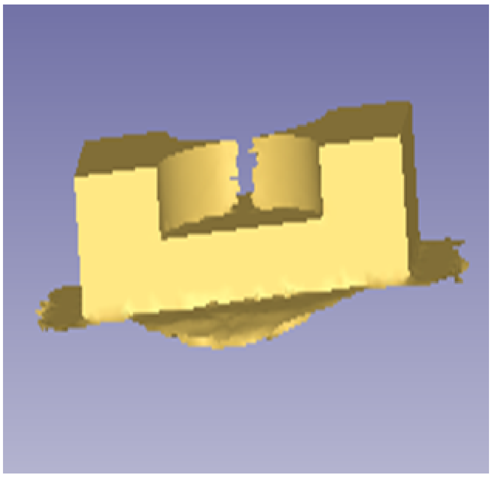


Figure 3(b) Component at the end of simulation

V. Fuzzy Logic Modeling

A fuzzy logic approach helps to predict the responses to multi inputs so that any uncertainty or imprecision can be handled with comfort [9]. This approach is being adapted for multiple criteria decision making techniques in different manufacturing processes [10]. A fuzzy expert system basically consists of four parts namely knowledge base, fuzzifier, inference engine and defuzzifier [11]. A typical schematic representation is shown in Fig. 4.

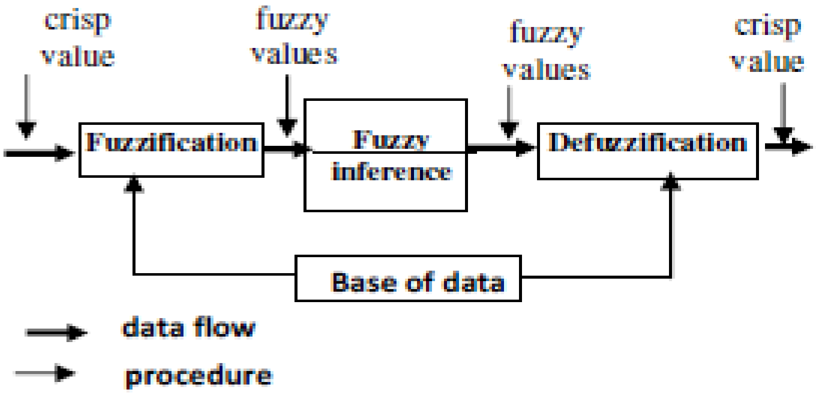


Fig 4 Representation of Fuzzy Expert System

In the Fuzzifier, the crisp inputs are converted into imprecise quantities with a degree of belongingness like ‘large’, ‘medium’, ‘good’ etc. Usually the values range from 0 to 1. The knowledge base consists of both database and rule base. The database consists information about the membership functions of the fuzzy sets and rule base consists of IF – THEN rules.

A typical rule base for a two input (x1 and x2) and one output (y) would be as follows.

IF X1 IS A1 AND X2 IS B1 THEN Y IS C1 ELSE
IF X1 IS A2 OR X2 IS B2 THEN Y IS C2 ….

Where A1, A2, B1, B2 , c1, c2 represent the range of linguistic values

The inference engine performs the inference operations based on the rule base provided by an expert. The inference block generates output which is fuzzy in nature. The defuzzifier converts the fuzzy values to crisp output.

Mamdani Fuzzy Model and Sugeno Fuzzy model are widely used methods to solve fuzzy models. For the present study Mamdani model was chosen in MATLAB. The three input variables chosen were billet temperature (BT), ram speed (RS) and die temperature (DT) and Mould Filling Ability (MFA) as the output variable. Figure 5 represents the fuzzy controller as defined in MATLAB.

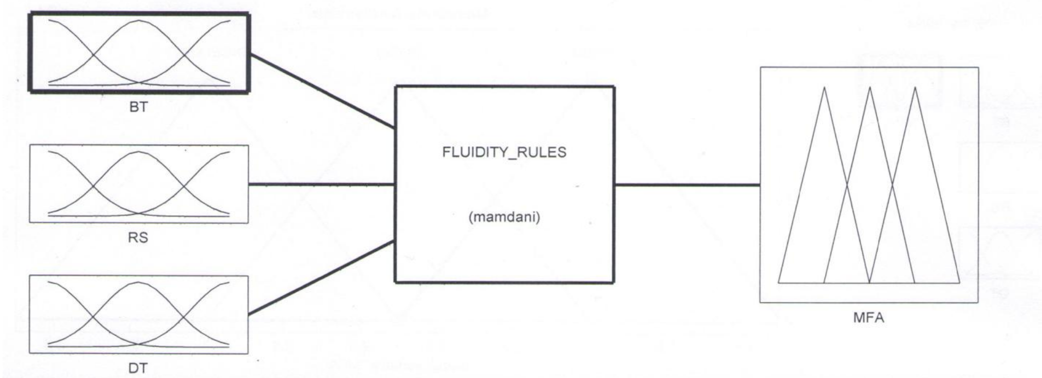


Fig. 5 Fuzzy Controller with three inputs and one output

Each input variable has three levels i.e. Low, Medium and High. The out has three levels namely poor, good and excellent. Fig represents the membership functions of input and output variables. Triangular membership functions were used to define the membership functions.

Triangle (x: a,b,c) = (1) where a,b,c are parameters of linguistic variables and x is range of input parameter. Table 3 represents the fuzzy intervals for input and output variables. Fig. 6 represents the membership function of output and input variables. Fig. 7 depicts the fuzzy rule base and the output screen in rule viewer.

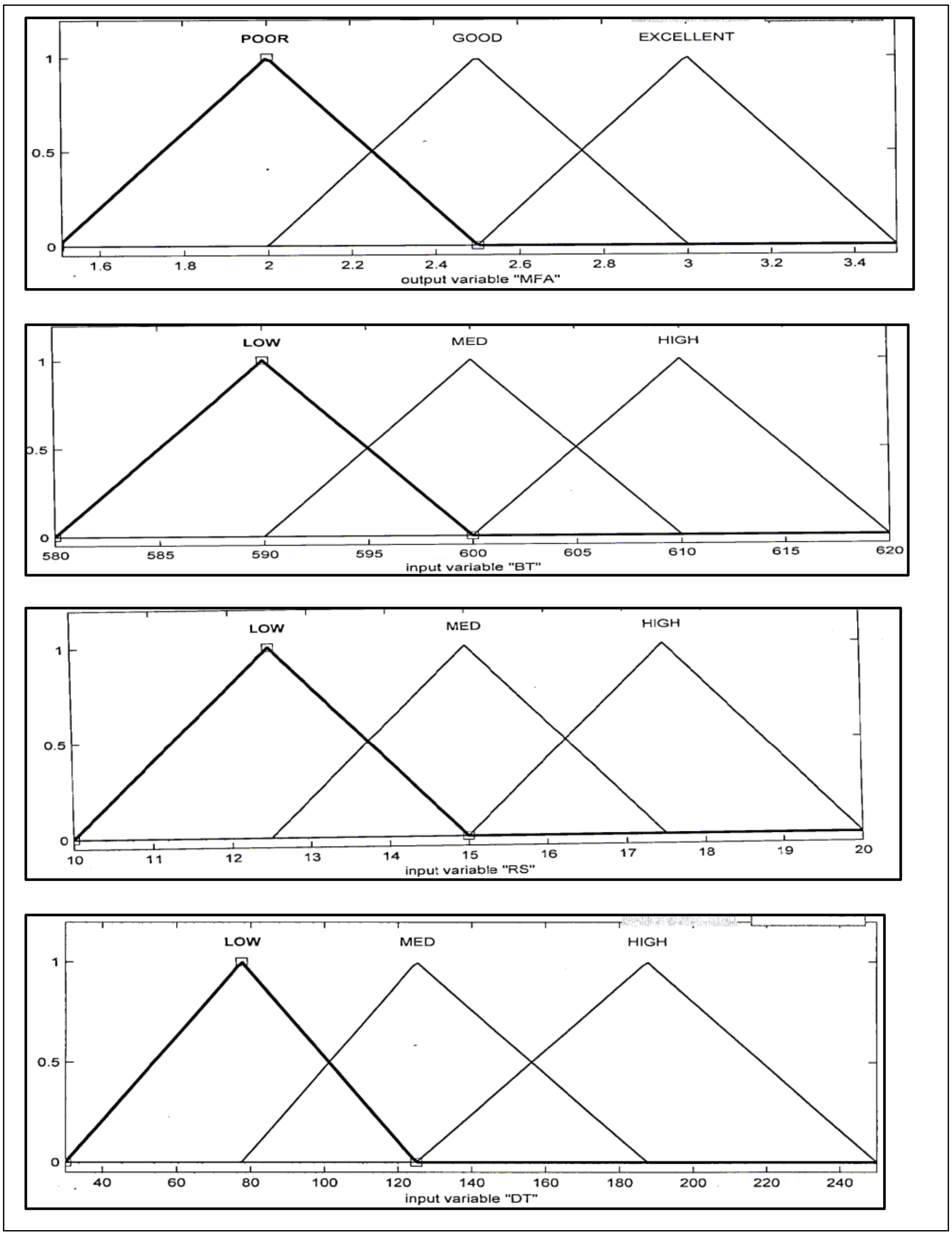


Fig. 6 Membership functions of output variable MFA and input variables of BT, RS and DT

Table 3 Fuzzy intervals for input and output parameters

SNO	Input Parameter	Linguistic Values	Fuzzy Intervals
1	Billet Temperature Range [70 ~ 80]	Low	70 – 72.5 – 75
		Med	72.5 – 75 – 77.5
		High	75 – 77.5 – 80
2	Ram Speed Range [10 ~ 20]	Low	10 – 12.5 – 15
		Med	12.5 – 15 – 17.5
		High	15 – 17.5 – 20
3	Die Temperature Range [30 ~ 250]	Low	30 – 77.5 - 125
		Med	77.5 – 125 – 187.5
		High	125 – 187.5 – 250

SNO	Output Parameter	Linguistic Values	Fuzzy Intervals
1	Mould Filling Ability Value	Poor	1.5 – 2.0 - 2.5
		Good	2.0 - 2.5 – 3.0
		Excellent	2.5 – 3.0 – 3.5

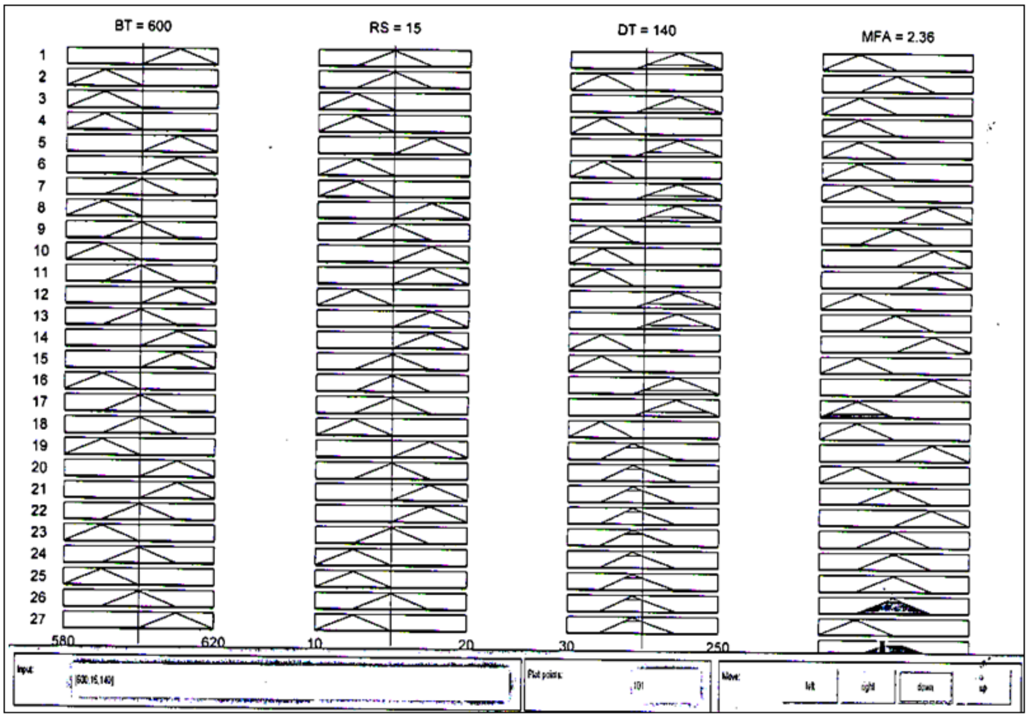


Fig. 7 Fuzzy Rule base in Rule Viewer

VI. Comparison and validation of results

The results obtained from simulation and fuzzy predicted values are shown in Table 4. A graph is plotted for comparing the MFA value between the simulation results and fuzzy predicted values and is shown in Fig. 8. Experiments have been conducted to validate the results. Fig. 9 and Fig. 10 represent the die used for experiment and cast component respectively. MFA was calculated and the comparative results are presented in table 5.

Table 4 L 27 Orthogonal array used in the simulation trials and fuzzy predicted values

RUN NO	TEMP OF BILLET ^{0}C	RAM SPEED mm/sec	DIE TEMP ^{0}C	MOLD FILLING ABILITY 1/D = (R-X) / X**2 1/MM	FUZZY PREDICTED VALUES 1/MM
1	620	15	250	1.84	2.0
2	580	15	30	2.29	2.5
3	580	10	250	1.93	2.0
4	580	10	30	1.99	2.0
5	620	20	250	1.92	2.0
6	620	10	30	1.51	2.0
7	600	10	250	1.63	2.0
8	580	20	250	3.08	3.0
9	600	15	30	2.39	2.54
10	580	20	30	2.84	2.99
11	600	20	30	3.37	3.0
12	620	10	250	1.91	2.0
13	600	20	250	2.07	2.50
14	620	20	30	2.73	2.99
15	620	15	30	1.83	2.0
16	580	15	250	3.22	3.0
17	600	15	250	1.82	2.43
18	600	10	30	1.96	2.0
19	580	20	125	2.86	2.99
20	620	15	125	1.92	2.0
21	620	20	125	2.13	2.25
22	600	20	125	2.74	2.74
23	580	15	125	2.40	2.63
24	600	10	125	2.12	2.25
25	580	10	125	2.14	2.45
26	600	15	125	2.30	2.50
27	620	10	125	1.73	2.0

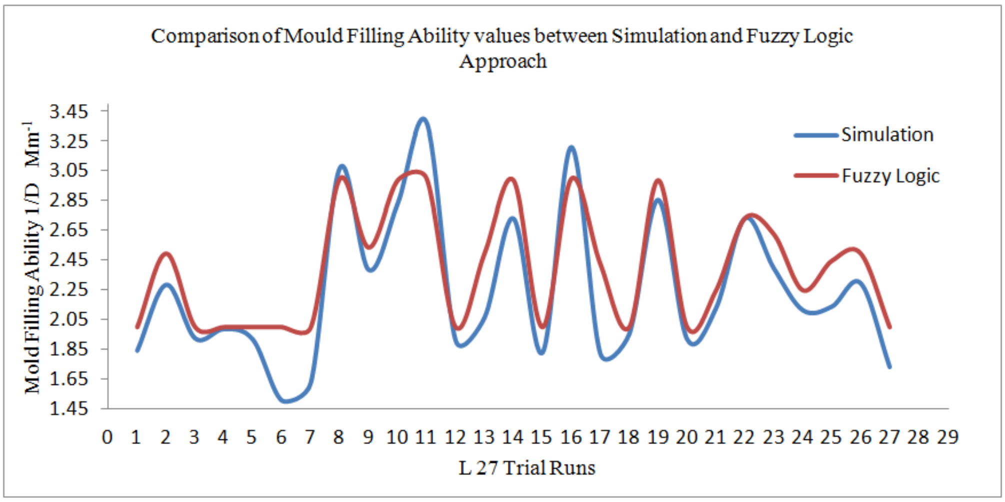


Fig. 8 Comparison of MFA values for simulation and Fuzzy Logic Predicted values

Fig 9 Die used for experimentation

Fig 10 Cast component

Table 5 Comparison of result among simulated, fuzzy logic predicted and experiment values

Billet Temperature ^{0}C	Ram Speed mm/sec	Die Temperature ^{0}C	Mould Filling Values MFA 1/mm		
			Simulation	Fuzzy Predicted Value	Experimental Value
580	10	30	1.99	2.0	1.71

VII. Conclusion

The present work focused on developing a mathematical model using fuzzy logic approach to understand the effect of process parameters on fluidity of aluminum alloys in semisolid metal forming. Simulation studies were conducted to determine the Mould filling ability values. The fuzzy logic model developed in MATLAB showed a satisfactory prediction to study the MFA within a range for process parameters. Experiments were conducted to validate the results and were found to conform to reasonable accuracy. This model helps the industry to manufacture components using thixoforming process where controlling the process parameters is a big challenge.

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