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# Impact of homogenization heat treatment on the high temperature deformation behavior of cast AZ31B magnesium alloy

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ABSTRACT

Uniaxial isothermal compression tests were conducted on cylindrical specimens extracted from a DC cast AZ31B ingot with and without a homogenization treatment in the temperature range of 300 °C–500 °C, at strain rates of $10^{-3}$ $s^{-1}$–1.0 $s^{-1}$. As-cast specimens (without a homogenization treatment) exhibited cracking at a strain rate of 1.0 $s^{-1}$ for deformation temperatures of 400 °C and above. The cracking is believed to be associated with incipient melting of the γ-$Mg_{17}Al_{12}$ phase. Homogenization of the specimens at 450 °C for 5 h improved the hot workability and no cracking was observed under the investigated conditions. Deformation of the cast-homogenized material was successfully conducted at 500 °C and 1.0 $s^{-1}$, to a final strain of 1.0. The volume fraction of dynamically recrystallized (DRX) grains was observed to increase with strain, but the DRX grain size exhibited little to no change. The DRX grain size however did increase with deformation temperature and with decreasing strain rate. Increasing the deformation temperature from 350 °C to 500 °C increased the maximum allowable strain before cracks were observed at the surface. Additional specimens were homogenized at temperatures of 400 °C or 500 °C, for times of 3 h or 5 h, followed by a water quench or air cooling. Under all circumstances, incipient melting of the γ-$Mg_{17}Al_{12}$ phase was no longer observed upon heating using differential scanning calorimetry (DSC). Furthermore, homogenization at a temperature of 350 °C for up to 8 h resulted in partial dissolution of the γ-$Mg_{17}Al_{12}$ phase, and an increase in incipient melting onset temperature was observed by DSC.

## 1. Introduction

Compared to traditional engineering materials such as steels and aluminum (Al) alloys, magnesium (Mg) alloys can possess higher specific strength due to their low density. In recent years, automotive manufacturers have focused on reducing the overall weight of their vehicles in order to reduce exhaust emissions. Aside from improvements in drivetrain efficiency, weight reduction is the most effective method of reducing vehicle emissions, as shown by Friedrich and Schumann (2001). Presently, the applications of Mg within the automotive industry have predominantly been limited to non-structural cast and/or sheet components (Friedrich and Mordike, 2004). Although recent developments in casting processes such as vacuum die casting have been able to lower porosity levels (Luo, 2013), the gains observed in terms of mechanical strength are in the range of 5–15% (Brown et al., 2009). Larger improvements in strength have been observed with the development of a wrought microstructure through forging of a cast ingot (Friedrich and Mordike, 2004).

Although Mg alloy research has picked up over the last decade, the number of studies relating to Mg castings and forgings is far fewer than those available for Al alloys and steels. Currently, part of the reason for the limited use and applications of forged Mg is the limited knowledge-base for this metal compared to other commonly used metals such as steels and Al alloys. One hurdle for Mg to overcome is the limited number of slip systems that can be readily activated at room temperature, which results in poor formability, according to the von Mises criterion of ductile materials (Mises, 1928). However, Chapuis and Driver (2010) reported that non-basal slip readily activated at elevated temperatures greatly improves the formability of Mg alloys. In addition to the activation of non-basal slip, high temperature deformation of Mg also promotes the occurrence of dynamic recrystallization (DRX), which allows for the development of a wrought microstructure (Beer and Barnett, 2007).

The low cost of AZ31B compared to other Mg alloys makes it an attractive material choice for forging from a production standpoint. Wong et al. (2018) had observed that, under certain high temperature processing conditions, a microstructure with minimal defects could be obtained through compression of extruded AZ31B. However, by

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starting with a cast material, it may be possible to reduce production costs further. In order to conduct a successful forging operation at high temperature, the as-cast structure of the alloy should be modified through a homogenization heat treatment. Several past studies have investigated the homogenization behavior of cast AZ31B. Prasad and Rao (2009) studied the impact of homogenization on the hot deformation behavior of AZ31B, where as-cast specimens deformed at 500 °C exhibited fractures when the strain rate exceeded $1.0\ s^{-1}$. It was observed that homogenization for 5 h at 450 °C dissolved the $Al_2Mg_3Zn_3$ intermetallic phase and γ-$Mg_{17}Al_{12}$ eutectic structure, with the end result being a widened working window. Bajargan et al. (2013) observed that specimens homogenized for 24 h at 400 °C could be deformed at higher strain rates without the occurrence of strain localization by increasing the deformation temperature. Finally, Mohammadi et al. (2014) observed rapid melting of the γ-$Mg_{17}Al_{12}$ phase in AZ31B when homogenization temperatures exceeded the eutectic temperature of 437 °C, with the presence of the liquid phase being detrimental to elongation during hot tensile testing at 437 °C. Similarly, presence of liquid γ-$Mg_{17}Al_{12}$ phase can be detrimental to the forgeability of AZ31B in areas under tensile stress during die filling due to the formation of surface cracks.

Despite the studies mentioned above, the range of homogenization conditions under which an improvement in workability is achievable is still unclear. The objective of the current study is to investigate the viability of forging a structural component from a cast Mg ingot, and to determine the homogenization and processing conditions that will produce a final product free of major defects. Isothermal compression tests were conducted in a Gleeble® 3500 thermal-mechanical simulation system to study the hot deformation behavior, and differential scanning calorimetry (DSC) was used to study the impacts of various homogenization conditions.

## 2. Materials and experimental methods

### 2.1. Compression tests

To study the deformation behavior of cast AZ31B, uniaxial compression tests were conducted on a Gleeble 3500® thermal-mechanical simulation system to replicate an open die upsetting operation. The forging temperature range of interest was 300 °C–500 °C, at constant true strain rates of $10^{-3}\ s^{-1}$–$1.0\ s^{-1}$. Cylindrical compression specimens, Ø10 mm by 15 mm, were machined from a Ø304.8 mm (Ø12”) direct-chill (DC) cast ingot purchased from Magnesium Elektron. The compression axis of the specimens was oriented along the casting direction, and was located along a Ø210 mm reference circle, concentric with the ingot. Homogenization treatments for the compression specimens consisted of 5 h at 450 °C in a Thermo Scientific Lindberg Blue M furnace with an air atmosphere. Additional homogenization studies were carried out for DSC, as discussed in the next section.

To minimize the influence of friction during deformation, a nickel-graphite-based lubricant was applied to the contact surfaces prior to compression. A k-type thermocouple was spot welded to the axial center of each specimen to measure and control the instantaneous specimen temperature. Each specimen was resistively heated to the specified temperature at 10 °C/s and held for 5 s to allow the temperature to stabilize across the specimen. After being deformed to the specified strain, each specimen was immediately water quenched.

Each specimen selected for metallographic examination was sectioned along the compression axis, followed by mechanical grinding and polishing, and chemical etching using an acetic-picral solution (containing 4.2 g picric acid, 10 mL acetic acid, 10 mL water, 70 mL ethanol). Images were taken using an Olympus BH2-UMA optical microscope.

### 2.2. Differential scanning calorimetry

The effect of homogenization heat treatments on thermal events which occur during heating to the forging temperature was studied using DSC. In heat flux DSC, the temperature difference between a sample and reference material is recorded as a function of the test temperature. During a thermal event, a temperature difference arises between the sample and reference material. The temperature difference appears as a peak in the thermal data, where the area under the peak is proportional to the enthalpy of the reaction, after instrument calibration. For example, during melting, the temperature of the sample lags behind the reference, and an endothermic peak appears in the thermal data.

A Netzsch DSC 404C Pegasus® instrument, which was temperature and enthalpy calibrated to a high degree of accuracy, was used throughout the current study. AZ31B samples, Ø5 mm by 3 mm, with masses of approximately 100 mg were contained in an alumina crucible and placed on the sample side of the DSC measuring head. To reduce the effect of the sample mass on the thermal results, a pure Mg sample of similar mass to the AZ31B samples was placed within an alumina crucible on the reference side of the measuring head. After lowering the furnace over the measuring head, the furnace chamber was evacuated and backfilled by flowing high purity (99.999%) argon (Ar) gas throughout the test duration. A constant heating and cooling rate of 10 °C/min was used for all tests. To eliminate the equipment and crucible thermal effects from the data, a correction file was run with empty crucibles on both sides of the measuring head, using the same experimental settings as the sample runs. Typically, samples were heated from room temperature to a specified peak temperature and cooled back to room temperature. Additional thermal analysis was performed to study the extent of solid-state dissolution of the γ-$Mg_{17}Al_{12}$ phase, where isothermal holds between 1 and 8hr were introduced into the temperature profile at 350 °C, before continuing to heat to 500 °C.

## 3. Results and discussion

### 3.1. Initial material characterization

Inductively coupled plasma optical emission spectroscopy (ICP-OES) was used to determine the actual composition of the AZ31B samples used in this study. Each specimen contained 4.12 wt.% Al, 1.03 wt.% zinc (Zn), and 0.38 wt.% manganese (Mn). As discussed by Zhang et al. (2011), DC cast Mg commonly exhibits inverse segregation, whereby the alloying content increases outward from the ingot centerline; hence the composition of the compression specimens deviated slightly from the nominal composition.

The initial microstructures obtained from the as-cast and cast-homogenized specimens are shown in Fig. 1. As discussed by Toscano et al. (2017), who studied the same alloy as the current study, the initial as-cast AZ31B microstructure contains a network of Al-Mg-Zn intermetallics, with the γ-$Mg_{17}Al_{12}$ eutectic structure and Mg-Zn intermetallic compounds forming in the inter-dendritic regions. Furthermore, a Bruker D8 Discover x-ray diffraction (XRD) system was used to verify the random initial texture in the ingot as seen in Fig. 2.

### 3.2. Deformation behavior

Although anisotropy of flow is commonly observed during deformation of strongly textured Mg (Yukutake et al., 2003), the random texture observed in the as-cast ingot allowed for isotropic material flow under all investigated conditions. Deformation of the as-cast specimens at high temperature and high strain rate resulted in the formation of large cracks at the surface, specifically for temperatures of 400 °C and above at a strain rate of $1.0\ s^{-1}$, as shown in Figs. 3 and 4. Furthermore, as a result of the large initial grain size, the unconstrained surfaces exhibited an orange peel effect during deformation.