Solidification Behaviour of Al-Si-Mg Alloys in the Gravity Die-Casting Process

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In the gravity die-casting of Al-Si-Mg alloys, the pouring of molten metal into the mould and its subsequent solidification are vital. The solidification time of these alloys in the die-casting process mould increases with increase in the pouring temperature of melt, decreases with increase in the pre-heat temperature of mould. It has been found that the Si content in the alloy reduces the freezing range whereas the Mg content widens it. Sufficient degasification of the melt improves the solidification process.

INTRODUCTION

A gravity die-casting process is also known as permanent mould casting process since the metal enters the mould under gravity. The gravity die-casting process makes use of a mould, which is permanent i.e., the mould (also called die) can be reused many times before it is discarded or rebuilt. The mould material is selected on the consideration of the pouring temperature, size of the casting and frequency of the casting cycle. If the casting is done with the cold die, the first few castings are likely to have miss-runs till the die reaches its operating temperature. To avoid this, the mould should be preheated to its operating temperature, preferably in an oven. The materials, which are normally cast in permanent moulds, are aluminium alloys, magnesium alloys, copper alloys and zinc alloys. The sizes of castings are limited to 15 Kg in most of the materials[1,2].

Generally, gravity die-castings, when compared with sand castings, have faster solidification rates and possess higher tensile properties. This is primarily because of finer constituents and smaller dendrite cells and grains[3]. Despite recent innovations and advances in die-casting technology that have significantly expanded the products, the development of complementary new alloys, the optimisation of existing alloys, and the documentation of reliable properties data for these alloys, have all categorically lagged behind.

The pouring of molten metal into the mould and its subsequent filling are quite critical steps in metal casting, since the behaviour of the liquid metal and its freezing determine whether the cast shape will be properly formed and free from defects[4]. Al-Si alloy and Al-Mg alloy castings have individual advantages and disadvantages over the other. In the present work, the Al-Si-Mg alloys are considered to investigate the solidification behaviour with respect to gravity die-casting process.

EXPERIMENTAL PROCEDURE

The experimental planning was carried out according to Taguchi's design methods[5-10]. The alloys were prepared and chemical analysis of their ingredients was done. The chemical composition of alloys is given in Table-1.

The solidification time of alloys is the quality characteristic to measure experimental outputs. The parameters, which influence the performance of the gravity die-casting process, are:

1. Alloy composition
2. Pouring temperature of the metal
3. Degasification
4. Preheating temperature of the mould.

The objectives at the end were developing good Al-Si-Mg alloy gravity poured diecastings. The selected levels for the chosen control parameters are summarised in Table-2.

Table-1: Chemical Composition of Alloys

Alloy	Composition determined spectrographically, %				
	Al	Si	Mg	Fe	Cu
1	93.99	2.0	4.0	—	0.01
2	91.99	5.0	3.0	—	0.01
3	88.49	9.0	2.0	0.5	0.01

Table-2 : Control Factors and Levels

Factor	Symbol	Level-1	Level-2	Level-3
Alloy composition	A	1	2	3
Pouring temperature of Melt, °C	T	675	700	725
Mould pre-heat temperature, °C	P	200	300	400
Degasification with Tetrachlorethane,%	D	0.75	1.00	1.25

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The orthogonal array, L_9 was selected for the present work. The assignment of parameters along with the OA matrix is given in Table-3.

The casting design shown in Fig. 1 was employed to study the solidification phenomena in gravity poured die-casting alloys[11].

The Al-Si-Mg alloys were melted in an oil-fired furnace. The melting losses of aluminium and magnesium were taken into account while preparing the charge. During melting, Coveral-11 (a Foseco Company product) flux was added to the charge to prevent dressing. The molten metal was then degasified by tetrachlorethane (in solid form) using a plunger ending in a small inverted crucible. The melt was also modified with sodium in the crucible before pouring. The crucibles were made of graphite[12-15].

The charge was reheated to the required pouring temperature in a muffle furnace. The temperature of the melt was measured using a dip-type thermocouple. The dross removed melt was finally gravity poured into the preheated mould.

Table-3 : Orthogonal Array (L_9) and Control Parameters

Treat No.	A	T	P	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

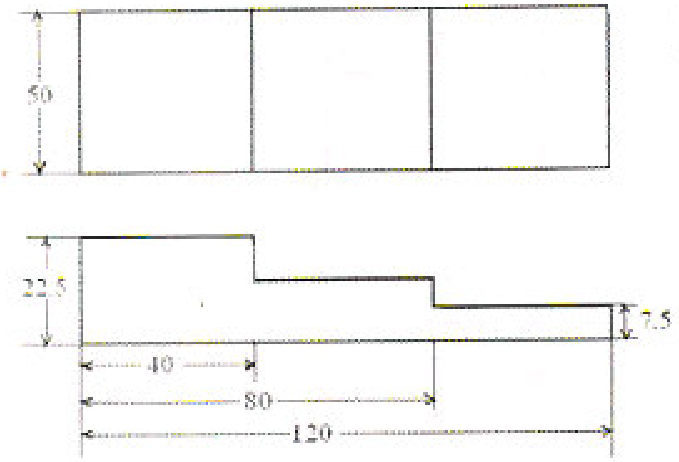

Fig.1 : Casting Design.

Measurement of Solidification Time

The setup for the measurement of solidification is shown in Fig. 2. With each casting poured, the temperature decreases due to solidification of liquid alloy. The time taken (i.e. solidification time) to reach solidus temperature was noted down using stopwatch. Four thermocouples were placed in the casting to record solidification time and one thermocouple was placed in the mould to record the temperature of the mould.

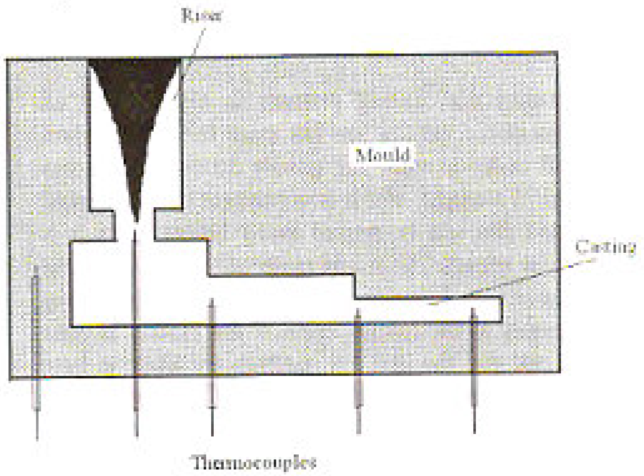

Fig. 2 : Setup for the Measurement of Solidification Time.

Analysis of Variance (ANOVA)

After all tests were conducted, the decisions were made with the assistance of ANOVA, which is a statistically based, objective decision-making tool for detecting any differences in average performance of groups of items tested. The total sum of squares (total variation).

$$SST = \sum_{N} Y_i^2 - \frac{T^2}{N} \qquad \text{—(1)}$$

Variation due to parameter (for example)

$$= \frac{A_1^2}{n_{A_1}} + \frac{A_2^2}{n_{A_2}} + \frac{A_3^2}{n_{A_3}} - \frac{T^2}{N} \qquad \text{—(2)}$$

$$\text{F-ratio} = \frac{S_{y1}^2}{S_{y2}^2} \qquad \text{—(3)}$$

where,

Y_i = value of the observation under A_j level

S^2_{v1} = the variation of averages

S^2_{v2} = the variation of individuals

T = Sum of all observations

The parameter which has F-ratio larger than the criterion (F-ratio from the tables) are believed to influence the average value for the population, and parameters which has a F-ratio less than the criterion are believed to have no effect on the average. Per cent contribution indicates the relative power of a parameter and/or interaction to reduce variation. If the parameter and/or interaction levels were controlled precisely, then the total variation could be reduced by the amount indicated by the per cent contribution.

The percent contribution of parameter A,

$$P_A = \frac{SSA^1}{SST} \times 100 \qquad \text{—(4)}$$

where,

SST = Total sum of squares

$$SSA^1 = SS_A - (V_e)\, v_A \qquad \text{—(5)}$$

Confirmation Tests

The key task was the determination of the preferred combination of the levels of the factors indicated to be significant by the analytical methods. The insignificant factors may be set at any desirable levels. The purpose of the confirmation experiment was to validate the conclusions drawn during the analysis phase.

$$\text{Confidence interval, C.I.} = \sqrt{\frac{F_{\alpha:1:v_e} V_{ep}}{n_{eff}}} \qquad \text{—(6)}$$

where,

$F_{\alpha:1:ve}$ = F-ratio

α = risk

V_e = degrees of freedom for pooled error

V_{ep} = pooled error variance

Effective sample size,

$$n_{eff} = \frac{N}{1 + \text{Total degrees of freedom associated with items used in mean estimate}} \qquad \text{—(7)}$$

If the average of the results of the confirmation experiments was within the limits of the confidence interval, the significant factors as well as the appropriate levels for obtaining the desired result were properly chosen. If the average of the results of the confirmation experiment was outside the limits of the C.I, the chosen factors were wrong or the measurements might be with excessive error, necessitating further experimentation.

RESULTS AND DISCUSSION

The experimental results are given Table-4. Each experiment was repeated two times.

Effect of Process Parameters on the Solidification

Table-5 gives the pooled ANOVA summary of raw data. The per cent contribution indicates that the parameter T (pouring temperature of melt) contributes 37.95% of variation, parameter P (mould pre-heat temperature) aids 33.09% of variation, parameter A (alloy composition) influences 22.84% of variation and parameter D (degasification with tetrachlorethane) contributes 15.83%.

A low temperature level of solidification (difference between pouring temperature and mould pre-heat temperature), which reduces temperature gradients between the mould and casting, decreases the temperature gradient within the casting. Figure 3 shows the influence of pouring temperature of melt on the solidification time of the die-casting. It can be seen that the solidification time increases with increase in the pouring temperature of melt.

Yamamoto et al.[16] studied the solidification behaviour of Al-Mg binary alloys. In their experiments, the molten metal was poured into the die-casting sleeve at 640°C. It was found that the temperature of the melt decreased and reached the solidifying temperature rapidly. They did not obtain the mathematical relation between pouring temperature and solidification time of binary Al-Mg alloys.

Table-4: Experimental Results of Taguchi's Design Matrix

Treat No.	Solidification time, min	
	Trial-1	Trial-2
1	9.6	9.8
2	9.8	9.6
3	9.6	9.7
4	9.5	9.4
5	9.6	9.5
6	9.7	9.9
7	9.5	9.5
8	10	9.8
9	9.8	10.1

Table-5 : ANOVA Summary of Solidification Time

Column No.	Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
1	A	58.1	57.6	58.7	0.101111	2	0.050556	2.527778	22.84
2	T	57.3	58.3	58.8	0.194444	2	0.097222	4.861111	37.95
3	P	58.8	58.2	57.4	0.164444	2	0.082222	4.111111	33.09
4	D	58.4	58.0	58.0	0.017778	4	0.004444	0.222222	15.83
5	e	—	—	—	0.14	7	0.02	—	13.13
6	T	—	—	—	0.617778	17	—	—	100.00

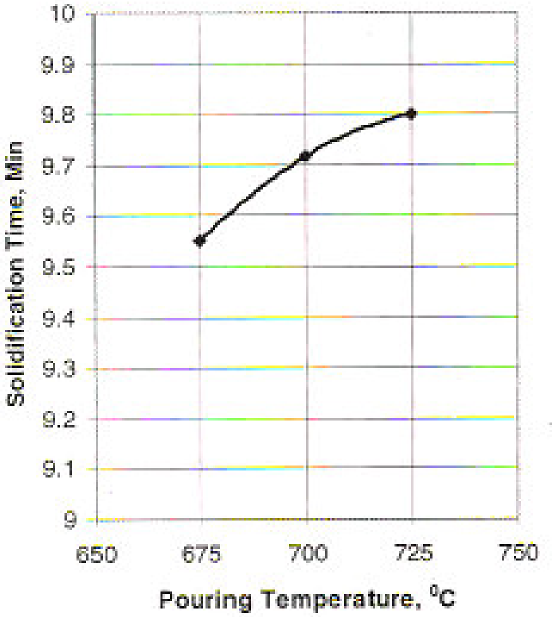

Fig. 3 : Influence of Pouring Temperature of Melt on the Solidification Time of Casting.

In the present work on the solidification behaviour of Al-Si-Mg trinary alloys, it is also proved that the solidification is faster at low pouring temperature than at high pouring temperature. It is also observed that the relation between pouring temperature and solidification time is quadratic in nature. The mathematical relation between pouring temperature and solidification time is given by

$$S = -7x10^{-5}T^{2} + 0.0983T - 26.45 \quad \text{............} \quad [7]$$

where,
S is the solidification time, Min
T is the pouring temperature, °C

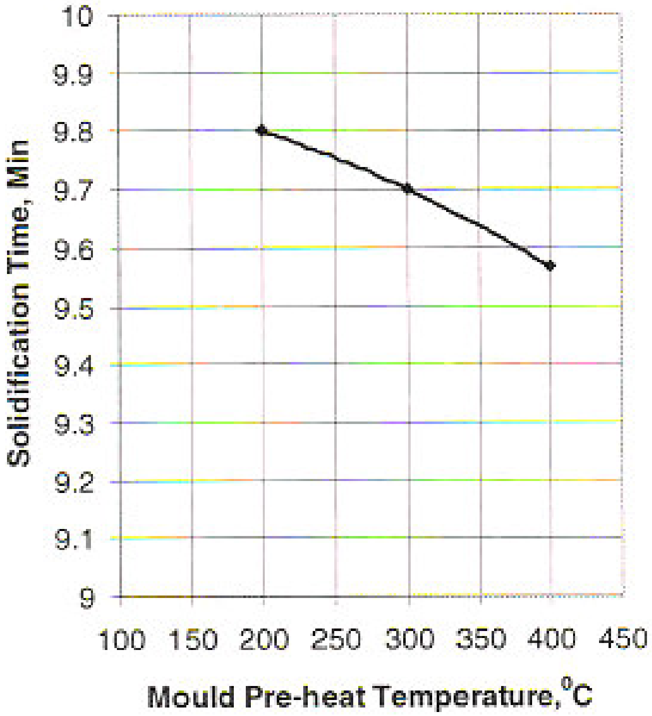

Fig. 4 : Influence of Mould Pre-heat Temperature on the Solidification Time of Casting.

Figure 4 illustrates the influence of mould pre-heat temperature on the solidification time of the die-casting. The graph indicates that the solidification time decreases with increase in mould pre-heat temperature. The temperature level of solidification (difference between pouring temperature and mould pre-heat temperature) decreases with increase in mould pre-heat temperature for the specified pouring temperature of melt. The mould pre-heat temperature decreases the temperature gradient within the casting. Hence, there is a reduction in the solidification time of the casting. The mathematical relation between pouring temperature and solidification time is given by

$$S = -0.2x10^{-6}P^{2} - 0.0002P + 9.9 \quad \text{....} \quad (8)$$

where,
S is the solidification time, Min
P is the mould pre-heat temperature, °C

The influence of alloy composition on the solidification time of die-casting is presented in the Figs. 5 and 6. Figure 5 illustrates the effect of Si content in the alloy on the solidification time. The freezing range of the alloy decreases with increase in the Si content. The decrease in the cooling rate is accompanied by a contraction in the solidification range that resulted from an increase in the end temperature. From the Fig. 5, it can be seen that as the Si content increases from 2% to 4%, the solidification time decreases. It can also be observed that as the Si content increases from 4% to 9%, the solidification time increases. It is contradictory to the above-said statement. The reason could be the presence of Fe in the alloy-3. Fe results the precipitation of AlSiFe type phase during the solidification of melt. This results in the decrease of Si content in the remaining liquid. Hence, the solidification time is increased. Spear and Gardner[17] proved that in alloys containing elements that form intermetallic constituents with high solidification temperatures, the constituents could grow to such that they would impede feeding. The mathematical relation between Si content in the alloy and solidification time is given by

$$S = 0.0105A_{Si}^2 - 0.1014A_{Si} + 9.844 \quad .... (9)$$

where,

S is the solidification time, Min

A_{Si} is the Si content in the melt, %

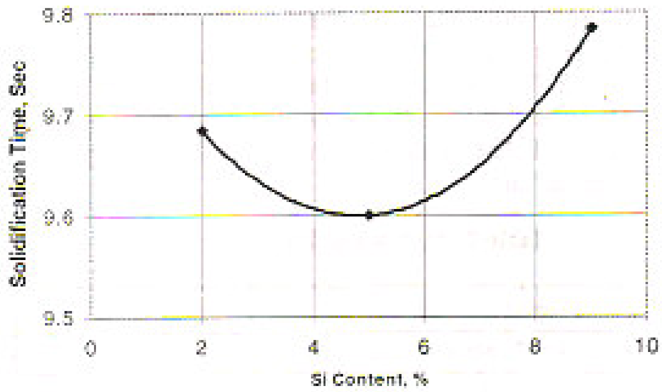

Fig. 5 : Influence of Si Content in the Alloy on the Solidification Time of Casting.

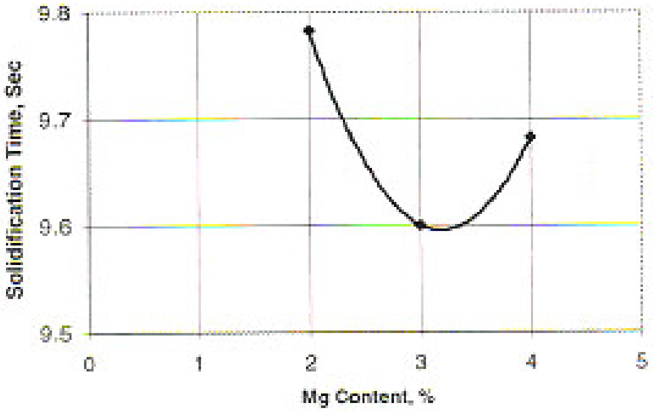

Fig. 6 : Influence of Mg Content in the Alloy on the Solidification Time of Casting.

Figure 6 represents the effect of Mg content in the alloy on the solidification time. The influence of Mg content is just opposite to that of Si content. The influence of Mg addition could be attributed to the tendency of Mg to react with other elements. Mg results in wide freezing range of die-casting alloys. Mg has a strong tendency to react with refractories and oxides, and introduces finely dispersed particles into the melt. These finely dispersed particles may reduce melt fluidity. In alloys containing Mg (2-4%), the eutectic phase Mg_5Al_8 may appear. When these alloys contain considerable amount of Fe, the following ternary eutectic reaction results

$$L \rightarrow Al + FeAl_3 + Mg_5Al_8$$

where,

L is the liquid melt

Mg also reacts with Si to form Mg_2Si phase. A complex eutectic reaction completes the solidification process as follows:

$$L \rightarrow Al + FeAl_3 + Mg_2Si + Mg_5Al_8$$

The mathematical relation between Mg content and solidification time is given by

$$S = 0.1333A_{Mg}^2 - 0.85A_{Mg} + 10.95$$

where,

S is the solidification time, Min

A_{Mg} is the Mg content in the melt, %

The influence of degasification of melt with tetrachlorethane on the solidification time is shown in Fig. 7. At low content of tetrachlorethane, the solidification time is high. This is owing to the presence of dissolved gases present in the melt. The dissolved gases hinder the heat transfer from melt to the mould. The gases are poor at heat transfer by conduction or convection from melt to mould. Once the dissolved gases are removed from the melt, there is no effect of degasification on the solidification.

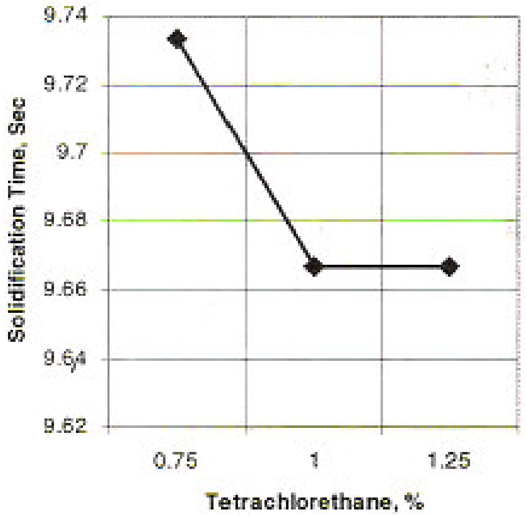

Fig. 7 : Influence of Degasification on the Solidification Time of Casting.

1% of tetrachlorethane is sufficient to remove the dissolved gases from the melt. Because of combustible nature of tetrachlorethane, there is a possibility of fluxing and purging of the melt.

Optimisation of Process Parameters

The solidification process of die-castings depends upon the removal of heat from the castings through the mould. The modes of heat removal are by conduction, convection and radiation. The role of radiation is very much limited in the foundry environment, but conduction and convection play vital role in the removal of heat from the castings. The above-characteristics depend on the alloy composition, pouring temperature of melt, mould pre-heat temperature and degasification of the melt for gravity die- casting process.

Fe is often added unintentionally through the use of steel or cast iron tools during melting and metal die used for casting, and the reuse of remelting materials containing rust. In aluminium die-casting alloys, it is added purposely to minimise die soldering. Looking into the importance of die-casting characteristics, the statistical confirmation test was carried out (Appendix-A). The predicted value of solidification time for the die-casting alloy is 9.5 min, which is equal to the average value of treatment No. 7 (9.5). The solidification pattern in the casting is seen in Fig. 8. The riser fed the casting sufficiently during solidification. The feeding of the riser is characterised by the parabolic metal flow. Hence, all the process parameters with the levels of treatment No. 7 are chosen for the manufacturing of Al-Si-Mg alloy castings. The process parameters with their optimum levels are given in Table-6.

Table-6: Process Parameters with Optimum Levels

Parameter	Level
Alloy composition	Alloy-3
Pouring temperature, ^{0}C	675
Mould pre-heat temperature, ^{0}C	400
Tetrachlorethane, %	1.0

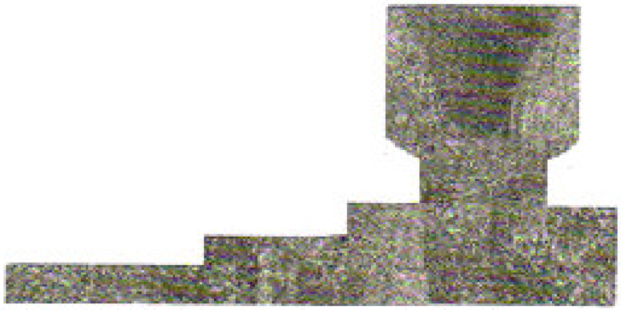

Fig. 8 : Gravity die-casting section having the process parameters: alloy-3, pouring temperature = 675^{0}C, mould pre-heat temperature = 400^{0}C, and degasified with 1.00% Tetrachlorethane.

The reaction during the solidification of alloy-3 (88.49% Al - 9% Si - 2% Mg - 0.5% Fe - 0.01% Cu) may be as follows:

$$L \rightarrow Al + Si + Mg_2Si + Al_2Cu + Al_3Fe + Al_3FeSi + Al_5Mg_8Cu_2Si_6$$

where, L is the liquid melt.

In the alloy-3, Fe concentration increases in the interdendritic areas and Al_3Fe needles precipitate. The dendrites of alloy-3 are bigger than those of alloy-1 and alloy-2. The tensile strength is affected by the coarse structure of alloy-3. The microstructure of alloy-3 is shown in Fig. 9. The mechanical properties of the alloy-3 are given in Table -7.

Table-7: Mechanical Properties of Alloy-3

Property	Quantity
Tensile Strength, MN/m^2	268
%Elongation	8
Hardness, BHN	77

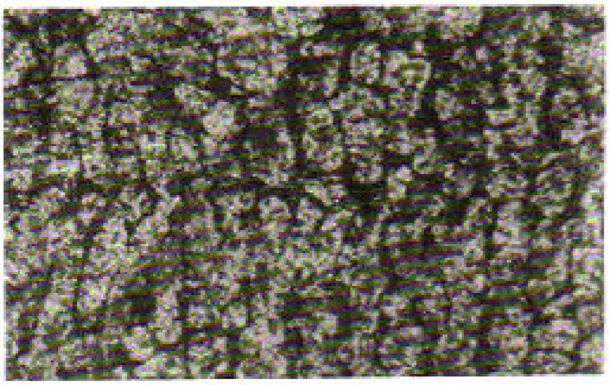

Fig. 9 : Microstructure of Al-Si-Mg Alloy (alloy-3) Die-castings, 200X.

CONCLUSIONS

The following conclusions are drawn from the present work:

1. The solidification time of the liquid metal in the mould increases with increase in the pouring temperature of melt.
2. The solidification time of the liquid metal in the mould decreases with increase in the pre-heat temperature of mould.
3. The freezing range of Al-Si-Mg alloy decreases with increase in the Si content.
4. Mg content results in wide freezing range of Al-Si-Mg alloys.
5. Sufficient degasification of the melt helps in the reduction of solidification time of Al-Si-Mg alloys.
6. The optimum solidification time 9.5 minutes has been achieved at the following values of the process variables:

Alloy composition : 88.49%Al-9%Si-2%Mg-0.5%Fe-0.01%Cu
Pouring temperature : 675^{0}C
Mould pre-heat temperature : 400^{0}C
Degasification : 1% tetrachlorethane

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Appendix-A : Confirmation Test

The significant process parameters which affect the solidification time of castings are alloy composition (alloy-3), pouring temperature of melt (T_1), mould pre-heat temperature (P_3) and degasification of the melt (D_2).

The estimated mean of solidification time = $A_3 + T_1 + P_3 + D_2 - 3T$
$= 9.78 + 9.55 + 9.57 + 9.67 - 3 \times 9.69 = 9.5$

where , T = grand mean
= 9.69

The confidence interval, CI = $\sqrt{\dfrac{F_{\alpha;2;v_e} V_e}{n_{eff}}}$

where,

$F_{\alpha;2;v_e}$ = Fisher's ratio
α = risk
v_e = degrees of freedom for error
V_e = error variance

$$n_{eff} = \frac{N}{1+\text{total degrees of freedom associated with items in the estimate of mean}}$$

$$n_{eff} = \frac{18}{1+4} = 3.6$$

For 95% confidence level, the Fisher's ratio is

$F_{5;2;9} = 4.26$

$$CI = \sqrt{\frac{4.26 \, x0.015556}{3.6}} = 0.14$$

The predicted range of solidification time is 9.36 < solidification time < 9.64.