Study of process parameters on Al-7.0 % Si-0.45 % Mg alloy cast trough strain induced melt activation technique

Študija procesnih parametrov v zlitini Al-7,0 % Si-0,45 % Mg, uliti s tehniko aktivacije taline z deformacijo

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Abstract: The effect of process parameters on microstructure evolution of semi-solid Al-7 % Si-0.45 % Mg alloy produced by strain induced melt activation (SIMA) process were investigated. Predeformation of 20 %, 30 %, and 40 % were used by hot working at 380 ºC. After predeformation the samples were heated to a temperature above the solidus and below the liquidus point and maintained in the isothermal conditions at three different temperatures (580 °C, 590 °C and 600 °C) for varying time (10 min, 20 min, and 30 min). It was found that increased predeformation reduced the soaking time to obtain globular α_{Al} grains. It was observed that strain induced predeformation and subsequently melt activation has caused the globular morphology of α_{Al} grains.

Izvleček: Raziskan je bil vpliv procesnih parametrov na razvoj mikrostrukture kašaste zlitine Al-7 % Si-0,45 % Mg, proizvedene s tehniko aktivacije taline z deformacijo (SIMA). Uporabljene so bile preddeformacije 20 %, 30 % in 40 % pri vročem preoblikovanju na 380 °C. Vzorci so bili po preddeformaciji segreti na temperaturo, večjo od temperature solidusa ter manjšo od likvidusa, ter vzdrževani v konstantnih razmerah pri treh različnih temperaturah (580 °C, 590 °C in 600 °C) različno dolgo (10 min, 20 min in 30 min). Ugotovljeno je bilo, da večja preddeformacija zmanjša čas predgretja za dosego globularnih zrn α_{Al}. Razvidno je bilo, da preddeformacija in posledično aktivirana talina povzročata globularno morfologijo zrn α_{Al}.

Original scientific paper

Key words: Al-Si alloy, semi-solid, SIMA, microstructure, globular α_{Al}
Ključne besede: zlitina Al-Si, kašasto stanje, SIMA, mikrostrukture, globularni α_{Al}

INTRODUCTION

Light weight structural materials, especially Al-alloys, play an important role in achieving vehicle weight reduction and improving fuel economy in the automotive industry. Liquid metal high pressure die-casting (HPDC) currently satisfies the bulk of the automotive industry's needs in this regard. Last two decades have seen a rise in the consumption of Al-alloys in car and in light weight truck market. Growing demands for improved quality and weight reduction, however, have been driving the development of new processing technologies. Problems inherently associated with liquid metal HPDC have resulted in enhanced interest in semi-solid metal (SSM) casting processes.[1]

Semi-solid processing can be done in two ways namely: Rheocasting and Thixocasting.[1, 2] Shaping of materials in the semi-liquid state includes both casting and deformation processes. The critical volume fraction of liquid phase, which allows the material to maintain its shape, is the criterion for the distinction between casting and forming processes. The volume fraction of liquid phase is a function of temperature in the range between solidus and liquidus. The research, which has been carried out in recent years, has proved that deformation of materials with the presence of a liquid phase exhibits some abilities, which are not attainable in conventional metal forming. These processes are referred to in the literature as forming in mushy state or forming in semi-liquid state or thixoforming.[3, 4] The basic principle of these processes is deformation at temperatures between solidus and liquidus points. However, the alloy has to be prepared before deformation in a special way, so that it has a very fine spherical microstructure. The low melting temperature phase should be located at the grain boundaries. Such a microstructure is called thixoforming microstructure. As one of the SSM processes, the strain induced melt activation (SIMA) process is adapt to produce the semi-solid Al and Mg based alloys.[5] SIMA has been reported to obtain near equiaxed grain structures by deformation followed by a heat treatment in the semi-solid region. Liquid phase is located at high angle grain boundaries and alloy achieves a microstructure consisting of almost spherical solid particles. These particles are separated by a low melting-temperature liquid phase. Size of these particles depends on;

- chemical composition of the alloy, which determined the solidus–liquidus temperature interval
- microstructure at the beginning of melting
- heating rate below the solidus
- and holding time in the semi-liquid state

Kirkwood[6, 7] suggested that recrystallization of a previously deformed specimen in the semi-solid isothermal process is the main reason of this modification. In the study, the effect of predeformation rate, as well as holding time and temperature at semi-solid state on the microstructural characteristics of A356 specimens were investigated.

Materials and methods

The alloys were cast in the form of rectangular strips of size 250 mm × 15 mm × 10 mm. The experiment consisted of mainly three stages.

In stage 1, Al - 7 % Si - 0.45 % Mg alloy was prepared according to conventional melting and casting procedure. The mass fraction 0.2 % of Al-5Ti-1B master alloy was also added into the melt for grain refinement of α_{Al} phase. The ingot was cut breadth wise to get samples of length 25 mm.

In stage 2, the samples were mechanically worked with the help of a forging press and a rolling mill. The present alloy under investigation has relatively high Si content which decreases ductility at room temperature, hence warm working was used instead of cold working. Later, the samples were heated to 380 °C and a reduction of 20 % to 40 % was given in the incremental steps of 10 %. Initial reduction up to 10 % was done by forging and the remaining amount of reduction was done by rolling.

In the last stage, the worked samples were given heat treatment in an electric resistance furnace. The temperature was in the freezing range which was varied from 580 °C to 600 °C in the incremental steps of 10 °C, the soaking time was 10 min, 20 min, and 30 min. After this the samples were quenched in water. The quenched samples were taken for microstructural study. The specimens were polished by standard metallographic practice and etched with the Keller's reagent to reveal the microstructure.

Results and Discussion

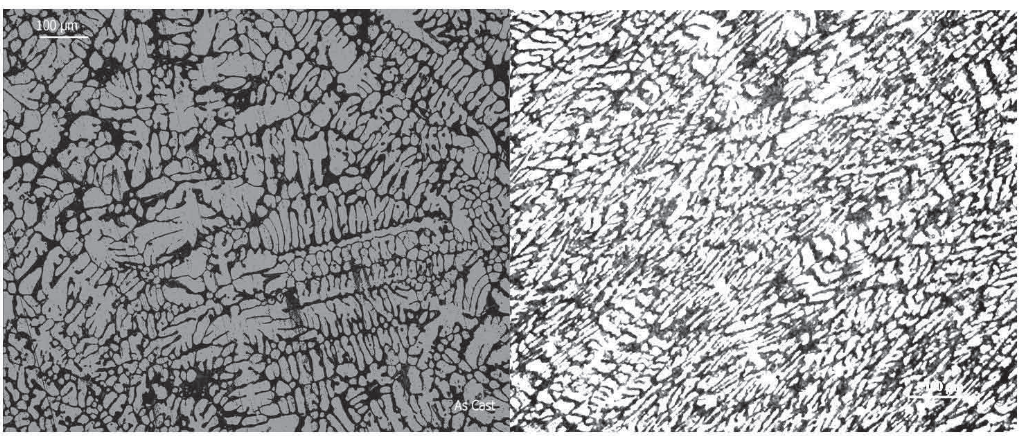
Effect of predeformation, temperature and holding time

Advantages of thixoforming process are due to the mechanism of deformation, which is different than in the conventional metal forming. Due to a localization of the liquid phase at grain boundaries, the plastic deformation involves sliding along the boundaries and rotations of grains. This mechanism of deformation involves low yield stress, as the workability of the alloy increases significantly.[8]

There exists an optimum for the required amount of predeformation which results in the occurrence of recrystallization. It is important to consider that after predeformation, the density of vacancies and dislocations increases, which increases the atomic diffusion capacity on reheating. In specimens with a little amount of predeformation, the density of the vacancies and dislocations is low, which results in a low atom diffusion rate. However, when sufficient amount of predeformation is exerted to the alloy, the final semi-solid microstructure may have equiaxed morphology by diffusion of the eutectic melted phase into the high stress containing regions of the dendrites.[8]

Figure 1a shows optical photo-micrograph of conventionally cast Al-7 % Si-0.45 % Mg alloy where α_{Al} dendrites can be seen along with the eutectic mixture. Figure 1b shows 30 % predeformation which clearly exhibits heavily oriented α_{Al} dendrites in the direction that was vertical to the hot working direction.

During plastic deformation of samples, internal strain energy is stored in the form of dislocation multiplication, elasticity stress and vacancies, which provide the driving force for recovery and recrystallization. The energy increases with the degree of predeformation which promote the morphological

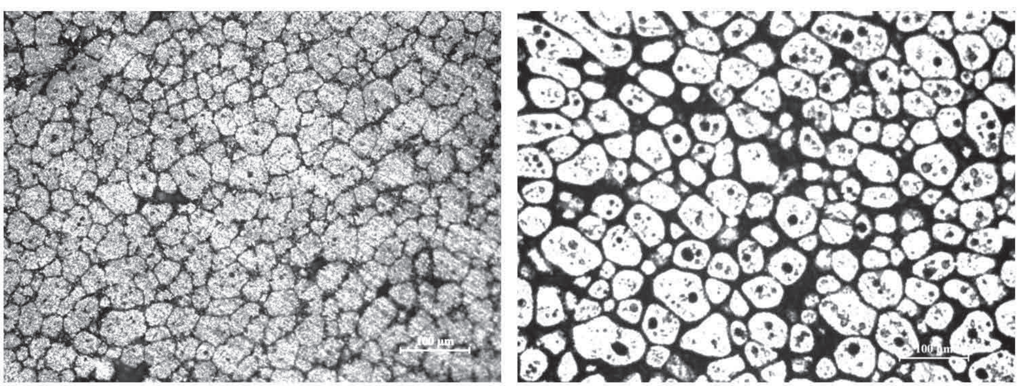


(a) (b)

Figure 1. Optical micrographs of cast Al-7 % Si-0.45 % Si alloy (a) as cast and (b) at 30 % predeformation

transition from dendritic to globular structure.

Figure 2 (a&b) shows representative microstructures of cast alloy heat treated at 580 ºC and 600 ºC for 10 min. at varying predeformation of 20 % and 40 % respectively. The microstructures consist of α_{Al} grains, liquid phase and the entrapped liquid inside the α_{Al} grains. The experimental results show the effect of predeformation and temperature at 10 min of holding time on α grain size and morphology Figure 2 (a&b). The adjoining grain coalesces and coarsens quickly at 580 ºC. In other words, coalescence and coarsening occurs in the stage of low liquid fraction. However, with an increase of isothermal temperature to 600 ºC, the large α grains coarsen continuously and the small grains melts gradually as shown in Figure 2b. Where it could be observed that with increase in temperature and predeformation, the amount of semi - solid particles reduce and the size of α_{Al} grains increase, solid volume fraction lowers down and shape of the grains becomes more globular (average aspect ratio of around 0.8). The average α_{Al} grain size increases from 40 μm to 60 μm. The particles with large curvature show lower melting point at the protuberant part. Due to this the protuberant part of the solid particles melts, which makes the solid particles more globular.[8] This is known as the Gibbs-Thompson effect. It is clear that the high semi-solid isothermal temperature reduces the volume fraction of solid and accelerates the spherical evolution of the solid particles (Figure 2b). At temperatures higher than the eutectic temperature, the eutectic phase dissolves completely and the atoms diffuse to the α_{Al} grains due to increasing of the diffusion capacity and the solubility



(a) (b)

Figure 2. Optical micrographs of Al- % Si-0.45 % Mg alloy at 10 min holding time at (a) 20 % predeformation and 580 ºC (b) 40 % predeformation and 600 ºC

of the elements in α_{Al} at higher temperatures. Since the secondary arms are small, they coarsen, combine and disappear when the eutectics between them is melted completely. Entrapped liquid[7] is also observed inside the α_{Al} grains. It is also observed that coalescence of complex shaped grains results in large liquid entrapment as shown in Figure 2b. When the isothermal holding temperature is increased, the ability of atomic mobility increased, which promotes coalescence ripening.

Figure 3(a–c) shows representative microstructures of 30 % predeformed alloy heated treated to 590 °C for 10 min, 20 min and 30 min. On comparing the microstructures of Figure 3 (a–c) it can be seen that there is coarsening as well as deviation from globularity as the holding time increases i.e. with increase in holding time α_{Al} solid particles loose their globularity and become irregular and large (Figure 3b&c). With the increasing the isothermal holding time, coalescence ripening does an effect on

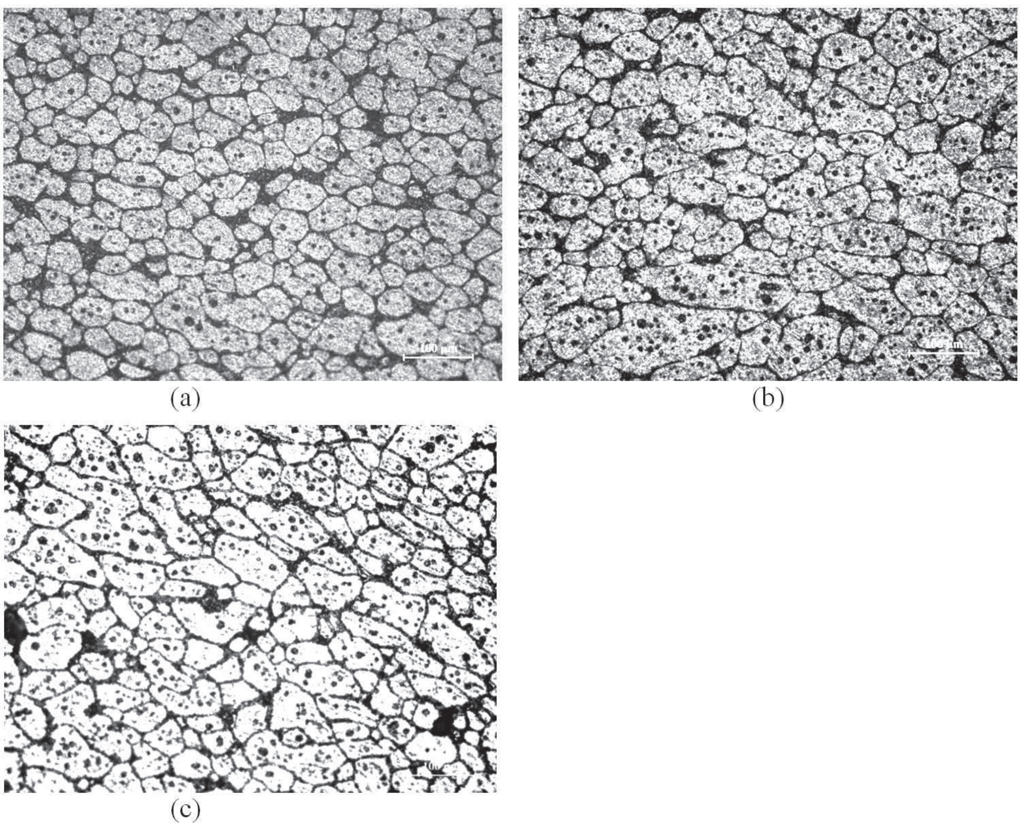


Figure 3. Optical micrographs of cast Al-7 % Si-0.45 % Mg alloy at 30 % predeformation and 590 ºC with varying holding time (a) 10 min (b) 20 min and (c) 30 min

the average size of the solid particles and allow the particles to grow larger. As time passes from 10 min to 30 min, the total number of grains decreases however, volume fraction of α_{Al} (the grain constitution) is constant.

Coalescence and Ostwald ripening mechanisms[9] play an important role to increase the average size of the α_{Al} particles. The coarsening mechanism is the coalescence of α_{Al} grains, which occurs between adjoining grains at low liquid fraction. Liquid content plays an important role in kinetics of coalescence since it defines the number of solid necks between grains. It has been shown that the coalescence frequency is proportional to the number of adjacent grains. Therefore, coalescence is expected to occur at early stages of heating or in high fraction solid in the semi-solid regime where the number of necks per grain is relatively high and grains are discrete.

Ostwald ripening involves the growth of larger α_{Al} particles at the expense of smaller α_{Al} particles, and it is governed by the Gibbs–Thompson effect. This effect changes the chemical potential of solutes at the particle/liquid interface, depending on the curvature of the interface.[16] The lowering of interfacial energy between the solid phase and liquid phase supplies the driving force for grain coarsening. The larger grain gradually becomes spheroidal to lower the solid/liquid interfacial energy. Ostwald ripening is active at higher liquid fraction, in which α_{Al} grain continuously coarsen and the small grain gradually melts. According to the LSW theory[18] third power diameter of α grain is proportional to holding time;

$$D^3 = Kt + D_0^3$$

where D and D_0 are the final and initial grain sizes respectively is the initial size of a solid phase particle; and t is the holding time measured from the moment when annealing temperature is reached; K is a coarsening rate constant.

The isothermal holding time, temperature and degree of predeformation have effects on the average size and degree of spheroidization of α_{Al} particles of semi solid slurry.

Conclusion

High semi-solid heat treatment temperature make the α_{Al} particles more globular. However, the solid fraction reduces. Size of the particles grow larger due to coarsening. Higher soaking time also causes coarsening of α_{Al} particles and globularity is also lost. The whole microstructure evolution process of SIMA processed Al-7 % Si-0.45 % Mg alloy can be divided in to two steps: first is recovery, recrystallization and partial melting and second is sheroidizing and grain coarsening as holding time increases.

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