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Improvement of high temperature fatigue lifetime in AZ91 magnesium alloy by heat treatment

Mehdi Mokhtarishirazabad [a], Mohammad Azadi [b,*], Gholam Hossein Farrahi [c], Gerhard Winter [d], Wilfred Eichlseder [d]

[a] School of Metallurgy and Materials Engineering, Iran University of Science and Technology, Tehran, Iran
[b] Fatigue and Wear Workgroup, Irankhodro Powertrain Company (IPCO), Tehran, Iran
[c] School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran
[d] Chair of Mechanical Engineering, University of Leoben, Leoben, Austria

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ABSTRACT

In the present paper, an improvement in high temperature fatigue properties of the AZ91 magnesium alloy with rare earth elements has been obtained by a typical heat treatment, denoted by T6. For this objective, out-of-phase thermo-mechanical fatigue, room temperature and high temperature low cycle fatigue tests are performed to compare lifetimes. Several rare earth elements are initially added to the AZ91 alloy during a gravity casting process in permanent molds. Also, the type of the heat treatment is examined. Results of specimens with only the solution (the T4 heat treatment) and the solution with the ageing process (the T6 heat treatment) are compared under isothermal fatigue loadings. Microstructural investigations are carried out, before and after fatigue experiments to demonstrate the heat treatment effect. Results showed that both low cycle fatigue and thermo-mechanical fatigue of the alloy at high temperatures increases tremendously after the T6 heat treatment. This behavior attributes to the variation of the ductility, which was a result of microstructural changes during the heat treatment and the varying temperature in fatigue tests.

1. Introduction

Magnesium alloys are the lightest structural alloys and thus, they are suitable for several applications in the automotive industry. Today, magnesium alloys are used in several automotive and engine components such as valve covers, due to their advantages, including greater fuel economy and environmental conservation. Recent developments in alloying with rare earth (RE) elements and the coating process of magnesium have improved creep and corrosion resistance properties at elevated temperatures and in corrosive environments. The invention features engine cylinder blocks and heads made of magnesium alloys. Using magnesium alloys results in 22–70% of the weight reduction in comparison to aluminum alloys or cast irons [1–4]. Lastly, the use of magnesium in automotive components is increasing as the knowledge of forming processes of magnesium alloys increases. Therefore, the goal of this research is to achieve the improvement in high temperature fatigue properties of a cast magnesium alloy with RE elements, by using a typical heat treatment process in engine components applications.

Several researches have been carried out in the field of the heat treatment effect on magnesium alloys, which focus on microstructures and mechanical properties. As an example, effects of heat treatments on the microstructure and mechanical properties of the AZ91 alloy were presented by Fujii et al. [5]. They demonstrated that the solution heat treatment increased values of the ultimate tensile strength and the elongation than that of the as-cast condition. They also showed that increasing the ageing time had no significant effects on the ultimate tensile strength. However, the proof strength increased and the elongation decreased, obviously. Li et al. [6] investigated the microstructural evolution of the AZ91 alloy during the heat treatment. Wang et al. [7] discussed the effect of solution and solution plus ageing treatments on the microstructure and mechanical properties of the rheo-die cast AZ91D alloy. They illustrated that the solution treatment (the T4 condition) improved the ductility, but decreased the strength. The solution plus the ageing treatment (the T6 condition) increased the ultimate tensile strength, but reduced the yield strength and the ductility. They also demonstrated that the hardness of the rheo-die cast alloy reached to the maximum value after 5.5 h at 413 °C. Effects of heat treatments on the microstructure and mechanical properties of the Mg–15Gd–5Y–0.5Zr alloy were investigated by Yan et al. [8]. They demonstrated that the ultimate tensile strength and the yield stress of the alloy

* Corresponding author. Tel.: +98 910 210 7280; fax: +98 21 22243621.
E-mail addresses: m_azadi@ip-co.com, m.azadi.1983@gmail.com, azadi@mech.sharif.ir (M. Azadi).

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decreased by the T4 heat treatment and increased by the T6 heat treatment in comparison to the as-cast state. However, this discussion for the elongation was reverse. They obtained an optimized process, which was the solution at 525 °C for 12 h and ageing at 225 °C for 24 h. Wu et al. [9] reported beneficial effects of Ce-rich RE additions and heat treatments on the microstructure and tensile properties of the Mg–Li–Al–Zn alloy. Lei et al. [10] showed that the Mg–15Gd–3Y alloy with the T6 heat treatment had superior mechanical properties in comparison to as-cast and T4 heat-treated alloys.

Several studies have been done in the field of the heat treatment effect on fatigue properties of magnesium alloys. As an example, Uematsu et al. [11] presented the effect of the ageing treatment on the fatigue behavior in extruded AZ61 and AZ80 magnesium alloys. They showed that mechanical properties were not affected by the ageing treatment in the AZ61 alloy. While in the AZ80 alloy, they were significantly improved. Results of rotary bending fatigue tests (at the room temperature) illustrated that the AZ80 alloy had higher fatigue strength than that of the AZ61 alloy, because of higher aluminum content. Also, in AZ61 and AZ80 alloys, T6 heat-treated specimens exhibited slightly lower fatigue strength than as-received ones. The influence of the load frequency and the ageing heat treatment on the fatigue crack propagation rate of the as-extruded AZ61 alloy was studied by Zeng et al. [12]. Their results demonstrated that fatigue crack propagation rates of the AZ61 alloy were significantly affected by the microstructure and loading frequencies, as well.

Dong et al. [13] worked on the influence of the heat treatment on the high cycle fatigue (HCF) behavior of the high-strength Mg–10Gd–3Y alloy. Their results illustrated that the T5 heat treatment could improve the fatigue behavior, while T4 and T6 heat treatments were detrimental to the fatigue behavior of the alloy. Zhu et al. [14] investigated the effect of the ageing treatment on the room temperature low cycle fatigue (RT-LCF) behavior of the extruded Mg–8Al–0.5Zn alloy. They demonstrated that the ageing process (at 200 °C for 21 h) decreased the fatigue lifetime.

As mentioned above, the literature review shows that several researchers worked widely on the effect of the heat treatment on the microstructure and mechanical properties of magnesium alloys. Recently, several investigations have been done in the field of the effect of the heat treatment on fatigue behaviors of magnesium alloys. In these studies, HCF properties were investigated more than LCF properties. Thus, there have been very few researches about high temperature low cycle fatigue (HT-LCF) properties and the heat treatment effect. Particularly, investigating thermo-mechanical fatigue (TMF) behaviors of magnesium alloys (with and without heat treatments) have not been studied.

In the present paper, the effect of the heat treatment on high temperature fatigue properties of the AZ91 magnesium alloy is investigated. To obtain this objective, out-of-phase thermo-mechanical fatigue (OP-TMF), RT-LCF and HT-LCF tests are performed on as-cast, T4 and T6 heat-treated AZ91 alloys, containing RE elements. In addition, to find the heat treatment effect, the microstructure of alloys is investigated based on optical microscopy and scanning electron microscopy (SEM) images.

2. Experiment

2.1. Materials and treatments

A gravity die cast magnesium alloy, which is studied in this article, includes the AZ91C alloy with RE elements. This alloy is the most widely used magnesium alloy in the industry. The chemical composition of this magnesium alloy is measured as 9.00% Al, 1.05% Zn, 0.06% Mn, 0.04% Si, 1.00% Ca, 0.68% RE and Mg is the remainder. It should be mentioned that RE elements are added to the alloy by the mischmetal, which is a compound of La, Ce, Gd, Nd, and Pr. By this element composition, the alloy is entitled as the AZE911 alloy, in this research. The casting process is a gravity manner in permanent molds.

Commercial magnesium alloys are limited because of their poor creep resistance and poor mechanical properties at elevated temperatures. This phenomenon is resulted from the grain boundary phase, $Mg_{17}Al_{12}$, which softens at high temperatures. It is important to reduce the amount of the $Mg_{17}Al_{12}$ phase and introduce thermally stable precipitates at grain boundaries, as well as in the grain interior, by adding proper alloying elements [15]. Therefore, Ca and RE elements are added to the alloy during the casting process, which can remarkably refine the microstructure and improve mechanical properties, fatigue and creep behaviors at ambient and high temperatures [7,9,11,16–19]. Wu et al. [9] showed that 1% (mass fraction) RE containing alloy attained superior tensile strength. It is also recommended to add 1% (mass fraction) RE to the AZ91D alloy to get the best mechanical property [20].

A typical heat treatment, denoted by T6 in this research, is applied to the AZ91 alloy to improve the fatigue lifetime at high temperatures. This process was optimized by Huang et al. [21] for the heat treatment of the AE42 magnesium alloy, based on the hardness. The mentioned heat treatment includes a solution at 415 °C for 5 h, quenching in the compressed air, and ageing at 215 °C for 5 h [21]. Both solution and ageing stages are performed in a special atmosphere (includes the CO_2 gas) to protect the material from the oxidation. In some other cases, solution and quenching stages are carried out on the AZE911 alloy, which is denoted by T4 in this research, to find the solution heat treatment effect on the fatigue lifetime.

The hardness of the AZE911-T6 alloy is measured as 64 HB (in average), while the hardness of the AZE911 alloy, without the heat treatment (as-cast) and with the T4 process is 65 and 56 HB (in average). It should be mentioned that Brinell hardness tests are carried out on the specimen surface, with 31.25 kg force and an indentor with 2.5 mm diameter.

2.2. Test procedures

Strain-controlled TMF/LCF tests are performed under tensile-compressive loadings on cylindrical specimens. The geometry of the fatigue test specimen is shown in Fig. 1 with its dimensions. The strain is measured by the high temperature extensometer and the temperature is measured by K-type thermocouples (on the specimen surface). The heating system is an induction coil and the cooling process is performed with a compressed air jet.

In OP-TMF tests, the temperature reaches to its maximum value, when the strain has a maximum compressive value and

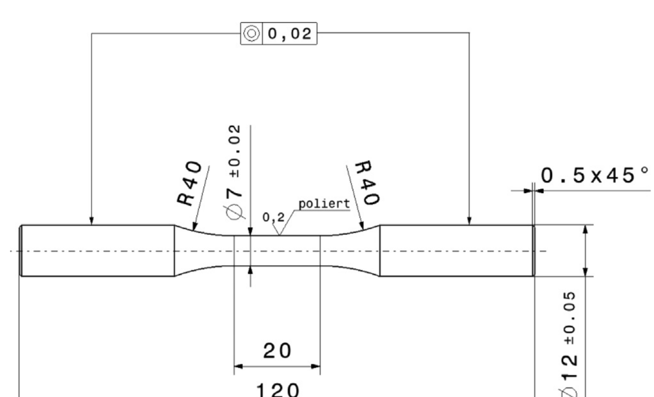

Fig. 1. The geometry of TMF/LCF specimens and their details (dimensions in mm).