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

Effect of cooling rate on solidified microstructure and mechanical properties of aluminium-A356 alloy

L.Y. Zhang[a,b,c,*], Y.H. Jiang[a], Z. Ma[a], S.F. Shan[c], Y.Z. Jia[b], C.Z. Fan[c], W.K. Wang[c]

[a] School of Mechanical Engineering, Liaoning Technical University, Fuxin 123000, PR China
[b] School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China
[c] State key laboratory of Metastable Materials Science and Technology, Yanshan University, Qinhuangdao 066004, PR China

ARTICLE INFO

Article history:
Received 17 February 2006
Received in revised form
12 October 2007
Accepted 16 December 2007

Keywords:
Fast cooling
Aluminium alloys
Dendrite arm spacing
Strength
Microhardness

ABSTRACT

A fast-cooling technology using a copper mould cooled by a phase-transition medium was used to prepare cast aluminium-A356 alloy by solidification of the melt. The cooling rate achieved with this technique is in the order of 10^2 K/s. As-cast samples with a diameter of 10 mm were produced. The microstructure and mechanical properties of this alloy have been investigated. The results show that both the primary and secondary dendrite arm spacing (DAS) are better refined by using this technology than with a conventional casting method. The cooling rate can be controlled to some extent by changing the amount of cooling medium. The DAS decreases with increasing cooling rate, and the microhardness and strength increase correspondingly.

1. Introduction

Cast aluminium-A356 alloy is one of the most well-developed aluminium alloys due to its outstanding properties. It is widely employed in numerous automotive and industrial weight sensitive applications, such as aeronautics and space flight, because of its low density and excellent castability.

Actually, in most cases high-level mechanical properties are needed for industrial applications, so the performance of this alloy has been the subject of many micromechanical investigations (López et al., 2003; Gokhale and Patel, 2005; Yu et al., 1999; Yang et al., 2005). Since the strength and hardness of alloys mainly depend on their microstructure, a lot of efforts have been made to refine the microstructure of the castings in order to enhance the mechanical properties of aluminium-A356 alloy. Adding modifier and refiner (Wang et al., 2003; Liao et al., 2002) to the melt is a common way of doing this, and has been adopted by many researchers. Power ultrasound (Jian et al., 2005) and electromagnetic stirring (Jung et al., 2001) have also been used to refine the microstructure of alloys. The methods mentioned above have been used by many researchers in recent years and their effect on refining the microstructure is known to some extent. However, there has been little research on refining the microstructure by improving the bulk melt's cooling rate. To our knowledge, a water-cooled copper mould is an effective fast-cooling method. However, the cooling rate achieved by this method is limited and is difficult to control for use in bulk-casting Al alloy.

Therefore, a novel method, that is a cast copper mould with phase-transition materials as the cooling medium is adopted

* *Corresponding author at*: School of Mechanical Engineering, Liaoning Technical University, Fuxin 123000, PR China. Tel.: +86 418 3351385; fax: +86 418 3351385.
E-mail address: zhangly6244@yahoo.com.cn (L.Y. Zhang).
0924-0136/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2007.12.059

Table 1 – Physical properties of Sn

Element	Sn
Density ($g\,cm^{-3}$)	7.3
Melting point (K)	504.9
Specific heat (J/kg K)	226.09
Heat conductivity (W/m K)	66.99
Latent heat of solidification (J/kg)	6.07×10^4
Expansion coefficient ($\times 10^{-6}$/K)	23

here to refine the casting of aluminium-A356 alloy. The results show that the dendrites are more refined than in conventional casting methods. The strength and microhardness of A356 alloy solidified in a fine microstructure have been investigated.

2. Experimental details

Commercial A356 aluminium alloy was used in this experiment, for which the nominal composition (wt.%) was 6.5–7.5Si, 0.25–0.45Mg, 0.08–0.20Ti, Fe < 0.2, with the balance being Al. The alloy ingot was remelted in a vacuum induction furnace with an argon atmosphere and kept for 10 min to make the melt homogeneous. The melt was then poured into copper moulds cooled by a phase-transition medium and water, respectively. Sn was used as the phase-transition cooling medium for its physical properties in this experiment, and the physical properties of Sn are listed in Table 1. Sn absorbed much heat when it was melt. The melt of A356 alloy was cooled just by this kind of heat, i.e., latent heat. So the cooling rate of melt increases with the increasing of Sn and reach a maximum value for a given amount of Sn. But when the amount of Sn is beyond this amount, it cannot be melt and the effect of cooling is weakened. Therefore, different cooling rates of the melt could be obtained by changing the amount of Sn.

A schematic diagram of the cooling device with a phase-transition medium is shown in Fig. 1. The solid Sn was remelted and poured slowly into the container. When it became semi-solid, the columnar-shaped copper mould with a NiCr–NiAl thermal couple in the center of copper mould,

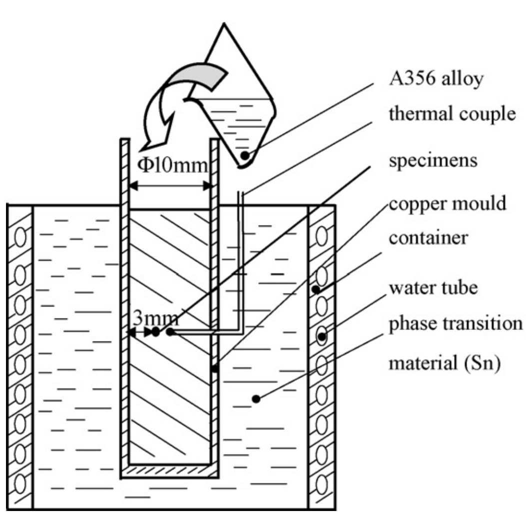

Fig. 1 – Schematic diagram of cooling device with phase-transition material.

which was shown in Fig. 1, was inserted into it and became fixed as the Sn solidified. The melt's temperature was detected by the thermal couple and recorded by an X–Y recorder.

For metallographic observation, specimens 10 mm in diameter were prepared in the normal manner, ground and polished on a burnishing machine. Specimens were etched in 0.5% HF for 15 s and observed with a MEIJI optical microscope. The as-cast dendrite arm spacing (DAS) was measured in specimens obtained from the bars cast with different cooling rates.

The microhardness was measured using a Vickers pyramidal indenter with a fixed load (50 g) and loading time (10 s) on an HVS-1000 digital microhardness apparatus. The hardness values are the averages of at least 10 indentations. Tensile tests were performed at room temperature on a Gleeble-3500 apparatus (Gleeble-3500, DSI, USA) using flat specimens with a 6 mm gauge length and a 2 mm × 2 mm gauge cross-section. An 8×10^{-3} mm s^{-1} cross-head speed was used. The mean of a minimum of three tensile specimens was taken to give a meaningful data point.

3. Results and discussion

3.1. *Microstructure observation*

Fig. 2 shows optical micrographs of specimens prepared with a copper mould cooled by using a phase-transition medium and water, respectively. The site of the microstructures was shown in Fig. 1 and they were taken in the same place. As can be seen, both them exhibited an ordinary dendrite structure consisting of primary α-Al dendrites and modified eutectic Si particles, but the main difference between them was that both of the primary and secondary dendrite arms of α-Al on the specimen obtained using the copper mould cooled with Sn (Fig. 2(a)) were more refined than those obtained with the water-cooled copper mould (Fig. 2(b)). The homogeneously distributed eutectic silicon particles in Fig. 2(a) were much smaller than those in Fig. 2(b).

The changes of microstructure were caused mainly by the different cooling rates of the melt. It is well known that the solidification rate plays an important role in the refinement of metal structures, and it significantly affects the mechanical properties. A high cooling rate and a short solidification time can lead to the formation of a more refined microstructure, an extended solute solubility and even metastable phases (Cantor, 2001; Jones, 1996; Haga et al., 2003; Katgerman and Dom, 2004).

3.2. *Effect of cooling rate on DAS*

As mentioned above, the DAS is mainly determined by the cooling rate. For the same alloys, the different DASs correspond to the relevant cooling rate, which depends on the different casting techniques, such as sand mould casting, permanent mould, etc. In this experiment the cooling rate is controlled by changing the amount of the cooling medium. The DASs obtained for a copper mould cooled with phase-transition medium depend on the different cooling rates. Fig. 3 shows the relationship between DAS and cooling rate, and the