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In-situ EBSD study of deformation behavior of Al–Si–Cu alloys during tensile testing

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ABSTRACT

This study deals with the microstructural aspects of the deformation behavior in Al–Si–Cu alloy A380. This has been carried out with in-situ tensile testing coupled with EBSD analysis. The alloy specimens having different microstructures with two different secondary dendrite arm spacing (SDAS) of 9 μm and 27 μm were produced by the unique gradient solidification method. The study of misorientation distribution and texture evolution was performed with different tools in EBSD analysis. The texture was not significantly affected by deformation in both types of alloy specimens. With increase in the deformation, the microstructures are characterized by degradation of EBSD patterns and generation of substructures including low angle boundaries (LABs) and high angle boundaries (HABs). In both the microstructures with low and high SDAS, the boundaries were concentrated around eutectic phases; however this behavior was more pronounced at higher SDAS. The increase in the fraction of LABs with deformation was much higher in the microstructure with higher SDAS than with lower SDAS. This localized strain concentration was especially attributed to the large and elongated eutectic Si particles and Fe-rich intermetallics. The lower mechanical properties obtained at higher SDAS are the result of inhomogeneous strain distribution in the microstructure.

1. Introduction

The increased use of Al–Si casting alloys in automotive applications is driven by their favorable characteristics such as excellent castability, high specific weight, high thermal conductivity and good corrosion resistance. Mechanical properties of these alloys are influenced by microstructural features such as porosity, SDAS, shape and distribution of the eutectic Si phase, as well as the presence of Fe-rich and other intermetallic compounds [1–4]. It has been observed that increase in the solidification rate leads to the decrease in secondary dendrite arm spacing and also leads to the refinement of the silicon eutectic [5,6]. In order to get the complete overview of the mechanical properties of Al alloys, it is necessary to understand the complete deformation behavior during mechanical loading. In this regard, it becomes imperative to analyze the role of microstructure in deformation. There are several questions that are interesting pertaining to this issue such as 'what is the role of intermetallics during deformation', 'does grain size have any effect', 'how does texture evolve' and 'how is the distribution of strain in microstructure'. The alloys with different microstructures could also be compared to understand the difference in their deformation behavior in response to the loading.

There has been a very limited study to understand the deformation behavior of cast Al–Si alloys with focus on microstructural aspects. EBSD is an effective technique to study the microstructural features such as crystal orientations, grain size and deformation characteristics at micro-level. EBSD is also now being increasingly utilized for strain analysis, both elastic and plastic strains [7–13]. The elastic strains are smaller and produce changes of just a pixel or two in EBSD patterns, therefore they need very careful analysis of high resolution images [14]. The analysis of plastic strain in polycrystalline material is more important in order to understand the deformation behavior and the failure mechanisms. There are two approaches to analyzing plastic strain; the first is based on degradation of diffraction patterns with strain and the second based on local misorientation.

Recently, tensile test stages have been developed to carry out in-situ SEM and EBSD studies. There have been a few recent studies on in-situ EBSD analysis on different materials. For example, Weidner and Biermann [15] investigated the tensile and cyclic deformation of TRIP steel by in situ SEM and 'pseudo in situ' EBSD. Kahl et al. [16] reported in situ EBSD investigations during tensile test of a soft-annealed AA3003 sheet in which grain rotations in and around the fracture zone were studied. In another study [17], the microstructural evolution of a cold drawn copper wire during primary recrystallization and grain growth was observed in situ by EBSD. The different steps of recovery, nucleation, twinning, and grain growth were described. However, all of the above studies have been performed on wrought alloys and low alloyed materials in which grain size is small, second phases are limited and texture evolution is significant. The behavior of cast alloys and especially high Si containing Al–Si alloys is expected to be quite different than Al and other wrought alloys.

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In the current study, Al–Si–Cu alloys have been cast by unique gradient solidification technique with two different solidification rates. An attempt has been made to understand the plastic deformation behavior of these alloys by in-situ EBSD testing during tensile deformation. The strain distribution, evolution of texture and the role of second phase in the deformation is studied with different types of tools used in EBSD analysis. The characteristic aspects of the deformation in two types of microstructures obtained with different cooling rates have been compared.

2. Experimental procedure

2.1. Casting of alloy samples

The alloy samples used in this study were prepared by remelting commercial Al–Si–Cu alloy (A380 alloy) in graphite crucible at 750 °C using the electrical resistance furnace. The melt was poured in a Cu mold preheated at 250 °C in order to produce rod shaped specimens. The composition of the alloys is presented in Table 1. The obtained die cast specimens were further remelted in the gradient solidification furnace. The samples inserted into the steel tubes were held in the furnace and melted at 710 °C under the protective argon atmosphere to avoid oxidation. The samples were left at that temperature for 20 min. Following this, the furnace is raised at a prescribed speed while the metal samples stay in a stationary position. The gradient solidification is achieved by cooling the samples with water jets at the base of rising chamber. Different cooling rates are obtained by changing the speed of the rising heating chamber. In this study, two different cooling rates corresponding to two different expected SDAS of ~8–12 and ~23–27 were used.

2.2. In-situ tensile testing

The samples for EBSD measurements were prepared by grinding and mechanical polishing with diamond paste up to 1 μm followed by 0.05 μm colloidal silica and then etching with 10% NaOH. For in-situ EBSD study, a two-step dumb-bell shaped flat tensile test sample with 1 mm thickness was cut from gradient solidified sample. The sample was cut with its length direction along the direction of solidification. The complete dimensions of the sample are shown in Fig. 1. A specially designed miniature tensile stage was used for in-situ EBSD measurements. The design of the tensile stage assembly, as shown in Fig. 2, is such that the sample rests at 70° required for EBSD acquisition. The tensile stage is connected to the controller outside SEM and sample is loaded in uniaxial tension with commands from the software. The tensile test software also generates load-elongation data which was used to calculate stress strain curve. While calculating stress strain values in the thinnest section of the sample, the error due to the strain generated in middle section of tensile sample as well as the deflection of the tensile stage were taken into consideration and suitable modifications were made.

2.3. In-situ EBSD study during tensile testing

Prior to the in-situ EBSD measurements, one specific area in the thinnest central section of the samples was selected to acquire good EBSD pattern. EBSD measurements were conducted in JEOL scanning electron microscope at an accelerating voltage of 25 kV with appropriate step size using OIM data collection software. The procedure for in-situ EBSD study involved loading the sample to specific strain intervals, stopping the test and collecting the EBSD scan from the same area of interest. Two scans with two different magnifications were obtained at each strain interval. In the case of Al–Si alloys, indexing Al and Si separately in EBSD becomes difficult because Al and Si have a similar crystal structure as seen by EBSD. This results in an ambiguous phase mapping, therefore in EBSD scanning, only Al was selected as indexing phase. EBSD analysis of the data was further performed using TSL-OIM Analysis software. It should be noted that all the EBSD maps in this paper were obtained by confidence index (CI) standardization followed by exclusion of points with CI less than 0.1. Tensile tests were carried out with Zwick/Roell Z 100 machine to compare the results with in-situ tensile tests. Tensile tests were carried out at room temperature using flat tensile test bars machined from gradient solidified round bars. The tensile sample had 25 mm gage length, 6 mm width, 6 mm radius of fillet and overall length of 100 mm. The tests were performed using displacement controlled mode. The crosshead speed was maintained at 1 mm/min and the strain was measured by clip-on extensometer until the samples fractured.

Table 1
Chemical composition of the cast alloy.

Element	Si	Cu	Fe	Mg	Mn	Zn	Ni	Al
wt.%	9.60	2.86	0.61	0.04	0.19	0.96	0.03	Balance

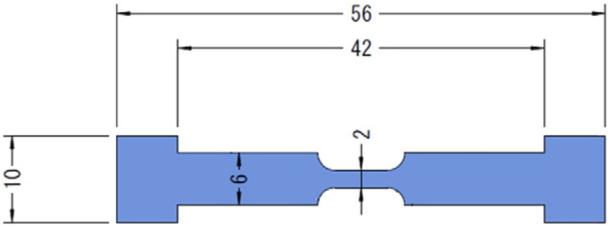

Fig. 1. Two-step tensile sample used for in-situ EBSD analysis, all dimensions are in mm.

3. Results and discussion

3.1. Optical microstructure

The microstructure of gradient solidified specimens was investigated with optical microscopy. Fig. 3a and b shows the microstructures of specimens cast with higher and lower solidification rate respectively. The SDAS values measured in two specimens were found to be 9 (±2.7) and 27 (±3.5) μm. Both the microstructures are characterized by the presence of primary dendrites, eutectic regions and intermetallic particles. Higher solidification rate results in well modified fibrous eutectic network and uniform distribution of intermetallics whereas lower solidification rate gives relatively random eutectic network consisting of plate shaped Si particles and larger intermetallics.

3.2. In-situ tensile test

The stress–strain curves plotted using load–displacement data from tensile stage are given in Fig. 4. The curves for both specimens show stress relaxation effects as the tensile test is interrupted at various intervals for EBSD scanning. The specific loading intervals were actually

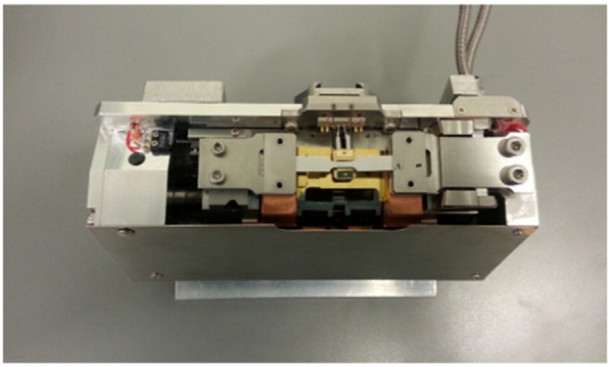

Fig. 2. Tensile stage with tensile sample used for in-situ EBSD analysis.