SEMI-SOLID ALUMINUM DIE CASTING PROCESS DESIGN FOR PREVENTING DEFECTS: POROSITY

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Abstract

Gas porosity is one of the most common casting defect in die cast parts and it has an undeniable effect on strength, leakage and heat treatability. Reducing and even preventing porosity level can be achieved by the integrative design of mold, vacuum system and optimized process parameters. Applying semi-solid processing also helps to improve quality; not only by preventing defects but also modifying microstructure to have stronger products. In semi-solid casting, generated globular primary phases cause reduction in apparent viscosity under increased shear stress in thixotropic behaviour. This leads to planar flow instead of turbulent, which helps reducing air entrapment during injection and mold filling. In this study, GISS (Gas Induced Semi-Solid) adapted high pressure die casting technique is used for producing AlSi9Cu3 alloy die cast parts. The effects of semi-solid processing temperature, rheo-casting time, changeover position and fast shot velocity are investigated on microstructural changes and porosity levels by using Taguchi method. Radiographic analysis is used for non-destructive testing for determining porosity state. Optic and field emission scanning electron microscope (FE-SEM) are used for microstructural and morphological characterization. Energy-dispersive X-ray spectroscopy (EDS) is also applied for chemical analyses of the phases involved. As results, fast shot velocity and rheo-casting time are found to be the most effective parameters on the porosity level and globular microstructure, by increased shear stress.

Keywords: High pressure die casting, semi-solid, aluminum, Taguchi method, characterization

1. INTRODUCTION

High pressure die casting (HPDC) technique is one of the most used production method for aluminum components. In HPDC technique, melt aluminum is injected in steel moulds and applied pressure via plunger. Injection is carried out in 3 phases as slow shot, fast shot and intensification. During slow shot and fast shot stage gas entrapment in melt can be occured because of turbulent flow; which causes porosity defect while solidification of the melt. To avoid this, semi-solid processing can be used succesfully. Semi-solid processing is a method for producing slurry which contains globular α-Al particles. These globular particles are proned to slide each other under applied shear stress, this also helps to reduce the viscosity of the slurry. Laminar flow is obtained and mold filling can be done in proper way.

GISS method is a novel rheo-casting process discovered by Dr. Wannasin and his team in MIT (Massachusetts Institute of Technology). Since then, developments are done and released as a licensed process by GISSCO Ltd. Several topics as application of GISS process [1], semi-solid grain refinement [2], heat treatment of GISS processed alloys [3], flow characteristics of GISS processed alloys [4] are studied by Wannasin et al. Application of GISS process consists cooling a superheated (melt temperature above liquidus) aluminum alloy with inert gas to a specific liquid-solid temperature; inert gas is blown in fine particles from a permeable graphite diffuser that is immersed in ladled melt just before pouring into shot sleeve. Graphite diffuser acts as a cold finger and blown inert gas agitates the melt; α-Al particles are formed with decrease of temperature to semi-solid range. Inert gas flow breakes the dendritically formed α-Al particles and these broken particles acts as secondary nuclei. This process provides particle refinement and helps primary phase globularization. Desired solid fraction can be defined with gas blowing (rheo-processing) time and initial holding temperature of the melt. Distinctly from other major rheo-casting methods, in GISS process; obtained initial solid fraction in shot sleeve is about 10-20 %, which is nearly two more times lesser than mentioned methods. This relatively low solid fraction also helps GISS process to be applicable to sand casting [5]. GISS process is succesfully applied for casting of several aluminum alloys; A356 [6] as low pressure die casting alloy, ADC12 [7] and EN AC 48000 [8] as near-eutectic high pressure die casting alloys, also 6061 [9] and 7075 [10] as wrought alloys, and magnesium alloys [11]. Some studies show [12] it's hard to semi-solid process near-eutectic alloys because solid + liquid range is very narrow. However, some studies reveal that binary eutectic and even pure metals can be semi-solid processed in proper ways [13-14]. To achieve this, heat transfer must be concerned and rheo-processing must be carried out rapidly [15].

In this study, EN AC 46000 (AlSi9Cu3) near-eutectic high pressure die casting alloy is used as material. Process parameters are chosen as semi-solid processing temperature, rheo-casting time, changeover position and fast shot velocity. Semi-solid processing temperature and rheo-casting time define the method as conventional die casting and semi-solid casting. Zero (0) in rheo-casting time means GISS process is not used in related trial. Semi-solid processing temperature is measured just before inert gas blowing. Rheo-casting time refers applied inert gas blowing time into the melt in GISS method. Changeover position and fast shot velocity are injection parameters; changeover position is slow shot distance in shot sleeve and fast shot velocity is plunger's speed during mould filling stage. These parameters are used for creating a Taguchi L9 orthogonal array; with 4 parameters and 3 levels. Radiographic analysis is applied for grading casting process quality based on porosity defect. Metallographic and morphologic characterizations are carried out for examining casting characteristics and obtaining phases involved in microstructure.

2. EXPERIMENTAL STUDIES

2.1. Material and methods

EN AC 46000 (AlSi9Cu3) secondary ingot alloy is melted in 250 kg capacity electric furnace and initial holding temperature is set to 730 °C. 120 seconds degassing and after refining is carried out. Density index is calculated with reduced pressure test method and found out as 1.6 %. Chemical composition of the alloy taken from melt is given in **Table 1**. AlTiB like grain refiner or Sr as eutectic modificator are not used.

Table 1 Chemical composition of EN AC 46000 aluminum alloy (wt%)

Element							
Al	Si	Cu	Fe	Mg	Zn	Mn	Cr
86	9.21	2.5	0.72	0.27	0.99	0.16	0.03

Die casting trials are carried out by using Zitai brand 5500 kN clamping force capacity cold chamber high pressure die casting machine. Semi-solid slurry is generated with N_2 gas by using GISS device and process. Process design according to Taguchi L9 orthogonal array is given in **Table 2**.

Other process parameters such as mould temperature, intensification pressure e.g. are kept constant during casting trials. Vacuum system or chill vents are not used during casting trials, mould contains air pockets in specific areas. Process design of casting trials are given in **Table 2**.

Table 2 Process design of casting trials, Taguchi L9 orthogonal array

Trial No	**SSP temperature** (°C) **(A)**	**Rheo-casting time** (s) **(B)**	**Change over position** (mm) **(C)**	**Fast shot velocity** (m/s) **(D)**
1	620	0	240	3
2	620	3	260	4
3	620	6	280	5
4	650	0	260	5
5	650	3	280	3
6	650	6	240	4
7	680	0	280	4
8	680	3	240	5
9	680	6	260	3

2.2. Radiographic analysis

Bosello industrial X-Ray device is used for radiographic analysis. Each part of the trials are applied to radiographic analysis in 120 kV and 1.6 mA settings. 49 mm thick section of the part is investigated. Each image of the trial is numbered from 0 (worse) to 5 (best) for casting quality.

2.3. Metallographic and morphologic characterization

Specimens cut from as cast part of each trial and optimized process then cold moulded with resin. Metallographic specimen preparation is carried out with grinding and polishing. Specimens are etched with Keller's reagent for 5 seconds. Zeiss AxioCam optic microscope is used for metallographic analysis. Shapes and size of primary phases are investigated. Jeol FESEM is used for SEM & EDS analyses. Morphological characterization is applied to optimized part.

3. RESULTS AND DISCUSSION

3.1. Radiographic analysis results

According to radiographic analysis, X-Ray images of the parts are given in **Figure 1**.

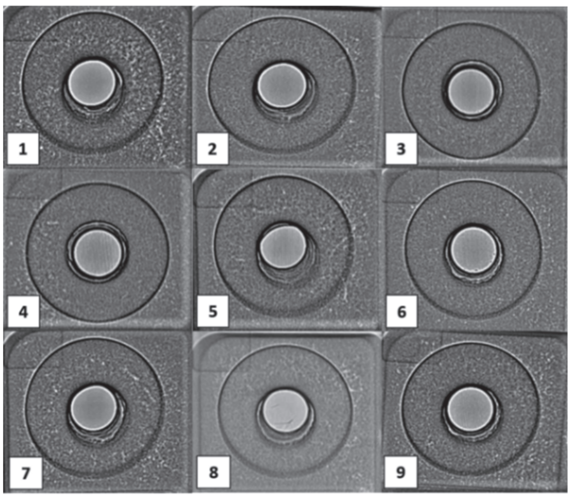

Figure 1 X-Ray images of part from trial 1 to 9, each part represents related process

Casting quality results numbered from 1 to 5. Casting quality results are given in **Figure 2** as the results from radiographic analysis.

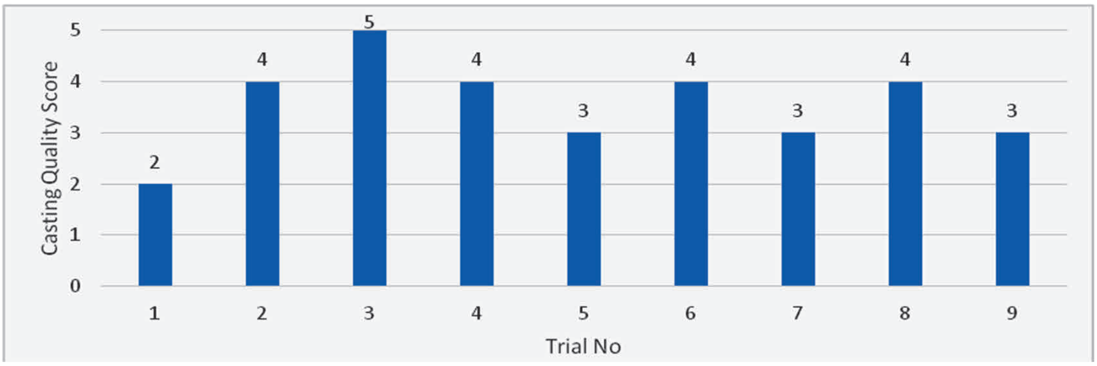

Figure 2 Casting quality results for each process

The best quality score as 5 is obtained with 3rd casting trial with minimal casting defects as porosity and shrinkage. 2nd, 4th, 6th and 8th casting trials are scored as 4 with more dinstinct defects. 5th, 7th and 9th casting trials are scored as 3 with large porosity and shrinkage defects. 1st casting trial is numbered as 2 with worst quality. Because of bad mold filling and solidification low quality is obtained in 1st casting trial. Taguchi optimization is applied based on quality results. 'Larger is better' S/N ratio is chosen because highest casting quality is desired.

$$S|N = -10\log\frac{\Sigma\left(\frac{1}{y^2}\right)}{n} \quad (1)$$

where

S/N - signal to noise ratio,
y - value of result,
n - number of results.

Taguchi optimization is run in Minitab 18 program. Effect of each parameter is given in **Figure 3**.

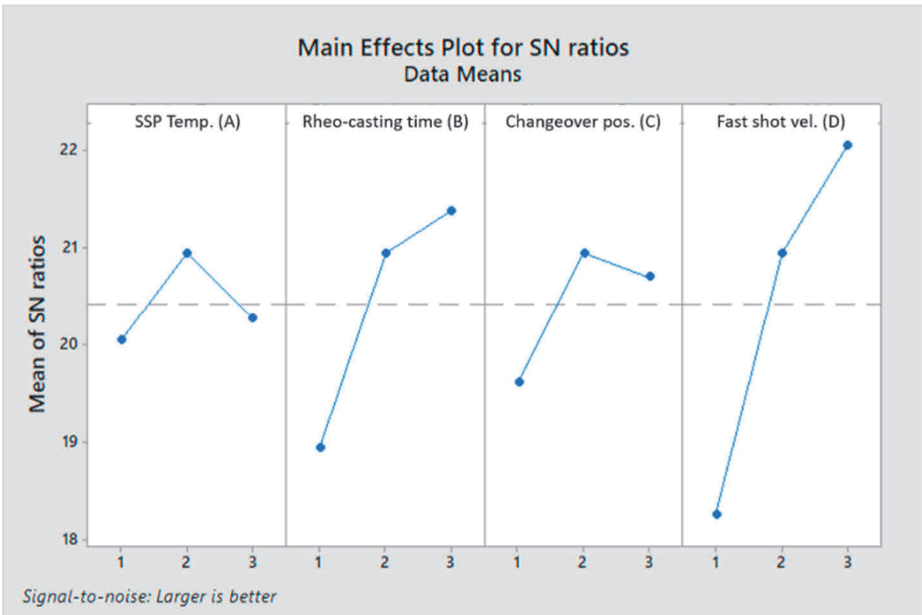

Figure 3 Effects of parameters

According to Taguchi optimization results, the most effective parameter can be seen as fast shot velocity with larger difference between levels. Fast shot velocity has an undeniable effect on both mold filling characteristics and occured primary phases [16]. Rheo-casting time is the 2nd effective parameter on casting quality. According to results there is a positive correlation between fast shot velocity and rheo-casting time. This can be explained by thixotropic flow behaviour of the slurry, increased shear stress reduces the viscosity of the melt. Changeover position also has an effect on quality but 2nd level and 3rd level seems nearly equal to each other in obtained casting quality manner. SSP temperature seems the least effective parameter on casting quality. Study shows that casting in low melt temperature without semi-solid casting, causes undesirable results.

3.2. Metallographic and morphologic analyses results

Metallographic images taken from same area of the parts. Microstructures related to labeled casting trials is given in **Figure 4**.

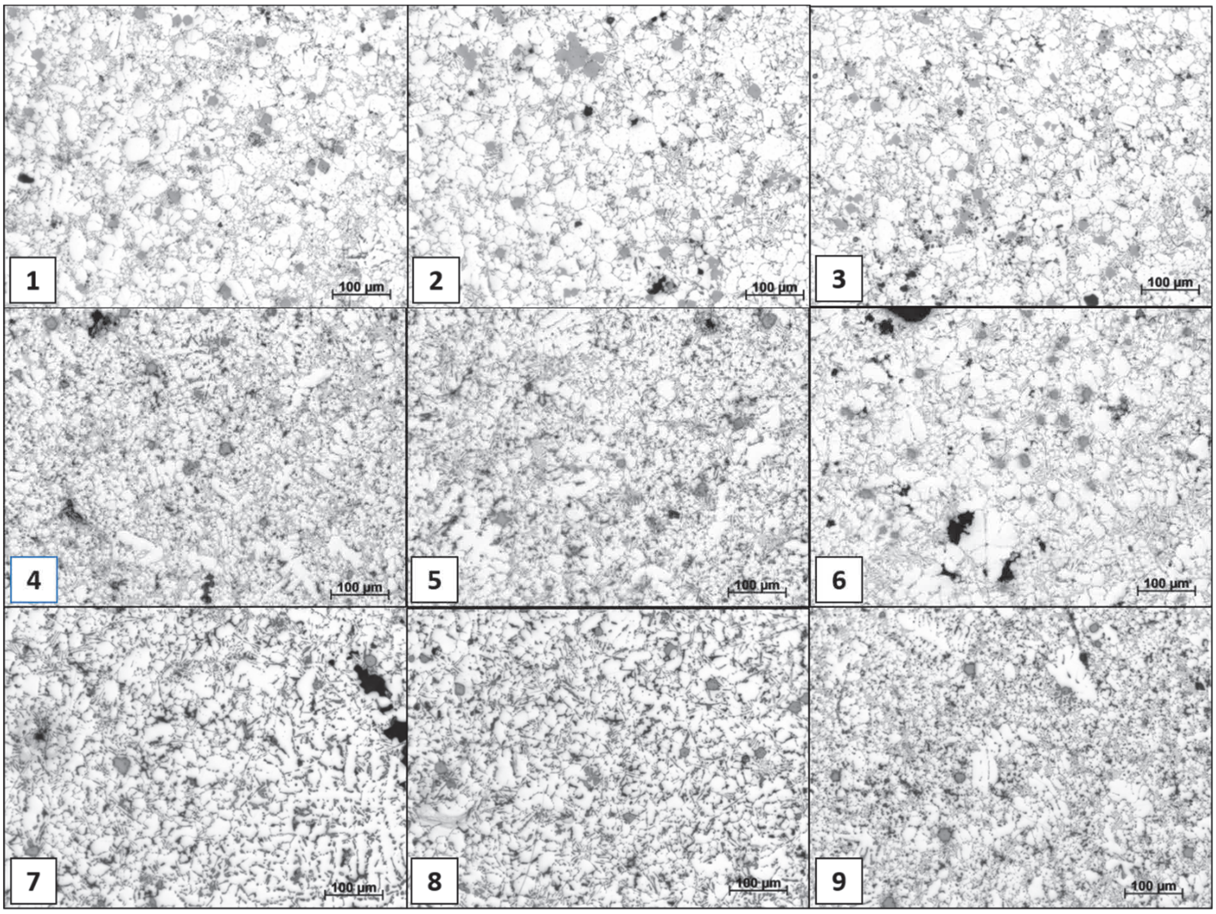

Figure 4 Microstructures of casting trials, from trial 1 to 9

Based on microstructure images, trial number 1 have rosette like α-Al particles with coarse Al-Si eutectic structures. Due to low casting temperature, extreme early solidification causes drammatic decrease in fluidity, and it's resulted with bad mold filling which can be seen in **Figure 1** (1). Trial 2 and 3 have globular α-Al particles under favour of semi-solid casting. Applied shear stress (injection speed) leads the melt to thixotropic flow and it is resulted in good mold filling with minimal porosity defect. Long dendritic structures can be seen in trial 4 and trial 5. Trial 4 can be referred to conventional die casting method due to casting temperature. Trial 5 is also GISS processed but because of high melt temperature, no solidification occured during GISS process so it was not able to get globular particles. Also, trial 6 includes rosette type and near globular α-Al particles; which shows with higher rheo-casting times it's possible to produce globular α-Al including slurry. But still, inital melt temperature keeps it importance for producing globular α-Al. Microstructural differences can be seen between trial 3 (620 °C, 6 s) and trial 6 (650 °C, 6 s). Trial 7 is high temperature die casting with including dendritic structure. Same situation can be seen between trial 5 and trial 8-9. In these trials GISS processing is also used but high melt temperature leads to dendritic structures which are probably occured in shot sleeve. Obtaining globular α-Al particles is a must for usability of thixotropic behavior.

3.3. Optimization results

As for the radiographic analysis results, the most promising levels are 650 °C for SSP temperature, 6 seconds of rheo-casting time, 260 mm of changeover position and 5 m/s of fast shot velocity. A verification experiment is carried out with these process parameters and levels to see suitability of the model and real conditions. Radiographic analysis result of the specimen is given in **Figure 5**.

Figure 5 Verification experiment radiography test result

The test result can be numbered as 5 according to quality scores given. For quality score 5, S/N ratio equals to 13.97 with 'Larger is better' characteristics. Predicted S/N ratio is calculated as 14.69 in Minitab 18 program. Result is given in **Table 3**.

Table 3 Best score giving process levels and estimated S/N ratio

SSP Temp.	Rheo-Casting Time	Changeover Pos.	Fast Shot Vel.	Predicted S/N
2	3	2	3	14.69

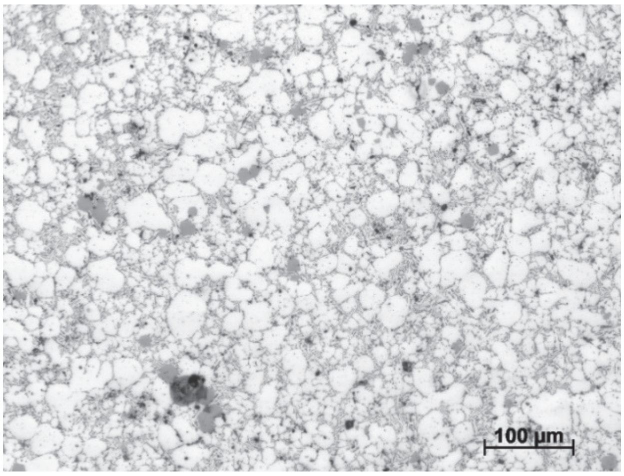

Figure 6 Microstructure of optimized and semi-solid processed part

According to the results, model fits well with the results gathered from the trials by 95 %. In **Figure 6**, microstructure of optimized part is given.

SEM & EDS analysis of optimized part is given in **Figure 7**.

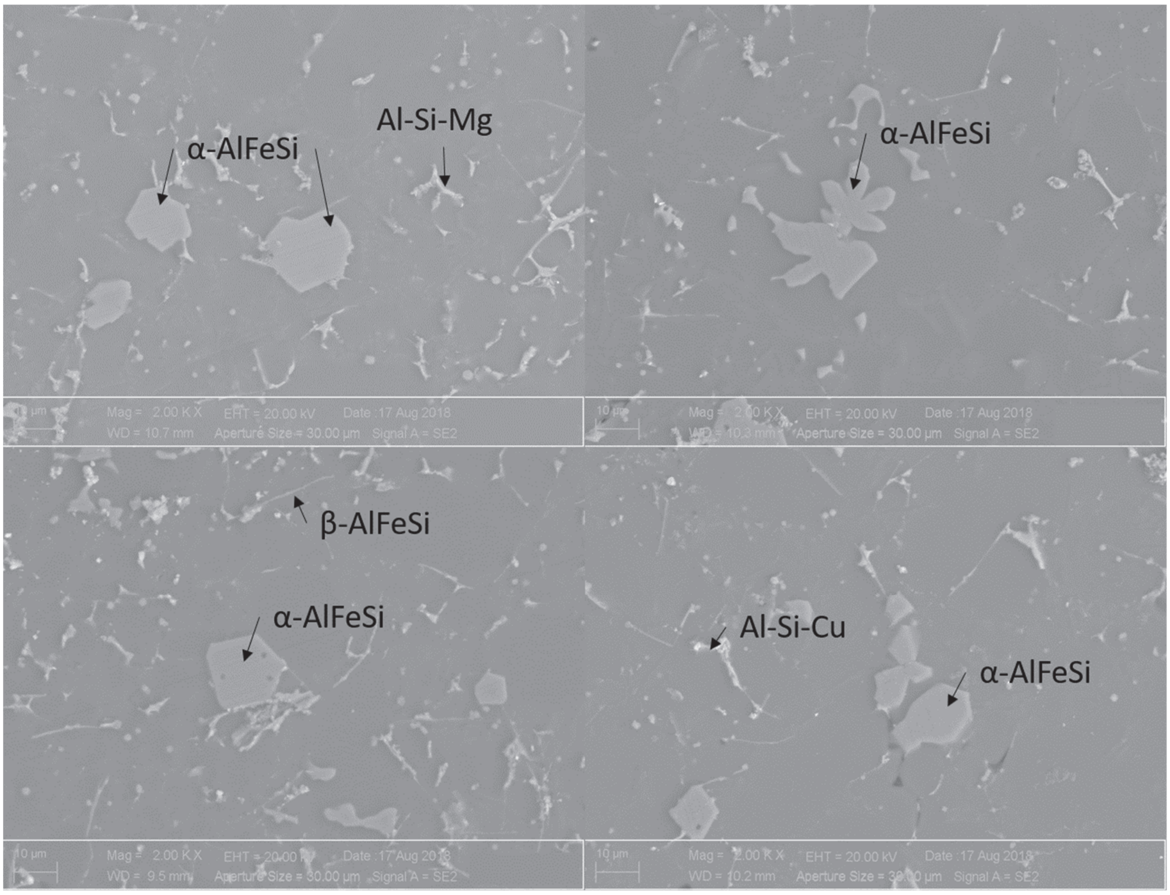

Figure 7 SEM & EDS images of optimized part, with involved intermetallic phases

Many high pressure die casting alloys contain approximately 8 wt.% iron, which leads needle-like (β-AlFeSi) harmful intermetallic phases in microstructure. These needle-like iron containing intermetallic phases reduces the yield strength of the alloy [17]. Mn addition is a common way to suppress iron's harmful behaviour on mechanical properties. Fe and Mn generates poligonal or star-like intermetallic phases (α-AlFeSi) which have lesser harm on mechanical properties. These intermetallic phases also acts as hardspots and cause tool failure during machining operations [18]. According to SEM & EDS results, β-AlFeSi and α-AlFeSi intermetallics are mostly found. Addition to this, Cu and Mg containing relatively smaller intermetallic phases can be seen in the morphological results.

4. CONCLUSION

- Porosity level of the die cast parts are reduced by semi-solid processing.
- Via Taguchi method, the optimization is done and 650 °C, 6 s, 260 mm, 5 m/s is obtained to be the best levels for parameters chosen.
- Optimum levels have been verified and 95 % fit is achieved between predicted and observed values.
- Microstructural analysis revealed the differences between high temperature conventional die casting, low temperature conventional die casting and semi-solid die casting processes.
- Intermetallic phases are identified with SEM and EDS analysis.

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