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Influence of Fe content on the damage mechanism in A319 aluminum alloy: Tensile tests and digital image correlation

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ABSTRACT

In order to study the role of Fe content on the damage mechanisms of Al–Si–Cu alloy on a microstructural level, a Digital Image Correlation (DIC) method has been developed and performed on two Al–Si–Cu alloys: a high-Fe alloy (0.1 wt.% Fe) and a low-Fe alloy (0.8 wt.% Fe). Tensile tests on flat specimens have been performed, and a Questar long distance microscope has been used for the in-situ observation during tensile tests. The field measurements allow to identify and track the development and localization of deformation, and the fracture surfaces of the tensile specimens are analyzed using Scanning Electron Microscopy and Energy-Dispersive X-ray spectrometry (SEM-EDX) to identify the damage mechanisms. The results show that crack initiation occurs through the fracture of hard inclusions, i.e. Si particles, iron-intermetallics and Al_2Cu particles in the high stress concentration region. Cracks often propagate through the fracture of hard inclusions rather than by their decohesion from the matrix.

1. Introduction

The 319 type alloys have received increased interest in the automotive industry in the recent years, and are being widely used in cylinder heads [1]. Due to its application and high demand in the automotive industry, the A319 alloy requires detailed information on the relationship between the microstructures and the mechanical properties.

More than half of all the aluminium currently produced in the EU originates from recycled raw materials due to ecological and economic advantages [2]. The production of recycled aluminium requires 95% less energy than primary aluminium, and producing aluminium by recycling creates only about 5% of CO_2 quantity produced as by primary production [3]. However, iron, which is present in much higher concentrations in recycled aluminium [2], forms brittle intermetallic inclusions such as β-Al_5FeSi phase. Yi et al. [4] found that, in the absence of other defects such as porosity, the large plate-like β-Al_5FeSi intermetallics in high Fe-content castings of A356 alloy promote crack initiation by raising the stress-strain concentration in the eutectic region. Consequently, effect of Fe content on the damage mechanisms of the Al-Si-Cu alloy requires more study.

Digital Image Correlation (DIC) has become more common and essential as a measurement method for the deformation analysis [5]. It was first developed by a group of researchers at the University of South Carolina in the 1980s [6]. It is an optical-numerical measurement technique for determining complex displacement and strain fields on the materials surface for static as well as dynamic application [7]. This technique consists in measuring displacement fields between two images of

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the same specimen at different stages of loading. The displacement field is obtained using the so-called brightness conservation, so that the image of the loaded sample is matched to the reference image [8]. The accuracy and the spatial resolution of the measurement directly depend on the presence of numerous and finely dispersed markers on the specimen surface [9]. Paint is generally used to obtain a surface speckle pattern; however, this random texture could mask the microstructure underneath and thus prevent the study of the relationship between microstructural features and strain heterogeneities. Some interesting application of DIC can be found in Refs. [10,11].

In order to study the role of Fe-rich intermetallics on the damage mechanisms of Al–Si–Cu alloy, two Die Cast (DC) alloys which contain different values of Fe/Mn content have been prepared. Then, an experimental protocol has been successfully developed to study the crack initiation and propagation during in-situ tensile tests using DIC. An appropriate colour etching on flat specimen's surface provides a natural pattern suitable for image correlation in order to obtain field measurement at small scales, i.e. at intermetallics or at eutectic Si.

2. Experimental procedures

2.1. Material and preparation of specimens

The experimental alloys used in this investigation are two DC AlSi7Cu3 alloys obtained from PSA Peugeot Citroën having the chemical compositions shown in Table 1, in which the alloy with low Fe/Mn content (0.1 wt.% Fe; 0.007 wt.% Mn) was designated as 'Low-Fe' and high Fe/Mn content (0.85 wt.% Fe, 0.510 wt.% Mn) was designated as 'High-Fe'.

The specimens used for microstructure characterization and the specimens for in-situ tensile testing were cut out from round bars with a 20 mm diameter and a 200 mm length. The 2D microstructures were examined in the unetched condition using a Nikon YM-EPI light microscope equipped with a Sony colour video camera. The images were processed and analyzed using ImageJ/Fiji software. The parameter used to characterize the size of iron-intermetallics is the Feret diameter, which is defined as the longest distance measured between two parallel tangents on each side of the 2D object of interest [12].

For the in-situ tensile test specimens, as is shown in Fig. 1(a), a shallow hole (Ø = 1.5 mm) was drilled in the centre of specimen to have a stress concentration (gross stress concentration factor K_{tg}, i.e. the ratio of maximum local stress at the edge of the hole and the applied far-field stress remote from the hole, at the edge of the hole is about 3.15 according to [13]) in the chosen Region Of Interest (ROI) that could force the final fracture to occur here. According to Wang et al. [14], the maximum size of pores is more than 1.5 mm in Lost Foam Cast (LFC) A319 alloy; thus the hole in the present study was chosen so that it can be representative of the large pores in LFC A319.

Besides, after cutting specimens of appropriate size from the original cylindrical bars, a conventional grinding and polishing process was performed on the specimen surface. In order to obtain field measurement at small scales, i.e. at intermetallics or at eutectic Si, an appropriate colour etching was performed on polished flat specimen's surface to provide a natural pattern suitable for image correlation; the protocol is:

- Etchant solution: 100 ml distilled water, 4 g potassium permanganate and 1 g sodium hydroxide.
- The etching time is 15 s [15].

Compared to the conventional random speckle pattern that is usually applied on the specimen surface for use with DIC image analysis, this method does not mask the microstructure underneath, i.e. hard inclusions, and thus we can study the relationship between microstructural features and strain heterogeneities.

2.2. Tensile testing

In-situ 2D tensile tests were performed at a displacement rate of 16 μm/s using an Instron 8501 servo-hydraulic testing machine. During the tensile test, the applied load was recorded by an extensometer, which was installed across the centre area of the specimen (see Fig. 1(a)), to measure the macroscopic deformation. The experimental set-up is illustrated in Fig. 2.

In order to record the deformation images during the tensile tests, the test was interrupted at different loading steps. The images were taken using a JAI 500 CCD camera with a resolution of 2048 × 2048 pixels and fitted with a long distance microscope (Questar QM100). The camera was mounted on a translation stage perpendicular to the tensile test set-up. Digital pictures were taken in several adjacent zones of the ROI with a pixel size of about 0.23/0.27 μm in order to cover the area of interest (see Fig. 1). Stitching of the images acquired at each loading step was performed using the plugin MosaicJ in Image J software [16] which allows rigid registration of images. An appropriate overlap between adjacent images is necessary for the further stitching of the images to a larger image which covers the ROI.

Table 1
Chemical compositions of the two experimental AlSi7Cu3 alloys (wt.%).

Alloy	Al	Si	Cu	Fe	Mn	Sr	Mg	Ti	Pb	Zn
Low-Fe	bal.	6.91	2.89	**0.10**	**0.007**	0.0047	0.29	0.11	0.003	0.022
High-Fe	bal.	7.00	3.45	**0.80**	**0.510**	0.0100	0.28	0.12	0.05	0.24

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