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On the formation mechanism of the ring-like microstructure of high-pressure die-cast A390 alloy

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ABSTRACT

The microstructure of the A390 alloy during high pressure die casting (HPDC), including pores, primary silicon particles (PSPs) and Cu-rich phases was characterized using synchrotron X-ray tomography. On the cross section of the sample exhibited ring-like or band microstructure, which comprised multiple PSPs-free and PSPs-rich zones. The PSPs distributed evenly in both size and morphology regardless of the ring-like microstructure. The size of aluminum dendrites changed according to the location of the ring-like microstructure, and was highly dependent on the local latent heat released from the PSPs as well as the distribution of the 'net' Cu-rich phases. Along the radial direction of the sample exhibited an abrupt increase of pores, indicating a tendency for forming a defect band in but such tendency was inhibited because of the huge amount of latent heat released by the PSPs during solidification, which was quite different from that of either magnesium alloys or hypoeutectic aluminum alloys.

1. Introduction

Hypereutectic Al-Si alloys are widely applied as a wear resistant material because of the presence of the primary silicon particles (PSPs) in the microstructure. One of the most important applications of the hypereutectic Al-Si alloy is the automotive engine block: beside weight saving, the wear resistance [1–3] and mechanical performance [4–7] can be significantly improved by exposing the PSPs at the friction surface.

High-pressure die casting (HPDC) is one of the most efficient ways for massive production of automobile components. In HPDC, because of fast filling and rapid solidification, unique microstructures like external solidified crystals (ESCs) [8–10] and defect bands (DBs) [11–14] normally present and significantly influence the ultimate performance of the casting.

Dahle et al. [11,12] studied the band-like distribution of both pores and ESCs, and believed that those defect bands formed due to insufficient feed of the liquid through the interdendritic network during solidification. Metz and Flemings [15] found that the solidifying alloys exhibit zero mechanical strength before dendritic coherency. However, beyond the dendritic coherency, the shear yield strength of the alloy increased exponentially as solid fraction. Spencer et al. [16] found that shear yield strength was closely related to the morphology of grains and decreased significantly when the solid became more globular. Nabulsi [17] and Sumitomo et al. [14] characterized the morphology transition of microstructure due to shear deformation and found that the ultimate spherical grain microstructure was formed due to dendritic fragmentation caused by interdendritic shearing. Gourlay and Dahle [18] studied the influence of solid fraction on the shear yield strength of the mushy zone and found that defect bands also presented in Al-Si [19], Al-Si-Cu [14], Al-Si-Mg [18] and Al-Si-Mg-Mn [13] alloys.

However, to the best knowledge of the author, most of the existing studies on band microstructure focused on either magnesium alloys or hypoeutectic aluminum alloys and very little attention has been focused on the hypereutectic aluminum alloys in HPDC. In particular, the precipitation of the PSPs of the hypereutectic aluminum alloys could significantly alter the microstructure distribution from both thermodynamic and kinetic aspects, leading to very different formation mechanisms for the band microstructure.

The advancement of the 3rd generation synchrotron X-ray techniques enables one to characterize the 3-D microstructure morphology without any damage of the sample. Extensive studies have been performed to investigate dendrite [20], defect [8,21], intermetallic [22] and PSPs [23,24]. Accordingly, in this study, we employed both synchrotron and laboratory X-ray compute tomography to characterize the microstructure of a hypereutectic A390 alloy. Furthermore, by comparing different locations, the overall distribution of 3-D microstructures including PSPs, pores and Cu-rich phases was obtained and

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Table 1
The composition of the A390 hypereutectic Al-Si alloy.

Type [wt%]	Si	Cu	Mg	Fe	Zn	Mn
A390	17.10	4.58	0.56	0.32	0.06	0.01

thus offered a direct and more effective way to analyze the ring-like band microstructure during solidification.

2. Experiment

In the experiment, a commercial hypereutectic aluminum alloy, namely A390, was employed with a composition listed in Table 1. A TOYOBD–350V5 cold chamber die casting machine was employed to produce standard tensile testing bars with a diameter of Φ 6.4 mm. Fig. 1 shows the configuration of the specific casting, sample extraction position, and the processing parameters during HPDC.

The metallographic samples were extracted from the tensile bar and mounted in a holder, grinded on SiC papers (400–2000 grit size) and then polished with ethyl alcohol based colloidal silica suspension (0.5 μm). The polished cylinder was subjected to an electron probe micro-analyzer (EPMA, JXA-8530F) to determine the solute distribution on the cross section of the sample. For the synchrotron X-ray tomography experiment, cylinders of Φ = 1 mm were extracted using wire electrical discharge machining. The diameter of the electrical discharge wire was in a range of 0.4–0.5 mm and thus the three synchrotron tomography samples (marked as 'S' 'M' and 'C') were cut according to the position in Fig. 1c to represent the microstructural transition from surface to center. After the tomography experiment, each sample, i.e. 'S', 'M', and 'C' was further machined into five separate parts of 130 μm × 650 μm × 1330 μm. Accordingly, these sub-divided cuboids were labeled as 1–5, 6–10 and 11–15 along the radial directions from the surface to the center of the tensile bar.

The synchrotron X-ray tomography experiment was performed at the BL13W1 beamline in Shanghai Synchrotron Radiation Facility (SSRF). A high speed CCD camera was used to record the penetrable intensity information of monochromatic X-ray beam during rotating the sample over 180°. The X-ray energy was 18 keV and distance between the specimen and camera was 20 cm. After scanning, a total of 720 projections of images were collected, together with both dark field (without X-ray penetration) and flat field images (without samples). The raw 32-bit images were then converted to 8-bit using a software namely PITRE developed by INFN Trieste [25]. The 3-D reconstruction and rendering of the images were then performed in a sub-volume of 500 × 500 × 2048 voxels with a voxel size of 0.65 μm using a software namely Avizo® [26].

Image processing techniques such as phase retrieval [27], contrast enhancement, threshold filtering and smoothing were applied during the data processing. For a better illustration, detailed microstructure was extracted from the reconstructed images, rendered with different colors, and presented separately in Fig. 2. For pores, threshold filtering was enough to separate them from the rest microstructure. For Cu-rich phases, after removing the pore areas, threshold filtering and smoothing were employed to extract the microstructure and adjust the boundary of Cu-rich phases, respectively. For PSPs, after removing both pores and Cu-rich phases, threshold filtering was used to mark PSPs in the rest areas and shrinking and/or expanding [28,29] was applied to adjust the chosen areas until the boundaries of PSPs were fitted properly. Finally, sharpening method was applied to restore the polyhedron shape of PSPs.

The laboratory X-ray tomography experiment was performed using a CT machine namely phoenix nanotom m manufactured by GE [30]. A Φ-6.4 mm cylinder was extracted from the middle part of the tensile bar. The voltage and electric current were selected as 110 kV and 100 μA, respectively. After scanning, a total of 1000 projections of images were collected, together with dark field (without X-ray penetration) and flat field images (without samples). The raw 32-bit images were then converted to 16-bit using a software namely Datos 2.0 [31]. The 3-D reconstruction and rendering of the images were performed in a sub-volume of 1454 × 1446 × 906 voxels with a voxel size of 4.67 μm using Avizo®.

3. Results

3.1. Ring-like Inhomogeneous Band

Fig. 3a and b shows typical ring-like microstructures of the HPDC A390 alloy on the cross section for two different samples. For both cases, ring-like inhomogeneous bands could be clearly observed. The ring-like bands in Fig. 3a were marked by 'A' 'B' 'C' and 'D', while in

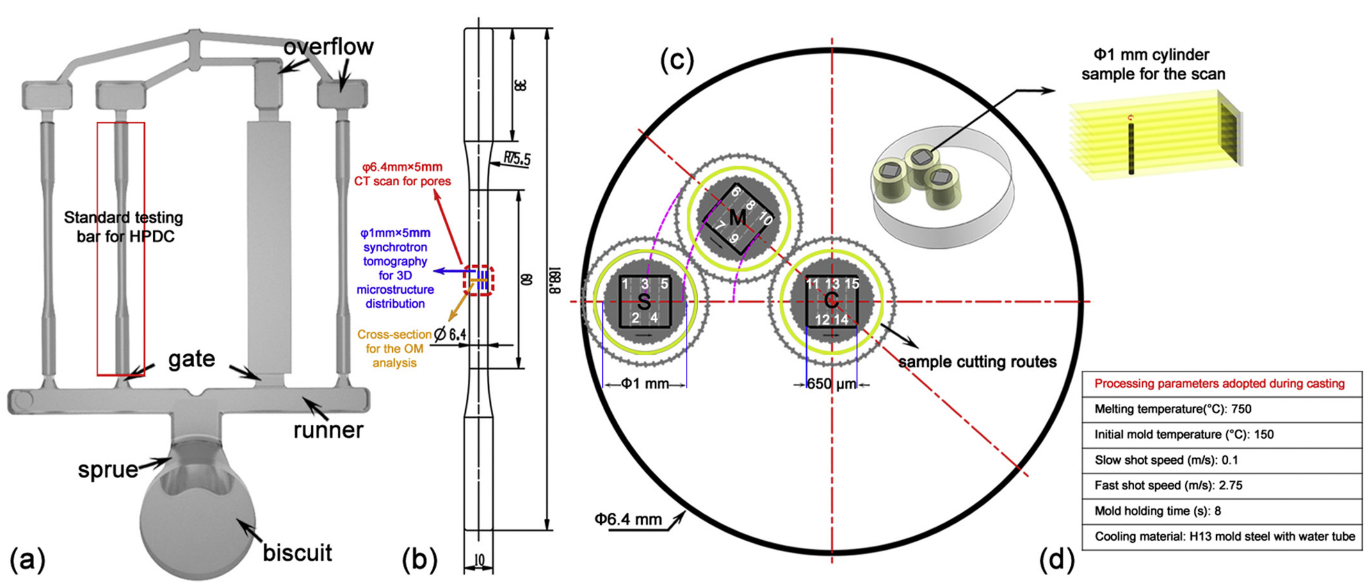

Fig. 1. The configuration of the casting employed in the HPDC experiment and sample positions. (a) and (b) show the geometry of the casting and standard bar for further analyses, respectively; (c) shows the three sample positons for synchrotron X-ray tomography experiment; (d) shows the HPDC processing parameters during sample preparation.