Influence of rare earth elements on microstructure and strengthening mechanisms of Mg-12Gd-3Y-0.5Zr magnesium alloy

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Abstract. Mechanical properties of Mg-12Gd-3Y-0.5Zr (GW123K) including tensile strength and isothermal fatigue limit were tested by MTS810 system. Experimental results show that it has higher mechanical properties at different temperatures than other magnesium alloys without rare earth elements addition. Influence of rare earth elements on its microstructure and strengthening mechanisms are discussed in this paper. SEM and TEM analysis indicates that rare earth elements addition leads to grain refinement and restricts grain boundary sliding and fatigue crack propagation.

1. Introduction

In recent years, many strengthening measures such as grain refinement, solid solution treatment and deformation strengthening have been applied in magnesium alloys[1]. However, magnesium alloys with high strength are rarely used at high temperatures due to their poor thermal stability. Mg-RE alloys were developed for application at elevated temperatures because of formation of stable solid solution in their microstructure[2].

By means of experimental tests and microstructure analysis of GW123K, its strengthening mechanisms were discussed and it is proved that rare earth elements play a more important role than other factors. The research shows that rare earth elements is beneficial to improve thermal stability of GW123k at high temperatures.

2. Experimental

GW123K have been treated by rolling process with a high rolling ratio. As a result of anisotropy led by severe plastic deformation (SPD), specimens for tensile and fatigue tests are cut along rolling direction. In order to test tensile strength and isothermal fatigue limit at high temperatures, a heater is equipped on testing machines.

SEM and TEM analysis were carried out on a field emission scanning electron microscope JSM-6330F and TEM JEM-F200, respectively.
3. Experimental result and discussion

3.1 Analysis of strengthening mechanism

Optical and TEM micrograph of GW123K after rolled at high temperature are indicated in Figure 1. (a) and (b). It can be estimated that the average grain size of GW123K is about 10 mm and a lot of second phases with size of 1 mm are homogeneously dispersed inside grains and in grain boundary. Zr and Y elements have been proved to have a strong effect in grain refinement in many research reports[3,4]. As shown in Figure 1. (b), β cubic phase and needle-like β’ phase are observed in its microstructure which are main strengthening phases. Based on composition analysis which is shown in Figure 2, β cubic phase was identified as Mg24(GdY)5 solid solution.

![Figure 1](image1.png)

Figure 1. (a) Optical micrograph of GW123K; (b) TEM micrograph of GW123K

![Figure 2](image2.png)

Figure 2. Composition analysis of β cubic phases in GW123K

In order to identify thermal stability of GW123K, tensile strengths of GW123K were tested at room temperature, 130, 170, 200 and 235 °C. GW123K shows the highest tensile strength (404MPa) at room temperature. As shown in Fig. 3, with the increase of temperatures, tensile strength of GW123K descend very gently when its serving temperature is below 200°C. On the one hand, Gd-riched β phases restrain the growth of grains at high temperatures. On the other hand, stable second phases keep impeding grain boundary sliding and dislocation movement at high temperatures. However, tensile strength of GW123K decreases greatly because its new slip system in prismatic planes will be activated about 225°C[5]. As a result, rare earth elements including Y and Gd elements play a important role in improving microstructure and mechanical properties of GW123K which leads to
strengthening effects such as grain refinement, solid solution strengthening, precipitation strengthening and dispersion strengthening.

![Graph showing tensile strength vs temperature for GW123K](image)

**Figure 3. Curve of tensile strength of GW123K VS temperatures**

### 3.2 Influence of rare earth elements on isothermal fatigue behaviors

It is well known that fatigue strength or fatigue limit of materials increases with its increase of tensile strength[5]. The same temperatures as tensile test were taken to test isothermal fatigue limit of GW123K in this paper. Figure 4.a-b show S-N curves of GW123K at room temperature and 235°C, respectively. It can be concluded that all fatigue data are very divergent and a horizontal platform can be observed on two curves. That is to say, GW123K has fatigue limit but not fatigue strength.

As shown in Figure 4, GW123K has excellent fatigue limit (σ_f=180Mpa) at room temperature. When testing temperature reaches 235°C, fatigue limit of GW123 decreases drastically which is the same as its changing tendency of tensile strength (as shown in Figure 3). It is proved that it has the same influence of rare earth elements on fatigue limit as that of tensile strength in GW123K. It can be concluded that Gd and Y elements improve fatigue strength of GW123K at different temperatures due to their thermal stability. With increase of temperatures, strengthening effect of grain boundary is impaired, but stable precipitation phase such as β cubic phase restricts fatigue crack propagation which leads to slower crack propagation rate and longer fatigue lifetime.

![Graph showing S-N curves for GW123K](image)

**Figure 4. S-N curves of GW123K (a) at room temperature, (b) at 235°C,**

### 3.3 Analysis of fatigue failure mechanism

SEM fracture morphology of fatigue origins in GW123K tested at different temperatures and different stress amplitudes are illustrated in Fig.5. It can be seen that all fatigue cracks origin at surfaces or...
subsurfaces of tested specimens. Analysis of the chemical composition of the fatigue origins shows that the white particles in the figure are oxide inclusions. When the isothermal fatigue test temperature exceeds 100℃, the plastic deformation mode is cyclic slip rather than twinning and de twinning. In the process of cyclic deformation, the surface of the specimen becomes rough due to the continuous slip, which eventually leads to the crack initiation on the surface.

At the same time, oxide inclusion is also one important causes of crack initiation. At this time, the fatigue failure of GW123K is actually the result of the competition between cyclic slip and oxide inclusion[6]. Obviously, oxidation is more likely to occur at high temperatures, and it is more prone to continual oxidation at the oxide inclusion in the surface. Because there are interface defects between the inclusion and the matrix, it is easier to oxidize at this zone at high temperatures. Once the fatigue crack is formed in the oxide inclusions, it will propagate rapidly. As a result, the fatigue failure of GW123k at high temperatures is also the result of the combined action of cyclic slip and oxide inclusions, but the initiation of oxide inclusions is the main mode of fatigue failure. However, basal slip and cylinder slip are also activated to participate in the deformation of GW123K at 235 ℃and cyclic slip will be more helpful to fatigue crack origin and propagation than that of oxide inclusion.

As shown in Fig. 5(c), many microcracks can be observed in microstructure of GW123K after isothermal fatigue test at 235℃. These microcracks are initiated in the large second phases, and some microcracks are connected and become one big fatigue crack after propagation. Once the main crack initiated on the surface encounters with these microcracks, the fatigue failure process of GW123K will be accelerated. It can be seen that crack initiation led by large second phases is also one of the fatigue failure modes at high temperatures.
4. conclusions

(1) GW123K has higher tensile strength at different temperatures than other magnesium alloys without RE addition due to grain refinement, solid solution strengthening, precipitation strengthening and dispersion strengthening.

(2) Isothermal fatigue cracks of GW123K originate on the surface or subsurface. With the increase of temperatures, multiple fatigue origins are observed in microstructure of GW123K.

(3) Fatigue failure mechanism of GW123K is a combination of cyclic slip and oxide inclusion. Moreover, with increase of temperatures, fatigue failure caused by oxide inclusion play a more important role than cyclic slip in GW123K.

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