Rheocasting of Aluminum Alloy A356 based on Various Parameters: A Review

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***Abstract*—Out of many casting techniques, semisolid casting has been proven to be one of the most reliable methods of metal processing, especially on the likes of aluminum, magnesium and copper based alloys. This method offers many advantages over other liquid and solid processing techniques. Many researchers have worked through this technique, in order to define the potential of this process in producing different products especially for automotive industry. This work narrates through the various techniques involved in Rheocasting of aluminum A356 alloy, based on many research works, which have wide range of application in industries. Heat treatment response, fracture behavior, wear behavior, micro-structural evolution are some of the phenomenon's that have been discussed in this review. A356 and A357 are the most commonly used aluminum alloys, used to obtain near net shaped products because of the relatively high volume of Al- Si eutectic, which gives fluidity and better castability. Over the course, rheocast aluminum A356 alloy have been compared with many other competing alloy materials.**

Keywords: Aluminum A356 alloy, Rheocasting, Semi solid slurry, Heat treatment.

I. INTRODUCTION

Semisolid processing of aluminum alloys have certain advantages over other kinds of conventional metal forming processes, it has emerged as a productive and potential route to make near net shaped components in automotive and aero spacing industries. Semisolid processing goes namely by four different techniques: Rheocasting, Thixocasting, Thixomolding and SIMA (Strain Induced Melt Activation). In this process the casting is done between the solidus and liquidus temperature of the metal. i.e., the molten metal should be 40 to 75% solid. Rheological property in alloys during semisolid condition is discovered by Fleming and Spencer at Massachusetts Institute of Technology (MIT) in 1970, which resulted in developing many processes to crack the dendritic structures with subsequent change in grain size and phase morphology. The Rheocasting processes proposed for aluminum alloys are Sub-Liquidus Casting (SLC), Rapid Slurry Formation (RSF), Thixomolding, Twin Screw Rheocasting (TSR), Continuous Rheocasting (CRC), Semi Solid Rheocasting (SSR), Direct Slurry Formation (DSF) and New Rheocasting (NRC) [2]. In Rheocasting, the semi solid is made in to slurry from the molten metal, produced under a typical die casting furnace. Slurry is formed by decreasing the melt temperature below liquidus temperature under intensive shearing. Semisolid processing combined with high pressure die casting is a new method of casting, which is a promising technique to produce high quality components with better grain shape and size.

II. REVIEW

Robin Gupta et al., used RSF process to cast A356 alloy, using an Enthalpy Exchange Material (EEM) with a mass of 30wt% to the melt. Slurry is formed by stirring the melt at 1000rpm using a stirrer equipped with EEM molds (50mm diameter, 73mm length and 373 grams of weight). Slurry is formed within 30 seconds of stir and kept at 597ºC. Experiments have been conducted with and without baffles in the crucible. Further, the experiment was carried by adding grain refiners (0.6 wt% of Al- 5Ti- 1B) in to the melt, with and without baffles. Then the semisolid mass is transferred to the die followed by pressing (30Mpa) of mass through the plunger. Cast samples were removed from the die and made ready for material testing. Results shows that, the phenomenon of agglomeration and de-agglomeration of particles take place while stirring the EEM in to the melt pool. Investigations were carried out between 5 differently made samples, (A) as cast, (B) without baffles and grain refiners, (C) baffles without grain refiners, (D) grain refiners without baffles and (E) baffles with grain refiners. Microstructural observation shows the dendritic morphology of primary α- Al phase in as-cast A356 alloy. Grain structure changes in to globular with average grain size of 90µm, while stirring without baffles using RSF process. Refinement in average grain size of α- Al up to 80µm has been noted, while cast with the provision of baffles. Also, the tendency of agglomeration of particles seemingly decreases with the use of baffles. The addition of grain refiners to the molten pool with and without baffles had further refined the primary α- Al phase and globularity of α- Al. Porosity level up to 2% in alloy decreases the mechanical property of the alloy. Non heat treated sample A has 1.67% of porosity, while heat treated sample shows 1.52% of porosity. Sample E showed 0.33% and 0.42% 0f porosity volume fraction with and without heat treatment. This work revealed that as-cast A356 alloy without heat treatment exhibits coarser dendrites, non-uniformly distributed Si particles and higher porosity. Non- heat treated sample A shows cleavage like pattern in tensile fracture surface, which is an indication of low ductility. Higher number of dimples is seen in samples B, C, D and E at tensile fracture, which can be helpful to improve the mechanical properties of the alloy. Heat treated samples left for artificial ageing, leads to the uniform distribution of dimple morphology, which is comparatively better than non-heat treated conditions [3].

S. Deepak Kumar et al., had made an attempt to investigate the coarsening behavior of semisolid aluminum A356 alloy and composite (reinforced with 5 wt % of TiB_2), produced by employing a cooling slope. Earlier through literature they have revealed that in semi-solid state the driving force for coarsening is seen as the reduction in free energy interface between liquid and solid phases. At 5 minutes of holding time, the average size of α-Al in the A356-5TiB_2 composite is lower and spheroidization looks prominent when compared to that of the alloy. It has also been observed that the average grain size of α-Al in gravity cast A356 alloy reduces to 64µm, from the earlier figure of 98µm. In case of Rheocast aluminum alloy and composite the average grain size figures gets reduced to 60µm, it further gets reduced to 48µm after cooling slope casting. This is known to be due to the pressure of sub-micron TiB_2 particles throughout the matrix which causes grain refinement of α-Al. Increase in average grain size is also attributed to the increase in holding time from 5 minutes to 15 minutes. By Ostwald's ripening Phenomenon, it is observed that the expense of finer grains increases the coarse grains. The coarsening observed in the globular particles is described by Lifshitz – Slyozov - Wagner equation, where K is taken as the coarsening rate constant. The obtained K value is compared with other semi-solid processed A356 alloys, learned from the literature. Varying the isothermal soaking time in both alloy and composite linearly increases the cubed average grain diameters. The obtained K value from the composite is found to be 339.73$\mu m^3/s$, which is 32% lower than that of the semi-solid alloy. The K value obtained from the composite is the least among all the other reported values, which is due to the presence of fine TiB_2 particles, that reduces the grain size and size of eutectic Si, thereby lowering the coarsening rate constant K in the semisolid A356-5TiB_2 in-situ composite [4].

Sk Tanbir Islam et al., had considered a micromechanical approach towards to study the deformation behavior of Aluminum A356 after Rheocasting. The ingot is melted in a crucible; the melt is left to cool for some time to set the required pouring temperature. Then poured along a stainless steel made cooling slope coated with Zirconia, at the exit the melt turns in to semi solid slurry, which is collected in a mild steel mould. Rheocast samples were made in to finite element models as RVE's (Representative Volume Elements), which reduces the risk of various loading at practical condition. The microstructure is assumed to contain elliptic grains. Near accurate boundary conditions were applied, though it's impossible to replicate the real life conditions. The microstructures observed from the optical micrographs turned out to exhibit better features, when compared to the initial ingot. Non dendritic spherical primary Al grains has been seen from the micrographs of Rheocast samples. Based on three differently cast samples (conventionally cast, cooling slope cast at 45ºangle and cooling slope cast at 60º angle), three RVE's of approximate microstructures have been considered for micro hardness based simulations. Later it is found that the rule of mixture doesn't seems suitable for the present study, so the yield strength of individual phases have been estimated by using a polynomial relation between the experimental micro hardness valued. The tensile fracture morphology of the cast samples as studied through low superheat SEM fractographs highlights quasi-cleavage features in conventionally cast samples. Mixed mode of fracture behavior is observed in Rheocast samples using cooling slope at 45º angle, whereas completely dimpled fracture is observed in case of 60º angled cooling slope made samples. Since no damage criteria have been assigned, microstructural in-homogeneity between the phases is the only basis for plastic instability. It is found, the failure mode of alloy is highly depended on its grain morphology. At 45º angle of loading, high strain bands are localized mostly on primary phase, which marks the local shear failure in primary Al phase. Simulation results signals the brittle failure in conventionally cast samples and complete ductile failure in rheocast sample using slope at 60 º angles, which bitterly accords with the tensile fracture surface morphology of the samples. The approximated RVE's are considered as ruination of this study [5].

S Deepak Kumar et al., has synthesized the A356 with TiB_2 (2.5 wt % and 5 wt %) by using flux assisted synthesis technique (K_2TiF_6 and KBF_4 are the fluxes used). In this process, K_2TiF_6 and KBF_4 halide salts undergo an exothermic In-situ reaction with a molten Al-7Si alloy to create titanium diboride (TiB_2) dispersoids in the melt. After the synthesis of In-situ composites, a cooling slope was employed to produce feedstock for both alloy and the composite. Alloy and composite were melted at 720º and 800ºC in a resistance furnace. The melt was then poured in to the mold through a zirconium coated mild steel cooling plate, which is 50mm wide and 400mm long, the desired angle of inclination set for the cooling plate is 60º . Samples were made ready and differential thermal analysis (DTA) was performed on the specimens made from both A356 alloy and A356+ TiB_2 composites using TG- DTA instrument, the results were later used to estimate the solid fraction (f_s) of the alloy and the composite during various temperatures. They found the eutectic temperature of the composites were little higher than that of base alloy at 3ºC and 4ºC respectively. It is also seen that the under cooling temperature experienced during the eutectic reaction of the composites were lower than that of alloy, which was due to ease in nucleating assisted by In-situ TiB_2 particles [6].

Prosenjit Das et al., studied the wear behavior of rheocast A356 alloy processed through the cooling slope. Resistance furnace with 5 kg capacity is used to perform the melt, set at 750ºC. Melt was degassed, poured in to a Sic crucible, with a hole at the bottom, to facilitate bottom pouring. Melt, after being cooled to 650ºC was allowed to flow through the cooling slope coated with boron-nitride to ensure laminar flow of the melt; slurry is formed up at the exit and collected in a mild steel mold. For comparison sake, conventionally cast samples are made, which are processed by direct pouring of melt. Dry sliding wear tests of conventionally cast and rheocast A356 samples are performed using a pin-on-disk wear testing machine. The microstructural morphology of the test samples shows dendritic grains in conventionally cast sample. Equiaxed and spheroidal grains are obtained from rheocast samples processed at 45º and 60 º slopes angles. The study tells that the dry sliding wear behavior in gravity die cast and Rheocast A356 alloy at 45 º sloping angle, involves micro-cutting abrasion and adhesion at lower loads (i.e.) 19.6 and 29.4N. At higher load of 49N, partially severe adhesion takes place which causes rapid loss of wear and leading to higher overall wear rate. In rheocast samples processed at 60º slope angle, adhesion coupled with micro-cutting abrasion is observed while loaded at 19.6 and 29.4N. The 60º slope rheocast samples shows considerably lower wear rate at 49N load, where very adhesion regions combined with oxide formation is seen. This is due to enriched volume fraction of primary Al phase. However a flaw that occurs throughout this study is the micro-porosity due to final solidification of cooling slope processed slurry within the mold, which is under further study [7].

Liao Bo Chao et al., used A356 aluminum alloy to study its effect on Rheocasting and heat treatment using microstructures and mechanical tests. The main aim of the work is to find the liquid-solid (slurry) temperature for a solid fraction of 0.5. After the melt was performed, a DSC curve has been obtained which shows 7 exothermic and 5 endothermic peaks during the reaction. Solid fraction of the alloy at various temperatures has been analyzed. The slurry metal is poured in a preheated mould at about 250ºC and forged using different pressure modes; stationery (P), rotation once (R) and rotation thrice (T) with temperature range varying from 580ºC to 620ºC. To improve the mechanical property of the A356 alloy, T5 heat treatment was carried out at 160ºC, after which mechanical investigations were performed. They concluded as, the best mechanical properties were obtained while the temperature of pouring is around 600ºC to 610ºC with rotating thrice pressure mode. T5 treatment had strengthened A356 alloy with better peak hardness value after ageing for 20 hours. But the plasticity decreases after the ageing treatment [8].

H Moller et al., used CSIR Rheocasting technique to study the heat treatment response of SSM high pressure die cast Al- 7Si- Mg alloys (A356 and F357). Binary alloys were cast from A356 and F357 by varying the composition using CSIR- Rheocasting. After casting all the alloys were T6 heat treated and aged for several hours. The work shows that the heat treatment behavior of F357 alloy is strikingly influenced by the firmness of the Mg containing π phase, which seems to work poor with A356 alloy. The stability pushes the Mg containing π phase to higher temperature, which also suppress the Mg free β-$FeSiAl_5$ phase at high temperature, thereby decreasing the amount of Mg in solid solution. The work concludes with optimizing the artificial ageing treatment for SSM-HPDC alloy F357 as 180°C for 4 hours, despite prior natural ageing period, also suggests that shorter T6 cycle than traditional cycle can acquire better tensile figures in both the alloys [9].

Prosenjit Das et al., used cooling slope to prepare semi solid slurry of Aluminum alloy A356. They have studied the physics of microstructure evolution during the cooling slope slurry formation, to gratify the needs of semisolid slurry with desired shape, size and morphology of primary Al phase. A stainless steel cooling slope coated with boron nitride is used to prepare A356 slurry, two different slope angles are used (45° and 60°). After melting the alloy ingots to the desired temperature of 750°C, the melt is cooled down to 650°C, which is set as the pouring temperature, through bottom pouring. Melt samples have been collected from the entry, middle and exit portion of the cooling slope. The samples are investigated using optical microscope and scanning electron microscope (SEM). The work shows that, cooling slope processing of alloy gives nearly spherical primary phase morphology. Ample nucleation due to swift heat extraction from the slant surface and crystal separation due to melt flow is spot out as the superior mechanism for the formation of nearly globular primary phase. Existence of some deteriorated dendrites is seen in the slurry while processed through the slope at 45° angle, which only goes to prove the existence of dendritic arm fragmentation to some extent [10].

Zheng Zhou Chen et al., used a water cooled serpentine pouring channel to produce semi solid slurry of A356 aluminum alloy. The serpentine channel is placed in a chamber, which also acts as a support for the channel to stay vertical. The chamber consists of a cooling jacket which is filled with cooled water. Serpentine channel is 25mm in diameter and consist of four bends arranged in opposite direction to each, to form a serpent like shape. The molten metal is poured through the channel, at the exit the melt is collected as slurry in a stain less steel crucible. Pouring is continued repeatedly with different pouring temperatures. Samples were cut from the centre of the quenched slurries. This work states that, with pouring temperatures at 640ºC to 680ºC and cooling water flux at $0.9m^3/h$, spherical primary α-Al grains can be obtained from the slurry. Circulating of cooled water turns out to show improvement in the microstructure of the slurry. Due to the chilling effect of the serpentine channel wall a large number of primary α-Al nuclei are generated, which are spheroidized finally after separating from the channel into the melt of the alloy [11].

Mao Wei-Min et al., made semi solid slurry from aluminum A356 alloy and rheosqueeze casted it. Different pouring temperatures (615, 630, 650 and 670°C), stirring powers (0.65, 1.27 and 2.15 kW) and specific injection pressure (22 Mpa and 34 Mpa) were used during Rheo-squeeze casting. Castings were then T6 heat treated (solution treatment at 535°C for 5 hours, ageing at 155°C for 12 hours). After T6 treatment, samples were made and investigated using metallographic images and tension tests. This work states that, spherical primary α (Al) grains can be prepared when poured at 630°C to 650°C with stirring at 1.27 kW. It also states that, higher injection pressure yields better mould cavity filling tendency for the slurry. Heat treatment raises the Ultimate strength, Yield strength and elongation to a noticeable level [12].

S Tahamtan et al., had investigated the microstructural features, defects, reheating temperature and fracture behavior of the thixoformed A356 samples, later compared them with rheocast and gravity cast samples. The optical microstructures off gravity cast, rheocast and thixoformed alloy (590ºC and 600ºC, reheating temperature for thixoformed samples) with and without heat treatment was investigated. Typical dendritic shape of primary α phase was seen in gravity cast samples and equiaxed primary α phase was found to be uniformly distributed through the matrix in case of rheocast samples. However the area equivalent diameter, aspect ratio of silicon particles and porosity level decreased in thixoformed samples. After, T6 it is seen that , in thixoformed samples area equivalent diameter of silicon particles increased, which seems decreased in gravity and rheocast samples. The work suggested that the applied pressure on the thixoformed samples had considerable effect in reducing the porosity level, better tensile figures and subsequently increasing the dislocation density, when compared with other casting samples [13].

O Granath et al., chose RSF technique which is based on exchange of enthalpy between two similar or dissimilar materials, to study the effect on parameters in aluminum A356 alloy while cast using slurry process. EEM's sized to 43mm (5 wt %) of diameter were made ready and was attached to a stainless steel rod, the melt superheat was set at 7ºC. The enthalpy exchange takes place through stirring the stainless steel rod, at different speed ranging from 0 to 2400rpm, slurry is formed quickly in time no more than 30 seconds of stir. Microstructures were studied using an optical microscope on at least 350 grains per sample. The grain structure seems disturbed in the micrographs made at 200µm, while stirring at 1800rpm. The fractions of α- phase formed at various rotating speeds has been observed, which clearly states that the disruption is due to the correlation between the slurry formation time and the cooling rate of the slurry. Slurry formation time decreases at higher rotation speed, which also reduces the shape of α-phase grain size. In the second series of experiment, the EEM amount was again 5 wt %, the rotation was held constant at 1200rpm. Experiments were conducted by varying the melt super heat at 7ºC, 17ºC and 27ºC, which helps in improving the steady state temperature after slurry formation, as studied earlier. Since the steady state temperature becomes closer to the melting point, the sensitivity of the slurry towards the residual heat increases, this is wholly due to the change in melt super heat, which also affects the slurry formation time. The authors revealed that, the RSF processing is not sensitive towards varying the temperature, as seen from the history of thermal response in this study. They also stated that higher fraction of α phase can form closer to the liquidus temperature of the alloy. A third set of experiment, conducted to study the combined effect of melt superheat and amount of EEM, after increasing both. Since the amount of EEM's and melt superheat are not balanced, it results in the decrease of steady state temperature for every 1 wt % of increase in amount of EEM and 5ºC of increase in melt superheat, this in turn decreases the slurry formation time and average grain size. Increased rotation speeds of EEM leads to grain refinement effect. The α phase in the slurry varied slightly with an average fraction at 0.28 to 0.35 throughout this study [14].

Jin Kyu Lee et al., had studied microstructure control concept and thermo-mechanical treatment process, to develop In-ladle direct thermal control Rheocasting, which requires no processing equipment outside of the casting machine, no grain refinement procedures and no additional cycling time, but must be cooled down to set the desired casting temperature. Three ladles with different wall thickness (20, 10 and 06mm) and materials have been made. Aluminum alloy A356 has been chosen as the study material. After furnacing, the molten metal was transferred in to the ladle, held for some time till solidification; experiments were repeated by varying the ladle temperature and melt temperature on all the three different ladles. The thermal modeling results, shows the optimum conditions for in-ladle DTC Rheocasting of A356 alloy process, as ladle temperature of 500ºC, wall thickness of 6mm and material as in 20mm thick ladle, with solid fractions ranging between 0.2 and 0.3. Increase of solid fraction by cooling was achieved by coarsening of primary dendrite arm spherically, but there was no coherency between solid grain at all experimental conditions. Small solid globules could be obtained through in-ladle DTC Rheocasting by using optimum conditions achieved by simulation, solid fractions of up to 0.65 – 0.7 could be attained through in-ladle DTC Rheocasting [15].

III. CONCLUSION

The Rheocasting technique usually involves melting of alloy to liquidus temperature, making it in to slurry and then will be pressure die cast. But this review shows some of the newest approach that is attempted to rheocast the aluminum alloy. Some of the works had proven to be fruitful, some turned in to collapse but none were catastrophic. In this review, a number of newer methodologies such as RVE's, serpentine channel casting, cooling slope method, In-ladle direct thermal analysis [15] etc., have been revealed. Through which we have discovered a set of newer list of parameters in casting such as ladle pre-heat, ladle geometry, slope angle, cooling slope coating, melt super-heat, approximation of values while using finite element modeled RVE's [5], channel diameter and number of bends in serpentine channel processing, coarsening constant which all have significantly influenced the final results of the rheocast aluminum A356 samples. Employment of cooling slope [7] and serpentine [11] channel seems economical and efficient in terms of productivity. The coarsening rate constant for rheocast A356 alloy reinforced with TiB_2 was found to be 339.73 $\mu m^3/s$, which is considerably lower than many of proposed works earlier [4]. The In-ladle DTC Rheocasting method proved that the solid fraction of Aluminum A356 alloy could be lowered to 0.65 – 0.7. Likewise, all the literatures reviewed in this work had gained better results in its own way; this work also inspires scope and idea for lots of further researches, which shall be reported in future publications.

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