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Scripta Materialia 60 (2009) 427–430
Scripta MATERIALIA
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Constitutive behavior of as-cast magnesium alloy Mg–Al3–Zn1 in the semi-solid state

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Received 18 September 2008; revised 13 November 2008; accepted 14 November 2008
Available online 24 November 2008

The first reported tensile semi-solid stress/strain data for as-cast magnesium alloy Mg–Al3–Zn1 are provided. The results show that the maximum tensile stress at the solidus temperature (460 °C) was 13 MPa. Furthermore, this alloy has no ductility above 540 °C, and cannot sustain tensile stresses above 560 °C. Based on these tests, an equation relating the maximum tensile stress with temperature was derived. The microstructure of the tested specimens was also examined to link the tensile properties to fraction solid and microstructure.

Keywords: Semi-solid; Magnesium alloy; Tensile properties; Hot-tearing; Direct chill casting

Magnesium alloys have the highest strength-to-weight ratio of common structural metals, and hence offer many benefits in terms of reduced weight and energy savings for both the automotive and the aerospace industries, in spite of their higher cost. These benefits have lead to a significant increase in the demand for cast and wrought magnesium products in recent years [1]. One of the most common commercial magnesium alloys used for wrought products is AZ31, due to its good mechanical properties. As compared to both aluminum and steel, the use of AZ31 provides a significant mass reduction for applications with large surface area. The direct chill (DC) casting process, which is utilized to produce the starting material for this alloy, is receiving more attention for the sake of process optimization [2] and defect reduction.

The DC casting process has been used to cast magnesium alloys for approximately 50 years. Although much work has been done to minimize solidification defects, hot tearing, cold cracks and dimensional control remain serious issues. Hot tears are thought to occur as a result of the development of tensile strains in the casting at high fraction solid (f_s) due to the temperature gradients and/or mechanical constraints [3], in combination with limited liquid feeding [4] and low ductility [5]. In recent years, a number of mathematical models [6–8] have been developed to quantify the influence of casting parameters on the development of semi-solid thermal stresses and strains, in an effort to reduce solidification defects. These models require prior knowledge of magnesium's constitutive behavior in the as-cast state over a wide range of temperatures and strain rates. While research has been performed to characterize AZ31 under compressive loading and in the fully solid state (e.g. [9,10]), little is known regarding the semi-solid constitutive behavior of AZ31 and of magnesium alloys in general.

Due to the technical challenges of thermal control, and stress/strain measurement, it is inherently difficult to measure the semi-solid constitutive behavior of metallic alloys. Methods for such tests can be divided into two categories: (i) cooling from the liquid state to the semi-solid state or (ii) reheating a cast sample from room temperature up to the semi-solid temperature range. A detailed summary of these methods has been previously provided [12]. In this research, reheating tensile tests were carried out on as-cast AZ31 in the high temperature solid and semi-solid states to determine the stresses and strains that can be sustained by magnesium alloys at high fraction solids. These measurements will improve the mathematical simulations of DC casting, and hence aid in reducing solidification defects related to deformation.

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doi:10.1016/j.scriptamat.2008.11.011

The as-cast AZ31 magnesium alloy used in this study, with composition Mg–3.21 wt.%Al–1.02 wt.%Zn–0.31 wt.%Mn, was industrially DC cast by Timminco Ltd., Canada. The material consists of equiaxed-globular grains with an average grain size of 203 ± 12 μm, and fully solid constitutive behavior as provided in Ref. [9] (the same billet was used for both studies). An optical micrograph of the original as-cast grain structure is shown in Figure 1. Cylindrical tensile specimens ($l = 120$ mm, $\phi = 10$ mm) were machined from the ingot with their long axis both normal to the casting direction and parallel to the ingot surface. Each specimen also contained a central reduced region ($l = 15$ mm, $\phi = 5$ mm).

The semi-solid tensile tests were performed using a DSI Gleeble 3500 thermomechanical simulator in combination with the two-thermocouple technique previously developed by Phillion et al. [12] for aluminum alloys. Tests were conducted at temperatures between 400 and 570 °C and at a strain rate of $\sim 10^{-3}$ s^{-1}. The relevant portion of the fraction solid–temperature relationship for AZ31, experimentally derived by Lu [13], is given in Table 1. During testing, the force, f, was recorded using a 4500 N load cell, and the current diameter, D, of the gauge region was recorded using a Beta LaserMike laser dilatometer. The true stress σ and true strain ε were derived from the recorded force and diameter, based on the standard equations of $\sigma = 4f/(\pi D^2)$ and $\varepsilon = 2\ln(D_0/D)$, where D_0 is the initial diameter.

One significant technical challenge in testing magnesium alloys at semi-solid temperatures is the risk of fire since these alloys are prone to burning. There is also the potential for an explosion if water is present since they can produce hydrogen gas. In order to perform the experiments, a number of precautionary measures were taken to minimize these safety hazards. These measures included modifying a fire extinguisher to interface with the Gleeble chamber and reducing the partial pressure of oxygen in the Gleeble chamber using a combination of air removal via vacuum and argon back-fill.

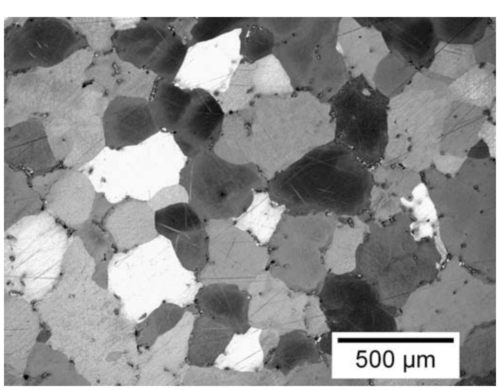

Figure 1. Optical micrograph of the initial grain structure of the as-cast AZ31 material used in this study.

Table 1. Variation in f_s with temperature for AZ31 after Lu [13].

f_s	Temperature (°C)	f_s	Temperature (°C)
1.0	460	0.90	562
0.98	504	0.85	572
0.95	545	0	630

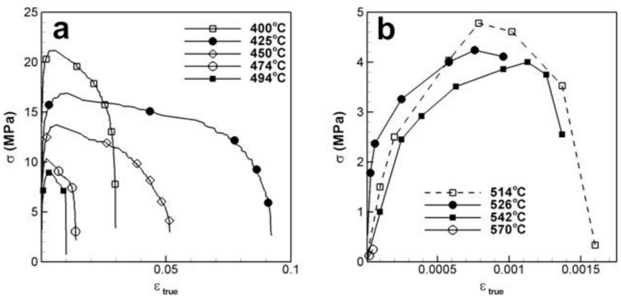

Figure 2. True stress vs. true strain results for as-cast AZ31 at (a) 402–494 °C and (b) 514–570 °C.

After the tensile tests, a number of the tensile specimens were sectioned parallel to the loading direction for optical metallography and scanning electron microscopy of the fracture surfaces. The specimens for optical metallography were mechanically ground, polished using diamond suspensions of 6 and 1 μm, and then etched for ∼20 s with an acetic–picric solution (10 ml acetic acid, 10 ml water, 4.2 g picric acid, 70 ml ethanol) to reveal the microstructure.

The stress/strain response of as-cast AZ31 as a function of temperature is shown in Figure 2. The results have been plotted on two separate graphs (Figure 2a, 402–494 °C; Figure 2b, 514–570 °C), as there is a substantial decrease in ductility between 494 °C ($f_s \sim 0.98$) and 514 °C ($f_s \sim 0.96$). As can be seen in both figures, the yield stress is observed to decrease as a function of temperature for all tests. In Figure 2a, the typical material behavior for the high temperature solid state and semi-solid state at low fraction liquid is shown – i.e. there is an increase in stress with deformation until a yield point is reached, the stress then decreases slightly with increasing strain (the material softens) followed by a period of rapidly decreasing stress (necking). In contrast, the material containing a higher fraction liquid, Figure 2b, shows little ductility.

In the solid state, the softening shown in Figure 2a is due to the time-dependent creep effects. In the semi-solid state, the rapid drop in stress is thought to be due to the rapid accumulation of internal damage (i.e. voids and cracks) during deformation [14]. Since stress is derived from the ratio of force to cross-sectional area based on the external specimen diameter, its true value is underestimated because of the presence of internal damage. In Figure 2a, it also appears that the observed ductility at 402 °C is much lower than the ductility at 425 °C. This is because in the test at 402 °C the centre of the neck formed outside the laser dilatometer measurement zone. The combination of considerable necking and erroneous dilatometer measurements results in apparent reduced ductility. When the post-deformed specimen diameter was measured using calipers, the ductility at 402 °C was found to be much larger than the ductility at 425 °C.

In Figure 2b, it can be seen from the stress/strain curves that the higher-temperature semi-solid AZ31 does not exhibit a well-defined yield point upon tensile loading. This is probably due to the deformation occurring in the liquid within the cross-section. Furthermore, the ductility at all temperatures is quite low, with true strain values less than 0.15%. Thus, it appears that the