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High temperature tensile deformation behavior and failure mechanisms of an Al–Si–Cu–Mg cast alloy — The microstructural scale effect

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ABSTRACT

In this study the high temperature tensile deformation behavior of a commercial Al–Si–Cu–Mg cast alloy was investigated. The alloy was cast with two different cooling rates which resulted in average secondary dendrite arm spacing of 10 and 25 μm, which is typical of the microstructure scale obtained from high pressure die casting and gravity die casting. Tensile tests were performed at different strain rates (10^{-4} s^{-1} to 10^{-1} s^{-1}) and over a wide temperature range from ambient temperature to 500 °C. The fine microstructure had superior tensile strength and ductility compared to the coarse microstructure at any given temperature. The coarse microstructure showed brittle fracture up to 300 °C; the fracture mode in the fine microstructure was fully ductile above 200 °C. The fraction of damaged particles was increased by raising the temperature and/or by microstructure coarsening. Cracks arising from damaged particles in the coarse microstructure were linked in a transgranular-dominated fashion even at 500 °C. However, in the fine microstructure alloy the inter-dendritic fracture path was more prevalent. When the temperature was raised to 300 °C, the concentration of alloying elements in the dendrites changed. The dissolution rates of Cu- and Mg-bearing phases were higher in the fine microstructure.

1. Introduction

Research on Al–Si based casting alloys has been re-focused as a lightweight structural material for automobile applications, because of their superior specific strength, encouraging mechanical properties, cost-efficient manufacturing and easy recyclability. The Si addition promotes castability and enhances strength, and Cu and Mg are commonly added to improve strength at room and elevated temperatures. Fe additions are made to reduce the die soldering tendency [1]. The microstructure of these alloys contains α-Al dendrites as the main constituents, which are decorated with eutectic Si particles and many intermetallic phases such as Al_2Cu, Mg_2Si and various Fe-bearing phases. Depending on the geometry of the die cast components, the cooling rates vary with the local thickness of the component. This leads to variations in the scale of as-cast microstructural features such as secondary dendrite arm spacing (SDAS) and the size and morphology of second phase particles. A high cooling rate results in a low SDAS while a lower cooling rate yields a higher SDAS. This affects the plastic deformation behavior and mechanical properties of the castings, which are affected significantly by the scale of the microstructure [2].

The solute level (Si, Cu and Mg), quantity and type of precipitates significantly influence the hardening rate of aluminum alloys [3–5]. Si precipitates from the as-cast supersaturated solid solution during exposure to temperature range of 200–250 °C [6]. The kinetics of Si precipitation is closely linked to the amount of excess vacancy [7]. A considerable fraction of the vacancies form a significant number of loops which act as heterogeneous nucleation sites for precipitation of Si atoms [8,9]. High temperature exposure of Al–Si–Cu–Mg alloys may lead to changes in the concentrations of alloying elements and vacancies in solid solution and spheroidization of Si particles [10]. The dissolution rate of the various secondary phases is dependent on time and temperature of the exposure and the chemical composition and coarseness of the microstructure.

Unlike many engineering components of Al–Si–Cu–Mg alloys which are designed to be loaded within their elastic range, in several applications, particularly motor components working at elevated temperatures such as cylinder blocks, cylinder heads, pistons and valve lifters, the alloy undergoes plastic deformation. The plastic deformation can occur at different rates of strain depending on service temperature, exposure time and magnitude of the applied load [11]. The influence of strain rate (SR) has been widely studied in wrought materials in order to optimize production rate and processing temperature during thermo-mechanical processing. Unlike wrought aluminum alloys, experimental data on the effect of strain rate on the deformation behavior of Al–Si based cast alloys is limited.

The effect of SDAS, size and morphology of various microstructural constituents on the tensile properties of Al–Si–Cu–Mg alloys has been thoroughly studied at room temperature [12–15]. Rincon et al. [16,17] investigated the tensile and deformation behavior of A319 die cast alloy, in both as-cast and heat treated conditions at elevated temperatures up to 400 °C. Several researchers have been focusing on improving

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the high temperature tensile properties of Al–Si alloys. The concept is based on the formation of thermally stable and coarsening resistant precipitates through addition of trace elements such as Ni, Zr, Ti, Cr and V [18]. A remarkable improvement in tensile strength of Al–7Si–1Cu–0.5 Mg [19], Al–12Si–Mg [20], and Al–13Si–Cu [21] at 250 °C and above was reported and related to the trace element additions. However an understanding of the role of cooling rate, which determines the scale of various microstructural features, on the high temperature behavior of Al–Si based casting alloys is still lacking. Most published works on Al–Si–Cu–Mg casting alloys have been focused on the room temperature tensile properties. As yet, the role of strengthening mechanisms at elevated temperature has not thoroughly been considered in these alloys. In addition, it is expected that at elevated temperature, the scale of microstructure and strain rate will influence the mechanical behavior and failure mechanisms. The objective of this work is therefore to study the tensile behavior, microstructural evolution and failure mechanisms of EN AC-46000 (a typical Al–Si–Cu–Mg casting alloy) by investigating the effect of temperature, microstructural scale and strain rate.

2. Experimental procedures

2.1. Materials

The material used was EN AC-46000 aluminum alloy, containing (in wt.%) 10.0 Si, 2.6 Cu, 0.24 Mg, 0.8 Fe, 0.8 Zn and 0.26 Mn. Chemical composition was obtained using SPECTROMAXx optical emission spectroscopy. Ingots of the alloy were melted in a 10 kW resistance furnace at 730 °C in a silicon carbide bonded graphite crucible. The coating was applied using a commercial coating spray. Cylindrical rods (length 20 cm, diameter 1 cm) were cast in a permanent copper mold with a thin graphite coating. The cast rods were then re-melted and heated to 710 °C for 20 min under Ar-atmosphere and subsequently solidified using the gradient solidification technique [2]. The gradient solidification set-up enables the production of well-fed and homogenous samples, with low levels of oxides, solidification shrinkage and gas-porosity over the entire length of the sample. The pulling rate of the furnace was used to control the scale of the microstructure and defect-free samples were produced with a microstructure scale similar to high pressure die casting (HPDC) and gravity die casting. The pulling rate of the furnace was set to 3 and 0.3 mms^{-1}, which leads to average SDAS of 10 and 25 μm, respectively.

2.2. Tensile testing

Cylindrical tensile test bars according to ASTM B557M-10 [22] of 6 mm in diameter and 100 mm in length were prepared by machining the as-cast rods. The tensile test was conducted right after casting of specimen in order to exclude any aging effect on the results. Tensile tests were carried out using a Zwick/Roell Z100 tensile testing machine, at six different temperatures ranging from 25 °C to 500 °C. Four strain rates in the range from 10^{-4} to 10^{-1} were used. The highest strain rate, 10^{-1}, was selected due to the intrinsic limited ductility of the alloy, especially at temperature below 0.5 T_m. The lowest strain rate, 10^{-4}, was selected to avoid creep-like deformation of the alloy. The tensile strain was measured through an accurate laser extensometer. A wide test temperature range from room temperature up to slightly below the solidus temperature was chosen to allow using the experimental date to define a deformation behavior model of the alloy in a separate work. Stress–strain curves, the maximum stress value (R_m), the stress at 0.2% offset strain ($R_{p0.2}$) and the strain at which failure occurs (ε_F) were obtained from the data acquisition system of the machine. ε_F is overall strain in the gauge length (40 mm) until the failure. The tensile characteristic data was obtained according to engineering system. The flow curves were plotted according to true system. In order to have statistical significance in the results, at least four replicates for each case were performed. Prior to tensile testing, the specimens were heated to the pre-set temperature and held for 15 min to homogenize.

2.3. Microstructural analysis

The microstructures and fracture surfaces were studied using optical microscopy, (OLYMPUS GX71) and a scanning electron microscope (SEM, JEOL7001F) equipped with an energy dispersive spectrometer (EDS). In order to study concentration profiles and micro segregation of the alloy elements (Mg, Cu and Si) across the dendrite arms, an SEM equipped with wavelength dispersive X-ray spectroscopy (WDS) was employed. The WDS samples were heated to given temperatures, held for 15 min. and quenched immediately in 40 °C water. Three analysis points were measured across a single dendrite arm, and at least nine dendrites were measured for each sample. Image analysis was used for qualitative study of microstructure evolution at elevated temperature. In order to study the evolution of microstructural features at elevated temperatures a region in the center of a prepared specimen was identified by micro-indentation. The specimen was then heated to temperatures in the range from 300 to 500 °C, held for 15 min and studied after each heating without any additional surface preparation. Grain size determination was made through electron backscattering diffraction analysis to (i) ensure that there were no texture effects from the sample manufacturing, and (ii) to measure size of the grains. In order to characterize the failure mechanisms, the broken tensile specimens were mounted with the exposed cross-section parallel to the tensile axis and ground and polished to expose the center of the cylindrical bar. The fraction of fractured particles was examined by optical microscopy and quantitatively assessed using the Stream Motion image analyzer. A rectangular area 5 × 1 mm on both sides of the fractured surface, (not closer than 0.1 mm to the fracture surface) was measured. No attempt was made in the quantitative analysis to distinguish the type, size and orientation of fractured particles. Differential scanning calorimeter (DSC) analyses were carried out in a purified argon atmosphere using a NETZSCH 404C Pegasus® instrument with the scanning rate of 5 °C/min in order to study any non-equilibrium reactions which may occur during heating. All the error bars in measurement and analysis were calculated based on 95% confidence interval. This applies to all of the figures. The error bars which are not applied are just as small as the points.

3. Results and discussion

3.1. Microstructural characterization

3.1.1. The scale and morphology of microstructural features

Fig. 1 shows the microstructural features of the EN AC-46000 alloy as-cast at two different cooling rates. The cooling rate governs size, morphology and distribution of the eutectic Si particles and intermetallic compounds [23,24]. The microstructure consists of primary α-Al dendrites surrounded by eutectic Si particles and intermetallic phases. The intermetallic phases identified (Al_2Cu, α-Al_8Fe_2Si, β-Al_5FeSi) are indicated in Fig. 1, which illustrates the effect of cooling rate on the scale of the microstructure. Increasing the solidification rate refines all microstructural features, decreases the SDAS and changes the morphology of eutectic silicon from large and elongated plates to small and rounder particles. This is supported by quantitative measurements of eutectic particle aspect ratio, see Table 1.

3.1.2. Cu- and Mg-bearing phases

The change in microstructure after heat treatment (15 min) at various temperatures for both cooling rates is shown in Fig. 2. It can be seen that increasing the temperature results in dissolution of the Cu-containing particles (mostly Al_2Cu) formed during solidification. A final polishing step using colloidal silica (OP-S) was used to enhance the Cu-bearing phases, turning their color to one that is readily detectable.