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Research on mechanical properties and thermo-mechanical fatigue behaviours of Mg-12Gd-3Y-0.5Zr magnesium alloy at elevated temperatures

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Abstract. In this paper, tensile and thermo-mechanical fatigue tests were carried out on Mg-12Gd-3Y-0.5Zr magnesium alloy at elevated temperatures. It shows that Mg-12Gd-3Y-0.5Zr magnesium alloy has good mehanical properties at high temperatures and thermo-mechanical fatigue mechanism is disscussed in this paper.

1 Introduction

Tensile strength and plasticity of magnesium alloys at room temperature are poor due to their close-packed hexagonal structure which leads to restriction on their application. Many measures have been adopted to improve their mechanical properties [1]. However, magnesium alloys are limited to some noncritical parts as a result of the restriction of fatigue strength and creep resistance at high temperatures [2]. With addition of rare earth elements, Mg-12Gd-3Y-0.5Zr alloy show high tensile strength and modified fatigue strength at elevated temperatures. In this paper, strengthening mechanism and fatigue mechanism of Mg-12Gd-3Y-0.5Zr magensium alloy were discussed.

2 Experimental

The ingots of Mg-12Gd-3Y-0.5Zr alloy(hereinafter referred to as GW123K) were rolled with a ratio of 25:1 at 400℃. The second phase whose constituent is approately $Mg_{24}(Gd,Y)_5$[3] was precipitated in microstructre in the process of extrusion.

Tensile specimens were cut by electric spark machining along the rolling direction with a gauge sections of $3mm\times1.4mm\times1mm^3$. Tensile tests were carried out on an Instron 8801 testing machine equipped with a heater and temperature controlling system at room temperature, 130, 170, 200 and 235 ^oC and at a initial strain rate of $1\times10^{-3}s^{-1}$.

The fracture surface morphologies of the specimens were observed by scanning electron microscopy (SEM, Cambridge S360). TEM observation was carried out on TEM 2000FXⅡoperating at 200 KV.

3 Experimental results and discussion

3.1 Tensile properties at different temperatures

Fig.1 shows optical micrograph of microstructure for GW123K. It can be seen that microstructure of GW123K is composed of α-Mg solid solution and Mg-riched precipitation which precipitaed along or inside grain. Grain size of as-rolled GW123K is about 10μm.

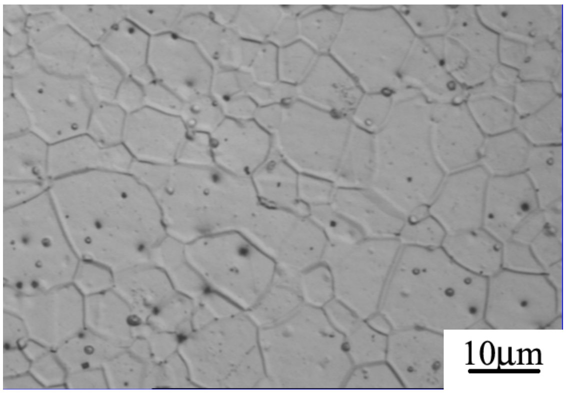

Figure 1. Optical micrograph of microstructure for GW123K.

Fig.2 and Fig.3 show temperature dependence of ultimate tensile strength and elongation-to-failure of GW123K, respectively. Tensile strength of GW123K at room temperature is about 405 Mpa which is well above other magnesium alloys. It is mainly caused by two reasons: on the one hand the grain size decreases to a little extent (Fig.1)after being rolled, on the other hand a large quantity of second precipitation phases impede

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grain boundary sliding. Futhermore, basal plane sliding can not be activated in microstructure of magnesium alloys at room temperature and twinning is main deformation mode which leads to their poor plasticity. Yttrium in microstructure of GW123K as an rare earth element addition plays a important role in grain refinement which results in improvement on strength and plasticity[4], and Gd-riched phases resulting from Gadolinium addition can effectively improve strength of GW123K by means of impeding grain boundary sliding[5]. Fig. 4 shows TEM micrograph of microstructures in as-rolled GW123k alloy after tensile test at 235 °C. Many slip bands can be observed from Fig. 4 that lead to a greatly decreasing strength and a greatly increasing plasticity for GW123K alloy at 235℃(as shown in Fig.2).

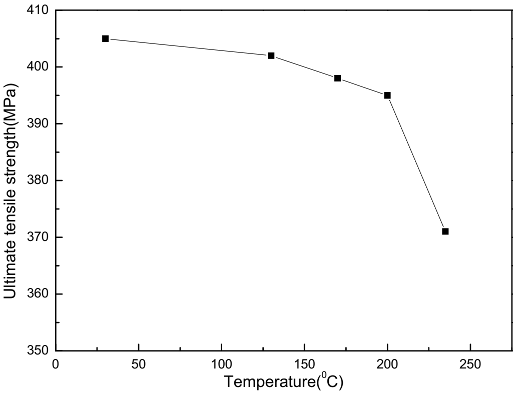

Figure 2. Temperature dependence of ultimate tensile strength of GW123K.

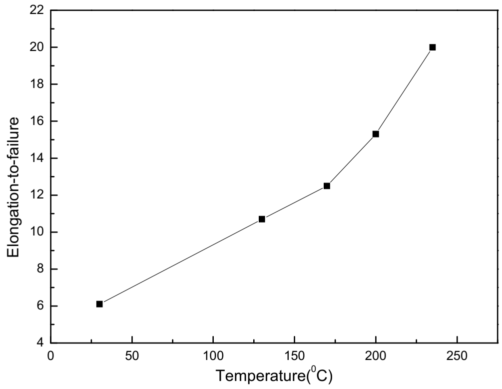

Figure 3. Temperature dependence of elongation-to-failure of GW123K.

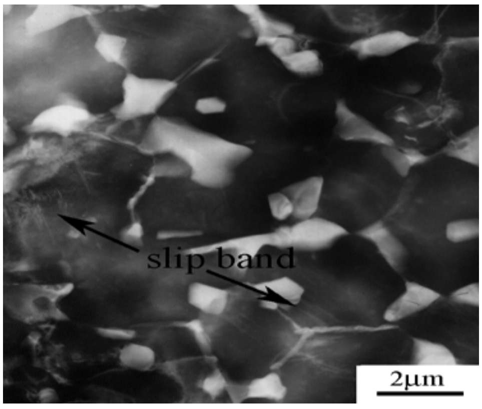

Figure 4. TEM micrograph of GW123k alloy after tensile test at 235 °C.

3.2 Thermo-mechanical fatigue behaviours

Fig.5 shows optical micrograph of GW123K tested by in-phase thermo-mechanical fatigue under stress amplitude 180Mpa at temperature cycle range from 150℃ to 250℃. It can be seen that average grain size of GW123K after thermo-mechanical fatigue test increases to 20μm, and grains are non-uniformly distributed. In the process of thermo-mechanical fatigue test, dynamic recrystallization led by temperature cycle and load loop results in formation of some grains with small size. However, the majority of grains in the microstructure become more and more coarse due to grain boundary diffusion and grain boundary migration at high temperatures. Coarse grains and non-uniform microstructure lead to descending of resistance to thermo-mechanical fatigue failure.

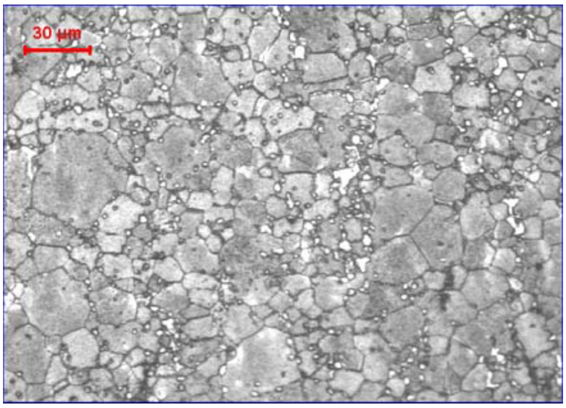

Figure 5. Optical micrograph of GW123K tested by in-phase thermo-mechanical fatigue under stress amplitude 180Mpa at temperature cycle range from 150℃ to 250℃.

Fig.6 shows hysteresis loops at 5 and100 cycles of GW123k alloy after in-phase thermo-mechanical fatigue test at the stress amplitude 180MPa. Hysteresis loop is charateristic of cyclic softening due to dynamic recrystallization at high temperatures.

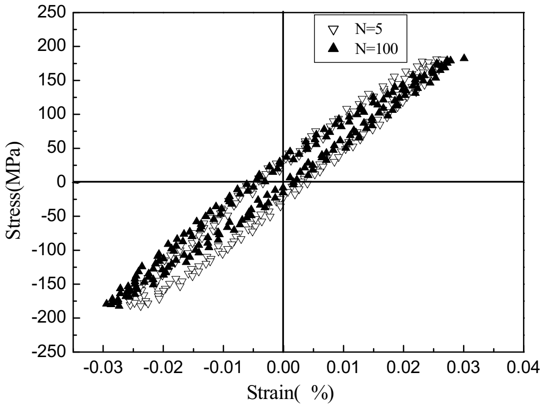

Figure 6. Hysteresis loops at 5 and100 cycles of GW123k alloy after in-phase thermo-mechanical fatigue test at the stress amplitude 180MPa.

Fig .7 shows SEM photographs of fatigue origin and analysis of fatigue crack initiate sites. It can be seen from Fig.7(a) that the overall fracture surface is very smooth and fatigue cracks initiate on the surface or subsurface. As shown in Fig.7(b) and (c), fatigue cracks initiate from oxide or slip bands led by cyclic slip. As a result of cyclic load under fatigue test, many slip bands become into being on the surface of specimens which will lead to stress concentration, at this moment fatigue cracks initiate from these slip bands. It can be concluded that fatigue crack initiating from slip bands at low testing temeratures is the main fatigue failure mechanism.With the increase of testing temperature, specimens are more prone to be oxidized, oxide inclusions will be main fatigue origins. In general, the main fatigue failure mechanism of GW123K under thermo-mechanical fatigue tests is oxide inclusion initiations, moreover, fatigue initiating from slip bands led by cyclic load plays a secondary role in fatigue failure.

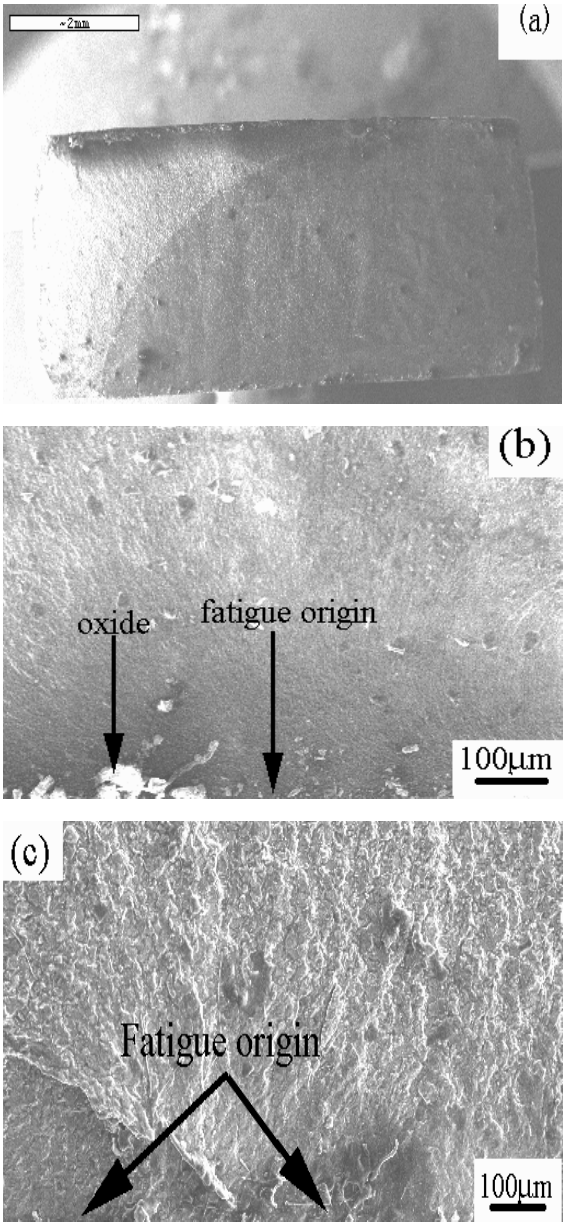

Figure 7. SEM photographs of overall fracture surface and analysis of fatigue crack initiate sites :(a)mophorlogy of thermo-mechanical fatigue test ; (b)fatigue crack initiate from oxide ; (c)fatigue crack initiate from slip bands.

Fig**.** 8 shows S-N fitting curves of GW123k alloy under thermo-mechanical fatigue test. It indicates that out-phase thermo-mechanical fatigue lifetime of GW123K is above that of in-phase thermo-mechanical fatigue lifetime. It is mainly because that fatigue specimens under out-phase thermo-mechanical fatigue test suffer from pressure stress at the highest temperature, and at the same time many micro-cracks caused by micro-voids(shown in Fig.9) were difficult to propagate due to crack closure effect led by pressure stress. Once fatigue cracks intiate from fatigue origins , they will propagate rapidly along micro-voids which result in decrease of thermo-mechanical fatigue lifetime[6]. In line with S-N fitting curves, the equations of in-phase (equation 1) and out-phase(equation 2) thermo-mechanical fatigue can be obtained and is shown as follows :

$$N_f = -13.23 + 4.52\times10^6 \exp(-\sigma_a/16.98) \quad (1)$$

$$N_f = -749 + 1.93\times10^6 \exp(-\sigma_a/22.76) \quad (2)$$

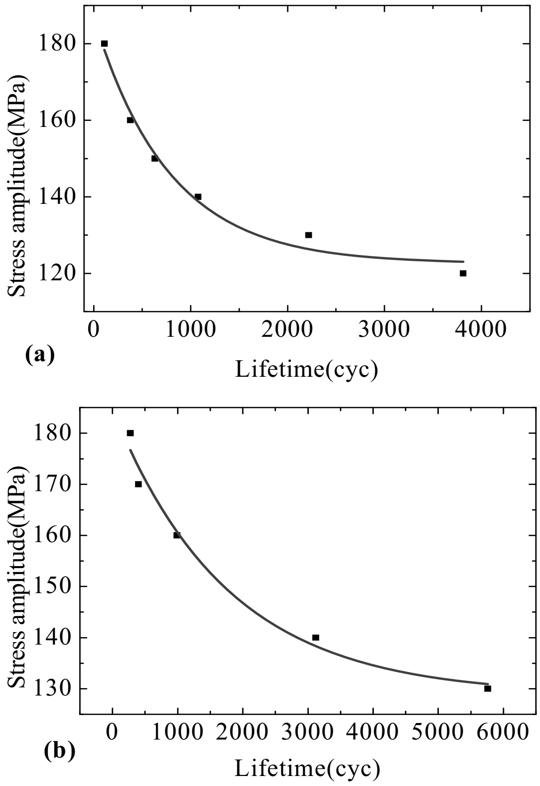

Figure 8. S-N fitting curves of GW123k alloy under thermo-mechanical fatigue test : (a)in-phase ;(b)out of phase.

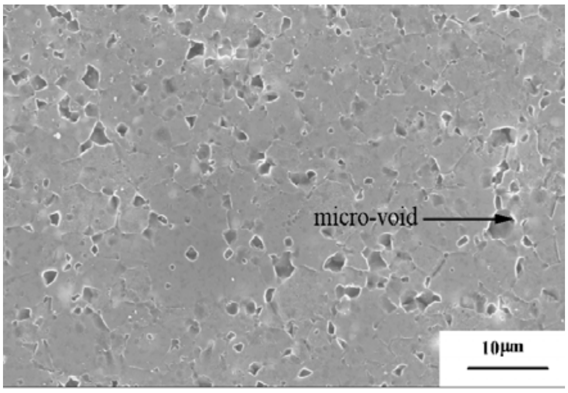

Figure 9. SEM images of GW123k alloys after thermo-mechanical fatigue test.

4 conclusions

(1) GW123K alloy has a good combination of ultimate tensile strength and plasticity at temperatures from ambient up to 200℃.

(2) The main strengthening mechanism of GW123K is precipitation strengthening. Tensile strength of GW123K decrease obviously at temperatue above 200℃ because of new slip systems are activated.

(3) Out-phase thermo-mechanical fatigue lifetime of GW123K is above that of in-phase thermo-mechanical fatigue lifetime due to crack closure effect.

(4) Micro-voids caused by cyclic load lead to decrease of thermo-mechanical fatigue lifetime.

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