Study on Microstructure Distribution of Al-Cu-Mg Alloy in Squeeze Casting Process

Longfei Li¹,²,a*, Yuankai Zheng¹,²,³b, Yunbo Chen¹,²c, Jian Feng⁴d, Chunming Li¹,²e, Lin Chen¹,²f, Lingli Zuo¹,²g, Yang Zhang¹,²h

¹ State Key Laboratory of Advanced Forming Technology and Equipment, Beijing, 100083, China
² Beijing National Innovation Institute of Lightweight Ltd., Beijing, 100083, China
³ Beijing Research Institute of Mechanical and Electrical Technology, Beijing 100083, China
⁴ GRIMAT Engineering Institute Co., Ltd., Beijing 101407, China

*a@camtc.com.cn, b13869168506@163.com, ccybcamtc@126.com, dfengjian@grinm.com, echm_li@126.com, fchenxxlin@126.com, g13811612433@126.com, hzhangy@camtc.com.cn

Abstract—The squeeze casting process is an advanced technology, which is suitable for a wide range of alloys including Al-Cu-Mg alloys. The high pressure in squeeze casting process both refines the microstructure and enhances the mechanical property of the alloys. The heat transfer and solidification process are complex with the chilling mould and pressure of machine punch. This results in the inhomogeneous microstructure and property in casting alloy. This study focuses on the distribution of microstructure, chemical composition, and hardness of Al-Cu-Mg alloy along the radial direction of casting. The composition and area fraction of eutectic phases are characterized. Moreover, the relationship between the microstructure and mechanical property was also analysed to show the characteristic of microstructure in squeeze casting process.

1. Introduction

Squeeze casting is an advanced forming technology in which the melt solidifies under high mechanical pressure [1-2]. During the process of squeeze casting, the melt contacts closely with the steel mould under pressure, which increases the heat transfer coefficient and cooling rate of the melt and thus refine the microstructure. The castings have high dimension accuracy, low surface roughness, low defects in microstructure and excellent mechanical properties [3-5].

Al-Cu-Mg alloy is a typical casting material with high strength, toughness and good corrosion resistance, so it is widely applied in aerospace field. However, many studies [6-8] show that the Al-Cu-Mg alloys have high sensitivity of hot tearing because the severe shrinkage of the alloy occurs during solidification, which impairs the castability of this alloy. The high mechanical pressure during squeeze casting process can effectively feed the shrinkage porosity and decrease the number of the defects in castings. Therefore, the squeeze casting process is applied to investigate the microstructure characteristic in Al-Cu-Mg alloys. The size of α-Al grain and eutectic phase are analysed along radial
direction of casting, and the hardness of alloys are also measured to illustrate the microstructural distribution in Al-Cu-Mg alloys.

2. Experimental methods

The nominal chemical composition of Al-4.5Cu-0.6Mg-0.4Mn-0.1Ti-0.15Zr was weighted using the pure Al, pure Mg, Al-60Cu, Al-5Mn, Al5TiB and Al5Zr master alloys. After loading the weighted ingots into the crucible, the resistance furnace was heated up to 730 °C. The melt was then degassed by the rotating graphited rod blowing argon. The degassing time was preferred to 30 minutes. The chemical composition of the studied alloy was measured by spectrometer (SPECTROMAXx-LMX08, Germany) and the results were listed in Table 1.

Table 1 Composition of Al-Cu-Mg alloy in experiment. (in wt.%)

| Alloy  | Cu   | Mg   | Mn   | Ti   | Zr   | Fe   | Others | Al    |
|-------|------|------|------|------|------|------|--------|-------|
| Al-Cu-Mg | 4.69 | 0.73 | 0.380| 0.093| 0.17 | 0.13 | <0.10  | Bal.  |

The pour temperature of the melt was 730 °C, and the pre-heated temperature of the mould was 200 °C. The squeeze casting process, which is shown in Fig.1, includes six procedures—cylinder tilt to pour melt, then back to straighten, cylinder rise, low-speed filling and high-pressure solidification, which is the most important stage to obtain castings with good quality, final open the mould to pick out castings. The schematic diagram of the casting was shown in Fig.2, and the cross section of A-A was chosen to observe the microstructure of Al-Cu-Mg alloy. Five equally spaced points (P1-P5) along the radial direction on A-A cross section were picked to display the microstructural distribution of Al-Cu-Mg alloys in the squeeze casting process.

![Fig.1 Process of squeeze casting](image1)

![Fig.2 Schematic diagram of sampling location of microstructure](image2)

The microstructure of Al-Cu-Mg alloy was characterised using Scanning Electron Microscope (ZEISS GeminiSEM 500, Germany) to show the distribution of eutectic phases. The method of transverse line was applied to measure the grain size of α-Al and the Image-Pro plus 6.0 software was used to compute the area fraction of eutectic phases in microstructure. The hardness of alloy was also measured using Vickers hardness tester (DHV-1000z, China).
3. Results and Discussions

3.1. Microstructure characterization

The SEM microstructure at five points was shown in Fig. 3. It is seen that the microstructure of Al-Cu-Mg alloy consists of α-Al phases and eutectic phases. Due to the high content of Cu element, eutectic phases are shown in bright white colour. From the measurement results as shown in Fig. 4a, the size of α-Al grains is significantly decreased from P1 to P5, while the area fraction of eutectic phases is obviously increased. At P1, the average size of α-Al grain is 18.8 μm and the area fraction of eutectic phases is 2.2%. At P5, the average size of α-Al grain is 9.4 μm and the area fraction of eutectic phases is 8.8%. The refined α-Al grains and high volume fraction of eutectics result in high hardness of microstructure. The hardness increases from 56.7 HV at P1 to 93.0 HV at P5. Moreover, Fig. 4b is the line scan results showing the contents of Al/Cu/Mg/Mn elements along the radial direction. It can be found that the Cu content has an obvious increase from centre to edge position. The increase in Cu content results to the enhancement in hardness of Al-Cu-Mg alloys.

![Fig. 3 Microstructure of Al-Cu-Mg alloy along the radial direction.](image)

![Fig. 4 (a) Measurement of grain size, area fraction of intermetallic, HV hardness and (b) content of element (Al/Cu/Mg/Mn) along the radial direction in Al-Cu-Mg alloy.](image)

Fig. 5 shows the microstructure at P4 and the eutectic phase in higher magnification. The magnified microstructure of eutectic phases consists of Al2Cu and Al2CuMg phases. The Al2Cu phases show bright white colour, and the Al2CuMg phases show grey colour in SEM picture. From the equilibrium phase diagram of Al-Cu-Mg [9], the solidification sequence of precipitated phases in Al-4.5Cu-0.6Mg alloys is α-Al, Al-Al2Cu and Al-Al2CuMg eutectics.
3.2. Microstructure-Hardness relationship
In pressure die casing process, the microstructure at the cross section of casting consists of three areas: refined grains at surface, eutectics band and coarse grains in centre [10]. The process of solidification is analysed as follow. Due to the chilling effect of the mould, the melt closed to mould has high cooling rate and then forms the solid shell. This “solid shell” impairs the chilling effect of mould, which results to the decrease of cooling rate in alloys. Thus, the temperature gradient of the melt at the cross section of casting is relatively uniform. As the solidification continues, the solidified particles (α-Al grains) with high volume fraction and liquid zone move forward under the push of the machine punch. The liquid zone has an obvious segregation and flows along the “solid shell”, while the solid particles are located in the centre of castings. At the end of solidification, the eutectics are completely precipitated in liquid zone and the coarse α-Al grains form in microstructure. Finally, three areas included refined grains at surface, eutectic band and coarse grains in centre. Typical microstructure on the cross section of casting is displayed in Fig. 6, and schematic diagram showing the microstructure characteristic is also summarized in Fig. 6.

4. Conclusion
The microstructure and hardness along the radial direction of castings are characterized in Al-Cu-Mg alloys in squeeze casting process. The conclusions are summarized as follows:
(1) From center to edge on the cross section of the casting, the size of α-Al grains in Al-Cu-Mg alloys has an obvious decrease from 18.8 μm to 9.4 μm, and the average area fraction of eutectic phase increases from 2.2% to 8.8%.
(2) The refined α-Al grain structure and higher volume fraction of eutectic phase result in the increase of hardness in Al-Cu-Mg alloys. The hardness at edge position is 93.0 HV, which is nearly 64% higher than that at center position.

(3) Three regions including refined grains at surface, eutectic bands and coarse grains in center exist in microstructure. Moreover, the increase in Cu content and decrease in Al content are also observed along the radial direction. It is presumably that the eutectic phase (Al2Cu and Al2CuMg) provides hardness and strength of Al-Cu-Mg alloy in great extent.

Acknowledgments
This work was supported by Open Fund of State Key Laboratory of Advanced Forming Technology and Equipment (SKL2020006) and Fund of National Lightweight Material Forming Technology and Equipment Innovation Centre (111902Q-F).

References
[1] Srivastava, N., Anas, M. (2020) An investigative review of squeeze casting: processing effects & impact on properties. Materials Today: Proceedings, 26.
[2] Natrayan, L., Kumar, M. S. (2018) Study on Squeeze Casting of Aluminum Matrix Composites—A Review. Advanced Manufacturing and Materials Science, 75-83.
[3] Hao, J. F., Yu, B. Y., Bian, J. C. et al. (2021) Comparison of the semisolid squeeze casting and gravity casting process on the precipitation behavior and mechanical properties of the Al-Si-Cu-Mg alloy. Material Characterization, 180, 111404.
[4] Ren, J., Wang, Z., Li, Q. H., et al. (2019) Technology of Squeeze Casting for Aluminium Alloy Automobile Triangle Arms. Lecture Notes in Electrical Engineering.
[5] Rosso, M., Peter, I., Bivol, C., et al. (2010) Development of industrial components by advanced squeeze casting. International Journal of Material Forming, 3(1 Supplement), 787-790.
[6] Lemieux, A., Langlais, J., Chen, X. G. (2013) Reduction of hot tearing of cast semi-solid 206 alloys. Solid State Phenomena, 192-193.
[7] Bozorgi, S., Haberl, K., Kneissl, C., et al. (2011) Effect of Alloying Elements (Magnesium and Copper) on Hot Cracking Susceptibility of AlSi7MgCu Alloys. John Wiley & Sons, Inc.
[8] Rathi, S. K., Sharma, A., Sabatino, M. D. (2017) Effect of mould temperature, grain refinement and modification on hot tearing test in Al-7Si-3Cu alloy. Engineering Failure Analysis, 79, 592-605.
[9] Buhler, T., Fries, S. G., Spencer, P. J. et al. (1998) A thermodynamic assessment of the Al-Cu-Mg ternary system. Journal of Phase Equilibria, 19(4), 317-333.
[10] Dahle, A.K., Sannes, S., St. John, D.H. et al. (2001) Formation of defect bands in high pressure die cast magnesium alloys. Journal of Light Metals, 1(2):99-103.