Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 20(2010) 1769−1773
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Rheo-squeeze casting of semi-solid A356 aluminum alloy slurry

MAO Wei-min(毛卫民), ZHENG Qiu(郑 秋), ZHU Da-ping(朱达平)

School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China

Received 13 May 2010; accepted 25 June 2010

Abstracts: The effect of pouring temperature, electromagnetic stirring power and holding process on semi-solid A356 aluminum alloy slurry was investigated, then the slurry was squeeze-cast. The results show that when the pouring temperatures are properly above the liquidus line, for example 630−650 °C, the slurry with spherical primary α(Al) grains can be prepared under the stirring power of 1.27 kW. The slurry is then homogeneously held for a short time, and the primary α(Al) grains are further ripened and distributed evenly in the slurry. The results of the rheo-squeezed casting experiments show that the injection specific pressure has a great effect on the filling ability of the semi-solid A356 aluminum alloy slurry, and the higher the injection specific pressure is, the better the ability for the slurry to fill the mould cavity is. When the injection specific pressure is equal to or above 34 MPa, the whole and compact rheo-squeezed castings can be obtained. The microstructure of the castings indicates that the shape, size and numbers of the primary α(Al) grains in different parts of the castings are highly consistent. After being held at 535 °C for 5 h and then aged at 155 °C for 12 h, the ultimate strength of the rheo-squeezed castings can reach 300−320 MPa, the yield strength 230−255 MPa, and the elongation 11%−15%.

Key words: low superheat pouring; weak electromagnetic stirring; semi-solid; A356 alloy; rheo-squeeze casting

1 Introduction

The thixoforming technologies of semi-solid metals have been used to make various kinds of cars component and other machine parts[1], but the cost of these parts is higher because of the longer thixoforming process. So, the semi-solid rheoforming technologies with a cheaper and shorter process are becoming an important study field. Now, there are many invented semi-solid rheoforming technologies which are being researched or have been applied, such as new rheocasting method, semi-solid rheocasting method, continuous rheoconversion method, swirled enthalpy equilibration device method, twin screw method, returning sloping pipe method, wave sloping plate method, mechanical stirring barrel method, multi-electromagnetic stirring method, and near liquidus casting method[2−13]. The low superheat pouring and weak electromagnetic stirring method is also a new semi-solid rheoforming technology, by which ideal semi-solid slurry of aluminum alloys can be made[14−16]. In this work, the effect of pouring temperature, electromagnetic stirring power and soaking time on semi-solid A356 aluminum alloy slurry was investigated, finally the slurry was squeeze-cast and the mechanical properties of the casting were tested.

2 Experimental

The experimental material is a commercial A356 aluminum alloy. Its chemical composition (mass fraction) is Si 6.5%, Mg 0.34%, Fe 0.15% and Al balance. The alloy liquidus and solidus temperatures tested by DTA are 615 °C and 555 °C, respectively.

The designed equipment for continuous preparation and holding of semi-solid A356 aluminum alloy slurry has 10 stations supporting 10 slurry crucibles: one station for liquid alloy pouring and slurry preparation, eight stations for slurry soaking and one station for taking slurry away from the equipment.

The A356 aluminum alloy was firstly melted in an electric resistance furnace, refined and the temperature was maintained at 630−670 °C. Secondly, the liquid A356 aluminum alloy at a given temperature was poured

Foundation item: Project(2006AA03Z115) supported by the National Hi-tech Research and Development Program of China; Project(2006CB605203) supported by the National Basic Research Program of China; Project(50774007) supported by the National Natural Science Foundation of China

Corresponding author: MAO Wei-min; Tel: +86-10-62332882; E-mail: weiminmao@263.net

DOI: 10.1016/S1003-6326(09)60372-1

into a stainless steel crucible on the pouring station and stirred by a weak electromagnetic field for a short time. Thirdly, the slurry was further held respectively in the 8 holding stations for about 9 min. Finally, the slurry after being held was removed away from the equipment, quenched into water or put into the chamber of a squeeze casting machine and squeeze-cast. The pouring temperatures of the liquid A356 aluminum alloy were 615, 630, 650 and 670 °C, respectively. The stirring powers were 0.65, 1.27 and 2.15 kW, respectively, and the stirring frequency was 10 Hz. The injection specific pressures for squeeze casting were from 22 to 120 MPa.

The rheo-squeezed castings were heat-treated based on T6 heat treatment specifications. The parameters of the T6 heat treatment are: solution treatment at 535 °C for 5 h; ageing at 155 °C for 12 h. The tensile samples were cut from the heavy bottom section of the castings and underwent a static tension test.

The metallographic samples were cut off from the quenched slurries and castings. Each sample was roughly ground, finely polished and etched by an aqueous solution of 0.5 % HF. The microstructures were observed and analyzed with an optical microscope.

3 Results and discussion

3.1 Effect of preparation process on slurry microstructure

The microstructures of semi-solid A356 aluminum alloy slurries are shown in Fig.1, which were prepared by soaking the alloy slurry at different pouring temperatures with the same stirring power of 1.27 kW. There are also many large rosette-like primary α(Al) grains in the microstructure, although the liquid alloy undergoes a weak stirring and proper soaking, as shown in Fig.1(a). But when the pouring temperature decreases to 650 °C, most of the primary α(Al) grains are spherical and only a small number of primary α(Al) grains are rosette-like, and the size of the primary α(Al) grains are also refined obviously, as shown in Fig.1(b). After being poured at 630 °C or 615 °C, almost all the primary α(Al) grains in the microstructure are spherical and distribute homogeneously, as shown in Figs.1(c) and (d). However, if the liquid alloy is poured at 615 °C, the liquid A356 aluminum alloy adheres very easily to the surface of the pouring ladle and it is very difficult to clean down the adhering alloy.

Many study results show that the final semi-solid microstructure of an aluminum alloy is sensitive to the pouring superheat, and pouring at a low superheat can promote the transformation of primary α(Al) grain from a dendrite or a rosette to a spherical grain[12, 14−15]. When being poured at a low superheat, the melt temperature is near the liquidus temperature, only a small amount of heat is conducted from the melt to the crucible before the melt begins to solidify and the crucible temperature is not too high. So, the cooling speed of the melt during solidification is increased, the solidification

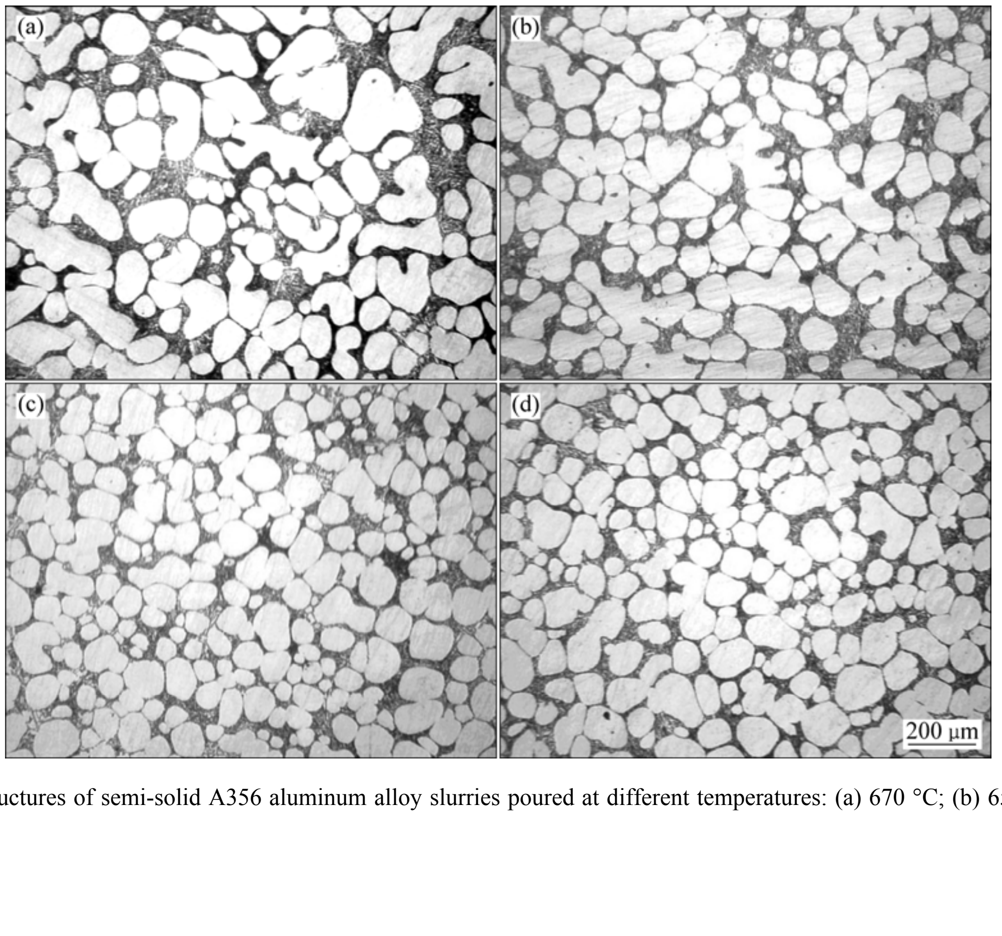

Fig.1 Microstructures of semi-solid A356 aluminum alloy slurries poured at different temperatures: (a) 670 °C; (b) 650 °C; (c) 630 °C; (d) 615 °C

time of the primary α(Al) grains is decreased and the primary α(Al) grains are refined. Meanwhile, stirring at a weak electromagnetic field can intensify the temperature fluctuation of the aluminum alloy melt, which helps the secondary arm roots of a dendritic or a rosette-like primary α(Al) grain to be fused and causes the fine primary α(Al) grains to become spherical eventually[14−15]. The results in this work show that the equipment for continuous preparation and holding of semi-solid A356 aluminum alloy slurry possesses the advantages from the above two aspects and so an ideal semi-solid A356 aluminum alloy slurry can be made.

The electromagnetic stirring power has an obvious effect on the semi-solid microstructure of A356 alloy slurry, and properly increasing the stirring power is favorable to causing spherical primary α(Al) grains to form. When the A356 aluminum alloy is poured at 630 °C and stirred at 0.65 kW, the effect of electromagnetic stirring on the melt is very small and the propelled fluid is hardly visible, so there are many large dendrites of primary α(Al) on the slurry periphery; moreover, large rosette primary α(Al) grains often appear in the inner slurry, as shown in Fig.2.

Along with the increase of stirring power, the flow motion of aluminum alloy melt is strengthened gradually and this is favorable to the formation of spherical primary grains. So, when the stirring power is increased to 1.27 kW, the microstructure on the slurry periphery is improved greatly and only small number of rosette-like primary α(Al) grains ripened are found. And all the primary α(Al) grains in the inner microstructure are spherical, as shown in Fig.3. But if the stirring power is increased further, for example 2.15 kW, the semi-solid microstructure has not been improved more. Therefore, the appropriate electromagnetic stirring power in this work is 1.27 kW under the condition of pouring at 630 °C.

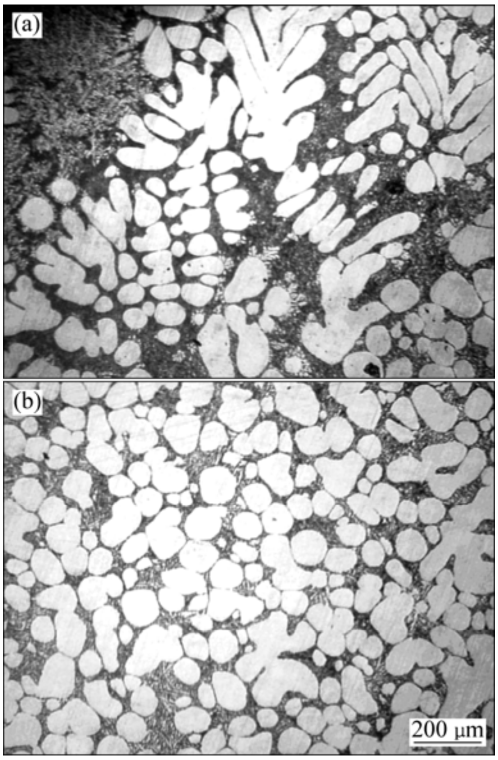

Fig.2 Microstructures of semi-solid A356 aluminum alloy slurry stirred at 0.65 kW: (a) Periphery; (b) Inner

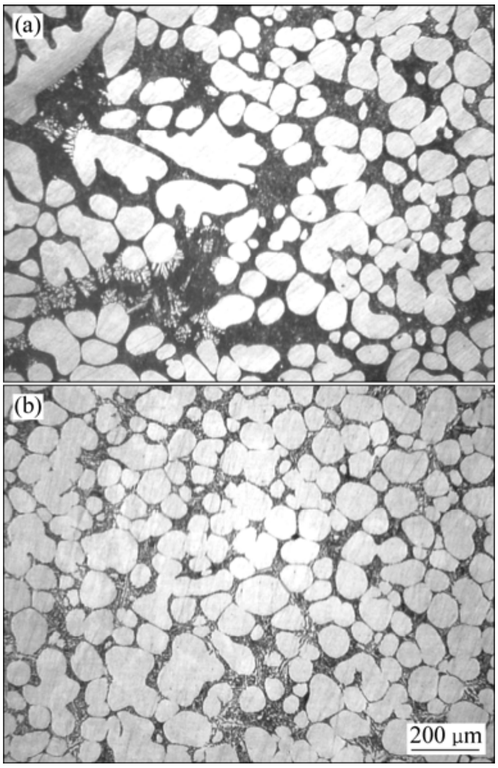

Fig.3 Microstructures of semi-solid A356 aluminum alloy slurry stirred at 1.27 kW: (a) Periphery; (b) Inner

3.2 Rheo-squeezed casting of slurry

During rheo-squeezed casting, the injection specific pressure and injection speed are the most important process parameters. But the injection speed of the squeeze casting machine is not adjustable, so only the injection specific pressure is varied during the experiments. The injection specific pressure means here the static pressure per unit area on the slurry. In the experiments, the effect of injection specific pressure on the rheo-squeezed casting has been investigated. When the injection specific pressure is 22 MPa, the mould cavity is not wholly filled, especially near the bottom and side rim, and the top overflow well of the casting, as shown in Fig4.(a). Even if the part of the mould cavity is wholly filled, the casting surface quality of that part is too bad, i.e. not smooth. However, when the injection specific pressure is increased to 34 MPa, the filling ability of the semi-solid A356 aluminum alloy slurry is

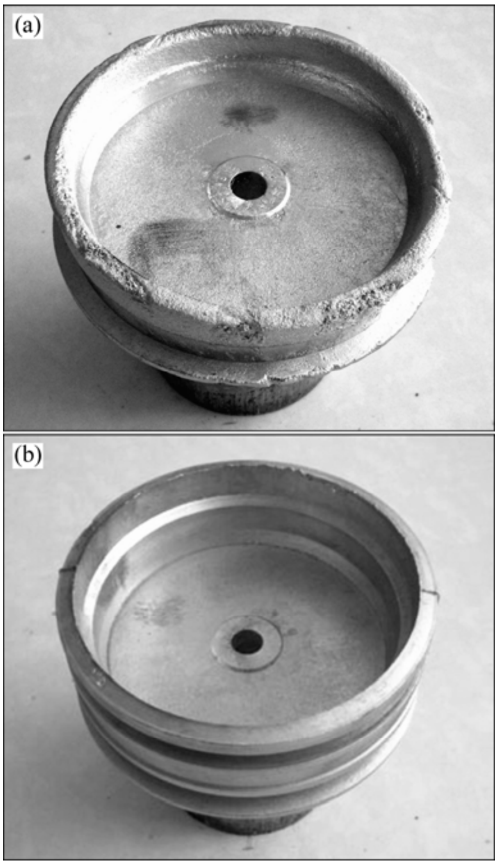

Fig.4 Rheo-squeezed castings of semi-solid A356 at different injection specific pressures: (a) 22 MPa; (b) 34 MPa

very high, and the whole cavity can be filled well and the surface quality of the castings are also excellent, as shown in Fig.4(b). The filling results also show that the higher the injection specific pressure is, the better the ability for the slurry to fill the mould cavity is. As a result, a higher injection specific pressure is helpful to the squeezed casting process.

The distribution situation of the spherical primary α(Al) grains in the rheo-squeezed castings of A356 aluminum alloy certainly affects the mechanical properties. According to Fig.5, metallographic samples were cut from a casting and examined. Fortunately the microstructures, i.e. the shape, size and numbers of primary α(Al) grains, at the different points of the casting are homogeneous, as shown in Fig.6. Only slight liquid segregation on the periphery is seen, as shown on the left in Figs.6(a) and (b), on the top in Fig.6(c) and on the bottom in Fig.6(d).

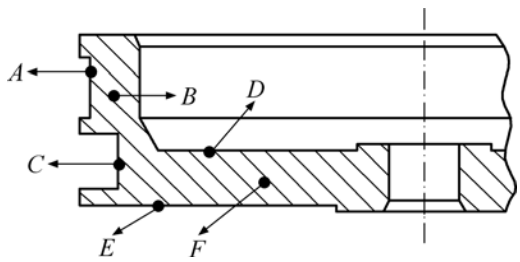

Fig.5 Schematic of metallographic samples cut from different points of casting

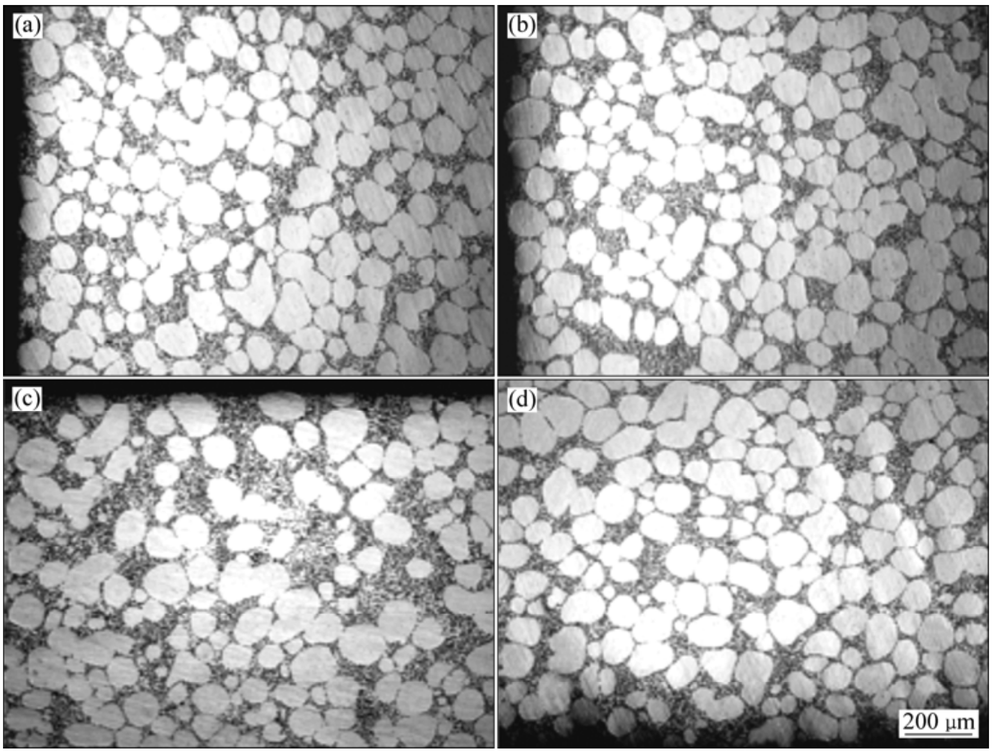

Fig.6 Representative microstructures of rheo-squeezed casting of A356 aluminum alloy: (a) Point A; (b) Point C; (c) Point D; (d) Point E

3.3 Mechanical properties of castings

The tensile samples were cut from the heavy bottom section of the castings heat-treated based on T6 specifications. The samples underwent a static tension test. The tension results show that the ultimate strength can reach 300−320 MPa, the yield strength can reach 230−255 MPa, and the elongation can reach 11%−15%. As a result, the semi-solid slurry prepared by the designed equipment for continuous preparation and soaking of A356 aluminum alloy can be used to form high quality squeezed castings.

4 Conclusions

1) Under the condition of pouring at 630−650 °C and stirring at 1.27 kW, the slurry with spherical primary α(Al) grains can be prepared. When the slurry is then held for a proper time, the microstructure is further ripened, becomes more homogeneous and is suitable for rheo-squeezed casting.

2) During rheo-squeezed casting, the higher the injection specific pressure is, the better the ability for the slurry of semi-solid A356 aluminum alloy to fill the mould cavity is. When the injection specific pressure rises to 34 MPa, the wholly filled castings can be obtained.

3) After heat treatment based on T6 specifications, the ultimate strength, yield strength and elongation of the rheo-squeezed castings can reach 300−320 MPa, 230−255 MPa and 11%−15%, respectively.

References

[1] FLEMINGS M C. Behavior of metal alloy in the semi-solid state [J]. Metall Trans A, 1991, 22(5): 957−981.

[2] KAPRANOS P. Semi-solid metal processing—A process looking for a market [J]. Solid State Phenomena, 2008, 141/142/143: 1−8.

[3] MIDSON S P. Rheocasting processes for semi-solid casting of aluminum alloys [J]. Die Casting Engineer, 2006, 50(1): 48−51.

[4] MARTINEZ R A, FLEMINGS M C. Evolution of particle morphology in semisolid processing [J]. Metall Trans, 2005, 36: 2205−2210.

[5] APELIAN D, PAN Q Y, FINDON M. Low cost and energy efficient methods for the manufacture of semi-solid (SSM) feedstock [J]. Die Casting Engineer, 2004, 48(1): 22−28.

[6] DOUTRE D, LANGLAIS J, ROY S. The SEED process for semi-solid forming [C]//Proc 8th Int Conference on the Processing of Semi-Solid Alloys and Composite. Limassol, Cyprus, 2004.

[7] HAGHAYEGHI R, LIU Y, FAN Z. Melt conditioned direct chill casting (MC-DC) of wrought Al-alloys [J]. Solid State Phenomena, 2008, 141/142/143: 403−408.

[8] GUO Hong-min, YANG Xiang-jie. Continuous fabrication of sound semi-solid slurry for rheoforming [C]//Proc of the 9th Int Conf on Semi-Solid Processing of Alloys and Compositions. Busan, Korea, 2006: 425−428.

[9] GUAN Ren-guo, XING Zhen-huan, WANG Chao, SHANG Jian-hong, KANG Li-wen. Preparation of semi-solid billets and its slurry by novel sloping plate process [J]. Special Casting and Nonferrous Alloys, 2007, 27(1): 31−34. (in Chinese)

[10] KANG Yong-lin, YANG Liu-qing, SONG Ren-bo, ZHANG Fan, TAO Tao. Study on microstructure-processing relationship of a semisolid rheocasting A357 aluminum alloy [J]. Solid State Phenomena, 2008, 141/142/143: 157−162.

[11] ZHANG Zhi-feng, XU Jun, SHI Li-kai. Study on rheo-diecasting process of Ai-Si alloys under multi-electromagnetic stirring [J]. Rare Metals, 2008, 27(8): 23−27. (in Chinese)

[12] WANG Ping, LU Gui-min, CUI Jian-zhong. Microstructure of nearby liquidus semi-continuous casting aluminum alloy A356 [J]. ACTA Metallurgica Sinca, 2002, 38(4): 389−392.

[13] FENG Peng-fa, TANG Jing-lin, LI Shuang-shou, ZENG Da-ben. On-line preparation technology of semi-sol id slurry of A356. 2 alloy [J]. The Chinese Journal of Nonferrous Metals, 2006, 16(1): 13−21. (in Chinese)

[14] TANG Guo-xing, MAO Wei-min, LIU Yong-feng. Effect of compound process on semi-solid slurry of A356 aluminum alloys [J]. Chinese Journal of Materials Research, 2008, 22(2): 167−170.

[15] ZHAO Zhen-duo, MAO Wei-min, LI Sha, ZHONG Rong-mao. Preparation of semi-solid AlSi7Mg alloy slurry through weak traveling-wave electromagnetic stirring [J]. International Journal of Minerals, Metallurgy and Materials, 2009, 16(5): 554−558.

[16] MAO Wei-min, ZHAO Ai-min, CUI Cheng-lin. A method and equipment for preparation of semi-solid metal slurry or continuously cast billet with spherical primary grains. China Patent, 00109540.4 [P]. 2000−07−03.

(Edited by YANG Bing)