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Microstructure and Element Distribution during Partial Remelting of an Al-4Cu-Mg alloy

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The effects of the isothermal temperature and holding time on the microstructure and element distribution have been investigated during partial remelting of the semisolid Al-4Cu-Mg alloy. The experimental results show that the optimal process parameter should be chosen at isothermal temperature of 540-580 °C with the holding time of less than 10 min. Coalescence and coarsening of α grains occur at low liquid fraction. At high liquid fraction, coarsening of α grains and melting of small grains were promoted by an increase of the isothermal temperature and the holding time. The coalescence of grains and Ostwald ripening are two main mechanisms of the microstructural evolution during partial remelting. Meanwhile, the higher the isothermal temperature and the longer the holding time, the more segregation of Cu at the grain boundary would be, which conform to the theory of element distribution affected by heating condition.

Keywords Al-4Cu-Mg alloy, microstructure, element distribution, partial remelting

1. Introduction

SSM forming, as one of the near net shape forming processes, consists of deforming the part at a temperature between the liquidus and the solidus. SSM forming is recognized as a technology offering several potential advantages over casting and forging, such as reduction of macrosegregations, reduction of porosity, and low deformation stresses (Ref 1). The key feature that permits the shaping of alloys in the semisolid state is the non-dendritic shape of the solid phases suspended in the liquid phase. Presently, there are several methods for obtaining non-dendritic microstructure, such as mechanical stirring (MS); electromagnetic stirring (ES); strain induced melt activation (SIMA); spray-deposition (SD) and so on. Compared with other method, the SIMA process is simple, does not need complicated equipment, and is applicable to both low- and high-melting alloys (Ref 2-8).

Generally, the semisolid billets with non-dendritic microstructure are remelted in the semisolid state prior to forming to obtain optimal liquid fraction and microstructure, and to meet subsequent thixoforming requirement. Hence, the partial remelting is a very important process for SSM forming and has been paid considerable attention (Ref 9-15). Loue and Suery (Ref 10) studied the influence of the thermomechanical history on the formation of globular microstructure in Al-Si7Mg alloys during partial remelting. Kliauga and Ferrante (Ref 11) carried out a series of experiments to study the microstructural evolution during partial remelting of an extruded A356 aluminum alloy and analyzed a number of experimental phenomena such as grain growth, low angle grain boundary formation, and primary phase coarsening. Wang et al. (Ref 12) investigated the microstructural evolution of the semisolid A2017 alloy fabricated by shearing/cooling roll technology during reheating. Chen et al. (Ref 13) investigated the microstructure of ZA27 alloy and the compositions of some structures during partial remelting. The results indicate that the eutectics between primary grains diffused toward the grain center and the eutectic layers tended to disappear.

In this paper, the microstructural evolution and element distribution during partial remelting of semisolid Al-4Cu-Mg alloy fabricated through SIMA have been investigated. The aim is to optimize process parameter during remelting of Al-4Cu-Mg alloy.

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2. Experimental Procedures

The experimental material is the semisolid Al-4Cu-Mg alloy, and the chemical composition (wt.%) is Al-4.1Cu-0.64Mg-0.54Mn-0.37Fe-0.34Si-0.019Ti measured with a KYKY Finder-1000 energy spectrometer. The semisolid Al-4Cu-Mg alloy was fabricated by the SIMA (Ref 16, 17). During the SIMA process, cylindrical samples with 15 mm in diameter and 25 mm in height were compressed to a height reduction of 20% at room temperature using a WEW-600C material testing machine manufactured by Jinan Shijin Corporation of China, and then were heated in a resistance furnace and held 5 min at a temperature of 600 ± 2 °C. After the isothermal treatment, the samples were immediately immersed in water at room temperature to retain the microstructure.

The solidus and liquidus of the semisolid Al-4Cu-Mg alloy are 504.9 and 643.3 °C, respectively, measured through a STA 409 CD differential scanning calorimetry made by NETZSCH Corporation of Germany. To investigate the effects of process parameters on microstructure and element distribution during partial remelting, *the samples were heated at isothermal temperatures of 520-620* °C *and holding times of 3-10 min, respectively*, and then quenched in water at room temperature to retain the microstructure. Holding time is calculated when the sample was heated uniformly at the required temperature. Metallographic samples were sectioned from the remelted samples, polished and etched in a *mixed acid solution of HCl, HNO_3, and HF with the proportion of 20, 30, and 50% respectively*. The microstructure was examined with a Leica LABOR-LUX12MFS/ST microscope for quantitative metallography linked with a SISC IAS V8.0 analysis software. The distributions of major alloying elements were measured by a SEM-360 scanning electron microscope (made by Leica and Cambridge) and an NSS-300 X-ray energy spectrometer (made by Thermo Electron Corporation, US).

3. Experimental Results and Discussion

3.1 Microstructure

Optical photomicrographs of the semisolid Al-4Cu-Mg alloy during partial remelting are shown in Fig. 1. Figure 1(a)-(e) shows the microstructures of semisolid Al-4Cu-Mg alloy at the isothermal temperatures of 520, 540, 560, 580, and 620 °C respectively, with the holding time of 3 min. From Fig. 1(a), due to lower isothermal temperature, the liquid phase is so less that it cannot soak into the grain boundaries. So, the grain boundaries are discontinuous as shown in Fig. 1(a). When the isothermal temperature is 540 °C, α grains are separated from each other because of liquid phase soakage between the grain boundaries as shown in Fig. 1(b). From Fig. 1(c) and (d), it is noted that when the isothermal temperatures increase from 560 to 580 °C, coalescence occurs between the adjoining grains, such as grain A and grain B shown in Fig. 1(c). The average size of grains increases from 57.5 to 62.2 μm. When the isothermal temperature is 620 °C, α grains coarsen continuously and become more globular. But, the coarsening velocity of grains is less than that at lower isothermal temperature. The low melting point eutectic melts fully at the grain boundary and distributes homogeneously between the α grains as shown in Fig. 1(e).

The effects of holding time on microstructure during partial remelting are shown in Fig. 2. The α grains coarsen and become more globular with an increase of the holding time. At the isothermal temperature of 540 °C, the average size of grains is 54.9, 76, and 80 μm, respectively, at holding times of 3, 10, and 30 min. From Fig. 2(b), it is observed that coalescence and coarsening occur between the adjoining grains at the holding time of 10 min. Meanwhile, it can be seen that the grains coarsen quickly when holding time is increased from 3 to

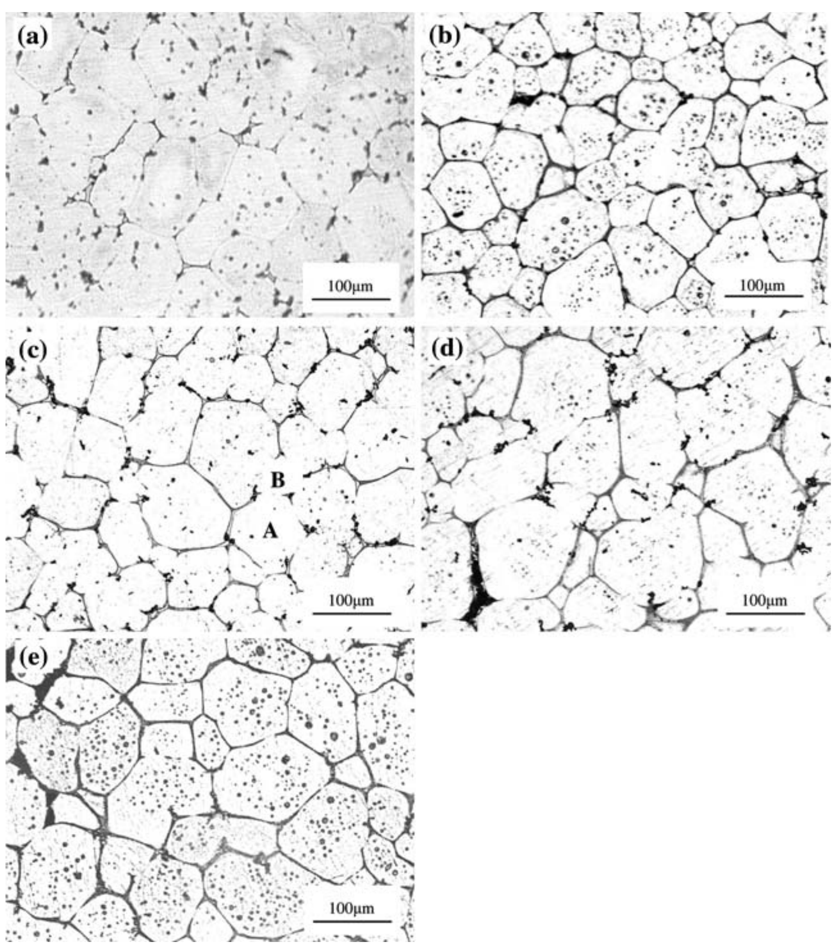

Fig. 1 Microstructure of the semisolid Al-4Cu-Mg alloy during remelting at holding time of 3 min (a) 520 °C (b) 540 °C (c) 560 °C (d) 580 °C (e) 620 °C

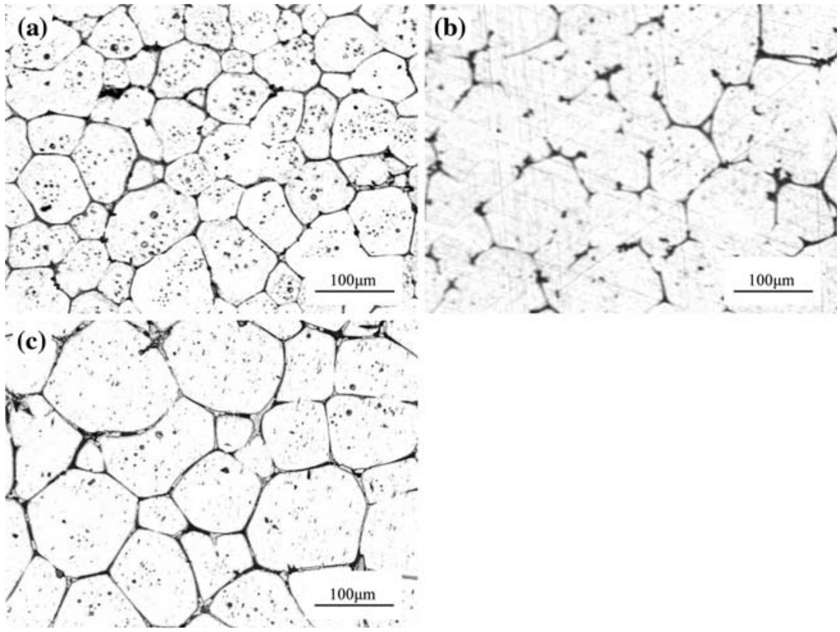

Fig. 2 Microstructure of the semisolid Al-4Cu-Mg alloy during remelting at isothermal temperature of 540 °C (a) 3 min (b) 10 min (c) 30 min

10 min. Above the holding time of 10 min, the grain size increases slowly. Compared with Fig. 2(b) and (c), the quantity of the small grains apparently decreases.

So, for the Al-4Cu-Mg alloy, the optimal process parameter during partial remelting should be chosen at isothermal temperature of 540-580 °C with the holding time of less than 10 min.

The experimental results show that the effects of process parameters, including isothermal temperature and holding time, on α grain size and morphology, are evident. The adjoining grains coalesce and coarsen quickly at the lower isothermal temperature and shorter holding time. In other words, coalescence and coarsening occur in the stage of low liquid fraction. With an increase of isothermal temperature and holding time, the large α grains coarsen continuously and the small grains melt gradually. The coarsening of grains in the stage of higher liquid fraction is slower than that at lower liquid fraction. The two main mechanisms of grain coarsening play an important role during partial remelting (Ref 11, 12). One of the coarsening mechanisms is the coalescence of grains, which occurs between adjoining grains at low liquid fraction. Liquid fraction increases with an increase of the isothermal temperature and holding time. Because of the liquid phase soakage, it is difficult for the adjoining grains to coalesce continuously. Under these conditions, Ostwald ripening is the dominating mechanism of grain coarsening in the stage of high liquid fraction, in which α grains continuously coarsen and the small grains gradually melt. According to the LSW theory (Ref 18), the third power of diameter of α grains is proportional to holding time.

$$d^3 = d_0^3 + kt$$

where d and d_0 are the diameters of α grains at the holding time of t and 0, respectively.

Figure 3 shows the experimental points and plot for the third power of diameter of α grains as a function of holding time at isothermal temperature of 540 °C during partial remelting of Al-4Cu-Mg alloy. It can be found that both experimental points and regression lines show good match.

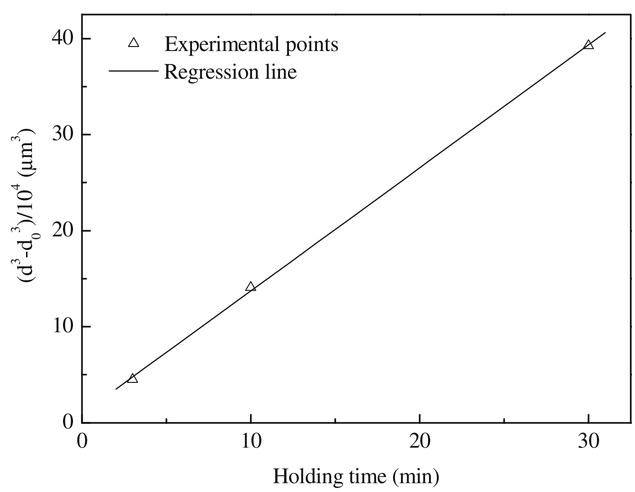

Fig. 3 Curves of $(d^3 - d_0^3)$ vs. holding time t at the isothermal temperature of 540 °C

According to the experimental data from the partial remelting of Al-4Cu-Mg alloy shown in Fig. 3, the LSW equation is as follows:

$$d^3 = 9257.9 + 213.4t$$

As a consequence, coalescence of grains and the Ostwald ripening mechanisms play an important role in the microstructural evolution during partial remelting.

3.2 Element Distributions

The elements Cu and Mg are major alloying elements in the Al-4Cu-Mg alloy, and the phases include mainly α-Al and θ

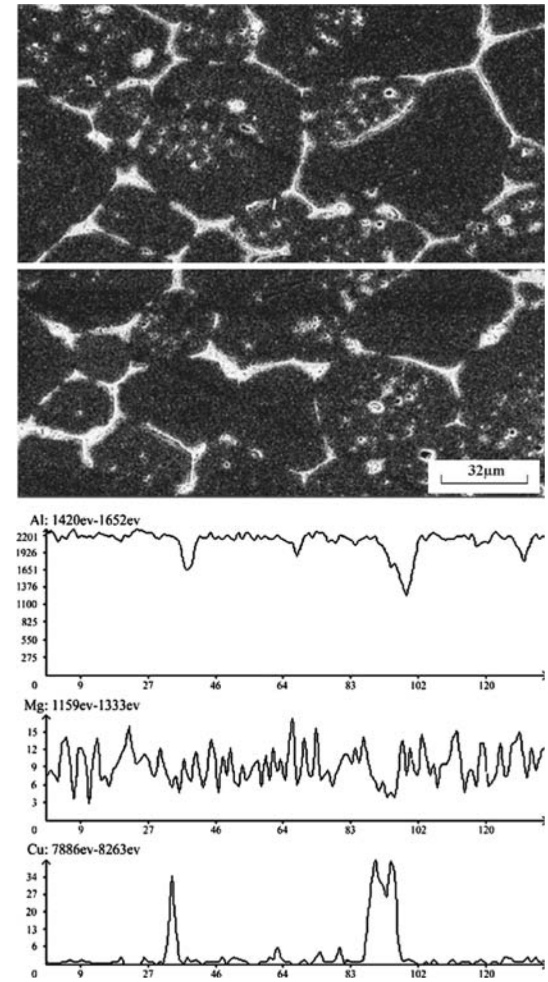

Fig. 4 SEM micrograph and line scan for the semisolid Al-4Cu-Mg alloy before partial remelting

($CuAl_2$). Figure 4 shows SEM micrograph and line scan for the semisolid Al-4Cu-Mg alloy before partial remelting. It can be seen that the white Cu-rich particles are dispersed homogeneously in the matrix.

During partial remelting, the distribution of elements Al, Cu, and Mg in the matrix and grain boundary is shown in Table 1. It can be found that distribution of elements Al, Cu, and Mg is uniform in the matrix. However, contents of the Cu and Mg at the grain boundary are much higher than those in the matrix. The diffusion of atoms is closely associated with the isothermal temperature and the holding time. The contents of Cu and Mg

Table 1 Element distributions of Al-4Cu-Mg alloy during partial remelting

Isothermal temperature, °C	Holding time	Location	Al, wt.%	Cu, wt.%	Mg, wt.%
560	3 min	Grain interior	95.6	3.94	0.2
		Grain boundary	54.5	37.72	2.04
560	10 min	Grain interior	95.5	4.19	0.08
		Grain boundary	58.01	39.2	2.05
600	3 min	Grain interior	96.76	3.92	0.09
		Grain boundary	57.04	42.69	1.29

decrease in the matrix and these elements segregate to the grain boundaries with an increase of the isothermal temperature and the holding time. The longer the holding time and the higher the isothermal temperature, the more segregation of Cu at the grain boundary would be, which results in a decreasing amount of Cu-rich phase (θ) in the intragranular regions. The reason is that the different diffusion velocities for Cu, Mg, and Al atoms in the intragranular and intergranular regions of grains are enhanced by an increase of the isothermal temperature and the holding time. Compared with the segregation of Cu, the effect of the isothermal temperature and holding time on distribution of Mg is very slight.

4. Conclusion

During partial remelting, the grains size and morphology are influenced by the isothermal temperature and holding time. For the Al-4Cu-Mg alloy, the optimal process parameter during partial remelting should be chosen at isothermal temperature of 540-580 °C with the holding time of less than 10 min. Coalescence and coarsening of grains at low liquid phase fraction occur between the adjoining grains. Because of the liquid phase soakage, the Ostwald ripening appears to be the main mechanism of grain coarsening during partial remelting of Al-4Cu-Mg alloy at high liquid phase fraction.

During partial remelting, the diffusion velocities of Al, Cu, and Mg in the intragranular regions and grains boundary are expected to increase with an increase of the isothermal temperature because of the heating condition. The higher the isothermal temperature and the longer the holding time, the more segregation of Cu at the grain boundary.

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References

1. M.C. Flemings, Behavior of Metal in the Semi-Solid State, *Metall. Trans.*, 1991, **22A**, p 957–981
2. V. Laxmanan and M.C. Flemings, Deformation of Semi-Solid Sn-15PctPb Alloy, *Metall. Trans.*, 1980, **11A**, p 1927–1937
3. W. Lapkowski, Some Studies Regarding Thixoforming of Metal Alloys, *J. Mater. Process. Technol.*, 1998, **80-81**, p 463–468
4. E.R. Cau and M.H. Robert, Obtention of Rheocasting Structures of M-2 and 308-L Stainless Steel by SIMA, *Proceeding of the 2nd International Conference on the Semi-Solid Processing of Alloys and Composites* (Cambridge, USA), 1992, p 119–129
5. J.C. Choi and H.J. Park, Microstructural Characteristics of Aluminum 2024 by Cold Working in the SIMA Process, *J. Mater. Process. Technol.*, 1998, **82**, p 107–116
6. D.H. Kirkwood, Semi-Solid Metal Processing, *Int. Mater. Rev.*, 1994, **39**, p 173–189
7. A. Turkeli and N. Akbas, Formation of Nondendritic Structure in 7075 Wrought Aluminum Alloy by SIMA Process and Effect of Heat Treatment, *Proceedings of the 4th International Conference on Semi-Solid Processing of Alloys and Composites*, D.H. Kirkwood and P. Kapranos, Eds., (Sheffield, UK), 1996, p 71–74
8. S. Lee, J. Lee, and Y. Lee, Characterization of Al 7075 Alloys after Cold Working and Heating in the Semi-Solid Temperature Range, *J. Mater. Process. Technol.*, 2001, **111**, p 42–47

9. P. Kapranos, R.C. Gibson, and D.H. Kirkwood, Induction Heating and Partial Melting of High Melting Point Thixoformable Alloys, *Proceedings of the 4th International Conference on Semi-Solid Processing of Alloys and Composites* (Sheffield, UK), 1996, p 29–35
10. W.R. Loue and M. Suery, Microstructural Evolution during Partial Melting of Al-Si7Mg Alloys, *Mater. Sci. Eng.*, 1995, **A203**, p 1–13
11. A.M. Kliauga and M. Ferrante, Liquid Formation and Microstructural Evolution during Re-Heating and Partial Melting of an Extruded A356 Aluminium Alloy, *Acta Mater.*, 2005, **53**, p 345–356
12. S.C. Wang, J.L. Wen, Y.B. Yan, F.R. Cao, and Y.L. Li, Reheating Process and Microstructure Evolution Mechanical of the Semi-Solid A2017 Alloy during Reheating in Semi-Solid State, *Foundry*, 2004, **53**, p 590–594
13. T.J. Chen, Y. Hao, J. Sun, and J.J. Di, Scanning Electron Metallographic Investigation on ZA27 Alloy during Partial Remelting, *Mater. Sci. Eng.*, 2002, **77**, p 47–50
14. M. Margarido and M.H. Robert, Influence of Thermamechanical Treatments on the Production of Rheocast Slurries by Partial Melting, *J. Mater. Process. Technol.*, 2002, **5814**, p 1–9
15. M. Ferrante and E. de Freits, Rheology and Microstructural Development of a Al-4wt%Cu Alloy in the Semi-Solid State, *Mater. Sci. Eng.*, 1999, **A271**, p 172–180
16. H.T. Jiang, Y.L. Lu, W.C. Huang, and M.Q. Li, Microstructural Evolution and Mechanical Properties of the Semisolid Al-4Cu-Mg alloy, *Mater. Character.*, 2003, **51**, p 1–10
17. H.T. Jiang, X.L. Li, A.M. Xiong, and M.Q. Li, Fabrication and Microstructure Evolution and of Semi-solid LY11 Alloy by SIMA, *J. Mater. Eng. Perform.*, 2003, **12**(3), p 249–253
18. W.M. Mao, C.L. Cui, and A.M. Zhao, Dynamical Coarsening Processes of Microstructures in Non-Dendritic AiSi7Mg Alloy Remelted in Semi-Solid State, *Trans. Nonferrous Met. Soc. China*, 2000, **10**(1), p 25–28