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Microstructure-based analysis of fatigue behaviour of Al-Si-Mg alloy

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Abstract: The effects of microstructural characteristics on the fatigue behavior in Al-Si-Mg alloy were investigated. The dislocation substructures of Al-Si-Mg alloy were observed by transmission electron microscopy (TEM). Dislocation evolution process of α(Al) matrix with [011] orientation of Al-Si-Mg alloy specimens was observed during fatigue process under different stress amplitudes and cycles. The results indicate that dislocation structure is closely dependent on stress amplitudes, and the density of dislocation in failure specimens increases with increasing stress amplitudes. The results show that Mg_2Si and secondary silicon phase could have a strong hindrance effect on the movement of dislocations during the fatigue process. The fatigue behavior is strongly dependent on the microstructure of material.

Key words: Al-Si-Mg alloy; dislocation; Mg_2Si; secondary silicon phase

1 Introduction

Cast Al-Si-Mg alloy as a new generation of aluminum alloy has been developed in recent years[1]. Due to its excellent weld ability, corrosion resistance, increased energy efficiency and concomitant environmental benefits, Al-Si-Mg alloy has been used in a broad range of industries, particularly in automotive industry[2−4]. In fact, Al-Si-Mg alloy is exposed to cyclic loadings in these applications. It is vital to gain a better knowledge of Al-Si-Mg alloy fatigue behavior as an important design parameter. In the last ten years, there were activities toward improving the understanding of the effect of some intrinsic and extrinsic factors on fatigue crack initiation and propagation in Al-Si-Mg alloy[5−8]. Extensive research efforts were focused on fatigue behavior under thermal aging and modification treatment which can improve the mechanical properties of materials[9−11]. However, the influence of microstructure on the fatigue behavior of Al-Si-Mg alloy was not studied deeply[12]. In this study, dislocation structure evolution of Al-Si-Mg alloy under different stress amplitudes and cycles is presented. Interactions between the dislocation and precipitates, dislocation and secondary silicon phase are investigated in order to understand the fatigue behavior and performance. In this way, an explanation of fatigue behavior and relationship of Al-Si-Mg alloy and its microstructure can be obtained.

2 Experimental

2.1 Materials

The material studied in this experiment was Al-Si-Mg alloy. It was hot isostatically pressed (HIP) prior to the heat treatment. The HIP process reduces microshrinkage and gas porosity within the casting to a negligible level by applying high temperature and isostatic pressure for a specified period of time. Its chemical composition was measured as 7.41%Si, 0.27%Mg, 0.138%Fe, 0.314%Mn, 0.001%Cu, 0.006%Zn, 0.006%Ti, 0.001%Cr and Al balance (mass fraction). Al-Si-Mg alloy was subjected to a T6 heat treatment, consisting of solid solution heat treatment at (538±5) °C for 5.25 h, followed by water quenching and artificial aging at 160 °C for 4 h. The yield strength ($\sigma_{0.2}$), ultimate tensile strength (σ_b), elastic modulus, shear modulus, reduction of area and elongation of Al-Si-Mg-T6 alloy are 170.2 MPa, 196.6 MPa, 70.0 GPa, 26.3 GPa, 0.68% and 1.53%, respectively. The specimens are in the shape

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of cylindrical rods as shown in Fig.1.

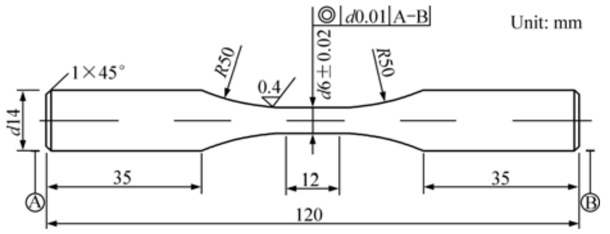

Fig.1 Schematic diagram of cylindrical rod specimen for fatigue test

2.2 Method

Each specimen was tested under uniaxial cyclic loading using Instron 8032 system. To investigate the fatigue behavior of Al-Si-Mg alloy, specimens were exposed to different stress amplitudes from 115 to 185 MPa. These experiments were conducted based on cyclic stress controlled at frequency of 10 Hz, a sine wave form at a stress ratio of −1, in air at 22 °C and relative humidity of 40%. The microstructure characteristics of Al-Si-Mg alloy after exposure to fatigue test was observed using H-800 TEM machine. TEM samples were prepared in following steps: a slice of about 1 mm thickness was cut beneath the fracture surface or the middle of the working segment, then the slice thickness was decreased to about 50 μm using carborundum paper, then the thickness of foil sample was continued to decrease to about 20 nm by twin-jet electropolishing.

3 Results and discussion

3.1 Fatigue properties of Al-Si-Mg alloy under different stress amplitudes

The fatigue characteristics under different stress amplitudes were examined and the effect on the fatigue life was shown in Table 1. From Table 1, the result shows that with the reduction of stress amplitude, the fatigue life of Al-Si-Mg alloy increases significantly.

Figure 2 shows the strain amplitude—cycles curve at different stress amplitudes (115−185 MPa). It is very clear that the strain amplitude increases with increasing

Table 1 Effect of stress amplitudes on fatigue life

Stress amplitudes, $(\Delta\sigma/2)$/MPa	Fatigue life/10^3 cycle
185	5.6
165	30
145	42
135	150
125	266
115	408
105	985
95	3 528
85	$>10^4$

stress amplitude. As can be seen from Fig.2, Al-Si-Mg alloy has a slight initial cyclic hardening phenomenon. In the case of 185 MPa stress amplitude, cyclic hardening phenomenon is more clear, while in the case of low stress amplitude, it is not clear because the materials are not significantly plastic deformed and the main problem is the elastic deformation leading to weak circulation damage. This may be related to the evolution of internal dislocation structure of Al-Si-Mg alloy, because constant stress dislocation tangles, piles up and interacts, which results in the softening of cyclic hardening softening[13]. A probabilistic explanation is developed to establish the relationship between fatigue behavior of Al-Si-Mg alloy and its microstructure, which will be discussed later.

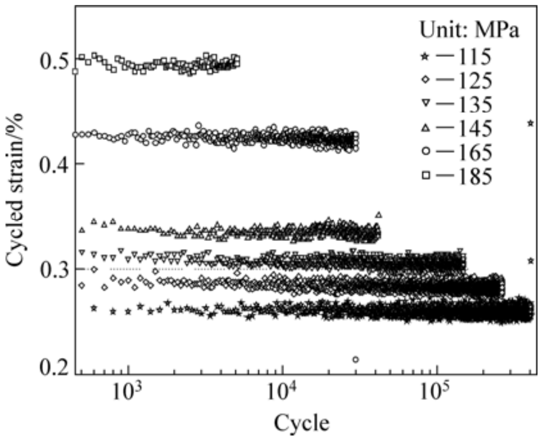

Fig.2 Effect of stress amplitudes on cyclic deformation

3.2 Evolution analysis of dislocation structure under different cycles

The microstructure of Al-Si-Mg alloy is typically composed of α(Al) dendrites, eutectic silicon and pores. Fig.3(a) illustrates the typical microstructure observed in Al-Si-Mg alloy. Fig.3(b) shows the dislocation structure of Al-Si-Mg alloy in raw materials. In that case, dislocation density is very low and the dislocation structure and distribution are irregular in Al-Si-Mg alloy, which is generated during processing. There are plenty of precipitates dispersed in Al matrix fixing dislocation and reinforcing matrix, which may be the reason for the higher strength of the alloy. Dislocation line entanglement around precipitates cannot be seen in samples with no deformation.

Evolution analysis of dislocation structures of Al-Si-Mg alloy under different cycles was investigated. Figure 4 shows dislocation structures in (011) crystal planes in a stress amplitude of 135 MPa. Comparing Fig.3(b) and Fig.4(a), it is clear that the increase in dislocation density is not rapid, but there are some relatively clear sliding linear structures only in one direction which would rearrange the distribution of the original dislocation network. Comparing Fig.4(a) and

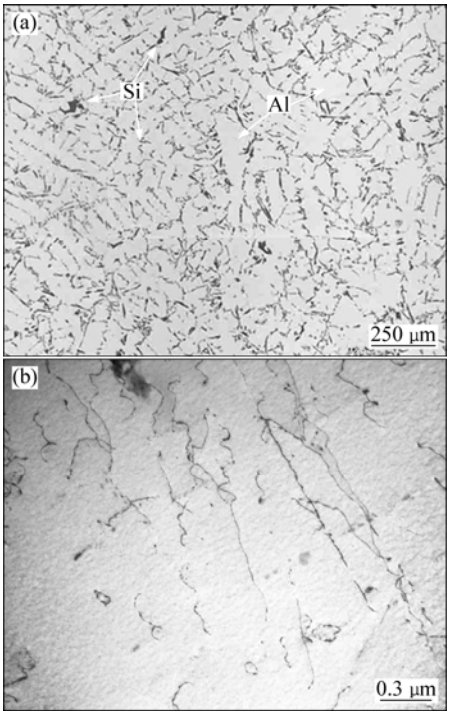

Fig.3 OM (a) and TEM (b) images of Al-Si-Mg alloy

Fig.4(b), dislocation structure develops into a ribbon and gradually widens to form cross-banded sliding structure. Banded structure of thicker slip may be due to the dislocation pile-up and interaction, so banded structure may be rich in slip dislocation dipoles, and the dislocations concentrate in the slip band structure. This indicates that in the initial cycles, the plastic strain concentrates in the slip band. Comparing Figs.4(c) and 4(d), the slip bands become thicker and denser, and the distance between slip bands decreases. What's more, if another slip system is activated, another dislocation line with rules would form.

From the dislocation structures, [011] crystallographic axis of dislocation structure is fairly clear. Two typical slip-lines are observed, the directions are $[2\bar{1}1]$ or $[21\bar{1}]$ and the cross-slip angle is 70.6°. This can prove that the movement of dislocation structure has a certain regularity during the process. From these results, it is found that slip systems are activated through the process, and the slip line starts and bears a lot of plastic deformation. With other factors such as pile up of dislocations against boundaries, the energy for further movement is greater than the needed, then another set of slip systems starts and begins to develop cross-banded sliding structure, some other slip systems may be also activated later.

3.3 Evolution analysis of dislocation structure under different stress amplitudes

Figure 5 shows the dislocation structure of Al-Si-Mg alloy under different stress amplitudes. Two dislocations with cross direction are formed and the dislocation bands are mainly constituted by dislocation lines with clear direction. The evolution process of dislocation configuration is the slip bands become thicker and denser, and the distance between slip bands decreases with increasing stress amplitude.

Al-Si-Mg alloy has high-level stacking fault energy,

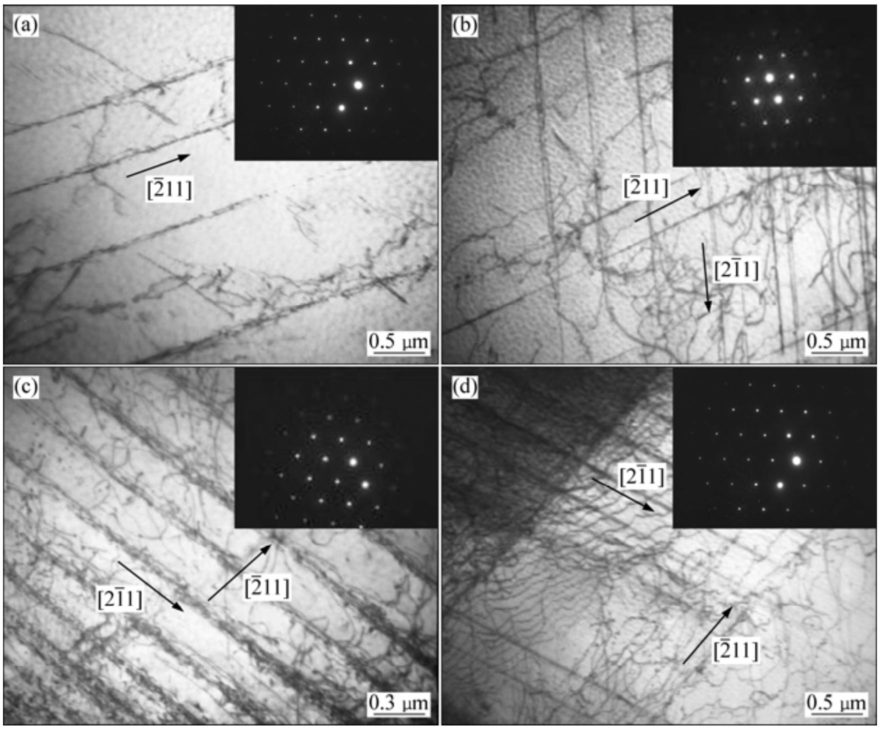

Fig.4 TEM images of dislocation structures with σ_a=135 MPa: (a) 20 cycles; (b) 200 cycles; (c) 2 000 cycles; (d) fracture

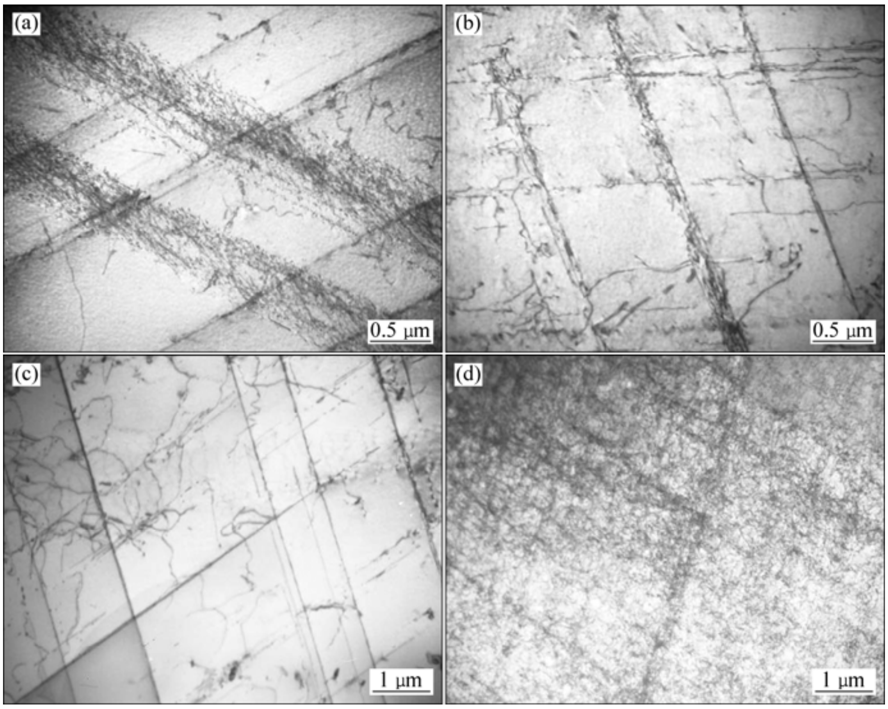

Fig.5 Dislocation characteristics of Al-Si-Mg alloy under different stress amplitudes: (a) 125 MPa; (b) 145 MPa; (c) 165 MPa; (d) 185 MPa

so it is prone to cross-slip under applied loads. From Fig.5, it can be seen that the dislocation configurations are two cross-slip directions with high density and there are some free movement dislocation lines between dislocation bands. For a large number of dislocations loop, interaction between dislocations is further strengthened and dislocation movement space and mobility can be further reduced. Eventually, it leads to macro-stress increasing. Dislocation structure of Al-Si-Mg alloy is dependent on stress amplitude, because under tension-compression cyclic loading, only when the external force achieves critical resolved shear stress of the most favorable orientation of aluminum, the slip system can start. With the increase of stress amplitude, more and more slip systems start and the dislocation density within the slip system accelerates with an increasing rate in order to enhance the interaction between dislocations. With the increase of stress amplitude, the material has more significant cross slips because a number of slip systems are activated and the speed increases. With cross-dislocation broadening and dislocation density increasing, dislocation moving space quickly turns narrow and the interaction between dislocations rapidly increases, so that dislocation structure of the deformation resistance increases.

3.4 Effect of precipitates Mg_2Si

By influencing slip mode of fatigue cracks, precipitate in the aluminum dendrites can influence the fatigue properties. Due to its high melting point, low density, high hardness and high elastic modulus, Mg_2Si is the most important precipitation strengthening phase in Al-Mg-Si alloy which can improve the performance of Al-Mg-Si alloy[14]. Al-Mg-Si series alloy precipitation sequence is generally described as: saturated α−GP1−GP2 (general GP zone) $-\beta'-\beta$ (Mg_2Si) phases. The precipitation product is GP area+β metastable phase when Al-Mg-Si alloy is age treated at 150−225 °C[14]. Fig.6(a) shows TEM image of the original shape of Mg_2Si in the specimen. It can be seen that Mg_2Si phase is mainly in needle or rod shape with 0.3 μm length and 0.03 μm width. During the deposition process, three kinds of metastable phases may be precipitated. This may lead to the matrix phase and Mg_2Si more complicated, which would cause different roles of dislocations and precipitates. In the fatigue cycle, due to the increased dislocation density and dislocation interactions between precipitate and phase, cyclic hardening of these materials occurs in the initial stage. And if the precipitates are small, closely-white and coherent with the matrix, precipitates dislocation may be cut and cyclic softening occur. Fig.6(b) shows the interaction between dislocation and Mg_2Si when the stress amplitude is 115 MPa in the fracture sample. It can be seen that plenty of Mg_2Si haphazardly distribute in the matrix, and there are many dislocations around Mg_2Si. These dislocations can cut part of Mg_2Si, resulting in Mg_2Si phase particle size increasing. A more complex dislocation network is formed because of some dislocations pile-up and multiplication around Mg_2Si

phase. Mg_2Si phase is in network-like arrangement and disorder inequality in the matrix, which can deter dislocation movement in the early stage. As cycles proceeds, although some coherent and semi-coherent metastable phases are cut by dislocations, other metastable phases can hinder the further movement of dislocations. With dislocation density increasing, Mg_2Si phase as pinning points changes to the grain boundary dislocation motion direction, so that the dislocation product in the grain boundaries of different locations has a great influence on the cyclic deformation behavior of Al-Si-Mg alloy.

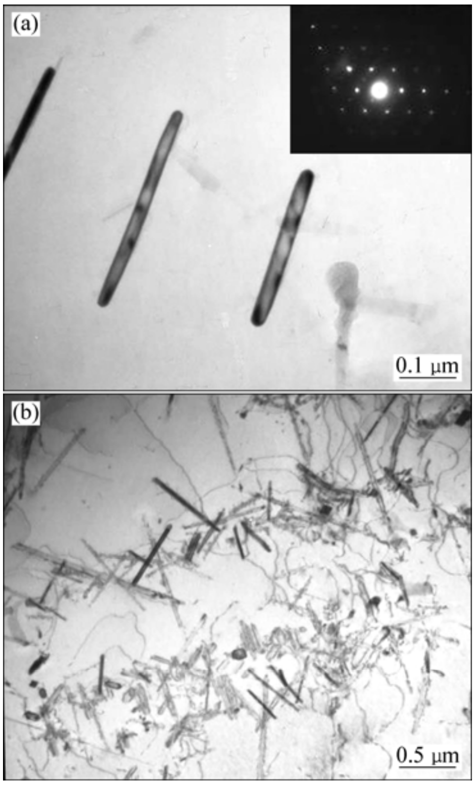

Fig.6 TEM images of Mg_2Si (a) and interaction between Mg_2Si and dislocation (b)

3.5 Effect of secondary silicon phase

Silicon content has an influence on the long fatigue crack growth behavior of Al-Si-Mg alloy due to the higher roughness-induced closure in the low Si alloys, because Si particles encountered along the crack path change the local slip orientation and crack path selection[15]. Eutectic silicon plays an important role in the initiation of micro-cracks of Al-Si-Mg alloy[6, 10, 15]. This work suggests that the focus should not be emissions of secondary silicon phase. At room temperature, the organizational components of Al-Si-Mg alloy are mainly primary α phase, (α+Si) eutectic, precipitation strengthening phase and Mg_2Si phase, as well as a small amount of secondary silicon phase. The secondary silicon phase mainly attaches to the primary α phase or the eutectic α-phase, which is difficult to identify by optical microscope. As Si—Si bonding combination is strong, excess of silicon is easy to form silicon groups as free silicon situation to distribute in the alloy in order to increase the elastic modulus and strengthen the alloy. It is difficult to find the secondary silicon phase by TEM observation because the amount may be lower than 1% (mass fraction) or so as some studies showed[16].

Figure 7 shows the interaction of the secondary silicon phase and dislocations. The morphology of secondary silicon phase is nearly circular and the diameter is 0.87−1.34 μm. In Fig.7(a), there are plenty of dense dislocations networks around secondary silicon phase because dislocation movement is strongly hindered. The dislocation density in the lower right corner is significantly higher than that in the top left corner as asymmetry of polycrystalline internal structure, while the dense forest dislocations of the lower right corner can produce a strong impediment of other dislocation movement in the vicinity. From Fig.7(b), the degree of dislocation pile-up around secondary silicon phase is lower than that in Fig.7(a) due to the existence of Mg_2Si phase which can prevent the dislocation and further the movement of secondary silicon phase. However, with further dislocation movement, the stress concentration increases, and some of the Mg_2Si phase may be cut or dislocations multiplication would happen, resulting in the

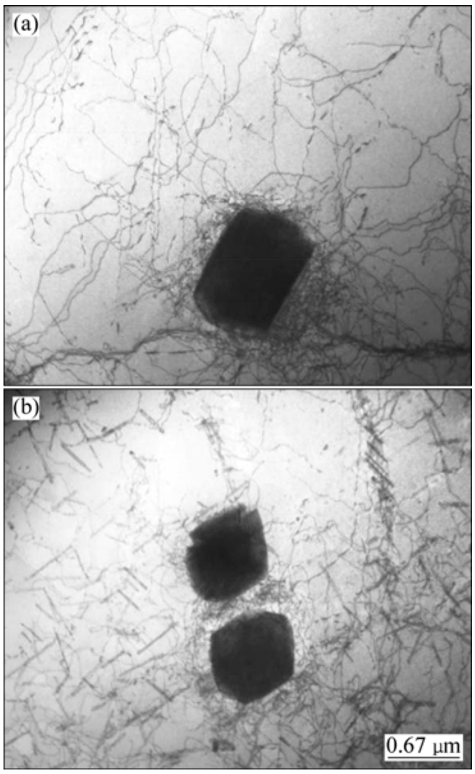

Fig.7 Interaction between secondary silicon phase and dislocation (σ_a=115 MPa fracture)

high level of secondary silicon phase around dislocations. Overall, the secondary silicon phase has relatively strong disincentives of the dislocation movement, just like the role Mg_2Si phase plays in the cycling process, setting the dislocation density increased and leading to a cyclic hardening effect.

4 Conclusions

1) The dislocation structures of Al-Si-Mg alloy are researched during the fatigue process. The slip bands develop from single to multiple and the slip-band dislocation density is high because the dislocation takes much plastic deformation, and the bandwidth increases and slip-band distance decreases gradually. The experiment also shows that the dislocation structure of Al-Si-Mg alloy is dependent on stress amplitude.

2) Mg_2Si phase and secondary silicon phase play an important role in the dislocation movement. Mg_2Si phase is in network-like arrangement and disorder inequality in the matrix, which can deter dislocation movement in the early stage. Secondary silicon phase also hinders the movement of dislocations and leads to the formation of dislocations. The degree of pile-up dislocations around the secondary silicon is related to the amount of surrounding Mg_2Si.

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基于微结构变化的 Al-Si-Mg 合金的疲劳行为分析

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摘　要：研究 Al-Si-Mg 合金的微结构对其疲劳性能的影响。利用透射电子显微镜观察不同条件下 Al-Si-Mg 合金中位错的结构，对同一应力幅下不同循环周次试样的基体(011)面进行位错观察。结果表明，Al-Si-Mg 合金的位错结构随应力幅的变化而变化，并具有一定的规律性；Mg_2Si 与二次硅相对位错运动具有强烈阻碍作用。材料的疲劳行为强烈地依赖于的材料的微观结构变化。

关键词：Al-Si-Mg 合金；位错；Mg_2Si；二次硅相

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