Low-cycle fatigue behavior of extruded Al-7Zn-2Mg-1.5Cu-0.2Sc-0.1Zr alloy at room and low temperatures

Zhu Qingyan¹, Chen Lijia¹, Xu Chengji², Che Xin¹, and Li Feng¹

¹School of Materials Science and Engineering, Shenyang University of Technology, 110870 Shenyang, China

²Liaoning Equipment Manufacturing Vocational and Technical College, 110161 Shenyang, China

Abstract: Due to the low density and high specific strength, aluminum alloys have been considered for automotive and aerospace applications. The aluminum components usually service in the conditions of low temperature and dynamic loading. Therefore, the research on the low temperature fatigue performances of Al alloys has great significance. The low-cycle fatigue tests for the extruded Al-7Zn-2Mg-1.5Cu-0.2Sc-0.1Zr alloy subjected to solution plus aging treatment have been conducted at 25°C and -40°C, respectively. The strain ratio and cyclic frequency applied in the low-cycle fatigue test were -1 and 0.5Hz, respectively. The experimental results show that at 25°C, the alloy exhibits the cyclic hardening at the total strain amplitudes of 1.0% and 1.2%, and the cyclic stabilization at the total strain amplitudes of 0.4%, 0.6% and 0.8%. At -40°C, however, the cyclic stability is observed during whole fatigue deformation at the total strain amplitudes of 0.4%, 0.5%, 0.6%, 0.7% and 0.8%. The relationship between the elastic strain amplitude, plastic strain amplitude and reversals to failure can be described by Basquin and Coffin-Manson equations, respectively. In addition, the observation results of fatigue fracture surfaces reveal that the cracks initiate at the free surface of fatigue specimen and propagate in a transgranular mode.

1 Introduction

The Al-Zn-Mg-Cu series aluminum alloys, as a structural material widely used in the field of aerospace, rail transit, automobile and ship, have good application prospect due to the high strength associated with low density^[1-3]. The optimum properties of aluminum alloys are generally attained by various kinds of alloying additions and heat treatments^[4, 5]. To further improve the mechanical properties of Al-Zn-Mg-Cu alloys, many attempts have been made by various methods. At present, the research of aluminum alloy with Sc and Zr is closely watched by many scientists and engineers^[6-8]. Liu et al^[9] investigated the effect of trace amount of Sc and Zr on microstructure and mechanical properties of novel Al-Zn-Mg-Cu-Sc-Zr alloys. The results indicated that abundant nanometer-sized Al₃(Sc, Zr) particles effectively pinned dislocations and subgrain boundaries, exhibiting excellent antirecrystallization behavior and precipitates strengthening effect. Besides, with the additions of Sc and Zr increased, a higher density of precipitates was detected obviously with excellent refinement effect. The grain refinement strengthening and precipitation strengthening play a dominant role in the additional strength of the Al-Zn-Mg-Cu-Sc-Zr alloys. In addition, heat processing deformation is also an effective method to improve the properties of alloys, such as rolling, extrusion and forging^[10, 11].

In fact, the structural parts usually suffer from different working conditions and fatigue loads during normal service. The complex kinds of service condition usually include different temperature and corrosive environments, which often influence the lifetime of the

components. Therefore, the fatigue properties of aluminum alloy were studied by scientific researchers. In order to approximate the actual service conditions, fatigue tests were designed to be different strain ratios, corrosion environment conditions and so on^[12-15]. Sreenivasan et al^[16] have investigated the role of accumulation of ratcheting strain on low cycle fatigue behavior of aluminum 7075-T6 alloy, the results indicated that ratcheting strain was detrimental to fatigue life of aluminum 7075-T6 alloy by comparing the low cycle fatigue behavior of the investigated alloy with and without ratcheting indicated. And fatigue life of the alloy decreased with the increase of previously imposed ratcheting strain. However, only few researchers studied the influence of low temperature on low cycle fatigue life of the material due to the winter temperatures are generally low in some region. Hence, it needs an study on low temperature-fatigue interaction of aluminum alloys.

In the present paper, the strain-controlled low cycle fatigue(LCF) tests were carried out on specimens of Al-7Zn-2Mg-1.5Cu-0.2Sc-0.1Zr alloy at room and low temperature. The effect of low temperature on the low cycle fatigue behavior of the alloy was delineated, and the damage mechanism related to the low temperature was also characterized in this study.

2 Material and experiments

The Al-7Zn-2Mg-1.5Cu-0.2Sc-0.1Zr alloy ingots after homogenization treatment, were subjected to hot extrusion deformation at 450°C with an extrusion ratio

* Corresponding author: chenlj-sut@163.com

of 40. The as-extruded alloy bars were solution treated at 475°C for 1h, and then artificial aging at 120°C for 44h. The monotonic tensile yield strength and ultimate tensile strength of the alloy at final state were 601.9MPa and 700.3MPa, and the elongation is 8.5%.

Total strain-controlled low cycle fatigue test was performed on a MTS Landmark 370.10 computer-controlled servo-hydraulic fatigue testing machine at room temperature and -40°C in an air environment. The cooling method was liquid nitrogen refrigeration. The low-cycle fatigue experiment was loaded with sinusoidal waveform, the strain-ratio R was -1, imposed cyclic frequency was 0.5Hz, and the specified strain amplitudes were from 0.4% to 1.2%. The samples size for room and low temperature fatigue tests are shown in Fig. 1. Specimens were tested up to failure, and the corresponding cycling number was defined as the low-cycle fatigue life. The fracture morphology of fatigue specimens was analyzed using S 3400 scanning electron microscope (SEM).

Fig. 1. Specimen designs for fatigue tests (mm)

3 Results and discussions

3.1 Cyclic stress response behavior

Fig. 2 shows the variety of cyclic stress amplitude with different strain amplitude of the alloy under room and low temperature. Obviously, as the total strain amplitude increase, the stress amplitude also increase. Besides, it can be seen from Fig. 2 that the cyclic stress response behavior of the alloy is related to the total strain amplitude and the experimental temperature. The cyclic stress response behavior of the alloy at room temperature is shown in Fig. 2a, the alloys exhibit obviously cyclic strain hardening characteristic during the fatigue deformation period at high total strain amplitudes of 1.0% and 1.2%. But at low total strain amplitudes of 0.4%, 0.6% and 0.8%, the stress response behavior of the alloy present cyclic stability, where the cyclic stress amplitude remain essentially constant as cyclic deformation progress. However, the stress response

behavior of the alloy have distinctly different at low temperature in Fig. 2b, the alloy display continuously cyclic stabilization under all the total strain amplitudes of 0.4%-0.8% until the cyclic stress fall fast due to the initiation and propagation of fatigue cracks.

The cyclic hardening of the alloy can be understood as: dislocation source can appear in the alloy internal during low cycle fatigue deformation, dislocation source can generate a large number of dislocations to make dislocation density increase. At the same time, the movement of dislocation can produce interaction to form dislocation tangles and also can pile up in ahead of grain boundary or sub-boundary, which hinder the movement of dislocation and improve the cyclic deformation resistance of the alloy^[17,18]. In addition, Al_3Sc , Al_3Zr and $\text{Al}_3(\text{Sc}, \text{Zr})$ particles can be formed in the alloy due to the addition of Zr and Sc elements, and these particles have a blocking effect on the dislocation motion resulting in cyclic hardening. But the main strengthening phase having enhanced effect is nano-scale $\eta'(\text{MgZn}_2)$ phase in Al-Zn-Mg-Cu alloy. These small precipitation can be cutted damage by moving dislocation during the process of cyclic loading, leading to the strengthening phase decrease in alloy and the strength of the alloy reduce, finally cause the cyclic softening. Besides, the dislocation in the process of movement and interaction, can rearrange to form regular array of dislocations and dislocation network. The annihilation of dislocations take place when opposite sign dislocations meet each other, which reduce dislocation density and decrease the

Fig. 2. Cyclic stress response curves of Al-Zn-Mg-Cu-Sc-Zr alloy
 (a) room temperature; (b) -40°C temperature

slip resistance of dislocations resulting in the cyclic softening^[19, 20]. In fact, cyclic hardening and cyclic softening are two competing relationships. When the hardening effect is offset by the softening effect, the stable cyclic response can be attained.

Fig. 3 shows comparison diagram of cyclic stress response curves for the alloy at the same total strain amplitude under the room and -40°C temperature. It can be seen that at the same strain amplitude, the stress amplitudes of the alloy at low temperature are higher than those at room temperature. And the gap of the stress amplitude between room and -40°C temperature gradually increase, as the increase of strain amplitude. In addition, the stress amplitude at strain amplitudes of 0.8% in low temperature close to the stress amplitude at strain amplitudes of 1.2% in room temperature. It illustrates that the reduction of temperature improve the

Fig. 3. The comparison diagram of cyclic stress response curves at room and -40°C temperature
 (a) $\Delta\epsilon_t/2=0.4\%$; (b) $\Delta\epsilon_t/2=0.6\%$; (c) $\Delta\epsilon_t/2=0.8\%$

deformation resistance of alloy.

3.2 Low-cycle fatigue life behavior

Fig. 4 shows the total strain amplitude ($\Delta\epsilon_t/2$) versus fatigue life (N_f) curves for the alloy at room and -40°C temperature. It can be seen that the fatigue life of the alloy at room temperature is higher than that at low temperature. And the gap of fatigue life between room and -40°C temperature gradually increase, as the increase of strain amplitude. This phenomenon is the same as the cyclic stress amplitude changes. It indicates that the enhanced deformation resistance influence on the fatigue life significantly as the decrease of the temperature.

Fig. 4. Total stain amplitude vs fatigue live curves for the alloy at room and -40°C temperature

In the LCF regime, materials usually undergo cyclic loading with a relatively high strain and stress, the total strain amplitude normally consists of elastic strain amplitude ($\Delta\epsilon_e/2$) and plastic strain amplitude ($\Delta\epsilon_p/2$). The relationship between elastic strain amplitude and fatigue life (N_f) can be described by the following Basquin equation, additionally, plastic strain amplitude and fatigue life can be described by Coffin-Manson equation. Which are expressed respectively as

$$\Delta\epsilon_e/2 = \frac{\sigma'_f}{E} (2N_f)^{-b} \quad (1)$$

$$\Delta\epsilon_p/2 = \epsilon'_f (2N_f)^{-c} \quad (2)$$

where ϵ'_f is the fatigue ductility coefficient and c is the fatigue ductility exponent, E is the elastic modulus, σ'_f is the fatigue strength coefficient, b is fatigue strength exponent.

Fig. 5 shows the curve of relation between strain amplitud and fatigue life in reversals to failure ($2N_f$). It can be seen from this figure that elastic the strain amplitude and plastic strain amplitude as a linear function of fatigue life in reversals to failure for the alloy, where the elastic strain amplitude and plastic strain amplitude are taken from the hysteresis loops at mid-life. And thus, the elastic and plastic strain amplitudes for the fatigue life satisfies the Basquin and Coffin-Manson formula, respectively. Furthermore, the strain fatigue parameters ϵ'_f , c , σ'_f and b for the alloy can

be obtained comparing with the room temperature, the reduction of

Table 1. Strain fatigue parameters at room and -40°C temperature

Temperature	ε'_f	c	σ'_f (MPa)	b	K' (MPa)	n'
room	0.62	1.069	1473.7	0.144	1306.5	0.113
-40°C	1.24	1.290	1177.7	0.120	1371.6	0.109

through the linear regression analysis, and their values are given in Table 1. It can be seen from Table 1 that temperature can improve ε'_f and c values as well as decrease σ'_f and b values.

Fig. 5. Strain amplitude vs fatigue life curves at room and -40°C temperature
 (a) elastic strain amplitude; (b) plastic strain amplitude

3.3 Cyclic stress-strain behavior

The cyclic stress-strain response depicts the relation between the cyclic stress amplitude and plastic strain amplitude, and is useful for understanding the strain-controlled cyclic deformation behavior of material. Usually, the cyclic stress-strain parameters are characterized using power law fits by the following relation

$$\Delta\sigma/2 = K'(\Delta\varepsilon_p/2)^{n'} \quad (3)$$

where $\Delta\sigma/2$ is the stress range, K' is the cyclic strength coefficient and n' is the cyclic strain hardening exponent. This equation provides a measure of the response of the material to cyclic straining. The cyclic stress-strain curve

is plotted by joining the vertices of the hysteresis loops at half life and illustrated in Fig. 6. The K' and n' values

of the both alloys can be determined through the linear regression analysis, and are also listed in Table 1. It can be seen from Table 1 that the reduction of temperature can increase the K' and decrease n' values of the alloy.

Fig. 6. Cyclic stress vs strain curve at room and -40°C temperature

3.4 Fatigue fractograph

In order to analyze the fatigue fracture mechanism of the alloy, the SEM observation was used to investigate the features of fracture morphologies of the low cycle fatigue samples. Two representative samples which have been tested at total strain amplitude of 0.6% under room and -40°C temperature, are chosen to examine their fractography. Fig. 7 shows typical fractographs in the region of the fatigue crack initiation on the alloy at room and -40°C temperature. It can be seen that fatigue crack source located at the free surface of specimens by a transgranular manner on the top right of images. Furthermore, the fracture surface exists a large number of tearing ridges at room temperature. But at low temperature, the fracture surface shows more cleavage characteristics. It indicates that the alloy has better toughness at room temperature.

Fig. 8 shows the characteristics of the fatigue crack propagation on the alloy at the temperature of room and -40°C. It can be clearly observed that a mass of fatigue strip exist in the crack propagation zones, and also exist some subtle differences. The fatigue crack propagation area is rough and have a large number of tear ridges on the fracture surface at room temperature. And yet it is relatively smooth at low temperature. In addition, the secondary cracks can be observed on the fracture surfaces. It indicates that the mode of fatigue crack

propagation is a transgranular way for the alloy both room and low temperature. It indicates that the fatigue fracture converts from ductile to brittle gradually with the temperature decreasing.

Fig. 7. Fatigue crack initiation sites of Al-Zn-Mg-Cu-Sc-Zr alloy
 (a) room temperature; (b) -40°C temperature

Fig. 8. Fatigue crack propagation region of Al-Zn-Mg-Cu-Sc-Zr alloy
 (a) room temperature; (b) -40°C temperature

4 Conclusions

(1) During the low-cycle fatigue deformation, the Al-Zn-Mg-Cu-Sc-Zr alloy exhibit the cyclic hardening and cyclic stability, mainly depending on the imposed total strain amplitude and the test temperature. The cyclic stress amplitudes of the Al-Zn-Mg-Cu-Sc-Zr alloy at low temperature are higher significantly under all total strain amplitudes.

(2) The fatigue life of Al-Zn-Mg-Cu-Sc-Zr alloy is higher at room temperature than that at low temperature. The relation between elastic strain amplitude and plastic strain amplitude with fatigue life in reversals to failure for the alloy can be described by the Basquin and Coffin-Manson equations, respectively.

(3) The fatigue cracks of Al-Zn-Mg-Cu-Sc-Zr alloy initiate from the specimen free surface. The mode of fatigue crack propagation is a transgranular way with some secondary cracks and tear ridges for the alloy under the condition of low cycle fatigue loading at room and -40°C temperature.

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