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Effect of process parameters on properties of Al-Si alloys cast by Rapid Slurry Formation (RSF) technique

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Abstract. Rapid slurry formation is a semi-solid metal forming technique, which is based on a so-called solid enthalpy exchange material (EEM). It is a fascinating technology offering the opportunity to manufacture net-shaped metal components of complex geometry in a single forming operation. At the same time, high mechanical properties can be achieved due to the unique microstructure and flow behaviour. The major process parameters used in the RSF process are rotation speed of the EEM, melt superheat, amount of EEM added (determining fs), and holding time. The process parameters can be well controlled with clear effects on the microstructure. There is a lack of theoretical modelling of the morphological evolution in these two-phase slurries.

1. Introduction

Semi-solid forming of metals is a fascinating technology offering the opportunity to manufacture net-shaped metal components of complex geometry in a single forming operation. It is carried out by two routes namely rheocastingand thixocasting.Thixoforming is used to describe the near net shaping of a partially melted non-dendritic alloy slug within a metal die. Rheocasting involves the application of shearing during solidification to produce a non-dendritic semi-solid slurry that can be transferred directly into a mould or die to give a final product.

A number of rheocasting processes (“slurry on demand”) are proposed for aluminium alloy; (i) Direct slurry forming (DSF) [1], (ii) Sub liquidus casting (SLC) [2,3], (iii) New rheocasting (NRC) [4-6], (iv)Thixomoulding [7,8], (v) Twin-screw rheocasting [9-11], (vi) Semi-solid rheocasting (SSR) [12,13], (vii) Continuous rheocasting(CRP) [14], and Rapid slurry forming (RSF) [15].

The RSF process differs from other rheocasting processes because heat extraction and temperature control are not necessary. The RSF process is based on enthalpy exchange of two alloys where one alloy is the low superheat melt (high enthalpy). The other one acts as the cold solid stirring material (low enthalpy) and is also known as enthalpy exchange material (EEM). During the process the EEM is submerged into the melt while stirring action is applied. Heat is absorbed from the melt during stirring operation, and the two alloys with different enthalpies will form a new alloy system with a new enthalpy level.

The principle of enthalpy exchange in the RSF process can be formulated with the help of the following equations [11] representing the cooling and partial solidification of the melt (dQ_{out}) and the heating and partial melting of the EEM (dQ_{in}):

$$dQ_{out} = \rho_{melt} \times C_{pmelt} \times V_{melt} \times (T_o^{melt} - T^{SSM}) + \Delta H_{melt} \times \rho_{melt} \times f_s^{SSM} \times V_{melt} \quad (1)$$
$$dQ_{in} = \rho_{EEM} \times C_{PEEM}\ x\ V_{EEM} \times (T^{SSM} - T_o^{EEM}) + \Delta H_{EEM} \times \rho_{EEM} \times (1-f_s^{SSM}) \times V^{EEM} \quad (2)$$

where ρ is density, C_p is specified heat, V is volume, T_o is the initial temperatures before mixing, ΔH is latent heat and f_s^{SSM}, and T^{SSM} are the final solid fraction and the final slurry temperature respectively.

$$dQ_{out}=dQ_{in} \quad (3)$$

From these equations, it is possible to calculate the volume or mass ratio between the melt, and the EEM provided that the desired solid fraction of the slurry is given.

Main process variables include amount of solid fraction, melt superheat, processing time and shear rate. It has been observed that these process parameters strongly influence the final properties of casting. In this paper an attempt is made to contribute to a better understanding of the governing relations between the process parameters to achieve quality casting from industrial point of view.

2. Experimental Procedure

The EEM was cylindrical in shape whose dimensions for different solid fractions are given in table 1.

Solid Fraction	Mass of EEM (kg)	Diameter of EEM (in cm)	Length of EEM (in cm)
0.15	0.24	4.4	6.2
0.30	0.32	5	6.9
0.45	0.52	6	7.1

Table 1. Details of EEM used to achieve different solid fraction

It was cast on a steel stirrer rod. The shape of the rod did not result in any shearing effect upon dissolution of the submerged EEM (figure 1). The rod with EEM was attached to a device having up to 1600 rpm rotation speed. 1.35 kg of Al-7Si alloy was melted in crucible at 700°C. After melting 0.2wt.% of SiB, grain refiner was added in melt to facilitate good nucleation potential. After grain refinement, the furnace temperature was lowered to isothermal annealing temperature. The EEM, initially at room temperature, was slowly lowered into the melt and stirring started with preset rotation speed with the help of stirring device. During stirring, the slurry was formed quickly within 30 seconds. The slurry was quenched in water. Similar experiments were repeated at different process parameters. For metallography, preparation and polishing of quenched samples were made using normal metallographic procedures for aluminum.

3. Results and Discussion

3.1 Influence of Solid Fraction

Figure 2 shows the effect of increase in solid fraction on microstructure of Al-7Si alloy. It can be noted that with increase in solid fraction, the particles are becoming more globular and a uniform size distribution is achieved.

An increase in solid fraction tends to produce larger [16, 17, 18] and rounder [19, 20] particles. At higher solid fraction, increased particle collisions increases coarsening by coalescence to form larger particles [17] while the effectively longer processing time improve spheroidization. Similarly, the degree of agglomeration increases as the collision frequency increases due to smaller interparticle distance [18]. Cheng et al [19] also reported a more uniform size distribution at higher solid fraction.

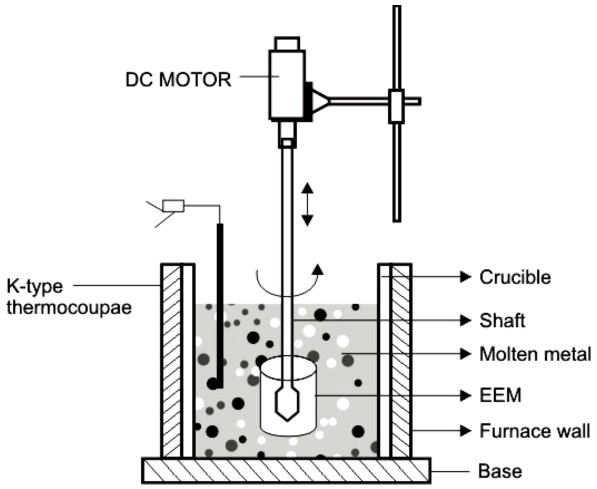
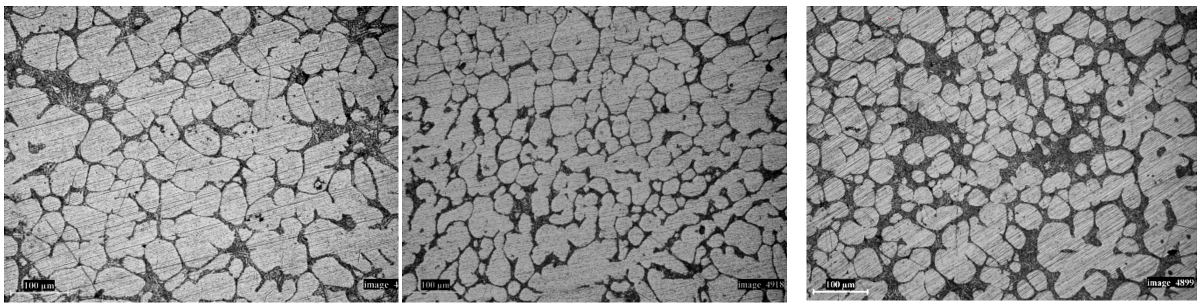


Figure 1. Schematic diagram of RSF set up

A different finding on the solid fraction effect was reported by Prasaad et al [21] for Al-4.5% Cu, where the particle size decreases with solid fraction due to the alloy's "nucleation dominant" solidification behavior. For Al-10% Cu, a "growth dominant" alloy, the particle size increases with solid fraction and the size distribution becomes broader. Solid fraction was found to have no effect on Al-6% Cu in which the nucleation and growth effects are said to be equivalent.



(a) **f_s=0.15** **(b)** **f_s=0.30** **(c)** **f_s=0.45**

Figure 2. Optical micrographs of Al-7Si alloy water quenched semi-solid slurry under different conditions (grain refined with SiB alloy) at 1000 rpm-5 min holding time

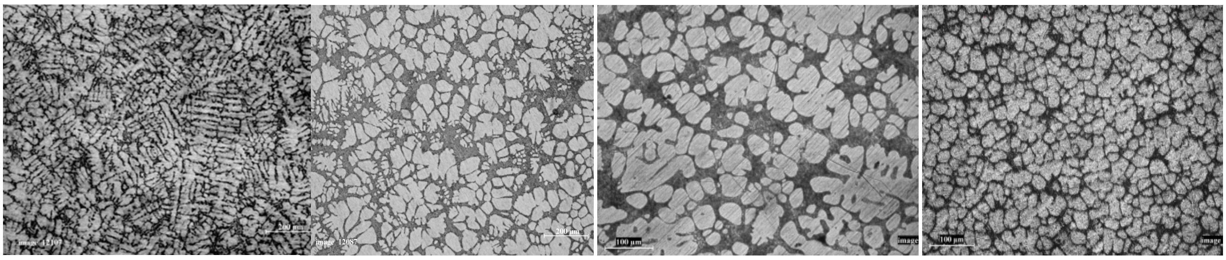
3.2. Influence of Shear Rate

An increase in shear rate leads to a higher rate of mass transport as well as of fragmentation of particles and agglomerates. Wan and Sahm [22] proposed that the particle size could increase or decrease with the shear rate depending on the processing stage. In the initial state of stirring where the fragmentation mechanism is dominant, increased shear rate tends to decrease the average particle size [23,24,25] because of increased fragmentation. Higher shear forces also means less particle coalescence to form larger particles. However, shear rate has been found to have little or no effect on particle size at high cooling rate [21,26]. In the later stage, e.g. at long isothermal stirring, where the particles are largely spherical, and the fragmentation mechanism is less dominant, the average particle size increases with shear rate [26] because of accelerated ripening due to improved mass transport. In all cases, increasing shear rate also tends to result in solid particles with rounder shapes, less entrapped liquid within spheroidized particles and lower degree of agglomeration.

Figure 3 shows the influence of increase in rotation speed on Al-7Si alloy. It can be noted that with increase in shear rate particle size is decreasing. An increase in shear rate leads to a higher rate of mass transport as well as of fragmentation of particles and agglomerates. Stirring leads to forced convection during the process which results in (a) copious nucleation of the primary phase, (b) dispersal of these nuclei throughout the bulk liquid, and (c) survival of these nuclei via heterogeneous nucleation fields. This gives rise to highly potent nucleation events along with uniform dispersion of these nuclei leading to grain refining effect. However, at very high rotation speeds (around 1800 rpm) grain refinement effect is not significant which is due to vortex formation, which reduces the contact between the EEM and the melt during slurry preparation, thus reducing the grain refinement effect.

Discrepancies in results do exist, however. Jabrane et al [17] working with Al-5.2% Si, reported that particle size increases with shear rate at high solid fraction, and decrease with shear rate at low solid fraction for stirring times up to 30 minutes. Molenaar et al [27] found no significant correlation between shear rate and the size of primary solid in Al-6% Cu at low cooling rates. Another work showed that an increase in shear rate decreases the particle size in Al-4.5%Cu but it has no effect in Al-10% Cu.

There is a wider consensus on the influence of shear rate on viscosity. In steady state and continuous cooling experiments, viscosity decreases with shear rate at a given solid fraction, a behaviour referred to as shear thinning. Higher shear rate produces rounder particles with less entrapped liquid and a lower degree of agglomeration, all of which reduce flow resistance, and hence, viscosity.



0 RPM **450 RPM** **800 RPM** **1600 RPM**

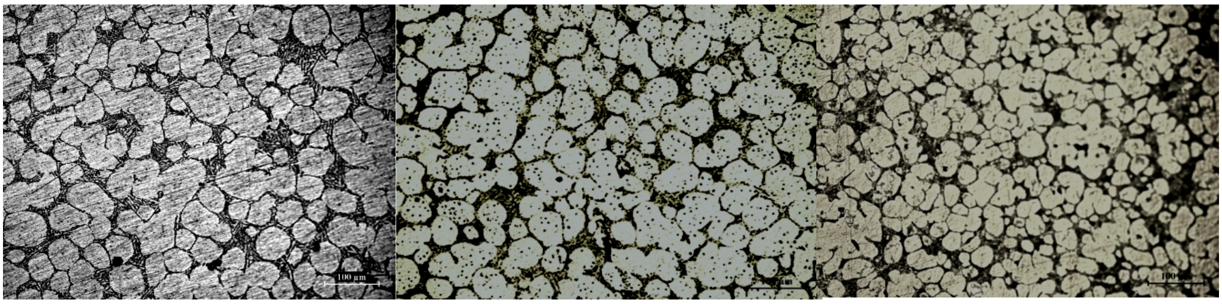
Figure 3. Optical micrographs of Al-7Si alloy water quenched semi-solid slurry under different conditions (grain refined with SiB alloy) at 0.3 solid fraction and 0 min holding time

It has been observed that the apparent viscosity also depends strongly on the actual shear rate [28,29]. The higher the shear rate the lower the viscosity. Without shear, the solid-liquid suspension is very stiff when the solid volume fraction exceeds 0.4. However, with shear rate of 750 s^{-1},the solid-liquid suspension is still conformable even when solid volume fraction exceeds 0.6.

The reason for the reduced viscosity in semisolid metals is the grain morphology. Experimental observation shows that the grain morphology is changing from dendrite to sphere via rosette as the increasing of the shear rate. Brown and co-workers [28,29] showed that viscosity increases with shear rate (shear thickening) if the structure is held constant. The phenomenon was described as the “inherent” flow behaviour of the slurry at a given solid fraction independent of morphology; however, the mechanism for this behaviour was not given.

3.3. Melt Superheat

An increased melt superheat increases the steady state temperature after slurry formation [30]. This is not surprising since the EEM has a distinct mass with a limited cooling ability only. The difference between steady state temperatures is slightly increased for an increased melt superheat. Apparently, as the steady state temperatures become closer to the melting point, the slurry becomes more sensitive to the residual heat in the furnace as well as the latent heat released at slurry formation. Slurry formation times are also affected by the melt superheat. For a higher melt superheat there seems to be a tendency for decreased slurry formation times. Average grain size decreases with increased melt superheats. The fraction of α-phase also tends to decrease with an increased melt superheat. This follows from the increased steady state temperatures obtained from the thermal history. The difference between calculated and experimentally evaluated solid fractions becomes significant in this case. Figure 4 shows the optical micrographs of Al-7Si alloy cast by RSF process at different melt superheat. Based on the microstructure measurements it becomes obvious that the RSF technology is not especially sensitive to the temperature variations seen from the thermal history.



(a) 675^{0}C **(b) 700^{0}C** **(c) 720^{0}C**

Figure 4. Optical micrographs of Al-7Si alloy water quenched semi-solid slurry under different conditions (grain refined with SiB alloy) at 0.3 solid fraction and 0 min holding time

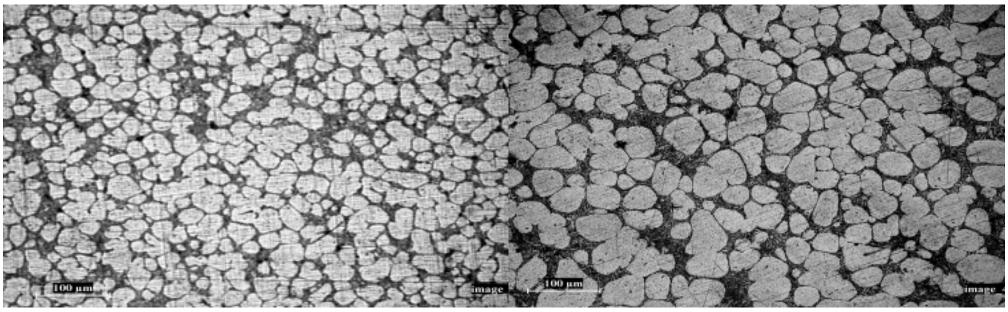
3.4. Processing Time

The effect of processing time is often determined widely by an isothermal stirring experiment. At a given solid fraction and shear rate, longer processing time is found to produce larger particles [28] with rounder morphology, less entrapped liquid within particles [21] and a lower degree of agglomeration [18] as the result of prolonged fragmentation, spheroidization, and coarsening. Increasing rest time or the period the slurry is left unstirred, increases agglomeration. Given enough stirring time, the agglomeration decreases to a steady state, after a dynamic balance between agglomeration and deagglomeration forces is established.

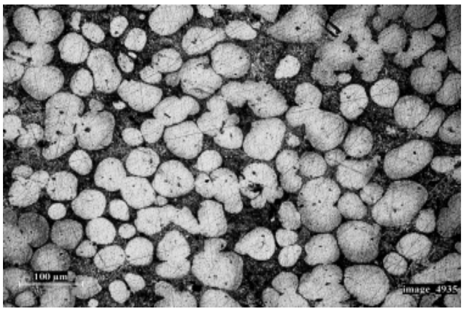
Figure 5 shows the influence of holding time on Al-7Si alloy cast by RSF process. It can be noted that during isothermal holding particle size increases. A more uniform microstructure is obtained with particles having shape factor close to unity at 10 min holding time. Further increase in holding time leads to excessive grain growth.

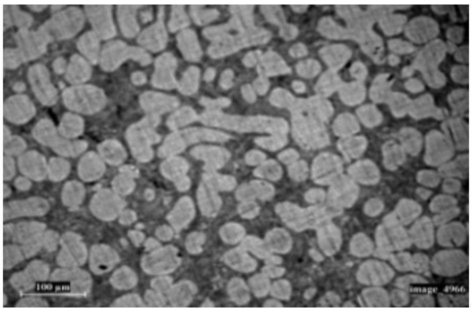
There are exceptions, however. Yan and Tsao [31] proposed that due to improved fragmentation, the particle size decreases in the early stages of isothermal stirring. Only at longer stirring times increases the particle size due to prolonged coarsening. Jabrane et al [17] reported a decrease in particle size with time at low solid fraction. Another work [21] showed that size is independent of stirring time. For slurry initially at rest, Martin et al [29] revealed that slurry agglomeration might increase with time if stirred at low shear rate. Mada and Ajersch [32] attributed the decrease of viscosity with time to a sequence of break-ups of agglomerate bonding and interparticle bonding (coalescence bonding) followed by a dynamic equilibrium of agglomeration and deagglomeration. Coarsening or ripening is an important aspect of the microstructure evolution in semi-solid processes.

The competitive growth of particles due to diffusive Ostwald ripening is one of the factors for controlling coarsening mechanism. In addition to diffusive Ostwald ripening, other phenomena like convective coarsening and coalescence also contribute to the formation of a globular structure. When two particles collide, welding occurs between the particles. Given enough time, the two particles sinter to form a larger particle, driven by the reduction of liquid/solid interfacial free energy. Thus, during isothermal holding, structural coarsening takes place via two phenomena: Ostwald ripening and liquid phase sintering via coalescence.



(a) 0 min **(b) 5min**





(c) 10 min. **(d) 15 min**

Figure 5. Optical micrographs of Al-7Si alloy water quenched semi-solid slurry under different conditions with SiB alloy at 0.3 solid fraction and 1400 rpm.

4. Conclusion

The major process parameters used in the RSF process; rotation speed of the EEM, superheat, amount of EEM added, holding time and cooling rate; all influence the thermal history during processing and microstructures after slurry preparation.
An increase in solid fraction tends to produce larger and rounder particles, and higher degree of agglomeration. Viscosity increases with solid fraction.
An increase in shear rate leads to a higher rate of mass transport as well as of fragmentation of particles and agglomerates.
Higher shear rate produces rounder particles with less entrapped liquid and a lower degree of agglomeration, all of which reduce flow resistance and hence viscosity.
Slurry preparation using the RSF technology is relatively insensitive to small changes in superheat. However, it is observed that average grain sizes decreases with increased melt superheats.
At a given solid fraction and shear rate, longer processing time is found to produce larger particles with rounder morphology, less entrapped liquid within particles. The viscosity of semisolid slurries decreases with time, exhibiting thixotropic behaviour.

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