Journal of Alloys and Compounds 504 (2010) L42–L45

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Letter

Effects of the casting temperature on microstructure and mechanical properties of the squeeze-cast Al–Zn–Mg–Cu alloy

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A R T I C L E I N F O

Article history:
Received 29 March 2010
Received in revised form 20 May 2010
Accepted 1 June 2010
Available online 11 June 2010

Keywords:
Squeeze casting
Microstructure
Mechanical properties
Aluminum alloy

A B S T R A C T

The effects of the casting temperatures on microstructure and mechanical properties of the squeeze-cast Al–Zn–Mg–Cu alloy have been investigated in this paper. The casting temperature is selected as 660, 680, 700 and 720 °C, respectively. The gravity castings of the same alloy are also prepared at the above casting temperatures for comparison. Both the grain size and the dendrite arm spacing (DAS) of the squeezing casting increase with the increase of the casting temperature, as like the gravity casting. However, the casting temperature has a more obvious effect on the DAS of the gravity casting than that of the squeeze casting. The optimum casting temperatures for gravity casting and squeeze casting are 720 and 680 °C, respectively. However, both the gravity castings and the squeeze castings show the highest tensile elongation at the casting temperature of 660 °C.

1. Introduction

With the increasing locomotive speed, the reduction of the unstrung weight is important to improve the safety and the flexibility of the high-speed locomotives. The Al–Zn–Mg–Cu alloy is one kind of the high-strength and light-weight structural materials, which is used to fabricate the hollow drive shafts of the high-speed locomotives [1–3]. However, some casting defects such as gas porosity and shrinkage are formed during solidification because of the wide mushy zone [4]. Squeeze casting is a commercial manufacturing process, in which metal is solidified under the pressure sufficient to avoid the casting defects [5]. Squeeze casting has many major advantages: (1) free of gas porosity or shrinkage porosity; (2) feeders or risers are not required and therefore no metal wastage is generated [6,7].

A great deal of studies on the preparation process of the squeeze-cast Al–Zn–Mg–Cu alloy have been conducted by many researchers in the recent years [8–13]. Among all the parameters, the effects of the applied pressure on the microstructure and mechanical properties of the squeeze castings have been extensively studied. However, very few studies have been conducted on the effects of the casting temperature on the microstructure and mechanical properties of castings up to now. Therefore, the effects of the casting temperature on the microstructures and mechanical properties of the squeeze-cast Al–Zn–Mg–Cu alloy have been investigated in the paper to offer some practical values for the practitioner engaged in the squeeze castings of the hollow drive shaft. Its effects on the microstructures and mechanical properties of the gravity casting of the same alloy have also been studied with an open steel mould for comparison.

2. Experimental procedures

The commercial Al–Zn–Mg–Cu alloy with the chemical compositions (wt.%) of Al–5.8Zn–2.4Mg–1.7Cu–0.3Mn–0.2Cr was selected for the present study. The alloy was melted in an electrical furnace. The crucible was then removed from the furnace and the melt was poured into the die made of the H13 steel at the preassigned melting temperature, which was controlled by a thermocouple. The schematic illustration of the die is shown in Fig. 1. It was preheated by some electrical bars, which make the uniform heating and the precise control of the die temperature available. Pressure was loaded by a hydraulic press with a capacity of 3200 kN.

The applied pressure and the die temperature were 160 MPa and 250 °C, respectively. The pouring temperature varied from 660, 680, 700 to 720 °C. In squeeze casting, the hydraulic pressure was applied to the casting for 2 min immediately after pouring. The as-solidified metal was then left in the mould to cool down further before the casting was removed. Gravity castings of the same alloy were also prepared for comparison. In gravity casting, molten metal was poured directly into the open steel mould and then cooled down to the ambient temperature. Some of the gravity-cast and squeeze-cast alloy samples were solutionized at 480 °C for 12 h prior to water quenching and then aged at 120 °C for 20 h before air cooling. Tensile testing was conducted on the alloys in both states.

As shown in Fig. 2, the block was sectioned from the same position of the ingot for microstructure characterization, DAS, density measurement and tensile testing. Samples for metallographic examination were prepared by the standard procedures and etched in a solution of 2 ml HF + 3 ml HCl + 5 ml HNO_3 + 250 ml H_2O. The microstructures and fracture of the gravity-cast and squeeze-cast Al–Zn–Mg–Cu alloys were characterized by optical microscopy (OM) and scanning electron microscopy (SEM). The average dendrite arm spacing (DAS) and the average grain size were measured according to the ASTM Standard E112. Tensile testing was conducted at ambient temperature on an Instron machine with the initial strain rate of

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doi:10.1016/j.jallcom.2010.06.012

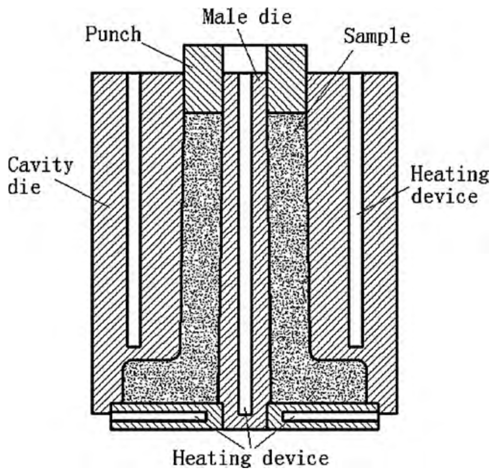

Fig. 1. The schematic illustration of the squeeze casting die.

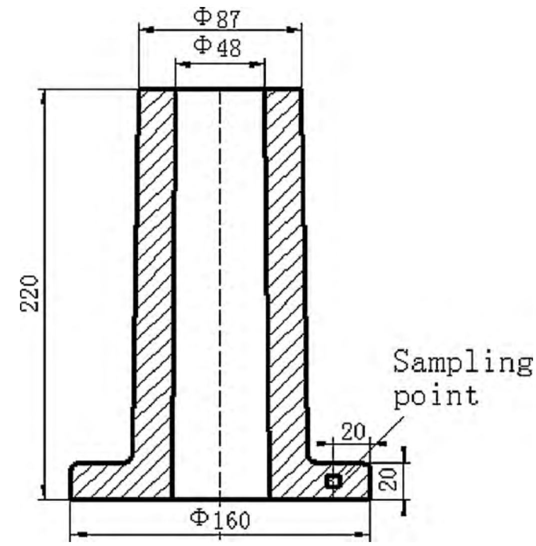

Fig. 2. The geometry and the sectioned position of the ingot.

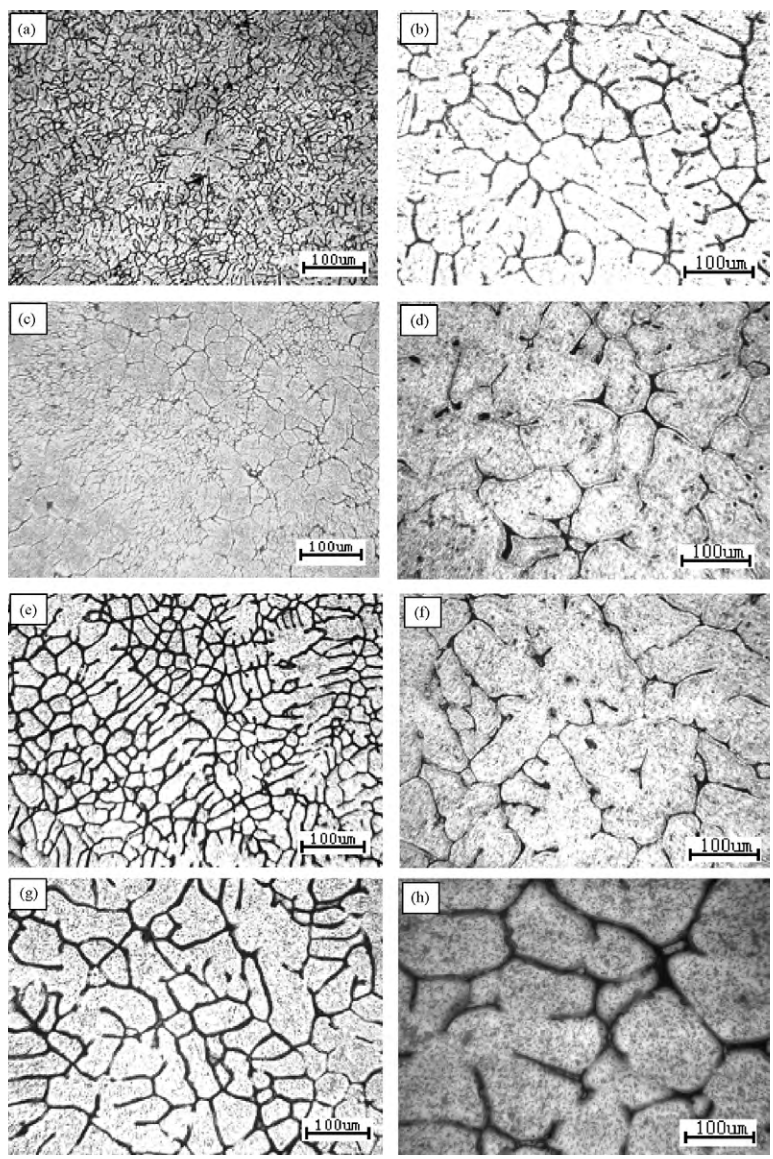

Fig. 3. Effects of the casting temperature on the microstructures of the squeeze-cast (SC) and gravity-cast (GC) Al–Zn–Mg–Cu alloys in the as-aged state (a) SC, 660 °C; (b) SC, 680 °C; (c) SC, 700 °C; (d) SC, 720 °C; (e) GC, 660 °C; (f) GC, 680 °C; (g) GC, 700 °C; (h) GC, 720 °C.

$2.7 \times 10^{-4}\,s^{-1}$ according to the ASTM E8M-04. The density was measured according to the Archimedes' principle.

3. Results and discussion

3.1. Microstructure

Increasing the pouring temperature has a dual role in the casting process. On one hand, it is beneficial to improve the fluidity of the melt and thus avoid the misrunning. On the other hand, the pouring temperature has a significant influence on the as-cast microstructure. The microstructures of the alloys prepared by squeezing casting and gravity casting at the different pouring temperatures ranging from 660 to 720 °C are shown in Fig. 3. It is evident that the grain size increases with the increasing pouring temperature in the squeezing casting and the gravity casting. However, the grain size and the DAS of the gravity casting are bigger than those of the squeeze casting at the same pouring temperature. As shown in Fig. 3(a) and (b), the microstructure of the alloy solidified under the lower melting temperature is characteristic of high porosity and inhomogeneity. It can be ascribe to the lower pouring temperature and the relatively high cooling velocity. The existent crystals are broken up by the turbulent flow during the pouring process and thus local nucleation and higher porosity occur. Therefore, it is a more important problem for squeeze casting to choose a suitable casting temperature in comparison with gravity casting [6,7]. It is suggested that the temperature of the molten metal inside the die is possibly away from the appropriate temperature range before the pressure is applied to the melt when poured at the temperature of 700 °C.

The effect of the casting temperature on the DAS of the primary α phase is shown in Fig. 4. The DAS is reduced with the decrease of the casting temperature due to the resultant larger cooling rate and thus the more desirable microstructure is obtained. At the same time, it should be noted that both the DAS and the curve slope of gravity casting are bigger than those of squeeze casting. It is related to the applied pressure. As shown in Fig. 3(a)–(d), the applied pressure leads to the decrease in the grain size and the DAS of the primary α phase. The applied pressure influences the as-cast microstructure in two different ways. This effect can be justified by the equation suggested by Ghomashchi and Vikhrov [6]:

$$P = P_0 \exp\left(\frac{-\Delta H_f}{RT_f}\right)$$

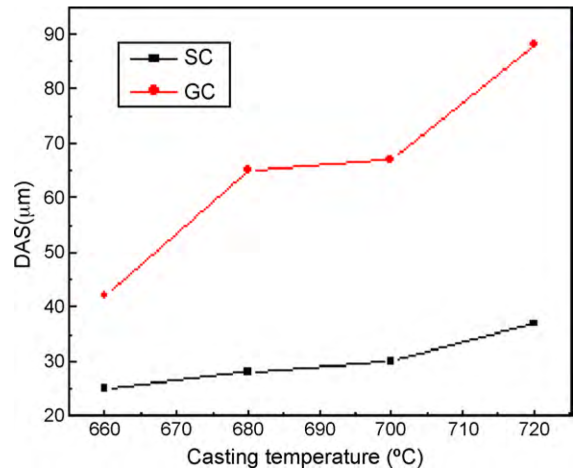

Fig. 4. Effects of the casting temperature on the DAS of the primary α phase of the squeeze-cast and gravity-cast Al–Zn–Mg–Cu alloys in the as-aged state.

where ΔH_f is the latent heat of fusion, and P_0 and R are constants. Increasing the pressure (P) causes an increase in the freezing point (T_f) of the alloy. The higher freezing point brings about the larger undercooling in the initially superheated alloy and thus elevates the nucleation frequency, resulting in a more fine-grained structure. Furthermore, the fine-grained structure is possibly due to the elevated cooling rate, which is related to the higher heat transfer coefficient when the melt and the die wall are intimately contacted [6,14].

3.2. Mechanical properties

The mechanical property data of the squeeze castings prepared with the same die temperature and at the different casting temperatures are shown in Fig. 5, with the corresponding gravity castings as the control.

Obviously, the squeeze-cast alloys exhibit higher ultimate tensile strength and larger elongation values than the gravity castings at all the casting temperatures. The squeeze-cast alloy prepared at the casting temperature of 680 °C has the highest ultimate tensile strength, while the ultimate tensile strength of the gravity-cast alloy decreases with the increase of the casting temperature. However, the elongations of both alloys decrease with the increase of the casting temperature and they show the highest tensile elonga-

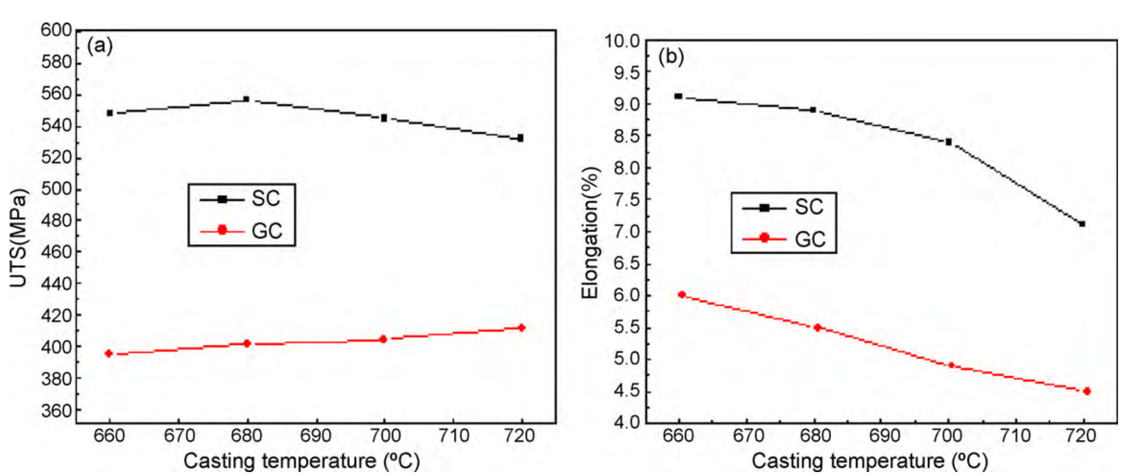

Fig. 5. Effects of the casting temperature on the ultimate tensile strength (a) and elongation (b) of the squeeze-cast and gravity-cast Al–Zn–Mg–Cu alloys in the as-aged state.

tions at the casting temperature of 660 °C. Therefore, the optimum casting temperatures for gravity casting and squeeze casting are 720 and 680 °C, respectively.

4. Conclusions

The effects of the casting temperatures on the microstructure and mechanical properties of the squeeze-cast Al–Zn–Mg–Cu alloy are investigated in this paper. The main conclusions are listed as follows:

1. The casting temperature has an obvious effect on the microstructure and mechanical properties of the gravity-cast and squeeze-cast Al–Zn–Mg–Cu alloys.
2. The grain size and the DAS of the primary α phase increase with the increasing casting temperature for the squeeze casting and gravity casting. However, the squeeze casting has the smaller DAS and the lower curve slope than the gravity casting.
3. The optimum casting temperatures for gravity casting and squeeze casting are 720 and 680 °C, respectively. Both the gravity casting and the squeeze casting prepared at the casting temperature of 660 °C exhibit the highest tensile elongation.

Acknowledgments

The present research was supported by the Natural Science Foundation of China (No.: 50974058). The authors would like to thank G. Chen, J.J. Li and Z.G. Chen for their helps in the preparation of the samples.

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