Fabrication and Microstructure Evolution of Semi-Solid LY11 Alloy by SIMA

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For semi-solid metal forming, it is essential to fabricate the semi-solid materials with spheroidal microstructure. Among several fabrication techniques of the semi-solid materials, (strain-induced melt activation (SIMA) is an ideal candidate with the advantages of simplicity and low equipment costs. In this paper, the microstructure evolution of LY11 alloy (approximately corresponding to ASTM 2017) was investigated in the SIMA process, which had two essential stages: deformation and isothermal heat treatment. The deformation stage was conducted using a CSS-1100C material testing machine and the isothermal heat treatment stage was performed in a resistance furnace. Different levels of deformation temperatures, ram velocities, isothermal temperatures, and holding times were used in this investigation. The microstructure of LY11 alloy was observed by a NEOPHOT-1 optical microscope. The results indicated that the processing parameters must be selected properly to obtain the fine, uniform and spheroidal microstructure by SIMA. The deformation-recrystallization mechanism for microstructure evolution in SIMA process was supported by experimental evidence.

Keywords deformation-recrystallization mechanism, semi-solid LY11 alloy, SIMA process, spheroidal microstructure

1. Introduction

Among many materials technologies, semi-solid metal forming (SSM) is one of the most important technologies in the 21st century to manufacture near net-shape components. Meanwhile, SSM can prolong mold life, reduce energy consumption, and improve operating efficiency.[1,2] The advantages of SSM have enabled it to compete effectively with a variety of conventional processes in the automobile, aerospace, and military industries. Compared with conventional casting and forging technologies, the key feature of SSM is the spheroidal nondendritic microstructure of semi-solid material. Furthermore, it is essential to prepare the semi-solid materials with spheroidal microstructure for SSM. The semi-solid metal forming technology has a wonderful prospect as long as the supply of the semi-solid materials is solved.

A variety of fabrication techniques is available to produce semi-solid raw materials, including mechanical stirring (MS), electro-magnetic stirring (ES), SIMA, and spray deposition (SD). Among these techniques, ES and SIMA have significant commercial advantage. Although ES can solve the problem of melt contamination of MS, it needs complicated equipment and large investment. Small diameter materials (<38 mm) and some wrought alloys are difficult and/or expensive to produce by ES. SIMA is an ideal candidate for solving these problems. It has the advantages of simplicity and low cost for equipment in the fabrication process and has been demonstrated to be applicable to most engineering alloy families, including aluminum, magnesium, copper, and ferrous alloys.[1,2] For SIMA technology, Lee et al.[3] investigated the microstructure characteristics of 7075 aluminum alloys in the SIMA process. The semi-solid materials of M-2 and 308-L stainless steel and LC4 alloy are also produced by SIMA.[4,5]

This paper presents the microstructure evolution of semi-solid LY11 alloy fabricated by SIMA.

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2. Experimental Procedure

The material used in the experiments was LY11 alloy, which was hot extruded and treated by a solid solution and natural aging. Chemical composition of this alloy is shown in Table 1. Figure 1 shows the microstructure of this material. The semi-solid temperature range of this alloy was measured by a differential thermal analysis (DTA) experiment and was found to be 514 °C~642 °C (Fig. 2).

The spheroidal microstructure may be obtained by deformation below solidus temperature and isothermal heat treatment in the semi-solid temperature range. At the stage of deformation, the upsetting was performed at different levels of deformation temperatures and ram velocities using a CSS-1100C material testing machine (Changchun Research Institute for Testing Machine, China). The initial dimensions of specimens for compression test in the SIMA process are 15 mm in diameter and 25 mm in height. All the specimens were compressed up to a height reduction of 30%. At the isothermal heat treatment stage, these specimens were heated in a resistance furnace at different isothermal temperatures and holding times, then dropped into water for quick quenching. Samples were cut at the cross-sections, then polished and etched in a mixed acid solution of HF, HCl, and HNO_3. Subsequently, the microstructures of samples were observed using a NEOPHOT-1 optical microscope (VEB Carl Zeiss JENA, Jena, Germany).

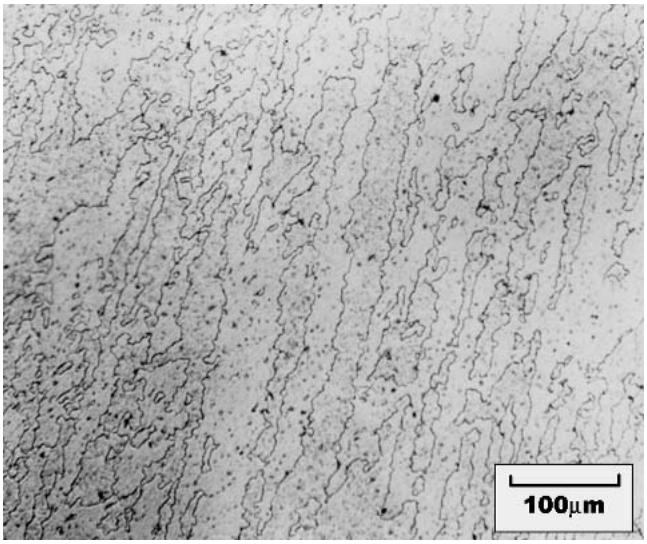

Fig. 1 Microstructure of LY11 alloy

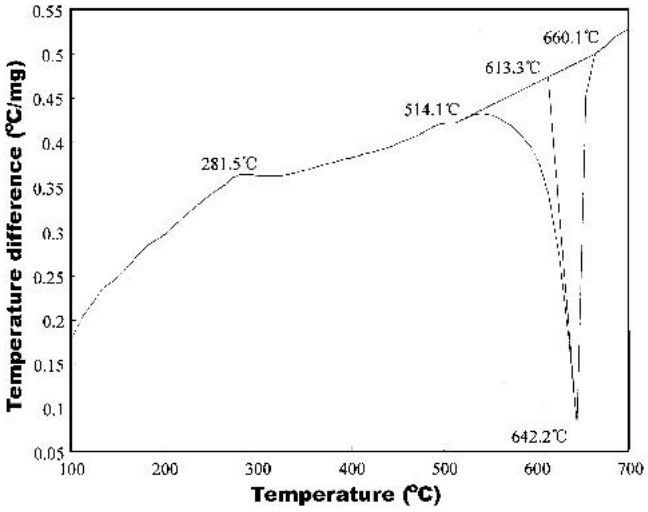

Fig. 2 DTA Experiment curve of LY11 alloy

Table 1 Chemical Composition of LY11 Alloy Used in the Experiments (wt.%)

Cu	Mg	Mn	Fe	Si	Zn	Ti	Al
4.10	0.64	0.54	0.37	0.34	0.10	0.019	Balance

3. Results and Discussion

3.1 Effects of the Deformation Conditions on Microstructure Evolution

Figure 3 presents the effect of the deformation conditions on microstructure evolution of LY11 alloy. Figure 3(a-c) shows the microstructures of samples that were deformed under different deformation temperature conditions then heated at 600 °C for 17 min. These three figures show that the average grain size increases slightly as the deformation temperature increases. The average size of spheroidal grains increased to 58.2 μm at the deformation temperature of 380 °C.

Generally, SIMA is considered a process in which the basic extruded or rolled bars are subjected to additional deformation to accumulate a large quantity of deformation energy for inducing sufficient strain, then heated to the semi-solid condition to transform the dendritic structure to a fine, uniform, and spheroidal microstructure. The deformation energy accumulated by increasing dislocation density is closely related to the deformation process. Under the high deformation temperature conditions, the samples will consume large deformation energy due to recrystallization so that the induced strain is insufficient. Therefore, after isothermal heat treatment the average grain size would be large due to high deformation temperature. To obtain the desired fine and spheroidal grains the low deformation temperature must be adopted. However, the samples of large deformation would crack easily if the deformation temperature were low.

Figure 3(b), (d), and (e) shows the microstructures of samples that were deformed under different ram velocity conditions then heated at 600 °C for 17 min. Comparing these three figures shows that the grains coarsened obviously with decreasing of ram velocity. The grains reached the finest size of 37.7 μm when the ram velocity was 10 mm/s (Fig. 3d).

The difference of ram velocity in the SIMA process has an influence on the grain size. Due to high deformation velocity the samples could not release a large amount of deformation energy in time and accumulate a large quantity of dislocation at the boundaries of subgrains and grains. While heating the samples to the semi-solid temperature, recrystallization occurs to fragment dendritic structure at the boundaries and then fine, uniform, and spheroidal grains appear. Figure 3(e) is an example that the coarse grains could be obtained due to low ram velocity of 0.1 mm/min. The mechanical performance of semi-solid materials would decrease so much that it could not be applied to thixoforming if coarse grains exist. It is favorable to increase the ram velocity while ensuring the distribution of fine, uniform, and spheroidal grains. But the processing cannot be easily controlled if ram velocity is very high.

3.2 Effects of the Isothermal Heat Treatment Conditions on Microstructure Evolution

The isothermal heat treatment of specimens is a very important step for fabrication of semi-solid materials. The samples were compressed at 1 mm/min ram velocity after they were heated to 280 °C and held for 1 h. The microstructure evolution of LY11 alloy at different isothermal temperatures and holding times are shown in Fig. 4. Comparing Fig. 4(a) and (b) with Fig. 3(a), the structure of grains were the biggest and most spheroidal when holding time was selected for 30 min. It was concluded that the structure of grains should gradually become irregular with decreasing holding time. At the deformation stage, the samples accumulated enough deformation energy at the boundaries of grains and subgrains to provide the kinetic of partial remelting. When the samples were heated to the semi-solid temperature, melting would occur at these boundaries and novel grains appeared. With increasing holding

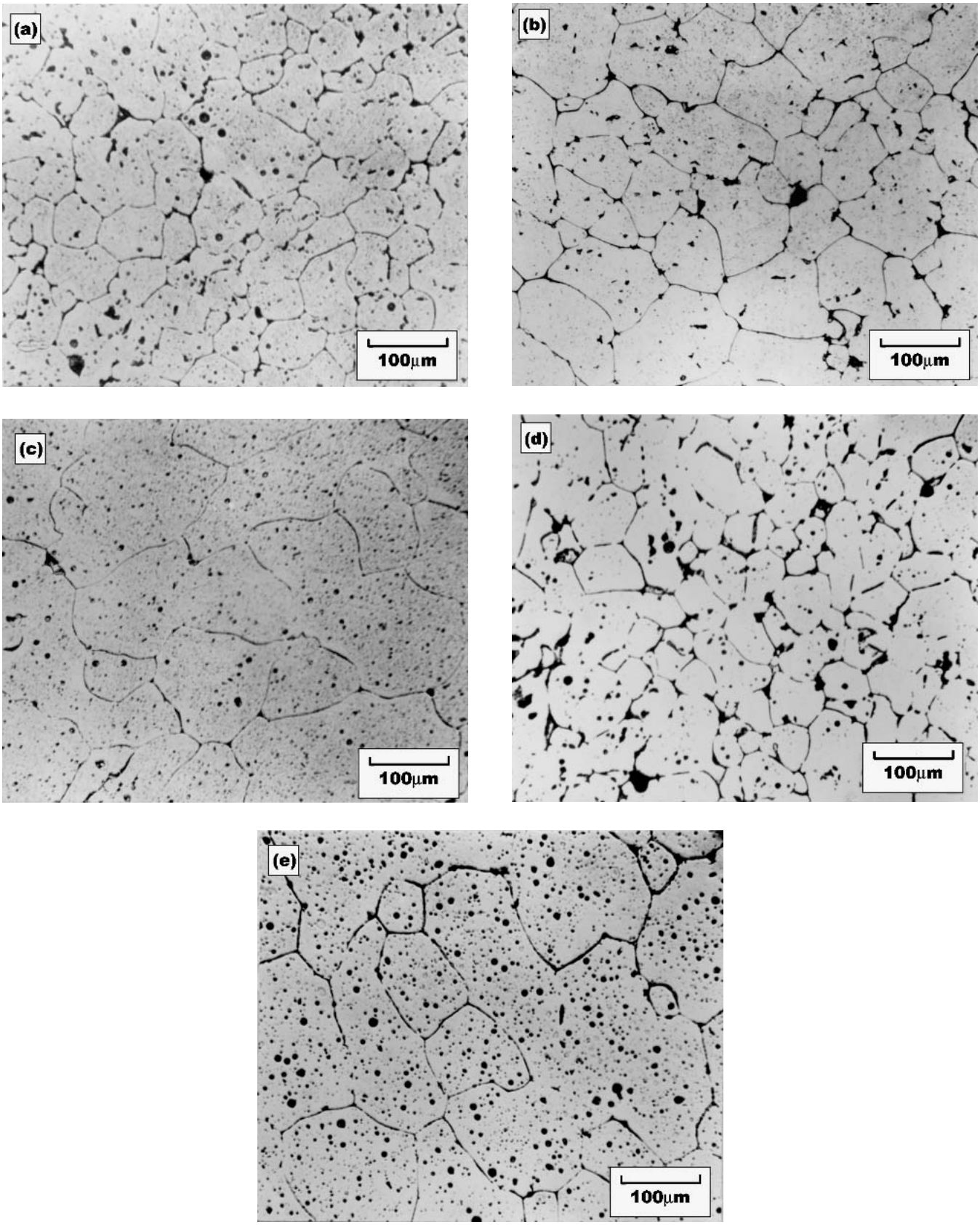

Fig. 3 Effects of the deformation conditions on microstructure evolution: **(a)** 280 °C, 1 mm/min; **(b)** 330 °C, 1 mm/min; **(c)** 380 °C, 1 mm/min; **(d)** 330 °C, 10 mm/min; **(e)** 330 °C, 0.5 mm/min

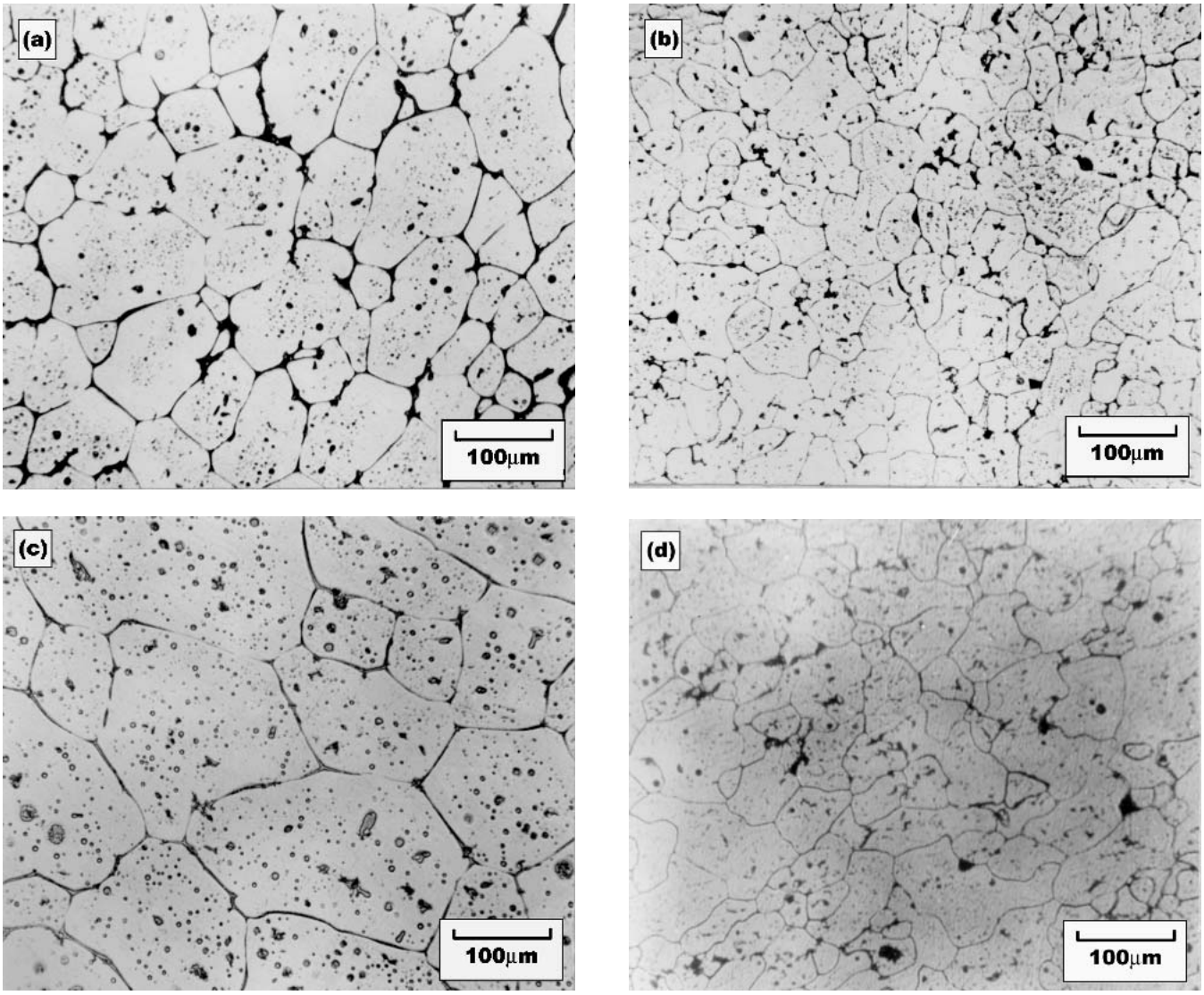

Fig. 4 Effects of the isothermal heat treatment conditions on microstructure evolution **(a)** 30 min, 600 °C; **(b)** 15 min, 600 °C; **(c)** 17 min, 620 °C; **(d)** 17 min, 580 °C

time, the structure of these grains became bigger and more spheroidal. Under the condition of long holding time, the grains coarsened due to the mechanisms of coalescence and Ostwald ripening.[1,6] The microstructure evolution to spheroidal structure was promoted by the reduction of the area of interface between the solid and the liquid phase. Apparently, enough holding time ensured the complete evolution of the microstructure. The fine and spheroidal grains could only be acquired if the rational holding time was selected.

Figure 4(c) and (d) and Fig. 3(a) show the effects of isothermal temperatures on microstructure evolution. When the samples reached the isothermal temperature 620 °C in the semi-solid temperature range (Fig. 4c), eutectic liquid both inside intrinsic grains and between grains increased and the boundaries of grains visibly widened. The structure became more spheroidal and coarse grains continued with increasing isothermal temperature. According to the DLA (diffusion-limited aggregation) model,[6] the fragment, growing, and spheroidizing time of grains is shortened greatly because the diffusion velocity of atom increased with increasing isothermal temperature. But the coarsening rate of grains increased at the same time. Molten pools and large grains can be seen at the high isothermal temperature of 620 °C in Fig. 4(c). The mechanical properties of semi-solid LY11 alloy will be greatly affected if large grains and molten pools exist.

3.3 The Mechanism of Microstructure Evolution

The experiment provides evidence that supports the deformation-recrystallization mechanism proposed by Doherty et al.[7] as the main mechanism responsible for the formation of the spheroidal microstructure via the SIMA process. Figure 5 shows an example of grain fragmentation that clearly caused deformation-recrystallization mechanism. As a result of isothermal heat treatment, liquid presented at the high-energy boundaries first, then penetrated along the new subgrain and

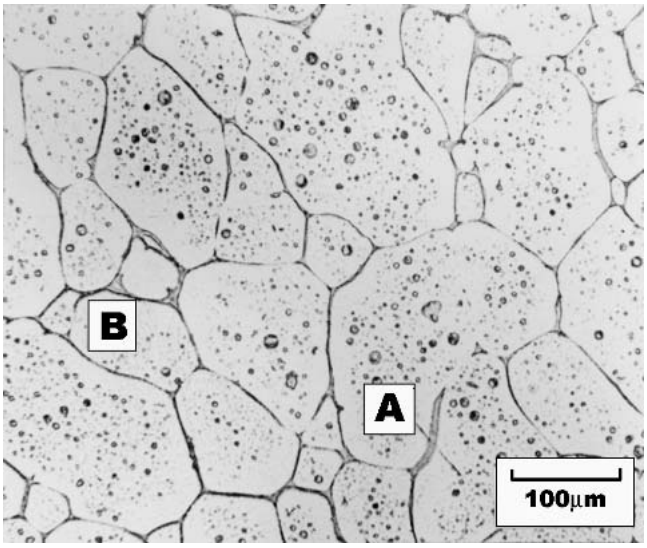

Fig. 5 Fragmentation of deformed LY11 alloy

grain boundaries rapidly to finish the fragmentation process. Grain spheroidization and coarsening started as soon as the deformed grain disintegrated into smaller grains. The volume fraction of liquid, the diffusion velocity of atoms, and interfacial surface energy play important roles in grain spheroidization and coarsening. These elements closely relate the conditions of deformation and isothermal heat treatment.

4. Conclusions

- The average size of grains increased with increasing deformation temperature, and decreased with the reducing of ram velocity.
- Elevating isothermal temperature and elongating holding time would benefit the fragmentation spheroidization and coarsening of grains.
- The processing parameters have great influences on the microstructure of semi-solid LY11 alloy in the SIMA process. To obtain the fine, uniform, and spheroidal microstructure the processing parameters must be selected properly.
- Experimental evidence is provided to support a previously proposed deformation-recrystallization mechanism as the main mechanism for microstructure evolution in the SIMA process.

Acknowledgments

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References

1. M.C. Flemings: "Behavior of Metal Alloys in the Semi-Solid State," *Metall.Trans.,* 1991, *22A,* pp. 957-81.
2. D.H. Kirkwood: "Semi-Solid Metal Processing," *Int. Mater. Rev.,* 1994, *39,* pp. 173-89.
3. S.Y. Lee, J.H. Lee, and Y.S. Lee: "Characterization of Al 7075 Alloys After Cold Working and Heating in the Semi-Solid Temperature Range," *J. Mater. Proc. Technol*., 2001, *111,* pp. 42-47.
4. E.R. Cau and M.H. Robert: "Obtention of Rheocasting Structures of M-2 and 308-L Stainless Steel by SIMA" in *Proc. 2nd Int. Conf. on Semi-solid Processing of Alloys and Composites,* MIT, Cambridge, MA, 1992, pp. 119-29.
5. S.J. Luo, W.T. Tian, and G.A. Zhang: "Structural Evolution of LC4 Alloy in Making Thixotropic Billet by SIMA Method," *Trans. Nonferrous. Met. Soc. China,* 2001, *11,* pp. 547-50.
6. T.A. Witten and L.M. Sander: "Diffusion-Limited Aggregation, a Kinetic Critical Phenomenon," *Phys. Rev. Lett.,* 1981, *47,* pp. 1400-03.
7. R.D. Doherty, H.I. Lee, and E.A. Feest: "Microstructure of Stir-Cast Metals," *Mater. Sci. Eng.,* 1984, *65,* pp. 181-89.