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Modeling Bolt Load Retention of Ca Modified AS41 Using Compliance-Creep Method

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Abstract. Adequate quantification of the degree of fastener clamp load retained at bolted joint of Mg-Al alloys is crucial to develop new elevated temperature resistant Mg-alloys. Several attempts have been made in the past to model Bolt Load Retention (BLR) behaviour of Mg-alloys using different approaches. It must be mentioned that whereas these models attempt to predict BLR of the alloys investigated, the results of the models differ in most cases with the experiments by great margin. The BLR behaviour of Mg-alloy is geometry and material dependent. This means that, the configuration of the test sample, the compliance of the bolt/joint and creep response of the material under investigation play important role in determining the joint response under load and temperature. In this work, BLR and creep behaviour of Ca modified AS41 is investigated and compared to that of Mg4Al and AS41. A compliance-creep approach is used to model the response of these Mg-Al alloys at bolted joints. The model prediction of the BLR response and experimental results as obtained in this work 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

Fastener clamp load retention has continued to be a concern to proper usage of Mg-alloys as power train components in automotive application. Traditional die-cast Mg-alloys like AZ and AM based alloys have found application in the automotive industry but can not be used effectively above 120 °C. These alloys, when bolted together with other materials at elevated temperature under load, loses fastener clamp load due to creep of the Mg-alloy component. This loss of bolt load could lead to unsatisfactory performance of the engineering part. Some of the approaches used in modeling the BLR response of Mg-alloys include mechanical element model [1]. This was applied in predicting the time dependent bolt load loss on AE42 and AZ91 [2]. Others include the application of Norton´s relationship to describe the time dependent drop in stress on Mg-alloys [3] and more recently the application of finite element program on both instrumented bolt and load cell measuring techniques [4].

Apart from the FEM approach, in most cases, the contribution of the thermal expansion properties of the component parts on the inception of the BLR test was not accounted for in the models. The thermal expansion mismatch occasioned by the differences in coefficient of thermal expansion coefficient between the steel bolt and the Mg-alloys are important in determining the final bolt load in a joint couple. Depending on the load and temperature at the bolted joint, plastic deformation may have occurred in the inception of the BLR test. Excluding this may lead to major discrepancy between models and laboratory results. In the past, models attempting to predict BLR of Mg-alloys have employed tensile creep properties. However, it is well known that Mg-alloys show differences in tensile and compressive creep deformation [5]. Again, most of the power train components are loaded in compressive mode. Models attempting to predict BLR of Mg-alloys should include among other things, the compressive creep behaviour of the alloy under investigation.

Experimental Procedures

Mg4Al, AS41 and AS41+0.15 % Ca produced using permanent mould technique was used in this investigation. 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 used in this work are shown in Table 1. Mg is the remaining balance in all the three alloys. Samples were machined to desired specification for each test. Scanning electron microscopy (SEM) and Energy dispersive x-ray (EDX) analysis were carried out using a ZEISS DSM-962 instrument operating at 15 kV. Creep 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 as described in [6]. Cylindrical specimens measuring 20 mm x 10 mm x 15 mm were used. That is outside diameter, inside diameter and thickness.

Table 1. 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

Concept of the BLR Model

Mg-alloy component in a bolted joint are influenced by several parameters. These include the stress at the joint, service 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 response of the Mg-Al alloys, these parameters were used in predicting the time dependent bolt load loss on the bolted joint.

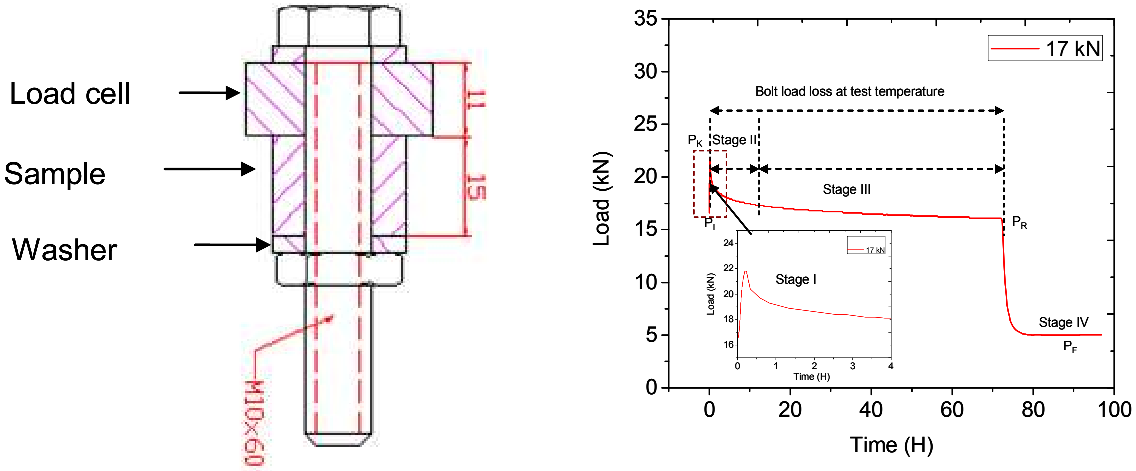

Fig 1. (a) Bolted couple used in BLR test, (b) Stages associated with typical BLR experiments

Fig 1(a) shows the bolted couple used in this analysis while Fig 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 Fig 1(b) is computed with Eq. 1, (P_k) is the highest point attained during the BLR process. P_R and P_F are the load at test temperature and final load after BLR test respectively.

$$\Delta P = \Delta T l_{mg} \left(\frac{\alpha_{mg} - \alpha_{steel}}{C_{eq}} \right) \tag{1}$$

In Eq. 1, ΔT is the change in temperature from room temperature condition to the temperature of interest. The symbol lmg is the thickness of the Mg-alloy component. The CTE 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 expressed as Eq. 2. The bolt load at point (P_k) could then be expressed as the sum of the initial load and ΔP. In Eq. 2, A_i and E_i are the area and elastic moduli of the members of the couple respectively. A_{mg} is the effective stressed area of the Mg-alloys expressed as Eq. 3, and obtained from the geometrical configuration of the joint.

$$C_{eq} = \sum_{i=1}^{n} \left(\frac{l_i}{A_i E_i}\right) \tag{2}$$

$$A_{mg} = \frac{\pi}{4}\left(D_H^2 - D_h^2\right) + \frac{\pi}{8}\left(\frac{D_J}{D_H} - 1\right)\left(\frac{D_H L_J}{5} + \frac{L_J^2}{100}\right) \tag{3}$$

$$P(t) = C\varepsilon_i t^{-k_i n_i} \tag{4}$$

Eq. 4, is then used to compute the time dependent bolt load loss at the joint. In Eq. 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 and k_i is dimensionless constant that depends on the joint-to-bolt stiffness ratio of the couple, C in Eq. 4 is a temperature and specimen geometry dependent material constant.

Results and Discussions

In predicting ΔP as a result of thermal expansion mismatch and compliance of the bolted couple, Eq. 1 was used. Thermal expansion coefficient of $26\text{x}10^{-6}$ m/mK and $12\text{x}10^{-6}$ m/mK were assumed for the Mg-alloys and steel components respectively. The equivalence compliance C_{eq} used in this work is the sum of all the compliances of the couple. C_{mg}= $1.41\text{x}10^{-9}$ m/N, C_b=$3.16\text{x}10^{-9}$ m/N, C_w=$6.57\text{x}10^{-11}$ m/N and C_s=$2.25\text{x}10^{-10}$ m/N. where C_{mg}, C_b, C_w and C_s are compliances of the Mg-alloys, steel bolt, steel washers, and the load cell, respectively. The parameter n_i calculated from typical creep experiment are given in Fig. 2(a). The model prediction and the experimental BLR results are compared in Fig. 2(b), up to 350 hours. The equation made slightly higher prediction of the retained load after 150 hours of bolt load measurement. The difference between the calculated prediction and measured values after 350 hours of BLR evaluation are 4 % for Mg4Al, 4.7 % for AS41+0.15 % Ca and 7 % for AS41. The differences could come from issues like volume fraction of second phases under clamped load, presence of porosity, etc. which were not included in the model. However, considering the scatter associated with creep experiments, the compliance-creep model applied in this work is in reasonable agreement with the measured bolt load results. At 70 MPa/ 175 °C, creep deformation of 3.2 %, 5.0 % and 13.6 % were observed for AS41+0.15 % Ca, AS41 and Mg4Al respectively after 150 hours.

As observed from Fig. 2(b), the BLR and creep properties of AS41+0.15 % Ca is better than that of AS41 and Mg4Al. Fig. 3(a), shows grain boundary sliding due to creep of AS41 while Fig. 3(b), shows the presence of CaMgSi and modified Mg_2Si at the grain boundary regions of Ca modified AS41. These phases were further confirmed by XRD measurements in Fig. 3(c). CaMgSi and refined Mg_2Si act as real obstacle to dislocation movement during creep and there by improve the BLR properties of the AS41+0.15 % Ca alloy. The decomposition of the saturated α-Mg near to the dendrite and grain boundary regions of the AS41 and the modified alloy were improved by Ca addition.

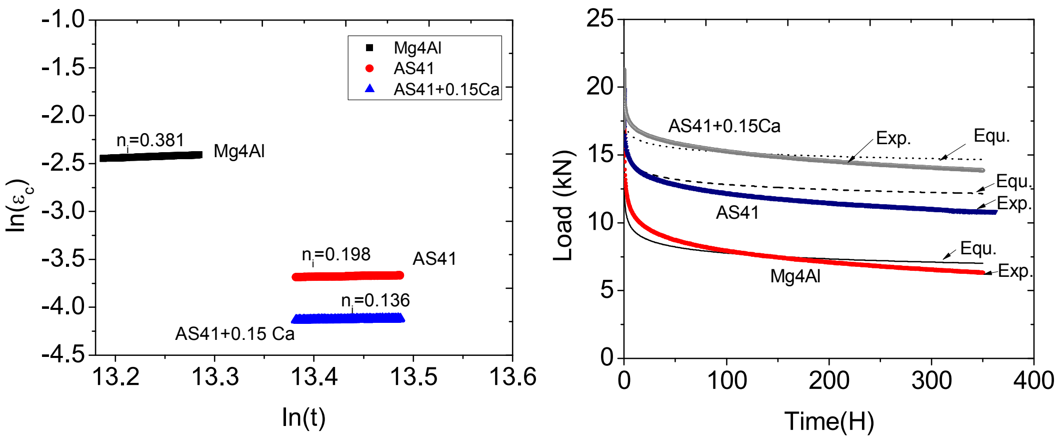

Fig. 2(a), Computed n_i parameter and (b) Experimental and modeled BLR results at 150 °C

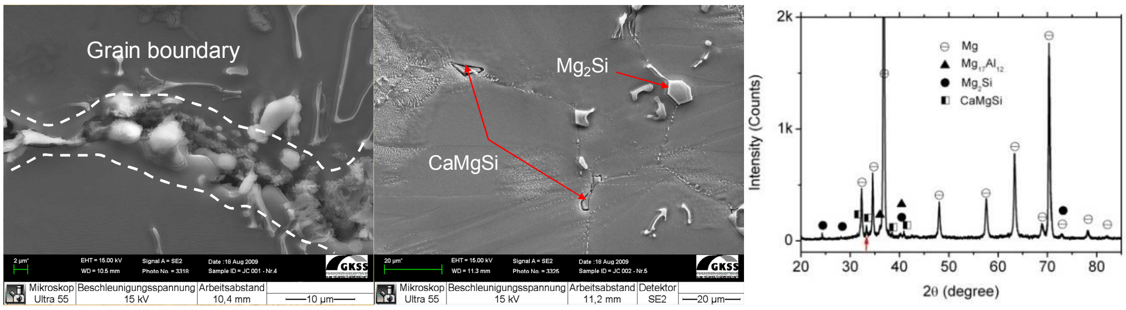

Fig. 3(a), SEM micrograph of AS41 showing grain boundary sliding due to creep, (b) Ca modified AS41 alloy and (c) XRD measurement showing the presence of CaMgSi phase on the modified alloy.

Summary

The BLR behaviour of Ca modified AS41 alloy was modeled using compliance/creep method. The model prediction and the experimental results show good agreement. AS41 micro-alloyed with 0.15 % Ca was found to show better BLR properties than either AS41 or Mg4Al. 0.15 % Ca addition refined the Mg_2Si to polygonal precipitate and also formed a ternary CaMgSi phase which acts to improve the creep and BLR behavior of AS41 alloy.

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