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Microscopic failure modes of hpdc AZ91HP magnesium alloy under monotonic loading

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Abstract

The microscopic failure modes of high pressure die cast (hpdc) AZ91HP magnesium alloy is identified by means of in situ tensile analysis. The study aims at: (i) explaining the consequence of different micro-inhomogeneities on failure and, (ii) confirming to which extent shrinkage porosity influences failure. Microstructural analysis at different deformation stages verify interaction of pores, $Mg_{17}Al_{12}$ (β) particles and inclusions during failure and indicates predominant intergranular brittle failure of the material.

Keywords: AZ91 magnesium alloy; Fracture; In situ tensile analysis; SEM; Pressure die casting

1. Introduction

Magnesium alloys have received increased attention for applications in automotive, aerospace, communication and computer industry recently because of its very low density, high specific strength, good machineability, castability and availability. Amongst different metal-casting techniques, high pressure die casting (hpdc) is the most attractive process for the manufacturing of magnesium components. It offers clear advantages such as thin walls, net shapes, fast cooling rates, good dimensional accuracy and stability, high productivity, and a high degree of automation over other processes. Due to these reasons, most magnesium components are currently produced by this process. The key problems facing hpdc of Mg alloys are the formation of porosity, surface defects and cracks inherited from the solidification behaviour of Mg alloys. AZ91 alloy accounts for more than 50% of all high pressure die castings [1,2] and this is due to its reasonable mechanical property and excellent castability. Typical microstructure of an hpdc AZ91 magnesium alloy consists of cored dendrites of primary Mg-solid solution, non-equilibrium eutectic constituents and aluminium rich intermetallic $Mg_{17}Al_{12}$ (β) compounds.

Inclusions (50–500 μm), microporosity (1–300 μm) and β-phase (1–4 μm) are the major multi length scale microstructural inhomogeneities expected to affect the fracture process of AZ91 Mg alloys. Brittle grain boundary shearing of magnesium alloys [3–5], β particle spacing and size effects on fracture of wrought AZ31 alloy [6], crack initiation from $Mg/Mg_{17}Al_{12}$ interfaces [3] and from grain boundary precipitates [7] are presented in various investigations. The combination of intergranular and transgranular [7,8] crack path in Mg alloys is discussed by various authors. The role of microporosity as the crack initiation source is found in fatigue analysis of Mg alloys [9–13]. Magnesium and its alloys exhibits moderate ductility due to the lack of independent slip systems [14] also influence this materials' fracture behaviour. Contrary to these topics microscopic failure modes of Mg alloys are not well understood yet and particularly little information is available on high pressure die cast (hpdc) alloys. Issues concerning the location of crack initiation, crack growth path and the competition between the influences of micro-inhomogeneities (pores, second phase, inclusions and grain boundary) of hpdc AZ91 alloy still remain unanswered. This research is therefore intended to aid the understanding of microscopic failure modes of hpdc AZ91 magnesium alloy by in situ tensile analysis.

Additionally, complex geometries of microstructural features, their locations and arrangements of this alloy are often non-uniform but are usually strongly correlated spatially. In these complex microstructures, the different length scale micro

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features leads to the multiple fracture micro-mechanisms, which contribute to the overall fracture behaviour while the spatial correlations and microstructural gradients influence the crack growth path. This paper aims at explaining the influences of different micro-inhomogeneities on failure and at identifying the micro-inhomogeneity, which has the greater influence on failure.

2. Experimental procedure

In situ tensile tests were carried out on AZ91HP hpdc specimens using a scanning electron microscope coupled with an in situ tensile loading device. One surface of each specimen was polished and etched which, in combination with the experimental apparatus allowed continuous observation of the specimen's damage evolution. In situ observations of damage evolution conveys crucial information about microscopic changes occurring during deformation. The experimental set up allowed grabbing microstructural images of the undeformed and consecutive deformation states as each experiment progressed. Fig. 1 illustrates the dimensions of the tensile test specimens used in this analysis.

The unetched and etched surfaces of the specimens from different locations (surface and centre) of the tested casting were introduced to optical microscopy for the microstructural quantification. A microstructural area of 25 mm^2 was grabbed at 100× as continuous microstructural frames with an optical microscopy from the unetched cross-section. This microstructural frames were used to create the microstructural montage and it was further introduced to image-processing to quantify the inclusions, gas and shrinkage microporosity. These three features were quantified by separating them using the visual difference and difference in the nearest neighbour values between them. The unetched cross-sections were further etched to reveal the β-phase. The microstructural area of 1.86 mm^2 was grabbed from the etched surface at 1000× for the quantification of β-phase by image-processing. The image-processing was performed by a developed automatic computer code. The details of the microstructural quantification process are presented elsewhere [15,16]. The etchent used for all the etching process is a combination of picric acid (6 g), water (10 ml), acetic acid (5 ml) and ethanol (100 ml). The chemical composition and the microstructural quantification results of the present material are presented in Tables 1 and 2, respectively.

Table 1
Chemical composition of the alloy (AZ91) investigated

% Al	9.3
% Mn	0.12
% Zn	0.79
% Si	0.02
% Cu	0.0007
% Ni	0.0006
% Fe	0.0046

Table 2
Microstructural quantification results

	Average size (μm^2)	Area fraction (%)
Inclusions	775.50	0.008
Shrinkage pores	25.99	0.56
Gas pores	23.75	0.23
β-Phase		
Surface	0.68	0.0177
Centre	1.03	0.0175

3. Results and discussion

3.1. Special arrangement of inhomogeneities

A processed image frame of a real microstructure of hpdc AZ91 alloy is shown in Fig. 2. The figure shows the spatial arrangement of different inhomogeneities, particularly showing the β-phase and shrinkage pores arranged along the grain boundaries. Intergranular arrangement of micro-inhomogeneities reduces the load bearing capacity of the grain boundary region. Such arrangement of micro-inhomogeneities therefore suggests an influence on the fracture behaviour of this material.

3.2. Fracture surface analysis

Secondary electron imaging and backscatter electron imaging of the fracture surfaces are shown in Fig. 3. In general, the fracture surface reveals cleavage type of failure with some sec-

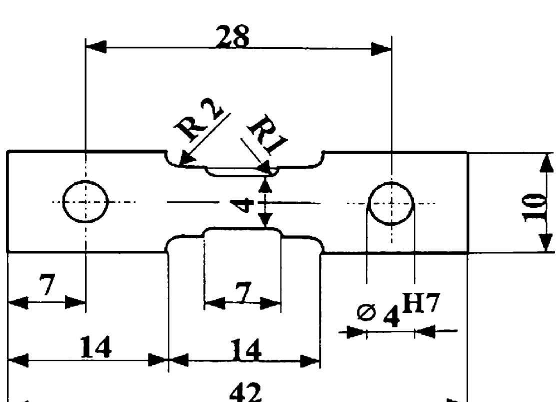

Fig. 1. Dimensions of in situ tensile specimens (in mm).

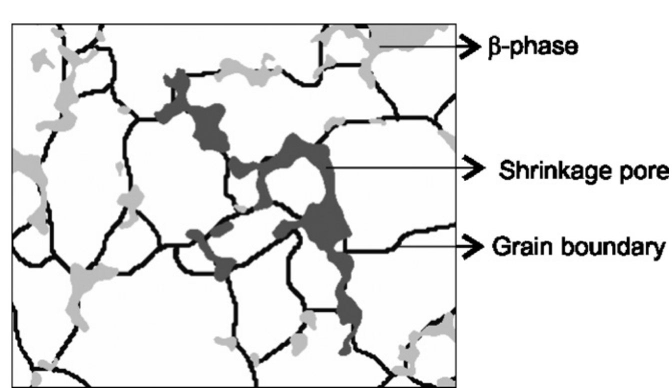

Fig. 2. Image-processed microstructure, which shows the arrangement of the β-phase particles and shrinkage pores along the grain boundary.