

Bolt Load Retention and Creep Response of AS41 Alloyed with 0.15 % Ca

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ABSTRACT

Understanding the creep and bolt load retention (BLR) behaviour of promising Mg-Al alloys are crucial to developing elevated temperature resistance alloys. This is especially true for elevated temperature automotive applications with a prevalence of bolted joints. In this study, creep and fastener clamp load response of Mg-Al alloy AS41 was investigated and compared to that of Mg4Al and AS41 micro-alloyed with 0.15 % Ca. A compliance-creep approach was used to model the response of these Mg-Al alloys at bolted joints. The equation prediction of the BLR response and experimental results are in good agreement. AS41+0.15 Ca shows improved creep and BLR properties up to 175 °C. A correlation between the microstructures, creep and BLR results reveal that the formation of a ternary CaMgSi phase is responsible for the improved elevated temperature behaviour.

INTRODUCTION

Successful weight reduction in commercial vehicles using Mg-alloys requires application of cost effective and suitable elevated temperature alloys. Most of the available high temperature resistance Mg-alloys are relatively expensive and cannot be conveniently applied on commercial vehicles. Reasonable progress has been made in producing Mg-alloy components for power train applications in recent years. These include HPDC (High Pressure Die Casting) Mg-alloys such as AJ (Al, Sr) series used as engine block with Al alloy inserts [1]. Others include transfer case, alternator bracket, cam cover, manual and automatic transmission casing etc [2, 3]. The amount of Mg-alloys used by the automotive industries however, has not increased significantly. This is partly because of the cost and its elevated temperature property profile. The demands of parts like gear box housings requires stable Mg-alloys with creep resistant and bolt load

retention properties up to 150 °C. Suitable fatigue and adequate corrosion behaviour is also necessary.

It was suggested that the poor creep response exhibited by AZ and AM alloys are connected with the softening of the intergranular β -Mg₁₇Al₁₂ phase which leads to grain boundary deformation [4]. Mg-alloys containing more than 2 wt. % of Al form the β -Mg₁₇Al₁₂ phase which increases as the Al level increases. Most of the die cast Mg-alloys use in the automotive industry (AZ and AM series) have between 2 to 9 wt. % Al content. This makes the precipitation of β -Mg₁₇Al₁₂ almost unavoidable. Reduction of the volume concentration of this Mg-Al phase or inhibition of its precipitation during solidification of Al containing Mg-alloys becomes necessary for improved elevated temperature property profile of Al bearing Mg-alloy series. Important also is encouraging segregation strengthening using inexpensive alloying elements within the grains and at the grain boundaries. This will delay dislocation movement at elevated temperature thereby improving its elevated temperature behaviour. Ca additions have also been effective in forming stable intermetallics such as Al₂Ca or Mg₂Ca [5, 6, 7].

Having a density of 1.9 g/cm³, the Mg₂Si is a high temperature stable phase with melting temperature of 1085 °C. Early works that gave birth to the AS series began in the 1960's to replace the highly stressed AZ81 that was used by Volkswagen for transmission casing and cam shaft gear wheels at the time [8]. Luo and Pekguleryuz did micro-alloying of AS41 with Ca between 0.08% - 0.18% and studied the microstructures [9]. In their work, it was reported that Ca content in the range of 0.11%–0.13% refined the microstructure of the brittle “Chinese script” (Mg₂Si) and improved castability. Additions of Ca slightly improved the room temperature yield strength and ultimate tensile strength of AS41. Up until now, the elevated temperature (BLR and

Table I. Alloy composition in (wt. %)

Alloys	Al	Si	Mn	Ca	Zn	Mg
Mg4Al	4.27	0.02	0.02	---	0.02	bal
AS41	4.14	1.03	0.24	---	0.06	bal
AS41+0.15 % Ca	4.33	1.05	0.29	0.10	0.01	bal

creep) behaviour of Ca micro-alloyed AS41 has not been studied.

In the past, several attempts have been made to predict bolt load retention behaviour of Mg-alloys [10, 11]. Others include the application of finite element method in predicting the time dependent stress state at bolted joint of Mg-alloys [12, 13]. The work of Chen et al. [14], was the application of Arimond's mechanical element model [15] to Mg-alloys. References [12, 13] used a “three parameter creep” approach coded in FEM program in describing the time dependent stress-strain response in both instrumented bolt and load cell measuring techniques.

This work studies the elevated temperature behaviour, including creep and BLR, of AS41+0.15 % Ca and compares it with those of Mg4Al and AS41 alloys. A compliance-creep approach is used to predict the bolt load retention response of these alloys up to 350 hours.

EXPERIMENTAL PROCEDURES

Permanent cast Mg4Al, AS41 and AS41+0.15 % Ca were used in this investigation. The alloys were cast into a detachable steel mould. This produces cast billet of 400 mm height and 100 mm diameter. The melt and mould temperature were 700 °C and 220 °C respectively. Casting was carried out under 0.2 % SF₆ - argon mix cover gas and cooled in air. The measured compositions of the alloys are shown in [Table I](#). Samples were machined to the desired specification for each test.

<[table 1](#) here>

The microstructure of the alloys under investigation was observed using scanning electron microscope (SEM) equipped with energy dispersive x-ray analysis (EDX). SEM and EDX were carried out using a ZEISS DSM-962 instrument operating at 15 kV. Samples for SEM investigations were prepared as presented in previously referenced literature [16]. A “2330 Lever Arm” Applied Test System (ATS) machine was used for creep testing. Experiments were conducted at constant stress and temperature according to ASTM (E 139 - 00) standard. BLR tests were conducted using continuous measuring load cell techniques. Complete information on the BLR testing procedure was described elsewhere [7, 13]. Cylindrical specimens with an outer diameter of 20 mm, an inner diameter of 10 mm and a height of 15 mm were used.

Baseline tests was conducted at 17 kN load and 150 °C using steel samples of the same configuration as the Mg-alloy samples. X-ray diffractions (XRD) were carried out using a D5000 Siemens diffractometer operating at 40 kV and 40 mA with CuK α radiation. Measurements were performed by step scanning 2 θ from 20 to 120° with a step of 0.02°. A count time of 3 seconds per step was used.

MODELING BOLT LOAD RETENTION: COMPLIANCE -CREEP APPROACH

The response of a Mg-alloy component at a bolted joint depends on various parameters. These include the stress at the joint, operational temperature, the equivalence compliance of the joint and coefficient of thermal expansion (CTE) of members of the joint. Others include creep behaviour of the Mg-alloy component and geometry of the sample among other variables. In modeling the BLR behaviour of the Mg-Al alloys, these parameters were used in predicting the time dependent bolt load loss on the bolted joint.

[Figure 1\(a\)](#) shows the bolted couple used in this analysis while [Figure 1\(b\)](#) represents different stages associated with a typical BLR experiment for a Mg-alloy component. Point (P_i) is equal to the initial clamp load operational at the joint. The change in bolt load (ΔP) from (P_i) to point (P_k) in [Figure 1](#) is computed with [equation 1](#). (P_k) is the highest point attained by the couple just before relaxation begins.

<[figure 1](#) here>

$$\Delta P = \Delta T l_{mg} \left(\frac{\alpha_{mg} - \alpha_{steel}}{C_{eq}} \right)$$

Equation 1

In [equation 1](#), ΔT is the change in temperature from room temperature condition T₁ to the temperature of interest T₂. The symbol l_{mg} is the thickness of the Mg-alloy component. The thermal expansion coefficient of the Mg-alloys and steel components were represented as α_{mg} and α_{steel} respectively. The equivalence compliance C_{eq} is the sum of the compliances of the bolted couple. These include Mg-alloy sample, steel bolt, washers and sensor. Compliance is the inverse of stiffness and is geometry dependent. It is directly proportional to length and inversely proportional to the

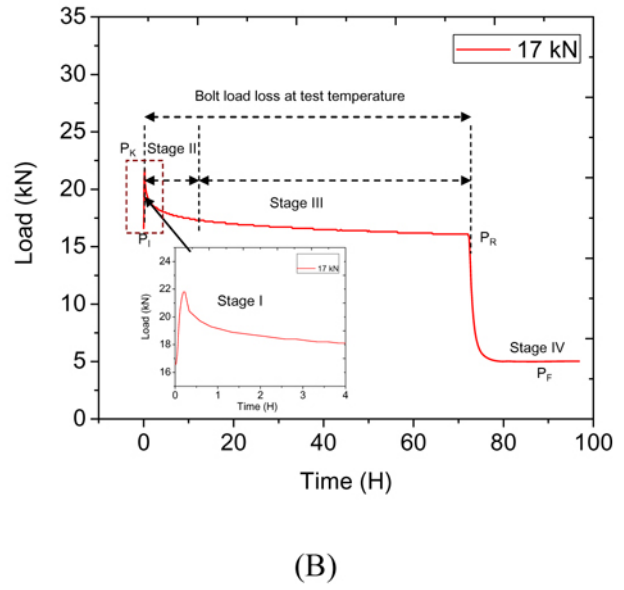
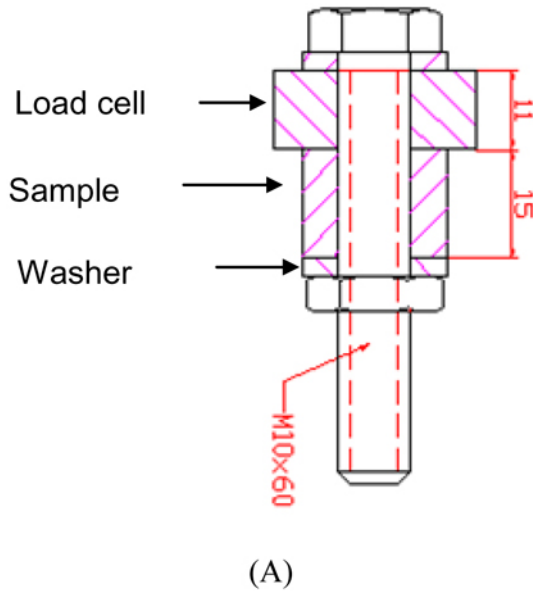


Figure 1. (a) Bolted couple used in BLR test, (b) Stages associated with typical BLR experiments

stressed area and elastic modulus. The bolt load at point (P_K) could then be expressed as the sum of the initial load and ΔP .

Stages (II & III) in Figure 1 represent the bolt load loss due to creep of the Mg-alloy at the test temperature. It is assumed that at the temperature of this investigation, steel bolts will not creep. Stages (II & III) could therefore be modeled using creep information of the Mg-alloy under investigation. Stage (IV) is the bolt load at the joint when cooled back to room temperature. The compressive creep behaviour of the Mg-alloys used for modeling the region between P_K and P_R in Figure 1 is giving by equation 2.

$$\varepsilon_c = \beta t^{n_i} \quad \text{Equation 2}$$

From equation 2, ε_c is the creep deformation, β is a material dependent constant and n_i is compressive creep parameter. Taking the natural logarithm of equation 2 results in equation 3, so that a plot of $\ln(\varepsilon_c)$ against $\ln(t)$ gives a straight line whose slope is n_i .

$$\ln \varepsilon_c = \ln \beta + n_i \ln t \quad \text{Equation 3}$$

The time dependent deformation due to creep of a Mg-alloy at a bolted joint is then represented using equation 4. In equation 4, ε_i is equal to the sum of elastic and partly plastic strain sustained by the magnesium component. While t is the creep time, n_i is the compressive creep parameter computed from equation 3 and k_i is dimensionless constant that depends on the joint-to-bolt stiffness ratio of the couple. The time

dependent bolt load loss due to creep of the magnesium component could then be expressed as $P(t)$ as shown in equation 5. C in equation 5 is a temperature and specimen geometry dependent material constant.

$$\varepsilon_{(t)} = \varepsilon_i t^{-k_i n_i} \quad \text{Equation 4}$$

$$P(t) = C \varepsilon_i t^{-k_i n_i} \quad \text{Equation 5}$$

RESULTS

MICROSTRUCTURES

<figure 2 here>

The SEM micrographs of as cast Mg4Al, AS41 and AS41+0.15 % Ca are shown in Figure 2(a, b & c) respectively. In Figure 2(a), the α -Mg matrix and the eutectic Mg-Al precipitate are clearly seen. The Mg-Al phase is observed mostly at the grain boundary and dendrite regions. For as cast AS41 in Figure 2(b), the presence of "Chinese script" (Mg_2Si) and Mg-Al precipitate are shown. The Mg_2Si is observed mostly within the α -Mg matrix and close to the grain boundaries. The SEM micrograph of AS41 microalloyed with 0.15 % Ca is shown in Figure 2(c). In addition to α -Mg, Mg-Al, Al-Mn and Mg-Si phases, the presence of the $CaMgSi$ phase is also observed. The $CaMgSi$ phase is seen in the grains and within the grain boundaries. Quantitative EDX point measurements of Figure 2(c) on the labeled spots are shown in Table 2. The presence of this ternary phase $CaMgSi$ has also been confirmed by XRD as shown in Figure 3.