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Methodology Article

The Effect of Deformation Ratio and Heat Treatment Time on the Microstructure and Mechanical Properties of A356 Aluminium Alloy During SIMA Process

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Abstract: The influence of Strain Induced Melt Activated (SIMA) parameters on the globularization of α-Al and microstructure in A356 aluminium alloy were investigated in the present study. After production of samples using conventional permanent mold casting and cold rolling at various reduction, they were heat treated at 590°C for different holding time to spherodize the microstructure. The results indicated that, the grains became smaller, more spherical and having a homogenous distribution by increasing the deformation ratio. Increasing the holding time in heat treatment results the growth of globular grains. The necessary strain for recrystallization is about 15% and the optimum condition was achieved in the samples were 15% rolled and heat treated for 15 minutes at semi-solid temperature, regarding the maximum shape factor and minimum globular grains size. Further increasing in holding time is responsible for grain growth and hardness decline.

Keywords: A356 Aluminium Alloy, Semi Solid Processing, SIMA, Globular Structure, Cold Work

1. Introduction

In recent decades, the semi-solid metal forming has gained considerable interest to produce near-net shape products, particularly in automotive industries. A fundamental research in this field was started by Flemings' group at MIT during 70s. It has been shown that semi-solid metal forming processes have several advantages over other conventional techniques. These include higher production rate and quality whereas lower forming temperature. Furthermore lower shrinkage and porosities are achieved. [1-4].

The primary requirement in this technology is to obtain a fine equiaxed or globular grain structure and free of dendrites during forming. Alloys with an equiaxed microstructure represent significantly lower flow resistant during shearing in the semi-solid state compared to alloys containing dendritic microstructure [1, 5]. Several methods have been applied to produce the globular structures. In general they are classified in two main groups: liquid and solid states. The liquid state techniques encompass CS[1] and MHD[2] [6-8], while solid state includes SIMA[3] and RAP[4] [9-11]. Among the mentioned methods, the solid states have special advantages such as the reduced amount of entrapped liquid and more globular particles which subsequently enhance thixoformability. Numerous researches have been allocated to study and investigate the microstructure alteration of different alloys during SIMA and RAP processes [12-15]. SIMA is a potential method with the significant commercial advantages of simplicity and low equipment cost in fabrication process and has been demonstrated to be applicable to most engineering alloys, including aluminium, magnesium, copper and ferrous alloys [14-16].

In a general point of view, this procedure involves the cold or warm deformation of an alloy to some critical reduction point and heat treatment in the solid-liquid temperature range. The semi-solid heat treatment is the most substantial aspect to control the microstructures in the SIMA process [17, 18]. During heat treatment, recrystallization and partially remelting occurs. Parameters such as heating time,

temperature and the degree of deformation are vital in this process [19-20].

Most of the recent studies in the field of Semi-Solid Metal Forming (SSMF) have been paid to Al–Si alloys as potential thixoformable materials due to their wide processing window and high fluidity in the semi-solid region [13, 21]. Therefore, a detailed knowledge about their thixotropic feedstock preparation criteria and rheological behavior as well as their final mechanical properties is very required. Consequently, the present study investigates the influence of SIMA process parameters on the microstructure evolution and semi-solid mechanical behavior of A356 aluminium alloy.

2. Experimental Procedure

Table 1 represents the chemical composition of A356 aluminium alloy which is used in this study. In casting process, 0.2 wt. % of Al-10%Sr master alloy was added to modify eutectic silicon morphology and in order to eliminate gas content, the melt was treated with 0.5 wt. % C_2 Cl_6 tablet for 4 minutes, followed by pouring at 700±10°C in a cast iron standard Y-block mold which was preheated to 250°C. Figure 1 represents the schematic of the sample after casting.

Table 1. *Chemical composition of used A356 alloy, in wt. %.*

element	Al	Si	Mg	Cu	Fe	Mn	Zn
wt. %	Bal.	7.18	0.33	0.12	0.31	0.01	0.01

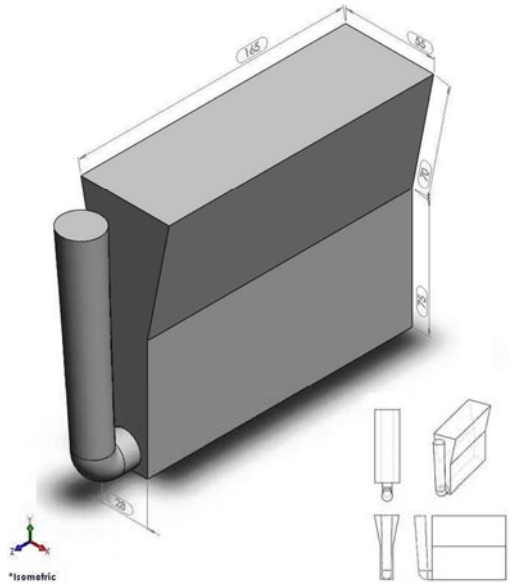

Figure 1. *Schematic of the sample after casting in standard Y-block mold.*

In order to homogenize the structure, samples were heated to 520°C, held for 5 hours and then quenched into the water at room temperature. Afterward some 7.5mm×3.5mm×2mm specimens were prepared and rolled with various reductions at 300°C. In 25% reduction the respective sample was cracked; so higher reductions were not considered in the study. In order to apply the SIMA process, the rolled specimens were consequently reheated to 590°C in an electric resistance furnace with ±5°C temperature accuracy for different holding times then they were quenched into water at room temperature.

DSC[5] analysis was employed to conclude the appropriate temperature for semi solid heat treatment. A disc-shape sample with 3mm diameter was heated to 700°C at 10°C /min in an argon atmosphere. The heat flow vs. temperature curve achieved during heating was used to calculate the variation of solid fraction with temperature between liquidus and solidus.

Some samples were prepared for metallographic observation and etched with 0.5% HF solution. Clemex image analyser software version 3.5.025 was used for microstructural evaluation. Shape-factor and the average size of globular particles were also measured using Eqs.1 and 2, respectively [22].

$$D_{eq} = \frac{\sum_1^N \sqrt{4A/\pi}}{N} \quad (1)$$

$$SF = 1/\left(\frac{\sum_1^N \frac{P^2}{4\pi A}}{N}\right) \quad (2)$$

In above equations, A and P refer to the area and perimeter of globular particles, respectively and N is the number of particles.

The Vickers micro-hardness examination was conducted on specimens in order to investigate the hardness of globular particles and eutectic phases.

3. Results and Discussions

3.1. Microstructure Development During SIMA Process

3.1.1. Effect of Deformation

Figure 2 represents the optical micrograph of A356 Aluminium alloy in as-cast state. The microstructure shows a modified hypoeutectic solidification structure that includes of primary aluminium phases (α-Al) which is surrounded by the darker regions of Al-Si eutectic phases. It worth mentioning that as a result of modification process with Al-10%Sr the morphology of eutectic silicon particles alters from plate-like to fibrous, however the microstructure still represents a dendritic structure and is not appropriate for semi-solid forming.

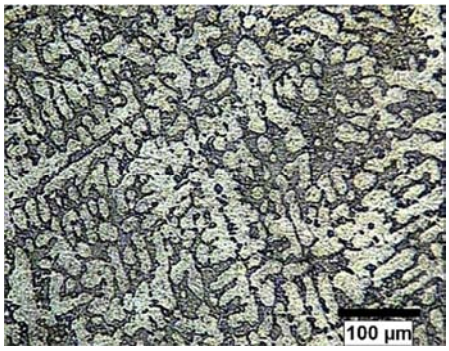

Figure 2. *As-cast microstructure of A356 alloy.*

Figure 3(a) demonstrates DSC curve. The solidus and liquidus temperatures were 565°C and 620°C, respectively. By integrating under the DSC curve between the liquidus and

solidus, the solid fraction curve was obtained (Figure 3(b)). The solid fraction in 590°C is about 58% which is appropriate for semi solid heat treatment.

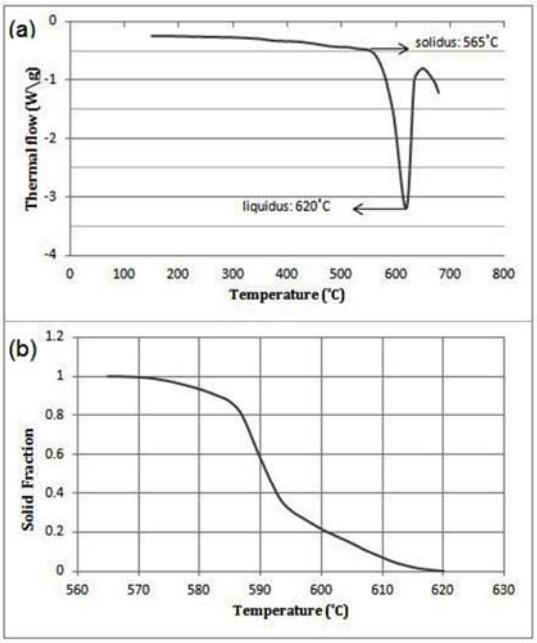

Figure 3. *(a) DSC curve (10°C/min) of the as-cast A356 aluminium alloy sample (b) solid fraction versus temperature.*

Figure 4 shows the microstructure of the alloy processed in semi-solid state with different reduction in thickness at 590°C for 15 minutes. As it can be seen, the 5% pre-deformed specimen (Figure 4a) contains a non-dendritic microstructure which consists of solid particles with large size and irregular shape. The particles have partially undertaken spheroidization which is attributed to the lower density of the vacancies and dislocations and thus the atomic diffusion rate. By increasing deformation ratio, solid particles become gently more globular. In fact, higher deformation ratio results in finer recrystallized grains and consequently makes the decrease of solid particle size through partial remelting.

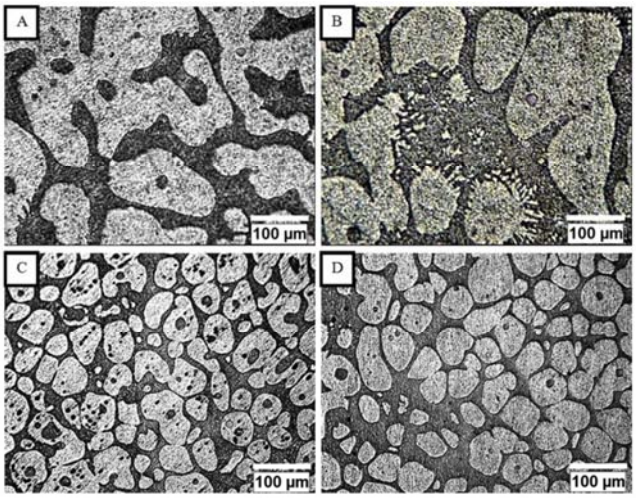

Figure 4. *Structures of the samples produced at 590°C for 15 minutes after; a) 5%, b) 10%, c) 15% and d) 20% reduction.*

The average globule size and shape factor as a function of deformation ratio after isothermal holding at 590°C for 15 minutes during SIMA process is shown in figure 5. It can be seen that by increasing deformation, average globule size decreases; whereas, shape factor increases. However, it seems that the average globule size does not noticeably declines when the deformation differs between 15% and 20% whereas shape factor slightly rises. The possibility is that vacancies, lattice defects and dislocations generated by increasing compression ratio may be neutralized. For example, two dislocations with opposite Burgers vectors will neutralize each other [26].

The minimum average of globule size was found to be 58 µm and the calculated shape factor shows a maximum value of 0.89 for 20% reduction. The important point in this graph is that with increasing of pre-strain from 10 to 15% a sudden fall in globule size occurs which is recognizable in figure 5.

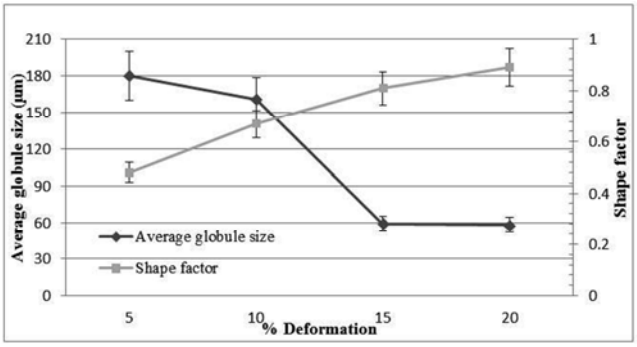

Figure 5. *Variation of average globule size and shape factor after SIMA process at 590°C for 15 minutes with percent of deformation.*

It is well-known that driving force for recrystallization process derives from stored strain energy in the forms of vacancies, lattice defects and dislocation provided by cold working and a critical pre-strain is required to start the recrystallization in SIMA process. In another word, in the present study the necessary strain for recrystallization is about 15%. Furthermore, the degree of spheroidization improves with increasing deformation ratio. With the increasing deformation ratio, the state of as-deformed alloy is more thermodynamically unstable during partial reheating, which rises the atomic diffusion capacity so solid particles become more spheroidal gradually.

3.1.2. Effect of Holding Time

The microstructure of samples after 15% reduction and different holding time at 590°C are presented in figure 6. When the holding time is 10 minutes, the microstructure consists of several solid particles with irregular shape besides most of them are still aggregated together and the fragmentation does not completely happen. Moreover the particles have not been entirely spheroidized. As it can be observed in Figure 6b, by increasing the holding time to 15 minutes, the morphology of the grains changes to globular. Figure 7 illustrates the variations of average particle size and shape factor with holding time at 590°C for as-deformed alloy with 15% reduction. It is shown that average particle

size decreases primarily, but then rises as the holding time increases. Meanwhile, the solid particles become more spheroidal. With further increasing the holding time, the thickness of liquid film rises and solid particles are significantly spheroidized. Furthermore the large solid particles evidently coarsen and the small ones gradually dissolve, as shown in Figure 6c and 6d.

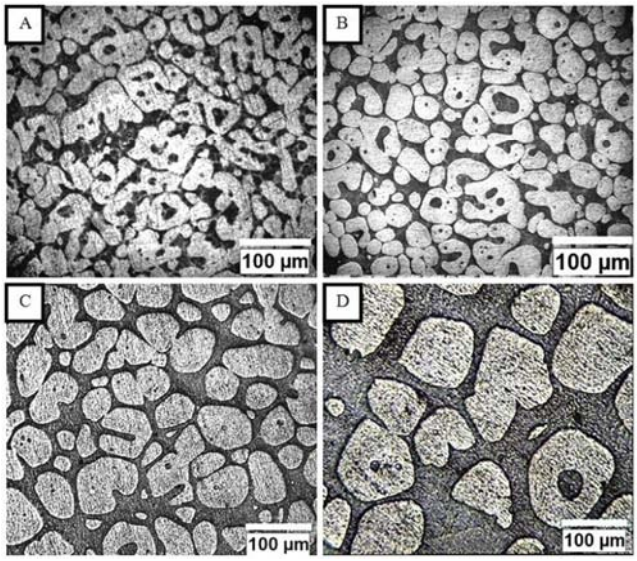

Figure 6. *Structures of the samples produced at 590°C for 15% reduction after different holding time; a) 10, b) 15, c) 20, d) 25 minutes.*

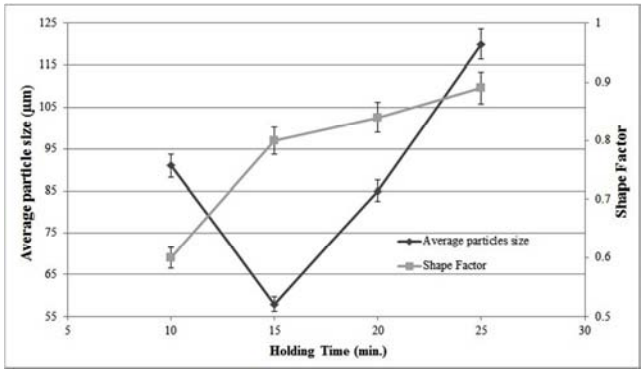

Figure 7. *Variations of average particle size and shape factor with holding time at 590°C for as-deformed alloy with 15% compression ratio.*

However, Ostwald ripening is considered to be the dominant coarsening mechanism during this process because solid particles are surrounded by thicker liquid film and no entrapped liquid are detected; as shown in Figure 6c and 6d.

The SIMA process happens in a two-step process. In the first step, dendritic material undergoes plastic deformation below the solidus temperature. In this study cold rolling is responsible for increasing the amount of plastic deformation in the alloy. After that, in the second step the alloy is rapidly heated to a temperature between solidus and liquidus. Microstructure evaluation in the first step is as follows: (1) In the presence of small plastic deformation, twinning is added to slip and cross-slip and cause material to deform; (2) where the atoms are not properly spaced, new grain boundaries will be formed (Figure. 8b); (3) higher levels of deformation make the grains rotate and elongate (Figure. 8c); (4) the grains will be divided as step (1) as grains (single crystal) elongate (Figure. 8e) [22, 23].

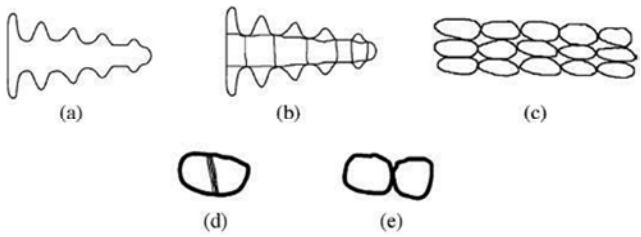

Figure 8. *Microstructure assessment for SIMA: (a) dendrite arm; (b) dendrite arm after small deformation; (c) microstructure after grain rotation and elongation; (d) grain interior after elongation; (e) break-up of grain [22, 23].*

The material is rapidly heated to the temperature between the solidus and liquidus in the second step. As a result, grain boundaries with more energy will melt and the grains progressively change to a globular shape. Ostwald ripening is driven by the variable curvatures of different particles. Thermodynamically, the effect of solid surface curvature and surface tension on equilibrium melting point can be expressed as [24]:

$$\Delta T_r = -\frac{2\sigma T_m V_S K}{\Delta H} \quad (3)$$

where $\Delta Tr = Tm - T$ is the decrease in the equilibrium melting point, T_m the equilibrium transformation temperature, K the mean surface curvature of the solid, V_S is the solid volume, σ is the surface tension and $\Delta H = H_S - H_L$ (which is negative) is the molar change in enthalpy of the solid and liquid. According to Eq. (3), when the surface curvature is positive, ΔT_r is also positive and thus the equilibrium melting point is reduced at the dendrites tips. The more the surface curvature, the more decline is expected in the equilibrium melting point. In other words the equilibrium melting point of the larger particles is higher than that of the small ones or the diameter of larger grains increases at the cost of smaller ones [25].

The relationship between percent of deformation vs. equivalent diameter and shape factor of the samples in two different holding times was shown in Figure 9. By increasing deformation percentage, equivalent diameter of the grains reduced while shape factor increased slightly. In fact, as a result of increasing in stored strain energy, the more deformation, the less equivalent diameter was expected.

It seems that by increasing the holding time from 15 to 25 minutes, shape factor has not altered significantly in all deformation percentages whereas globular grains have developed.

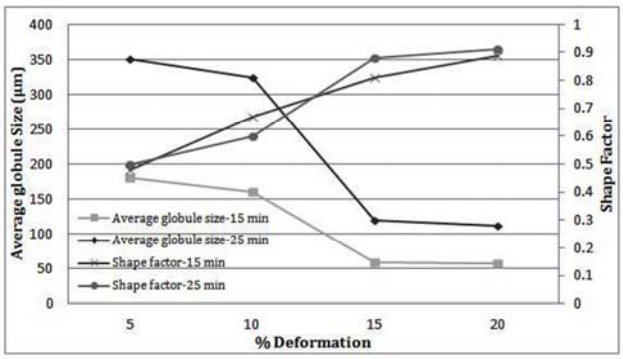

Figure 9. *The relationship between percent of deformation vs. equivalent diameter and shape factor of the samples in two different holding times.*

3.2. Mechanical Properties During SIMA Process

Figure 10 represents Microhardness of the samples at Semi-solid state for 15 minutes holding time. It can be seen that hardness of globular grains and eutectic phases increased gradually from 5 to 15% reduction while from 15 to 20% reduction, there is a significant drop. Work hardening effect is responsible for the increasing part of the graph. As the applied temperature of semi-solid heat treatment is near to solutionizing treatment temperature of A356 aluminium alloy (540°C), it is probable to dissolve a portion of Mg_2Si particles where the stored strain energy is on its maximum. So the hardness will reduce in absence of precipitate hardening phase.

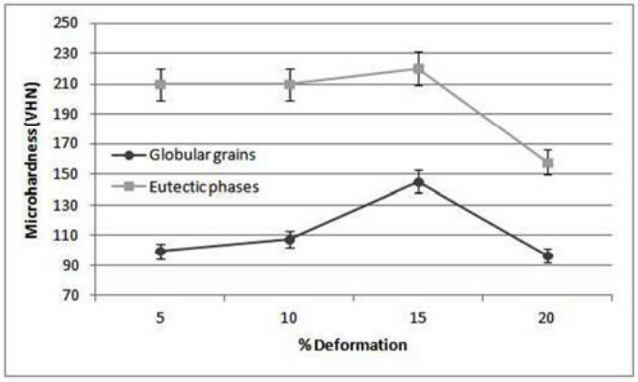

Figure 10. *Microhardness of the samples produced at Semi-solid state at 590°C for 15 minutes holding time.*

According to Figure 7, 9 and 10, the optimum condition is perceived to the samples with 20% deformation and 15 minutes holding time. In other words, these samples represent the maximum shape factor (near to 1), the smallest globular grain and minimum of hardness in comparison with other samples. For as cast structure the hardness of α-Al dendrites and eutectic phases are 149 and 199 VHN, respectively whereas the values related to optimum condition are 96.5 and 158 VHN. So the required force for the deformation of the alloy has significantly been decreased in optimum condition.

4. Conclusion

In this article the SIMA process of A356 aluminium alloy was investigated. It can be concluded from results:

a With increasing percentage of deformation from 5 to 20%, α-Al grains become more spherical and shape factor gets near to 1 for 15, 20 and 25 minutes holding times.

b Equivalent diameter of the grains reduces significantly for 10 to 15 holding times as a result of higher deformation whereas from 15 to 25 minutes holding time, equivalent diameter of the grains increases as a result of grain growth.

c The necessary strain for recrystallization is about 15% but the optimum condition is achieved in the samples with 20% deformation and 15 minutes holding time. These samples possess the maximum shape factor, the smallest globular grains in addition to minimum of hardness in comparison with other samples.

d Where the reduction is higher than 15%, the hardness of samples reduces. It would be as a result of dissolving Mg_2Si as precipitate hardening agent. More investigation will be needed for further study.

Abbreviations

a CS: Cooling Slope

b MHD: Mechanical stirring and Magneto – Hydro - Dynamic stirring

c SIMA: Strain Induced Melt Activated

d RAP: Recrystallization And Partial melting

e DSC: Differential Scanning Calorimetry

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