SOLIDIFICATION MICROSTRUCTURES OBTAINED BY A NOVEL TWIN-SCREW LIQUIDUS CASTING METHOD

A. Das, S. Ji and **Z. Fan**
Department of Mechanical Engineering, Brunel University, Uxbridge, UB8 3PH, U.K.

Summary

Thixo processing, where an alloy billet is reheated to the semisolid state and shaped into a component, has so far been the most common semisolid processing route. Feedstock preparation is important for thixo processing, as the billet should exhibit thixotropic behavior when reheated to the processing temperature. In the present investigation it has been shown that casting near the liquidus temperature has tremendous potential for such feedstock production. A modification of the normal liquidus casting involving shearing the melt in a twin-screw machine prior to casting at the liquidus temperature is employed. Using both a model Sn-15 wt.% Pb alloy as well as an industrially important AZ91D alloy it has been shown that the resulting liquidus cast structure is refined, uniform and globular throughout the billet. The twin-screw liquidus casting addresses the shortcomings of normal liquidus casting and, therefore, is promising as an independent processing technique or for preparing thixotropic feedstock that requires minimal or no holding at the processing temperature.

Keywords: thixo processing, liquidus casting, solidification, microstructure

1 Introduction

Semi-solid metal (SSM) processing within the freezing range of an alloy has been one of the most important technological innovations in the recent years and offers several potential advantages over conventional processing techniques [1-3]. Thixo-processing, the most investigated SSM processing technique, employs heating an alloy billet from the fully solid state to the semisolid temperature to obtain a slurry containing uniform fine non-dendritic solid dispersed in a low melting eutectic matrix prior to processing. Feedstock preparation is important for thixo processing in order to ensure a non-dendritic slurry structure when reheated, and melt stirring by mechanical means or by electromagnetic means as in magnetohydrodynamic (MHD) casting [4] is the most common technique employed. Non-agitating methods such as reheating plastically deformed dendritic casting to the semisolid temperature, popularly known as the stress induced melt activated (SIMA) process [5], spray casting [6], chemical grain refining [7] and partial remelting of castings [8] have also been explored.

A comparatively unexplored but promising route is casting the feedstock alloy at or near the liquidus temperature to produce fine equiaxed grain structure in the casting free of columnar zone [9]. However, the method received minimal attention so far perhaps due to the practical difficulties experienced in producing uniform microstructure in the casting and due to the problems of mould filling under low superheat. To address the inherent limitations of normal liquidus casting and design a practical alternative, a twin-screw liquidus casting method is developed in the present work that can be used as an independent manufacturing method or to produce thixotropic feedstock. Both a model Sn-15 wt.% Pb alloy and an industrially important AZ91D alloy are used to demonstrate the potential of twin-screw liquidus casting.

2 Experimental

A Sn-15 wt.% Pb alloy of nominal composition was produced by melting appropriate amounts of commercial purity (>99.8%) elemental metals and casting the alloy into billets. The Mg-base AZ91D alloy ingots were procured from the industry. Predetermined amounts of the alloys were then melted and homogenized under protective atmosphere and sheared in the twin-screw machine consisting of two intermeshing, self-wiping and co-rotating screws capable of producing high intensity turbulence in the melt [10]. Temperature in the melt was maintained near its liquidus by using alternating heating and cooling arrangements evenly dispersed along the barrel of the machine. Following shearing for predetermined intervals of time the molten alloy was cast in a preheated metallic mould. Representative sections were cut from the cast billet, polished using standard metallographic techniques, and observed under a LEICA optical microscope. The Sn-15 wt.% Pb specimen were reheated to 190 ^{o}C in an oil bath with an accurate temperature control (± 1 ^{o}C) and isothermally held for various lengths of time ranging from 5 to 60 minutes. Following the partial remelting the samples were quenched in water, metallographically polished and etched, and examined under the optical microscope to investigate the coarsening behavior of the liquidus cast samples. Each of the experiment was repeated to ensure the validity of the observation.

3 Results

3.1 Microstructures of liquidus cast Sn-15 wt.% Pb billets

In a Sn-15 wt.% Pb sample cast from 50 ^{o}C above the liquidus temperature (210 ^{o}C) of the alloy in the same experimental setup as in the liquidus casting investigations, the formation of chill zone and large columnar dendritic regions were obvious in the microstructure. The samples cast near the liquidus temperature of the alloy show a noticeable difference in the microstructure. **Figure 1** presents microstructures from the edge and the center of the Sn-15 wt.% Pb alloy cast at 215 ^{o}C (near the liquidus temperature of the alloy) in a metallic mould preheated to 100 ^{o}C. Liquidus cast microstructure without the application of shear shows extremely fine equiaxed dendrites at the edge of the billet in contact with the mould wall (**Figure 1a**) and equiaxed apparently globular particle morphology at the center of the billet (**Figure 1b**). Although this shows a significant refinement and improvement over normal cast structure (no columnar zone), there is a progressive increase in the particle size as one compares between the edge and the center of the billet. When the melt it sheared in the twin-screw machine (operating at 100 rpm) for 60 sec prior to liquidus casting in the preheated mould, there is perceptible change in the microstructure especially at the edge of the billet (**Figure 1c**), which is less dendritic and relatively uniform as compared to the corresponding microstructure from the unsheared sample (**Figure 1a**). The morphology of the particles at the center of the billet (**Figure 1d**) appears almost the same as observed in the unsheared specimen (**Figure 1b**). The twin-screw liquidus casting shows a noticeable improvement over normal liquidus cast microstructure, which is relatively globular and vastly uniform throughout the specimen, and provides an ideal microstructure for any subsequent thixo-processing.

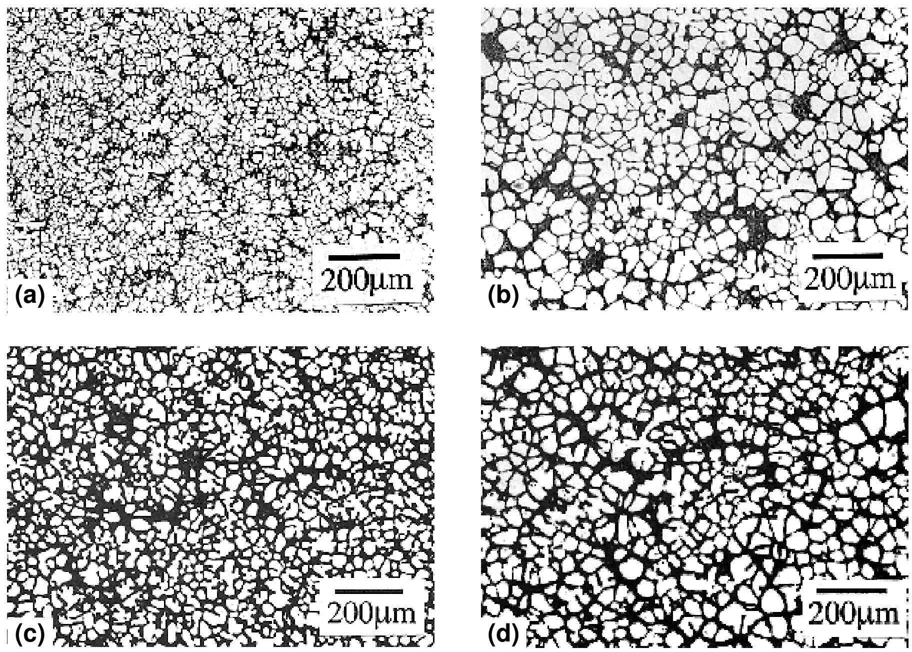

***Figure 1**: Quenched microstructure from the (a) edge and (b) centre of Sn-15 wt.% Pb alloy cast at the liquidus temperature without shearing. Also shown are corresponding microstructures from the (c) edge and (d) centre of the twin-screw liquidus cast billet.*

The difference in the microstructure between the sheared and unsheared liquidus cast samples is more obvious when the samples are reheated to 190 ^{o}C (volume fraction of solid around 0.6) to develop a slurry structure suitable for thixo-processing. **Figure 2** presents the remelted structures from the edge (**a**) and the center (**b**) of the unsheared liquidus cast specimen after 10 min holding. Corresponding microstructures from the sheared liquidus cast sample are shown in **Figures 2c** and **2d**, respectively. **Figures 2a, b** clearly indicate the presence of dendritic structure in the original liquidus cast sample as evidenced from the irregular shaped particles in the reheated sample and the liquid entrapment inside the particles resulting from the collapsing of the dendrite arms. However, the structure is not as irregular and shows significant improvement over coarse remelted structures obtained from the high superheat castings. Further holding promotes spherodization and coarsening of the structure, and extremely regular spherodized particles evenly distributed throughout the sample are obtained after 60 min holding. In contrast, the microstructures from the edge (**Figure 2c**) and the center (**Figure 2d**) of the sheared and liquidus cast sample shows extremely globular and evenly distributed particle morphology after only 10 min holding at 190 ^{o}C. This confirms that shearing indeed produces significant improvement over normal liquidus cast structure and the ensuing non-dendritic and uniform microstructure necessitates minimal remelting to produce ideal thixotropic slurry structure for further processing.

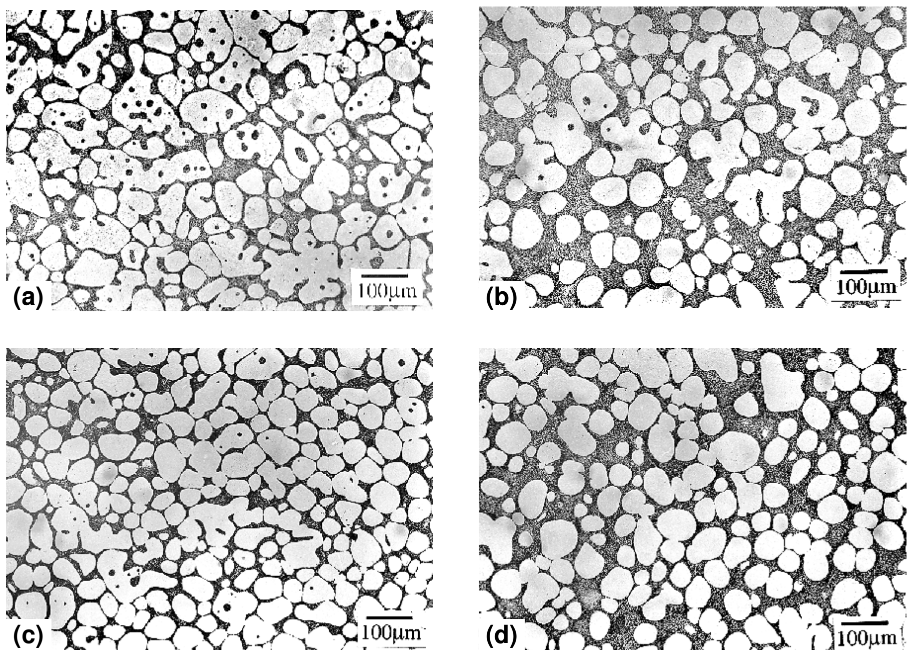

***Figure 2**: Quenched microstructure following reheating of the liquidus cast samples for 10 min at 190 ^{o}C from the (a) edge and (b) centre of unsheared specimen and from the (c) edge and (d) centre of the sheared specimen.*

3.2 Microstructures of liquidus cast AZ91D billets

The encouraging results obtained from the model Sn-15 wt.% Pb alloy prompted similar investigation using industrially important AZ91D alloy. **Figures 3a, b, c** show quenched microstructures from the as-cast, liquidus-cast and twin-screw liquidus-cast specimen, respectively. The microstructure of the specimen cast from 650 ^{o}C (liquidus temperature 600 ^{o}C) in a metallic mould shows large equiaxed dendrites throughout the entire cross section as shown in **Figure 3a**. By casting the alloy at 605 ^{o}C, near the liquidus temperature, refinement in the microstructure has been observed as shown in **Figure 3b**. The solid particles are relatively finer but still equiaxed dendritic in nature. Shearing the alloy in the twin-screw machine for 30 sec prior to casting at the liquidus temperature produced significant improvement in the resulting microstructure as observed in **Figure 3c**. Uniform nondendritic particle morphology has been observed throughout the specimen cross section and considerable amount of refinement of the particles size over the liquidus cast structure is evident from **Figure 3c**.

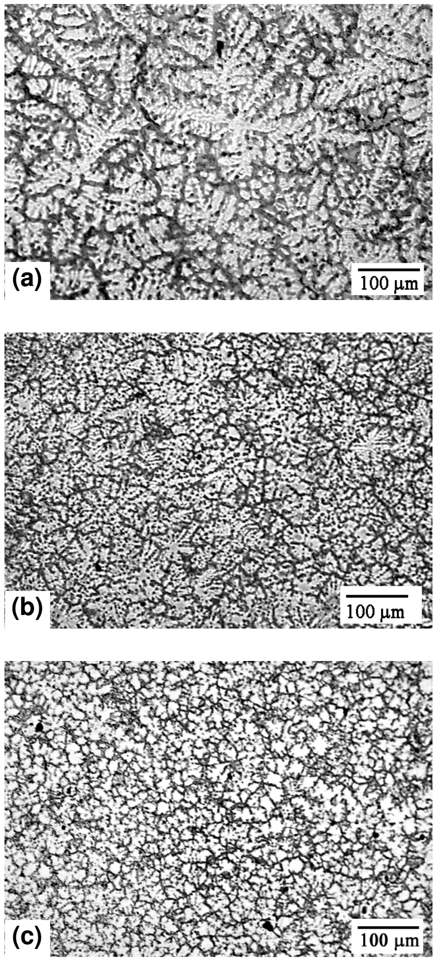

Figure 3: *Quenched microstructures from (a) normal cast, (b) liquidus cast and (c) twin-screw liquidus cast AZ91D alloy.*

4 Discussion

Feedstock preparation for thixo processing is an important consideration, as the billet should possess uniform and globular slurry structure at the processing temperature to ensure requisite thixotropic behavior. Elaborate processing such as stirring in the semisolid state, grain refining, and cold working all involve extra efforts and additional cost in the feedstock preparation while, partial remelting of normally cast structure involves prolonged holding time to produce useful structure apart from the likelihood of grossly ill-defined morphology of solid particles. The advantage of liquidus casting appears obvious considering the large refinement in the cast structure and the absence of columnar dendritic grain structure. However, the microstructure still suffers from somewhat non-uniform particle size and the presence of fine dendrites necessitating moderate holding at the remelting temperature. The present investigation clearly demonstrates that shearing in a twin-screw machine in conjunction with liquidus casting can be successfully employed to produce extremely uniform non-dendritic microstructure that requires minimal or no holding at the remelting temperature to produce an ideal thixotropic slurry structure. Apart from the microstructural advantage offered by a twin-screw liquidus casting, the positive pressure in the machine can assist mould filling at the liquidus temperature, which, otherwise, is a major limitation of normal liquidus casting methods. Furthermore, the extremely uniform, fine and non-dendritic microstructure of the twin-screw liquidus cast AZ91D alloy suggests that this process can also be employed as an independent fabrication method parallel to thixo-processing.

The origin of the unique microstructure in liquidus casting is still not clear. Crystal multiplication due to deformation or melting of the dendrite arms induced by the fluid flow has been suggested. It has also been argued that the non-dendritic structure in liquidus casting may originate from the critical particle size not being reached the limit of Mullins-Sekerka instability. However, it seems most likely that at low superheat the whole melt is undercooled to promote nucleation throughout the entire volume of the liquid. At this point it is difficult to apprehend why shearing the liquid produces such uniform and globular solidification morphology. It appears that shearing enhances the homogeneity in the alloy melt with respect to temperature and composition and uniformly distributes the nucleating agents throughout the melt. This, in effect, perhaps produces uniform nucleation throughout the melt and higher survival rate of the nuclei (increased effective nucleation rate) compared to normal liquidus casting.

5 Conclusions

A novel twin-screw liquidus casting method is demonstrated where the alloy is sheared and cast at the liquidus temperature using a twin-screw device. A model Sn-15 wt.% Pb alloy and an industrially important AZ91D Mg-base alloy were used to illustrate the improvement of microstructural aspects of the cast billet using the method.

Liquidus casting (without shearing) produces a microstructural refinement over normal cast structure but still contains non-uniform fine dendrites that coarsen to globular morphology with moderate holding at the remelting temperature.

Shearing the alloys in the twin-screw machine prior to liquidus casting shows significant improvement over liquidus cast microstructure producing uniform and globular particle morphology throughtout the casting. The method can be used independently or to produce thixotropic feedstock requiring no or minimal remelting.

5 References

[1] Flemings, M.C.: Behavior of Metal Alloys in the Semisolid State, Metall. Trans. A, Vol. 22A, (1991), 957-981.

[2] Kirkwood, D.H.: Semisolid Metal Processing, Inter. Mater. Rev., Vol. 39, (1994), 173-189.

[3] Fan, Z.: Semisolid Metal Processing, Inter. Mater. Rev., Vol. 47, (2002), 49-85.

[4] Vives, C: Elaboration of Metal-Matrix Composites From Thixotropic Alloy Slurries Using a New Magnetohydrodynamic Caster, Metall Trans., Vol. B24, (1993), 493-510.

[5] Young, K.P., Kyonka, C.P. and Courtois, J.A.: Fine Grained Metal Compositions, US Patent, US 4, 415, 374, 1983.

[6] Annavarapu, S. and Doherty, R.D.: Inhibited Coarsening of Solid-Liquid Microstructures in Spray Casting at High Volume Fractions of Solid, Acta Metall. Mater., Vol. 43, (1995), 3207-3230.

[7] Easton, M. and StJohn, D.: Grain Refinement of Aluminum Alloys: Part I. The Nucleant and Solute Paradigms - A Review of the Literature, Metall. Mater. Trans., Vol. A30, (1999), 1613-1623.

[8] Loué, W.R. and Suéry, M.: Microstructural Evolution During Partial Remelting of Al-Si7Mg Alloys, Mater. Sci. Engng., Vol. A203, (1995), 1-13.

[9] Xia, K., and Tausig, G.: Liquidus Casting of a Wrought Aluminum Alloy 2618 for Thixoforming, Mater. Sci. Engng., Vol. A246, (1998), 1-10.

[10] Ji, S., Fan, Z. and Bevis, M.J.: Semi-Solid Processing of Engineering Alloys by a Twin-Screw Rheomoulding Process, Mater. Sci. Engng., Vol. A299, (2001), 210-217.