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OVERVIEW OF SEMI-SOLID METAL PROCESSING OF AN ALUMINIUM ALLOY

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ABSTRACT

Aluminium and its alloys are regarded as the most versatile of all common foundry alloys and the variety of forms in which they exist give them significant opportunities to be used for many engineering applications and in cast form for critical safety structural automobile components. Aluminium alloy components are routinely produced by conventional casting, but quality limitations imposed by these conventional casting methods have restricted their range of application and make them unsuitable for critical safety structural components. These inadequacies associated with the conventional metal forming processes for the production of critical safety structural components have led to the development of innovative casting processes known as Semi-Solid Metal Processing (SSMP). Semi-Solid Metal (SSM) processing is widely known as a technology that involves the formation of metal alloys between solidus and liquidus temperatures. The aim of this paper is to do an overview of SSMP in order to have a better understanding of the fundamentals of the process. The paper discusses the primary route of SSMP, the advantages and disadvantages of the process and does a comparative analysis on the mechanical properties of a component produced by Rheocasting (RC) and Sand casting (SC) representing SSMP and conventional casting respectively. The analysis of the results shows that the superior properties are attainable with parts produced by rheocasting processes than by sand casting.

Keywords; Aluminium alloy, semi-solid metal processing, rheocasting and sand casting.

1.0 INTRODUCTION

Aluminium and its alloys are regarded as the most versatile of all common foundry alloys and generally have the highest rate of castability because of their good fluidity for filling thin sections; low melting point relative to those required for many other metals; rapid heat transfer from the molten aluminium to the mould, shorter casting cycles; freedom from hot-short cracking and tearing tendencies; chemical stability and good as-cast surface finish with lustrous surfaces and little or no blemishes(ASM Handbook,1990). These favourable characteristics and the variety of forms in which aluminium alloys exist make them useful for many engineering applications and in cast form for critical safety structural automobile components such **as** engine mount brackets, steering knuckles, and control arms.

Aluminium alloys are routinely produced by casting. Unfortunately, quality limitation such as porosity and the need for impregnation, trapped gas and the inability to heat-treat the parts for improved strength and uniform mechanical properties (Winterbottom,2000) imposed by these casting methods have restricted the range of application available to cast aluminium components and make them unsuitable for critical safety structural components. The minimum mechanical properties demanded by automotive industry in safety critical parts are hard to be achieved by the conventional casting (Birol, 2009).

These inadequacies associated with the above conventional metal forming processes for the production of such critical safety structural components on a broader scale have led to the development of innovative casting processes known as Semi-Solid Metal Processing (SSMP).

SSMP is a typical case of a technological innovation. The beginning of SSMP is based on an accidental discovery by a Ph.D student called Spencer during his studies under the supervision of Professor Flemings at the

Massachusetts Institute of Technology (MIT) in the early 1970s. Since then, it has progressed from a laboratory curiosity, to a fully commercial process for the production of near net shape components in a variety of materials and for a diverse industrial clientele (Moschznz ,1992)

Nowadays, the SSMP has found application in a number of manufacturing domains due to its ability to deliver the production of high-quality parts at costs that are comparable to or lower than those of conventional forming techniques such as casting or forging. In Semi-solid Metal (SSM) processing, a spheroidal or non-dendritic microstructure has to be obtained either as an initial prior step or an integral part of the forming process.

Semi-solid Metal (SSM) processing consists of two primary routes; thixocasting and rheocasting (Ratke, Sharma and Kohli, 2011). In the thixocasting route, one starts from a non-dendritic solid material that is specially prepared by a primary aluminium manufacturer, using continuous casting methods. Upon reheating this material into the mushy two-phase zone, a thixotropic slurry is formed, which becomes the feed for the casting operation. In rheocasting also known as “slurry-on-demand” (SoD) route, the thixotropic slurry is formed directly from the melt via careful thermal management of the system; the slurry is subsequently fed into the die cavity.

The thixotropic, laminar or non- turbulent flow behaviour occurring in the “two-phase” field of solid -liquid is the main property of semi-solid metal (slurry) that makes it superior to conventional casting processes (Flemings, 1991). Shearing of semi-solid slurry leads to a marked decrease in viscosity, so that a partially frozen alloy can be made to flow like a non-Newtonian fluid. In the semi-solid processes, the thixotropic, laminar or non-turbulent flow behaviour is as a result of an ideal small microstructure of non-dendritic and spherical α-Al particles suspended in a liquid matrix (Findon and Apelian, 2004). This microstructure must be produced consistently and uniformly distributed throughout the entire volume of the slurry for production of high-quality components.

In recent years aluminium alloys are widely used in automotive industries. This is particularly influenced by regulatory pressures to meet fuel efficiency standards by reducing vehicle weight, and to meet recycling standards. The real need for weight saving is for more reduction of fuel consumption. The advantages offered by semi-solid metallic alloys have been exploited to develop several processing routes such as in thixoforming, thixoforging, thixomoulding and rheodiecasting (Atkinson, 2002)

The aim of this paper is to do an overview of SSMP in order to have a better understanding of the fundamentals of the process. The paper has discussed the primary routes of SSMP, the advantages and disadvantages of the process and has done a comparative analysis on the mechanical properties of a component produced by Rheocasting (RC) and Sand casting (SC) representing SSMP and conventional casting respectively. Semi solid processing is now a commercially successful manufacturing route to produce net-shape parts in automotive industry with superior mechanical properties.

2.0 SEMI-SOLID METAL PROCESSING ROUTES.

There exist two primary routes for Semi-Solid Metal processing (SSMP). These are thixocasting and rheocasting routes

2.1 Thixocasting Route of SSMP

In the thixocasting route of SSMP, a solid billet, with a fine-grained equiaxed microstructure, is partially remelted to the semi-solid state and is then transferred to the shot chamber of a die cast machine and injected into the die (Poddar,2008). There are two separate stages involved in the thixocasting process as shown in Figure 1.0. The first stage involves uniform heating and partial remelting of the alloy slug to obtain a homogeneous structure. The second stage involves, transferring of the semisolid slug into forging die or shot chamber where it is injected in a controlled manner into a die cavity by a hydraulic ram (Fan,2002). After solidification, the shaped component is removed from the mould for further processing, such as minor machining or grinding.

Omar, Atkinson and Kapranos (2011) observed that under thixotropic condition, an alloy decreases in viscosity if it is sheared but thickens again if it is allowed to stand. Reheating to the semisolid state is an important phase in the thixocasting process that is aimed at providing semisolid slug with an accurately controlled solid fraction of fine and spherical particles uniformly dispersed in a liquid matrix of low melting point. Accuracy and uniformity of heating temperature and heating duration are important processing parameters needed during the reheating process to achieve semisolid microstructure. Heating temperature determines the solid fraction in the slug. Too high a heating temperature causes instability of the slug resulting in difficulties for slug handling, while too low a heating temperature leads to unmelted, coalesced, polyhedral silicon phase in the slug (Poddar, 2008). This has a negative effect on the rheological properties during die filling and on the ductility of the finished parts. Uniform temperature distribution throughout the slug is also important, because a non-uniform distribution of temperature may lead to fluctuation in solid fraction and rheological characteristics, which in turn may cause solid/liquid separation during mould filling (Poddar, 2008). The heating duration has to be also controlled; too long a heating time will cause structural coarsening, while too short a heating time will lead to incomplete spheroidisation of the solid particles compromising the rheological properties and leading to difficulties during mould filling.

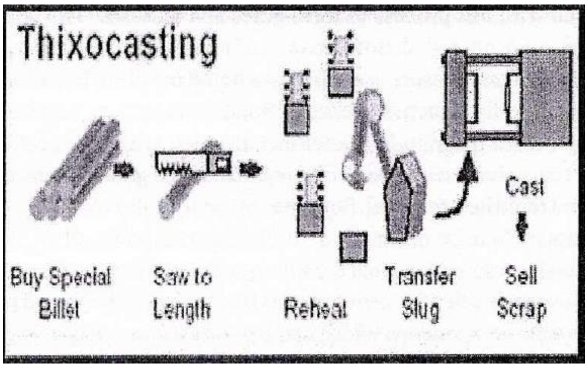

Fig. 1.0 : Schematic Layout of Thixocasting process.(Courtesy: Poddar, 2008)

Reheating of the slug is done mainly by induction heating. Convection furnaces are also used in some cases. Although Induction heating has the advantage of precise and fast heating, the relatively low energy efficiency of the induction heating station is a drawback. Possible improvement of energy efficiency for temperature homogenisation can be achieved by heating the slug initially to a critical temperature in a convection furnace followed by induction heating.

The main specific advantage of the thixocasting route is that the forming facility is free from handling liquid metal, and the process can be highly automated using approaches similar to those employed in forging and stamping. The basic concept of completely separating the two main parts of the process in thixocasting route (forming of the desired structure and forming of the part) has been intuitively appealing and much work has been done in developing the process route industrially. As time progressed, the disadvantages of the thixocasting route became apparent. It has been difficult to obtain fully homogenised billets with respect to both structure and composition in MHD stirred continuous castings. There is metal loss during the reheating process, which may amount to as much as 10% of the total part weight (Fleming, 1991). Gates and risers cannot be recycled within the forming facilities but must be sent back to the ingot producer. Thus, the metal former pays a premium to the continuous caster not only for the unique thixotropic structure in the metal, but also for the recycled materials. Currently, the cost for thixotropic feedstock accounts for up to 50% of the total component cost.

2.2 Rheocasting Route of SSMP.

Figure 2.0 shows rheocasting route of SSMP. It involves stirring the alloy either continuously during solidification or maintaining an isothermal state to produce semi-solid non-dendritic slurry and then pouring/injecting the slurry directly into the die to give a final product (Poddar 2008). Rheocasting process can also be adapted to produce complex-shaped components with modification of some processes. The main parameters that affect microstructure and mechanical properties of the metal slurry produced by mechanical or magneto hydro dynamic (MHD) stirring for the rheocasting process are; average shear rate, average cooling rate, volume fraction of primary solid, grain size, time of shearing, time of solidification and holding temperature of the slurry.

Rheocasting Mechanisms

The mechanisms of rheocasting are:

1. Dendrite arm fracture. This is a process whereby the arms of the dendritic structure are sheared off as a result of the force on them from the fluid flow;
2. Re-melting of the dendrite arm at its root as a result of normal ripening. The function of fluid flow in this case is to alter or accelerate the solid diffusion involved in ripening and carry the dendrite arm away from its "mother grain";
3. Enhanced re-melting by thermal perturbation, which results from turbulent convection.
4. Acceleration of the melting at the root of dendrite arm as a result of the stress introduced at the root by the force of fluid flow;
5. Enhancement of the melting at the root as a result of high solid content in the solid at the dendrite root;
6. Re-crystallisation as a result of the stress introduced by the force of the fluid flow, with rapid liquid penetration along the new grain boundaries.

2.3 Advantages and Disadvantages of SSMP

Advantages of SSMP:

The main advantages of SSMP, relative to other conventional casting according to Atkinson (2002) are:

1. Energy efficiency: metal is not being held in the liquid state over long periods of time;
2. The smooth filling of the die with no air entrapment and low shrinkage porosity gives parts of high integrity (including thin-walled sections) and allows application of the process to higher-strength heat-treatable alloys;
3. Lower processing temperatures reduce the thermal shock on the die, promoting die life and allowing the use of non-traditional die materials;
4. Fine, uniform microstructures give enhanced properties;
5. Reduced solidification shrinkage gives dimensions closer to near net shape and justifies the elimination of machining steps
6. Suitable surface quality for plating.

Disadvantages of SSMP:

The main disadvantages of SSMP, relative to other conventional casting according to Atkinson (2002) are:

1. High cost of raw material for thixoforming and small number of the suppliers;
2. Continuous build-up of the knowledge and experience in order to facilitate application of the process to new components;
3. Requires a higher level of training and skill for the personnel than with more traditional processes;
4. Temperature control: the solid fraction and viscosity in the semi-solid state are very dependent on temperature. Alloys with a narrow temperature range in the semi-solid region require accurate control of the temperature;

Liquid segregation due to non-uniform heating can result in non-uniform composition of the component.

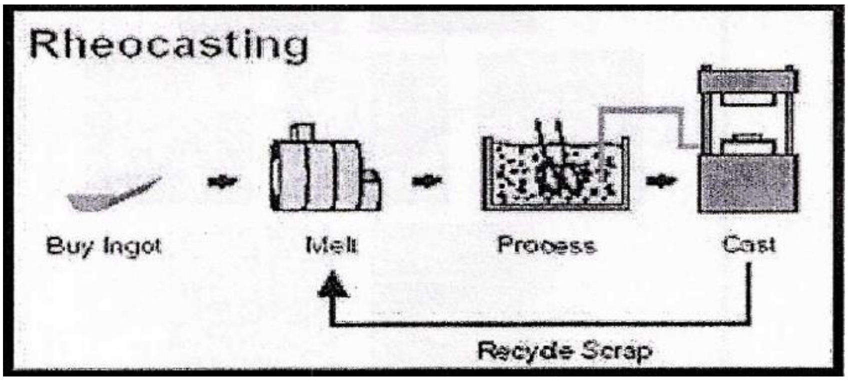

Fig. 2.0 : Schematic Layout of Rheocasting process.(Courtesy: Poddar ,2008)

In general, early rheocasting processes used mechanical stirring to obtain a globular microstructure directly from liquid,

3.0 MATERIALS AND EXPERIMENTAL METHOD

3.1 Material.

The material used for the experiment by Abdelgnei et al (2019) was Aluminium alloy scraps

3.2 Experimental Method

The methods adopted for the experiment were:

- chemical analysis to determine the chemical composition of the Aluminium alloy scraps;
- refining of aluminium scrap to remove impurities;
- Sample Preparation for mechanical testing;
- mechanical testing of component.

3.2.1. Chemical Analysis

The chemical composition of the aluminium scrap was determined using XRF hand held gun metal analyser. The analysis was performed by bringing the analyser in contact with the sample. The gun was triggered to activate a high-energy incident beam of short X-ray which showed the chemical composition of the sample.

3.2.2 Refining of Aluminium Scrap

1.5kg of thoroughly washed and properly dried Aluminium Alloy Scrap was charged into a 3 kg graphite crucible placed in an open-air charcoal fired furnace. When the charge reached a pasty condition at a temperature of 600^{o}C as measured by K- thermocouple, 0.25% by weight of Lite Salt (50/50 mixture of sodium chloride and potassium chloride) of the total weight of melt was sprinkled- over the surface of the melt and stirred down. The melt was further heated to the temperature of 760^{o}C so that there would be sufficient heat to sustain the temperature of the melt prior to degassing. The crucible was removed from the furnace and the surface flux cover was then pushed a little to one side and through the clean area, about 1% of hexachloroethane (C_2Cl_6) tablets by weight of the total weight of the melt was plunged and submerged into the melt. The melt was stirred until the tablets completely melted and the bubbling action ceased. Degassing was done to remove the dissolved hydrogen. The refined aluminium scrap was cast into experimental samples by sand casting (SC) and rheocasting (RC). The SC was done by heating the refined scraps in a coreless induction furnace into molten form and then pouring into a green sand to obtain a cast sample of dimension 80mm height by 60mm diameter.

In RC, the Refined Aluminium Scrap (RAS) was heated to a temperature of 620^{o}C to a mushy state and mechanically stirred for five minutes to get a uniform non-dendritic slurry before being poured into a die cavity to produce a casting of dimension 80mm height by 60mm diameter.

3.2.3 Sample Preparation for Mechanical Testing

All the samples for the test were prepared using the format of American Standard for Testing Materials (ASTM).

Mechanical Testing.

After successful preparation of the sample**,** mechanical test was performed on the **prepared sample** to determine the tensile strength, percentage elongation and hardness. Hardness test was conducted on digital Rockwell hardness tester. The tensile test was conducted on Monsanto tensometer testing machines and impact test was done on JBN 300J/150J impact testing machine.

4.0 RESULTS AND DISCUSSION

4.1 Results

The results of the chemical analysis of the Aluminium Alloy Scraps is given in Table 1.0 below

Table 1.0 Chemical Composition (wt. %, Al = balance) of the Aluminium alloy scraps

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Others
7.0	0.15	0.03	0.1	0.45	0.15	0.45	0.07	0.10	0.10

Table2.0 below shows the mechanical properties of aluminium alloy scraps fabricated by Rheo-casting (RC) and Sand casting (SC)

Table2.0 Mechanical Properties of Aluminium Alloy Scraps Fabricated by Rheo-casting (RC) and Sand casting (SC)

Method of Alloy Production	Mechanical Properties				
	YS(MPa)	UTS(MPa)	Elongation (%)	Hardness (HRB)	Impact Strength (Joules)
RC	228	300	16.0	77	7.0
SC	178	183	12	62	6.0

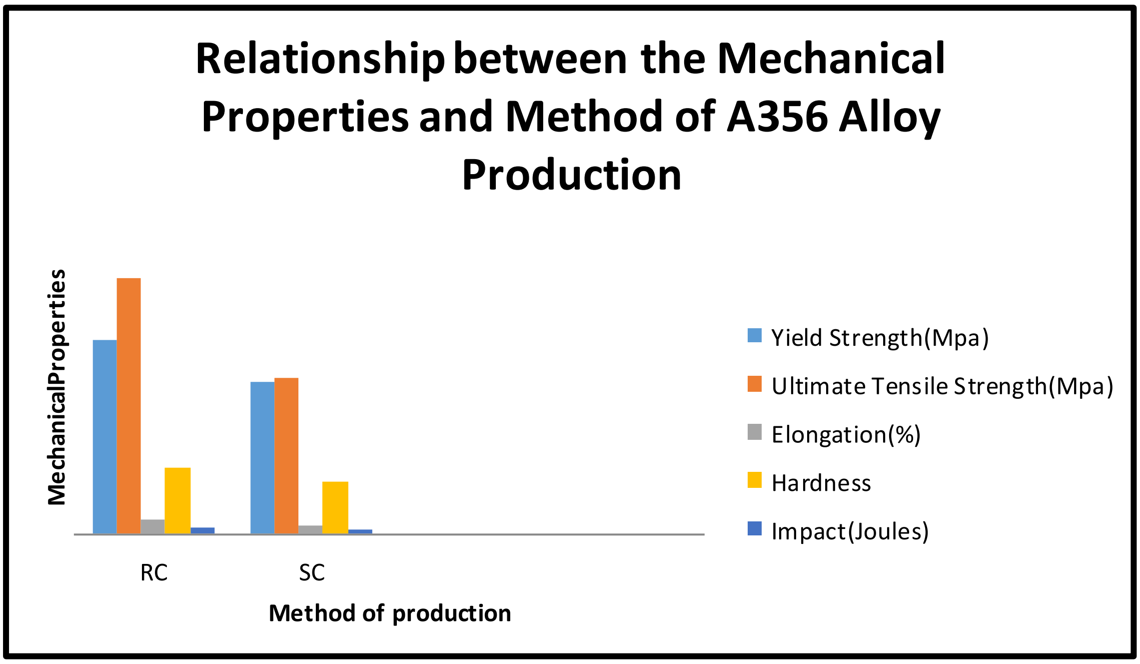

Figure3.0 Relationships between the Mechanical Properties and Method of A356 Alloy Production

4.2 Discussion

Right from conception and the very first production attempts, components produced by semi-solid process have enhanced performance ability compared to those of the forged material and traditionally cast parts because of their high mechanical properties. These findings have been confirmed by various studies conducted on families of Al–Si, Al–Cu and Al–Zn alloy by many authors

Table 1.0 shows the results of chemical composition of the sample. Table 2.0 shows the mechanical properties of the sample fabricated by Rheo-casting (RC) and Sandcasting (SC). Figure 3.0 shows the relationship between mechanical properties and method of production of the alloy samples.

In Table 1.0, the yield strength of RC product is 228MPa and SC product has yield strength of 178MPa. This implies that the same alloy cast by RC has a higher yield strength than the SC product .The value of ultimate tensile strength is 300MPa for product cast by RC, while the product cast by SC has a lower ultimate tensile strength of 183MPa.The per cent elongation of the RC sample is 16%,while the per cent elongation of the SC sample is 12% .The hardness value(HRB) of SC sample is 62 and that of RC sample is 77.The impact values in joules of RC and SC sample are 7.0 and 6.0 respectively.

The implication of the high values of mechanical properties of RC sample as compared with those of SC product is that the product produced by SSMP as represented by RC has superior mechanical properties than that produced by SC representing traditional casting process. This is in line with the work of Patel et al using ultra refining technique to demonstrate that semisolid metal processing of A356 and A357 aluminium alloys resulted in the component with the highest value for ultimate tensile strength and yield strength.

The high values of mechanical properties of the sample produced by RC as indicated by Table 1.0 is in line with Bergsma et al (2001) who reported from his work that when an effective optimization of heat treatmen parameters is achieved, the tensile strengths of 357 MPa obtained for 319 semisolid formed aluminum alloys are superior to conventionally cast alloys due to the reduction in porosity and the spherical microstructure. Higher values of mechanical properties shown in table 1.0 by RC component over SC component is in line with the work of Cerri *et al* (2000) in which they showed that excellent ultimate tensile strength and yield strength of SSM processed 319 alloy, is in the order of 350 MPa and 280 MPa, which is almost 100 MPa higher than values for the conventionally cast counterparts.

In figures 3.0, the ultimate tensile strength of the rheocast (RC) alloy is 64% higher than that of the sand cast alloy. The yield strength and elongation characteristics exhibited by the rheocast alloy were also better than those of sand cast alloy. The yield strength in the rheocast samples was 28% higher than that of the sand cast alloy samples. Improvement was seen in the elongation characteristic, which increased by approximately 14% as compared to the SC alloy. The hardness and impact strength values of RC sample show about 24% and 16% improvement respectively over those of the SC component.

The analysis of the results shows that the superior properties are attainable with parts produced by rheocasting processes than with those produced by sand casting. This is in line with Bosso (2012) analysis of the literature data for A356 and A357 aluminium alloys where he highlighted that the superior properties and performances attainable with parts produced using SMM processes are higher than those allowed by other traditional and well-established processes. He highlighted further that apart from tensile properties and fracture toughness, fatigue strength, as well as corrosion resistance are potentially among the best attainable, provided there is good control of the adopted process with a sensible reduction of casting defects with respect to traditional processes. He attributed the globular micro-structure, instead of the dendritic one and the possibility of finer Si particles associated with SSMP as the factors responsible for these superior qualities.

Abdelgnei et al (2019) attributed the superior values of the mechanical properties exhibited by RC over SC in Figure 3.0 and Table 1.0 as observed in their work to less shrinkage and associated porosity in the rheocast alloy.

5.0 CONCLUSION

An overview of SSMP in order to have a better understanding of the fundamentals of the process has been done. The paper discusses the primary route of SSMP, the advantages and disadvantages of the process and did a comparative analysis on the mechanical properties of a component produced by Rheocasting (RC) and Sand casting (SC) representing SSMP and conventional, respectively. The analysis of the results shows that the superior properties are attainable with parts produced by rheocasting processes than with those produced by sand casting.

Semi-solid casting processes, especially based on rheocasting, is now considered to be one of the most important manufacturing techniques in aluminum automotive casting industry. Rheo-diecasting system has advantages over other conventional semi-solid casting processes. At present, alloys available for rheocasting are very limited. In order to extend the application of rheocasting method to replace other types of manufacturing processes such as forging, press and extrusion, development of new alloy systems for rheocasting, which provide high mechanical quality and high efficiency in cost is necessary. Semi-solid Metal Processing (SSMP) has been identified to be a potential route to form near-net-shape products with higher product quality and improvement of the mechanical properties for use in the automotive, aerospace and other engineering industries.

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