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Estimation of Mold Filling Ability and Volume Deficit Characteristics of Cast Al-Si Alloys

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Abstract

Production of defect free castings requires good understanding of casting characteristics like mold filling ability and volume deficit characteristic. Pin test piece with cylindrical cores proposed by Engler and Ellerbrok was used to study the mold filling ability. Volume deficit characteristics experiments were conducted using the method designed by Engler. Alloy composition, Mold coat and Pouring temperature were considered as process parameters for the present study and experimental plan has been taken up through design of experiments. The alloy composition is most significant in influencing the mold filling ability, where as pouring temperature is for volume deficit. The Correlation Co-efficient value obtained is -0.98901 indicating strong a negative relation between mold filling ability and volume deficit characteristics. Negative values indicate a relationship between mold filling ability and volume deficit such that as values for mold filling ability increase, for volume deficit decrease.

Keywords: Cast Al-Si alloys, Mold filling ability, Volume deficit, Pouring temperature, Mold coat, Correlation coefficient

1. Introduction

A good mold-filling alloy has the ability to completely fill the mold pattern and reproduce fine details of the mold. Many defects in a casting generally establish at the filling stage as stated by R. W. Lewis et al. [1]. The mold filling ability characteristic depends upon the metallostatic balance between the prevailing metal pressure and surface tension of metal. J.A. Capadona et al. stated the importance of mold filling ability of casting where cross sectional area of channels is reduced [2]. A.R. Wood et al. stated that the mold filling ability is a casting characteristic and described it as the sharpness of reproduction of upper corners using a U shaped fluidity mold [3]. A good mold-filling ability alloy has the capacity to fill out the mold pattern and reproduce fine [4,5,6] details of the mold. For aluminum alloy castings, it has to be ensured that the metal velocity is continuously and gradually decreasing so as to minimize turbulence, metal splashing and in turn oxidation. Mold coat minimises surface tension and formation of oxide films in cast aluminium alloys and changes the rate of solidification, thereby increasing the mold filling ability and reducing the volume deficit [7]. Increasing superheat can be expected to increase mold filling and reduces shrinkage, excess thermal energy is removed from the leading metal front before it begins to solidify. Additional superheat extends the fluid life of the liquid metal front, so there is sufficient fill turbulence possible to promote remelting of the solidifying metal front during mold filling [8].

Volume deficit depends on both casting material and casting conditions. The mold dilation and mold deformation occur during the solidification of molten metal apart from micro and macro shrinkage. Hence volume deficit consists of surface sinking and volumetric contraction. Patterson and Engler (9) have classified the volume deficit into four types, namely, macro cavities (V_m), internal porosity (V_{int}), Surface sinking (V_{sink}) and volumetric contraction (V_{cont}) explained in Figure 1a and b.

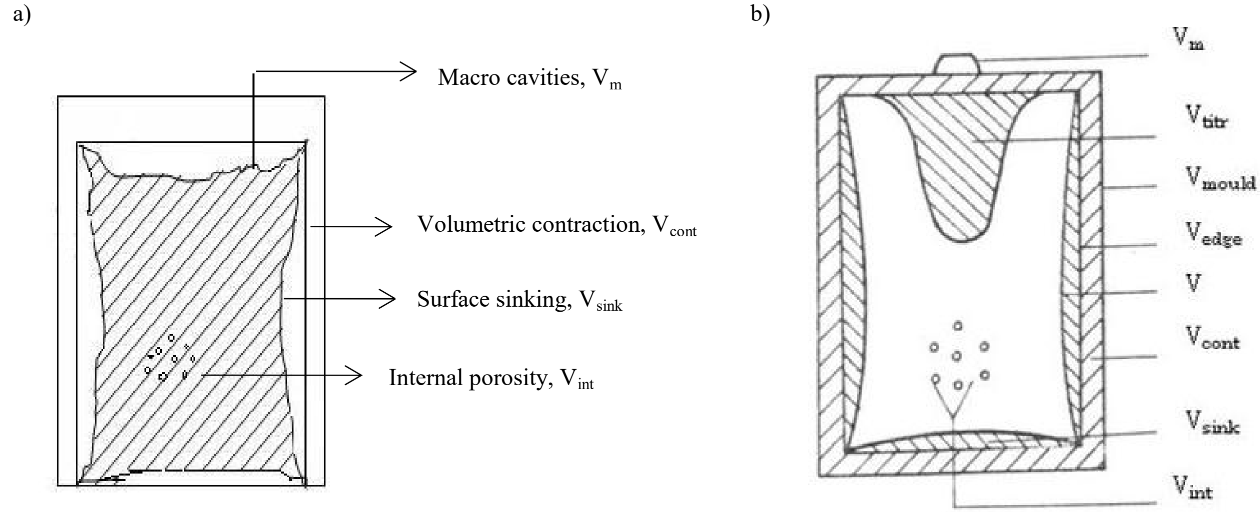


Fig. 1. Volume deficit: a) Classification of volume deficit, b) Categorization of volume deficit

2. Experimental Plan

Design of experiments is an efficient approach for improving a process to quickly obtain meaningful results and draw conclusions about how factors or process parameters interact [10,11] when more than one factor is changing at a time. An orthogonal array would mean a balanced design with equal weight age to each factor [12]. MINITAB software was used for experimental design [12]. Process Variables studied were Alloy composition, Mold coat and Pouring temperature. The chemical composition of US 413 and US A356 alloys are given in Table 1. Alloy composition influences properties and the microstructure of the cast product. The filling and shrinkage characteristics are largely influenced by the alloy composition. Mold coat is one of the process parameters that provides smooth surface and improves the casting quality [13,14]. Pouring temperature [15] influences fluidity, mold filling ability, volume deficit, strength and structure of the casting [16]. Additional pouring temperature increases the fluid life of the liquid metal. Hence, pouring temperature with 50^0C of super heat is considered.

Table 1.
Chemical composition (%wt)

Element	**US 413**	**US A356**
Silicon	11	6.8
Iron	0.65	0.55
Copper	0.15	0.2
Manganese	0.55	0.35
Magnesium	0.1	0.5
Nickel	0.1	0.15
Zinc	0.15	0.15
Lead	0.1	0.15
Tin	-	0.05
Titanium	0.2	0.05
Others (each)	0.05	0.05
Others (total)	0.15	0.15
Aluminium	Remainder	Remainder

Table 2 shows the details of the factors and their levels for the present study. Orthogonal array L6(2**3) is used with three factors and 2 level (8 runs for full factorial) as shown in Table 3.

Table 2.
Factors and their levels for Mold filling ability and Volume deficit characteristics

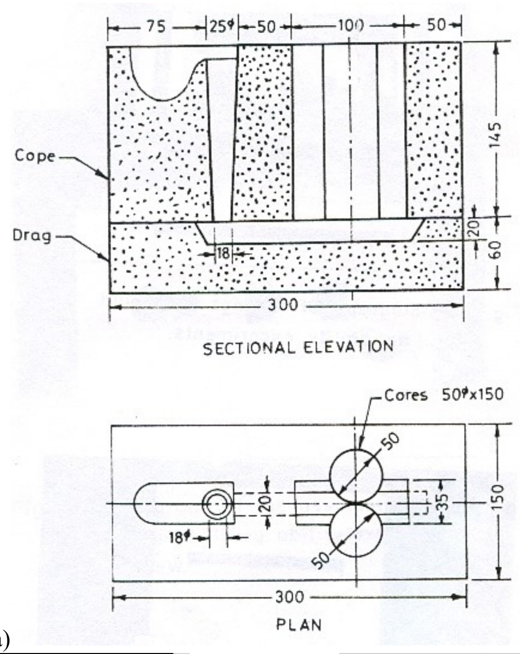
	Factor 1	Factor 2	Factor 3
	Alloy	Mold coat	Pouring temperature (^{0}C)
Level 1	US A356	Graphite	T
Level 2	US 413	No coating	T+50^{o}C

Table 3.
Set of Experiments

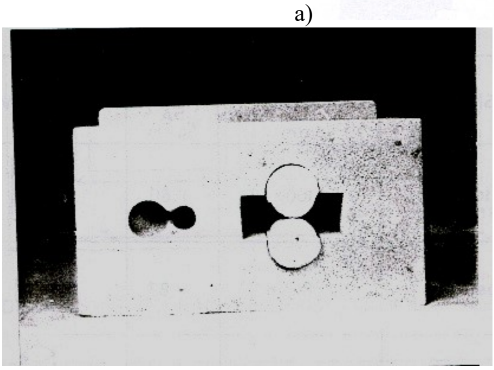
Exp no.	Alloy	Pouring temperature (^{0}C)	Mold coat
1	US A356	T	No coating
2	US A356	T+50	No coating
3	US A356	T	Graphite
4	US A356	T+50	Graphite
5	US 413	T	No coating
6	US 413	T+50	No coating
7	US 413	T	Graphite
8	US 413	T+50	Graphite

2.1. Mold filling ability

The mold filling ability was investigated by pin test piece with cylindrical cores designed by Engler and Ellerbrok [4] is given in Figure 2a. The cope box, drag box and cylindrical cores were given in Figure 2b. Top view of the assembled mold for mold filling ability experiment was shown in Figure 2c. The test casting consists of two fins of metal at both sides. The inverse of the diameter of curvature of the edge tip of the fin gives the value of the mold filling ability.



a)



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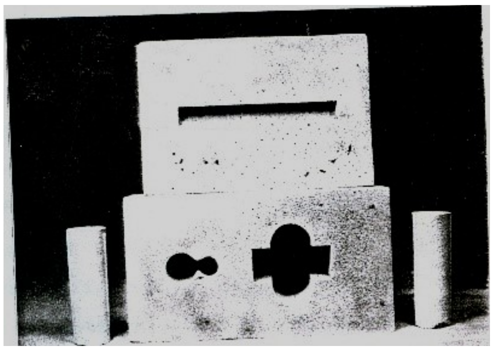

c)

Fig. 2. Mold filling ability: a) Schematic diagram of Mold filling ability with pin test piece with cylindrical cores, b) Cope box, drag box and cylindrical cores, c) Assembled mold for mold filling ability

2.2. Volume Deficit characteristic

Terms described regarding volume deficit in the Figure 1 are given in Table 4. The Internal porosity, macro cavities, surface sinking and volumetric contraction have been calculated using these mathematical formulae.

Table 4.
Terminology and Mathematical formulae of volume deficit

1.	ΔV	Total volume deficit $\Delta V = \frac{V_m + V_{sink} + V_{cone} + V_{int}}{V_{mold}}$	(1)
2.	V_{titr}	Titration volume	
3.	V_{cone}	Cone volume	
4.	V_{mold}	Mold volume	
5.	G_{air}	Weight of casting in air	
6.	G_{water}	Weight of casting in water	
7.	V_{patt}	Volume of the pattern	
8.	V_{theor}	Theoretical volume	
9.	γ_{chill}	Maximum density	
10.	V_m	Macrocavity $V_m = V_{cone} + V_{titr}$	(2)
11.	V	Actual volume $V = G_{air} - G_{water}$	(3)
12.	V_{edge}	Casting edge volume V_{edge} = length X width X thickness	(4)
13.	V_{cont}	Contraction volume $V_{cont} = V_{mold} - V_{edge}$	(5)
14.	V_{sink}	Surface sinking $V_{sink} = V_{edge} - (V_m + V)$	(6)
15.	V_{int}	Internal porosity $V_{int} = V - V_{theor}$	(7)

Volume deficit experiments were conducted using test piece as shown in Figure 3 and 4.

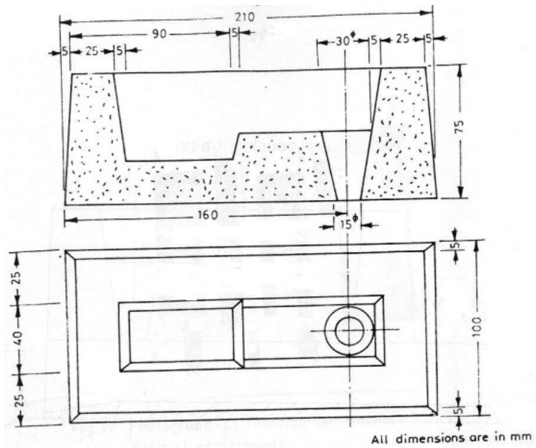

Fig. 3. Details of pouring basin

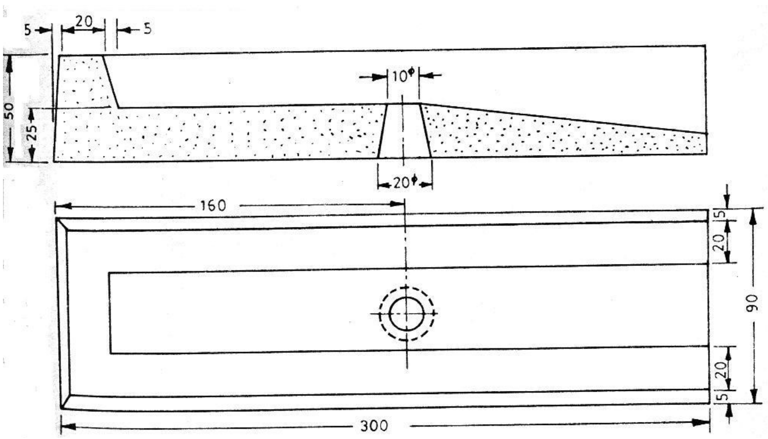

Fig. 4. Details of overflow core

2.3. Preparation of green sand mold

The molds were provided with dowel pins for perfect matching of cope and drag. Molds are prepared with slight ramming. The patterns were stripped after 3 hours. Molds were prepared using green sand process consisting of Bentonite (5%-6% of sand weight) and water (5%-8% of sand weight). The moisture level was adjusted in such a way that compatibility measured with + GF + compatibility meter was maintained between 45% and 50%, permeability was maintained between 400 and 500 and green compression strength was in the range of 700-900g/cm^2. The mold hardness was in the range of 75-80 on B scale. In case of mold coatings, the graphite paint was sprayed on to the mold and dried immediately by lightening a flame on the painted surface.

2.3.1 Green sand mold for Volume deficit

The overflow core was placed over the mold in order to ensure that only a fixed quantity of liquid metal was poured each time into the mold. Figure 5 shows the photograph of prepared mold, overflow core and pouring basin. The assembled mold for the volume deficit characteristic was shown in Figure 6.

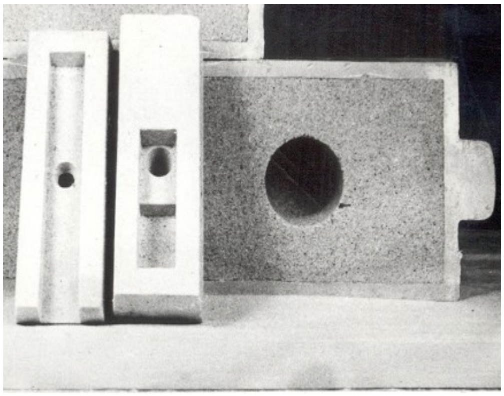

Fig. 5. Prepared mold along with, overflow core and pouring basin

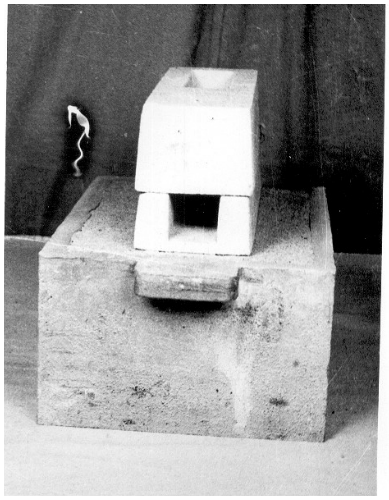

Fig. 6. Assembled mold for volume deficit

2.4. Melting and Pouring

The alloys were melted in an electric resistance furnace of capacity 20Kg provided with mild steel crucible. Temperature was measured with the help of a thermocouple. The furnace was put off and the crucible was lifted and put in a tilting device. The metal was tapped into a smaller crucible for pouring into the mold. The pouring height was maintained constant to avoid turbulence and difference in surface oxidation and oxide pick-up. Figure 7a depicts the mold filling ability test casting. For the volume deficit characteristic experimentation, the liquid metal was poured into the pouring basin and the pouring was stopped as soon as the metal over flows. Figure 7b and 7c show the casting of volume deficit characteristic experiments.

a) b) c)

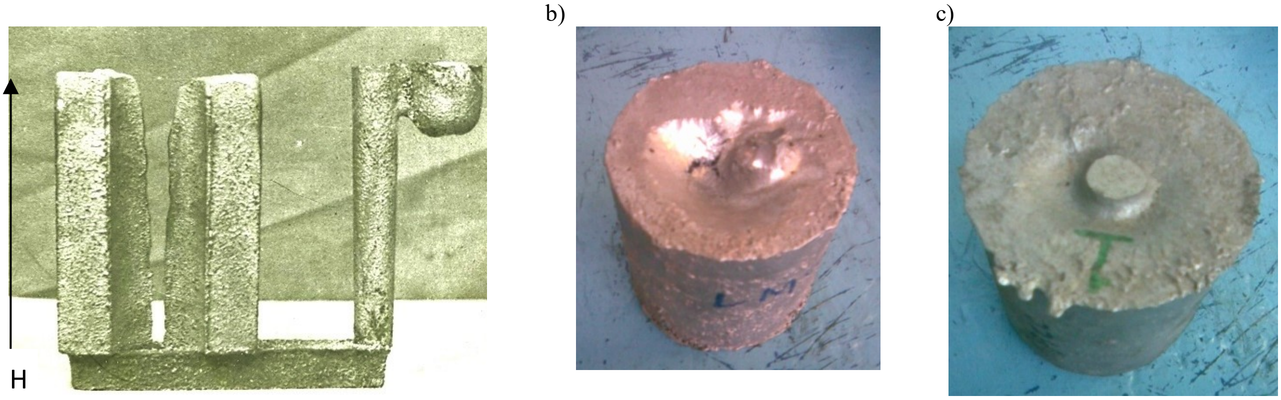

Fig. 7. Mold filling ability and volume deficit test castings: a) Mold filling ability, b) Volume deficit of US 413, c) Volume deficit of US A 356

3. Results

3.1. Mold filling ability

The inverse of the diameter of curvature of the edge tip of the fin gives the value of the mold 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 Figure.8. It is difficult to measure the diameter of the tip of the edge and hence an indirect way of calculation has been used.

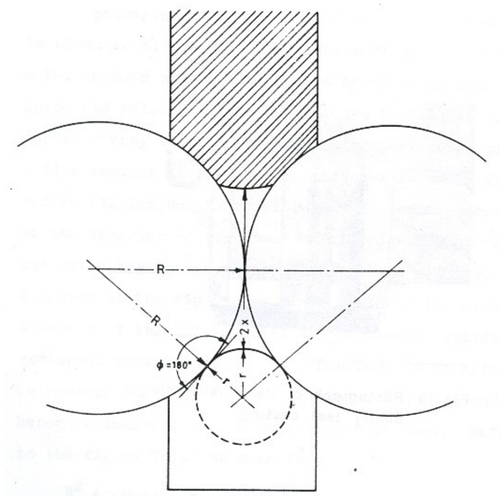

Fig.8. Measurement of mold filling ability

As per the Figure 8

$$R^2 + (r+x)^2 = (r+R)^2 \quad (8)$$

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

R = radius of the sand core, mm,

r = radius of the meniscus (2r=d), mm

2x = distance between edges, mm

1/d = mold filling ability, 1/mm

Height gauge was used to mark the height at every 5mm interval for solidified castings. The distance between the fin edges 2x was measured with vernier micrometer. The mold filling ability values were calculated for every 5mm increment by using Equation 8. The mold filling ability values at various pressure heads for experiment number 5 is given in Table.5.

Table 5.
Mold filling ability calculations

S.No	H,mm	2x,mm	1/d mm^{-1} ,[$(R-x)/x^2$]
1	0	5	0.278
2	5	5.5	0.34
3	10	6	0.408
4	15	6.2	0.438
5	20	6.5	0.485
6	25	6.8	0.536
7	30	7	0.569
8	35	7.5	0.662
9	40	8	0.762
10	45	8.1	0.783
11	50	8.2	0.806
12	55	8.3	0.826
13	60	8.5	0.871
14	65	8.5	0.871
15	70	8.5	0.871
16	75	8.6	0.892
17	80	8.7	0.916
18	85	9	0.99
19	90	10	1.25

The mold filling ability for the experiment number 8 at the pressure head of 90mm is 2.768mm^{-1} and the mold filling ability values for all 8 experiments are given in Table 6

Table 6.
Mold filling ability values for all 8 Experiments

H,	Mold filling ability values for Experimental run orders							
mm	3	1	4	2	6	7	8	5
35	0.3269	0.1478	0.597	0.124	1.140	1.183	1.4258	0.6617
40	0.3946	0.1562	0.6240	0.131	1.190	1.191	1.5512	0.7619
45	0.3667	0.1739	0.6427	0.220	1.2515	1.246	1.5836	0.7829
50	0.4090	0.220	0.6617	0.233	1.278	1.322	1.6164	0.8043
55	0.4100	0.330	0.7208	0.2777	1.307	1.350	1.8225	0.826
60	0.5183	0.338	0.7412	0.3398	1.395	1.380	1.8947	0.860
65	0.5351	0.3464	0.7619	0.409	1.410	1.440	2.0833	0.870
70	0.6481	0.3531	0.8708	0.4856	1.4258	1.470	2.2837	0.880
75	0.650	0.3598	0.8818	0.535	1.456	1.503	2.4965	0.890
80	0.6811	0.3639	0.9878	0.550	1.519	1.544	2.5406	0.9136
85	0.8043	0.3666	1.2250	05697	1.5512	1.717	2.7222	0.980
90	0.826	0.4091	1.5518	0.5879	1.5836	1.735	2.7684	1.250

3.2. Volume deficit

Volume deficit in 8 experiments was calculated usng the mathematical formulae given in Table 3. The volume deficit values for 8 experiments are given at Table 7.

Table 7.
Volume deficit values for 8 experiments

Parameter	Exp No.							
	1	2	3	4	5	6	7	8
Total volume deficit	0.044	0.048	0.065	0.066	0.036	0.045	0.054	0.06
% Total volume deficit	4.35	4.87	6.58	6.6	3.66	4.54	5.38	6
% V_{macro}	56.97	57.26	53.44	36.69	46.4	69	62.4	53.7
% V_{int}	0.91	1.0858	2.2	1.4	1.9	1.9	0.8	1.6
% V_{sink}	3.4	8.054	7.94	4.4	6.8	4.6	3.2	4.1
% V_{conc}	37.36	33.596	36.3	57.1	44.75	24	33.4	40.14

4. Discussion

Table 8 and figure 8 (Influence of process parameters on mold filling ability and volume deficit) were providing results from the 8 set of experiments for the mold filling ability and volume deficit characteristics respectively.

Table 8.
Mold filling ability and volume deficit values

Exp no.	**Alloy**	**Pouring temperature (^{0}C)**	**Mold coat**	**MF (mm^{-1})**	**%Shrinkage**
1	US A356	T	No coating	0.4091	6.58
2	US A356	T+50	No coating	0.5879	6.00
3	US A356	T+50	Graphite	0.8260	4.87
4	US A356	T+50	Graphite	1.5518	4.35
5	US 413	T	No coating	1.2500	5.38
6	US 413	T+50	No coating	1.5836	5.00
7	US 413	T+50	Graphite	1.7350	4.54
8	US 413	T+50	Graphite	2.7684	3.66

The mold filling ability increases with increase in Silicon content in the alloy as shown in Figure 9. Silicon additions improve casting characteristics by improving fluidity, feeding. Decrease in thermal conductivity and heat transfer coefficient increases the mold filling ability. Heat transfer coefficient describes the ratse at which heat is lost through the casting and the mold. Lower thermal conductivity and heat transfer coefficient means that the casting freeze at slower rate and hence mold filling ability increases and less volume deficit.
Higher heat conductivity intensifies the heat extraction from the molten metal during filling and so the time available for the metal to be in liquid state is less. US 413 alloy is characterized by a lower thermal conductivity than the US A356. Increased silicon content reduces the thermal conductivity of the cast aluminium alloys [13].

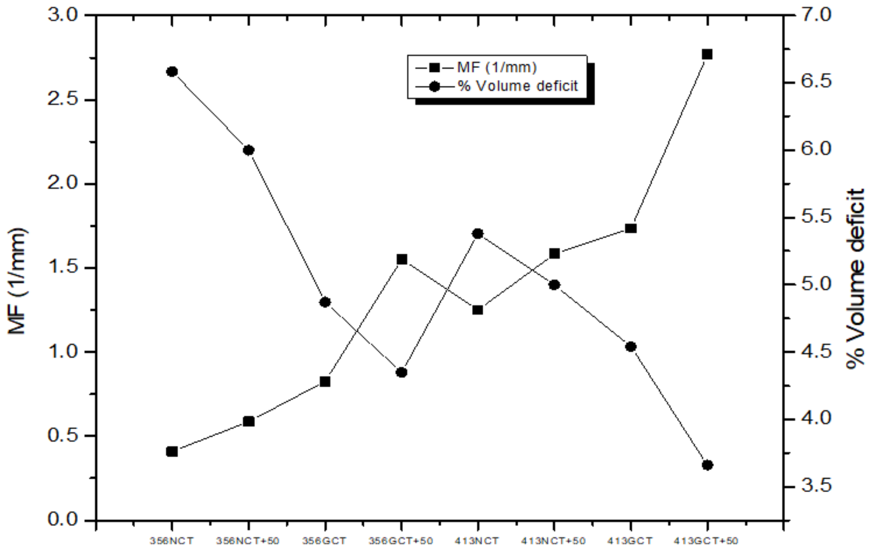

Fig. 9. Influence of process parameters on mold filling ability and volume deficit

Increased pouring temperature increases the heat content of the alloy, resulting in alloy being liquid for longer duration. The liquid metal easily enters the cavities between the cores and fills the fine contours. Increased pouring temperature delays the nucleation and growth of the grains at the tip of the flowing liquid metal in the mold, thus the mold filling ability increases, forcing the liquid metal to easily enter and reproduce contours. Additional pouring temperature or super heat increases the fluidity and considers the allowance for heat losses before they are in their final position in the mold. Increased pouring temperature results in lower rate of heat extraction by the mold, there by liquid metal flows to solidifying leads to less amount of volume deficit

Present study has been conducted with graphite coat on the mold. Uncoated surface of the mold prevents the molten metal flow and decreases the mold filling. To reduce the friction between the metal and mold, the surface on the mold is coated with graphite. Mold coat can increase solidification time, which results in greater casting fill. Mold coat provides smooth casting surface and influences the thermal gradient by promoting the directional solidification. Mold coat allows a passageway for feed metal to flow into the solidifying structure and compensates for normal metal shrinkage during solidification.

4.2. Correlation coefficient

Correlation coefficient quantifies the strength of the linear association between two variables. To ascertain the strength of association between the mold filling ability and volume deficit characteristic correlation co-efficient between the two results is calculated using the formula.

Correlation(r) = $[(N\Sigma XY - (\Sigma X)(\Sigma Y))/\mathrm{Sqrt}([N\Sigma X^2 - (\Sigma X)^2][N\Sigma Y^2 - (\Sigma Y)^2])]$

N = number of values (8 experiments)

X= Mold filling ability

Y = Volume deficit

N	X	Y	X*Y	X*X	Y*Y
1	0.409	6.6	2.7	0.167	43.56
2	0.588	6.583	3.87	0.346	43.34
3	0.826	4.87	4.023	0.682	23.72
4	1.552	4.35	6.75	2.408	18.92
5	1.25	5.38	6.725	1.563	28.94
6	1.584	5	7.918	2.508	25
7	1.735	4.54	7.877	3.01	20.61
8	2.768	3.66	10.13	7.664	13.4
∑	10.71	40.98	50	18.35	217.5

The correlation coefficient always takes a value between -1 and 1, with ±1 indicating perfect correlation. If *x* and *y* have a strong negative linear correlation, *r* is close to -1. An *r* value of exactly -1 indicates a perfect negative fit. Negative values indicate a relationship between *x* and *y* such that as values for *x* increase, values for *y* decrease

The Correlation Co-efficient value obtained is -0.98901 indicating strong a negative relation between mold filling ability and volume deficit characteristics. Negative values indicate a relationship between mold filling ability and volume deficit such that as values for mold filling ability increase, for volume deficit decrease

4.3. Main effects: Analysis of variance (ANOVA)

To study the characteristics of mold filling ability and volume deficit, it is necessary to study all the process parameters together.

In the present study orthogonal array L8(2**3) is used with three factors and 2 levels (for 8 runs), as indicated in Table 3 and response values are given in Table 7. The interactions selected for this study are

i. Alloy and Mold coat
ii. Alloy and Pouring temperature

ANOVA for mold filling ability and volume deficit is done using MINITAB and it is given in Table 9 and 10. P determines whether a factor is significant against an alpha value (α) of 0.1 where α is expressed as a probability ranging between 0 and 1.

Table 9.
ANOVA for Mold filling ability

Source	Degrees of Freedom	Sum of Squares	Mean squares	Factor	P
Alloy	1	1.9624	1.9624	8.98	0.040
Pouring temperature	1	1.1633	1.1633	5.32	0.082
Mold coat	1	0.0052	0.0052	0.02	0.884
Error	4	0.8742	0.2185		
Total	7	4.0051			

The factor is considered significant if P value is lower than 0.1. The analysis of variance indicates that the **alloy factor** is considered more significant in influencing mold filling ability, where as **pouring temperature** is considered more significant in influencing volume deficit characteristic.

Table 10.
ANOVA for Volume deficit

Source	Degrees of Freedom	Sum of Squares	Mean squares	Factor	P
Alloy	1	1.2985	1.2985	5.81	0.074
Pouring temperature	1	3.8406	3.8406	17.18	0.014
Mold Coat	1	0.0455	0.0455	0.20	0.675
Error	4	0.8940	0.2235		
Total	7	6.0786			

Use of main effects plot in conjunction with an analysis of variance (ANOVA) is useful when several factors are involved together. The effect is given by the difference between the mean for that level and the overall mean for the factor. The overall mean is 1.26 and 5 for mold filling ability and volume deficit characteristics respectively from the ANVOA calculations. Main effects plot for mold filling ability and volume deficit values are shown in Figure 10 and 11. The magnitude of an effect is related to its distance from the mean.

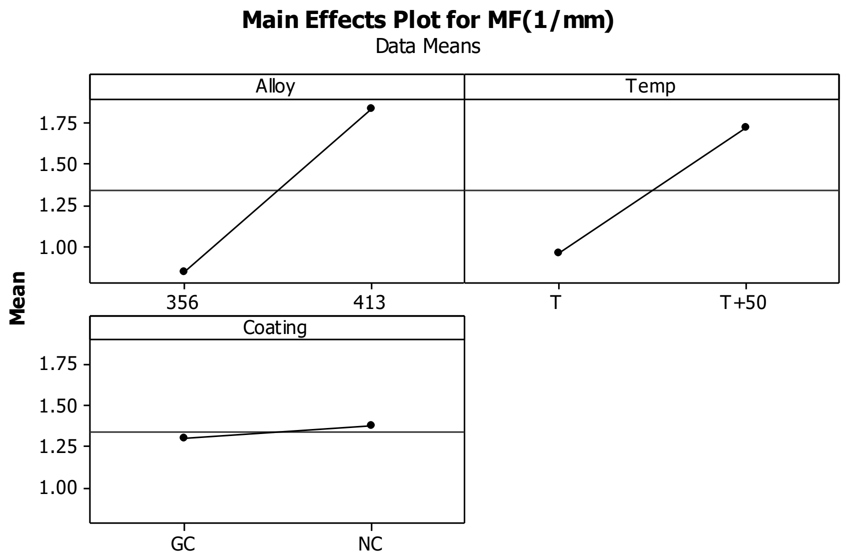

Fig. 10. Main effects plot for mold filling ability values

A reference line is drawn to represent the overall mean. Lines are not horizontal (parallel to the x-axis) for all the three factors of the present study, indicating the presence of a main effect. The main effects plot indicates that the Alloy, Mold coat and Pouring temperature influence the both parameters. In case of alloy factor, the difference in the vertical position of the plotted points is more, hence magnitude of the main effect is greater for mold filling ability. The pouring temperature is considered more significant in influencing volume deficit.

The Main Effects plot indicates an optimum combination of US 413, graphite coat and pouring temperature T+50 to attain better mold filling ability value and low volume deficit value. These results are in agreement with the experimental results.

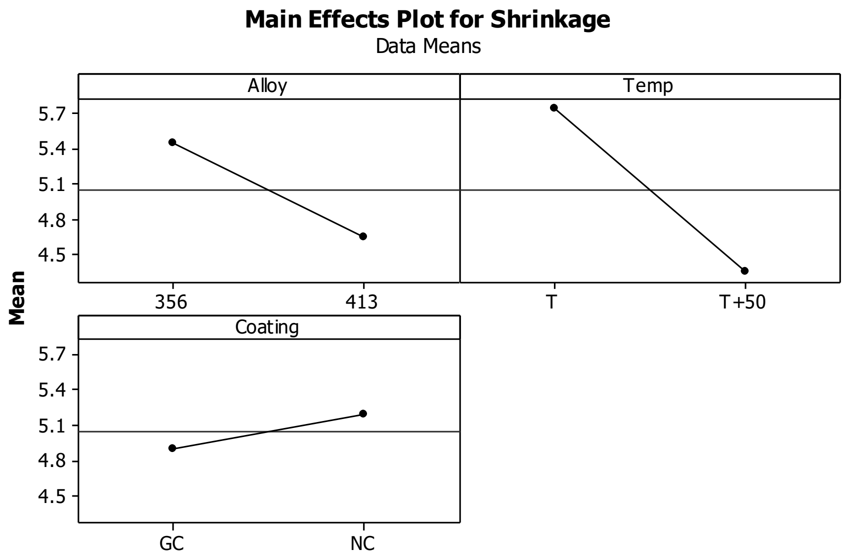

Fig. 11. Main effects plot for volume deficit

6. Conclusion

The correlation co-efficient values for mold filling ability and volume deficit characteristic are observed to be closer to -1 indicating a **negative relationship** between them. The main effects plot indicates that the Alloy, Mold coat and Pouring temperature influence the both casting characteristics. Lower thermal conductivity and heat transfer coefficient means that the casting freeze at slower rate and hence mold filling ability increases and less volume deficit, lower the Silicon content lower is the thermal conductivity. Increase in pouring temperature results in lower rate of heat extraction by the mold, there by liquid metal flows to solidifying leads to less amount of volume deficit and more mold filling ability. Mold coat allows a passageway for feed metal to flow into the solidifying structure and compensates for normal metal shrinkage during solidification and also results in greater casting fill.

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