ACTIVATION ENERGY OF FeAl ALLOYS DURING SUPERPLASTIC DEFORMATION①

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ABSTRACT The activation energy of large-grained FeAl alloys during superplastic deformation has been investigated. The flow activation energy was measured to be about 370, 290 and 260 kJ·mol^{-1} for Fe-36.5Al, Fe-36.5Al-1Ti and Fe-36.5Al-2Ti (mole fraction, %) alloys, respectively, which are much lower than the creep activation energy previously measured in FeAl alloys. Ti addition can decrease the grain size and the activation energy of FeAl alloy.

Key words FeAl intermetallic alloy superplasticity activation energy

1 INTRODUCTION

The increasing demand for materials possessing high strength and low density for high temperature uses led to a re-studying of ordered intermetallic alloys as structural materials. Iron aluminides, mainly B2-FeAl and DO_3-Fe_3Al, are examples of these ordered intermetallic alloys. Recent studies have shown that FeAl and Fe_3Al alloys are intrinsically ductile and the poor ductility generally observed in air atmosphere tests is resulted from extrinsic effect — environmental embrittlement[1, 2]. Moisture induced hydrogen embrittlement has been recognized as one of the major reason resulting in low ductility of these iron aluminides. These efforts have led to the improvement of mechanical properties of FeAl based alloys for structural applications. Up to now, the room temperature elongation of FeAl based alloys has been enhanced to no more than 10% by composition modification and microstructural control, which limits the materials assembled and started up at room temperature.

It is well known that ordered intermetallic alloys often either have poor fabricability or have a rather complicated and tedious fabrication process. Both hot processing and machining FeAl alloys are extremely difficult, which is a major obstacle to their commercial uses. As usual, superplastic forming technologies were used to fabricate the materials which are difficult for processing and machining. If FeAl alloys have superplasticity, they can be processed at high temperature. The superplasticity phenomena of FeAl and Fe_3Al have been observed in our laboratory and some results have been published recently[3- 8]. These results[4, 6- 8] revealed that the titanium-containing FeAl alloys with large grain size of more than 400 μm exhibited a large elongation of more than 200% at 900~ 1 000 ℃ at an initial strain rate of around 2.08×10^{-2} s^{-1}. The maximum m value and maximum elongation were up to 0.43 and 297% respectively. The superplasticity of FeAl based alloys is ascribed to the continuous recovery and recrystallization which take place during superplastic deformation at high temperatures.

In order to further investigate the mechanism of superplasticity in large-grained FeAl based alloys, the activation energy for FeAl alloys during superplastic deformation was measured in this paper.

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2 EXPERIMENTAL PROCEDURES

Fe-36.5Al, Fe-36.5Al-1Ti and Fe-36.5Al-2Ti alloys were prepared by arc melting under argon atmosphere using pure iron (99.0%), high purity aluminum (99.99%) and pure titanium (99.9%). The alloy buttons were remelted three times to improve their homogeneity. After homogenized for 24 h at 1 000 ℃, these buttons clad in stainless sheets were hot rolled to about 50%~60% reductions at 1 050~950 ℃. Tensile specimens with a gauge section of 8.0 mm × 4.0mm × 1.2mm or 12.0mm × 3.2mm × 1.2 mm (especially for Fe-36.5Al alloy) were cut from the bars using electro-discharge machining. The axis of tension is parallel to the direction of rolling. Tensile tests were conducted on a SHIMADZU AG-100kN testing machine equipped with a furnace and the testing temperatures were from 875 ℃ or 900 ℃ to 1 000 ℃. Tensile data were measured from the curve recorded by the machine itself. The initial strain rate was in the range of $1.39 \times 10^{-4} \sim 2.78 \times 10^{-1}\ s^{-1}$. Samples for optical microscopy were etched in a solution of $8C_2H_5OH + 4HNO_3 + 1HCl$ (volume portion). The optical micrographs were taken on a Neophot II microscope.

3 RESULTS AND DISCUSSION

3.1 Activation energy

A classical equation[9] in the form of

$$\dot{\varepsilon} = A \cdot \sigma^n \cdot \exp[-Q/(RT)] \tag{1}$$

was used here to calculate the flow activation energy in the FeAl alloys during deformation at high temperatures. In eq.(1), σ is the stress, $\dot{\varepsilon}$ is the strain rate, Q is the activation energy, n is the stress exponent which is a constant, A is a material constant, R is the universal gas constant and T is the absolute temperature. From eq.(1) it can be gained that

$$Q = n \cdot R \cdot [\partial \ln \sigma / \partial (1/T)] \tag{2}$$

where $n = 1/m$ in the formula[10] of

$$\sigma = K \dot{\varepsilon}^m \tag{3}$$

m value can be calculated by

$$m = \partial \ln \sigma / \partial \ln \dot{\varepsilon} \tag{4}$$

For two different strain rates m can be calculated by

$$m = \ln(\sigma_1/\sigma_2)/\ln(\dot{\varepsilon}_1/\dot{\varepsilon}_2) \tag{5}$$

m values for these FeAl alloys in a temperature range from 900 ℃ to 1 000 ℃ are given by Fig.1. The average index of strain rate sensitivity, m value, is 0.330, 0.353 and 0.382 for Fe-36.5Al, Fe-36.5Al-1Ti and Fe-36.5Al-2Ti alloys respectively. Therefore, n is 3.03, 2.83 and 2.62 for above three alloys sequently according to $n = 1/m$. Take these n values, from Fig.2 in the temperature range from 875 ℃ or 900 ℃ to 1 000 ℃ with a 25 ℃ increment according to eq.(2), the activation energy, Q value is about $370\ kJ \cdot mol^{-1}$ for Fe-36.5Al alloy,

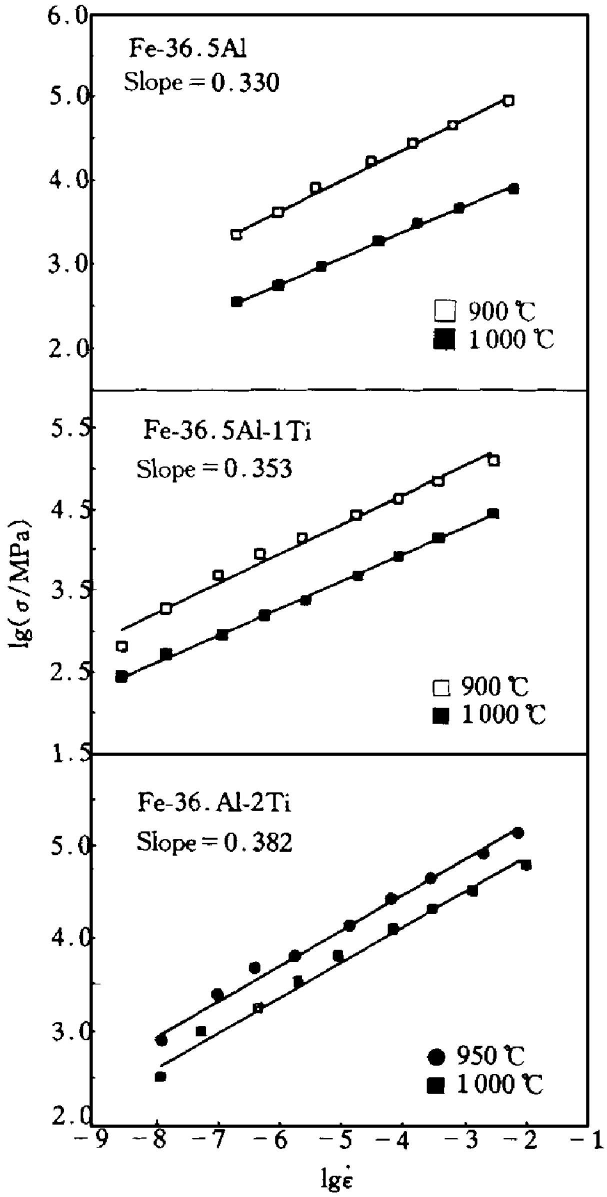

Fig. 1 Strain rate as a function of true flow stress for FeAl based alloys

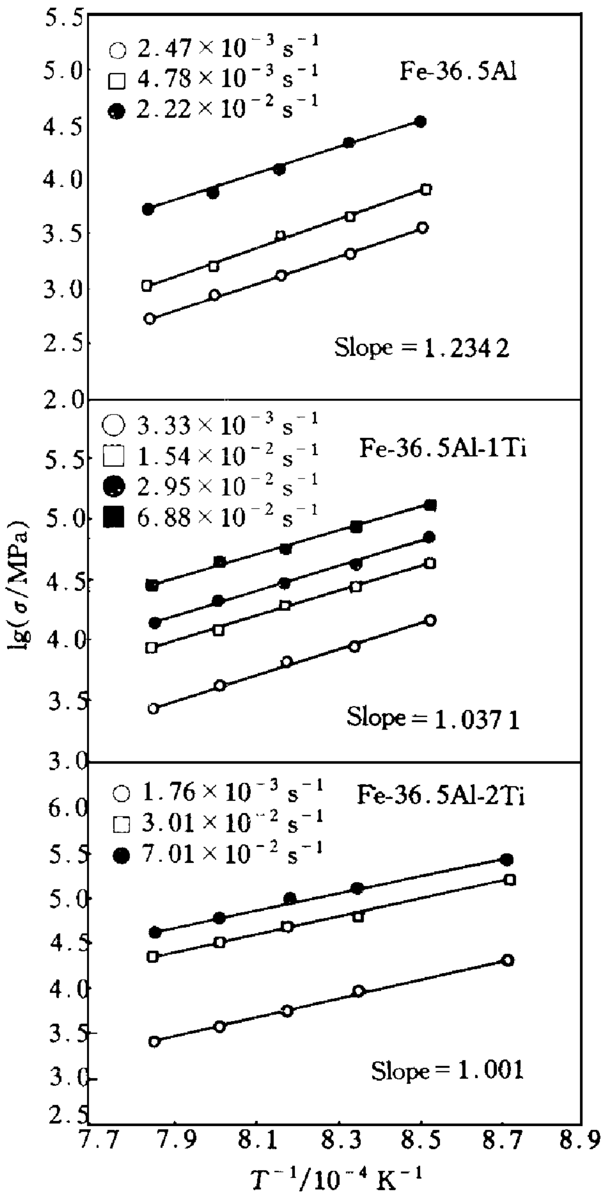

Fig. 2 $1/T$ as a function of ln σ for FeAl based alloys

about 290 kJ·mol^{-1} for Fe-36.5Al-1Ti alloy and about 260 kJ·mol^{-1} for Fe-36.5Al-2Ti alloy respectively, which are much lower than the creep activation energy of 450 kJ/mol reported for binary Fe-39.8Al alloy[11]. Low flow activation energy indicates that the superplastic deformation process cannot be controlled by lattice diffusion, but may be controlled by subgrain boundary and grain boundary diffusion.

3.2 Metallographic examination

Fig. 3 shows that the average grain sizes of Fe-36.5Al, Fe-36.5Al-1Ti and Fe-36.5Al-2Ti alloys are about 600, 550 and 500 μm respectively before deformation. After deformation to fracture at 1000 ℃, the average grain sizes of the alloys changed to about 85, 65 and 50 μm respectively (see Fig. 4).

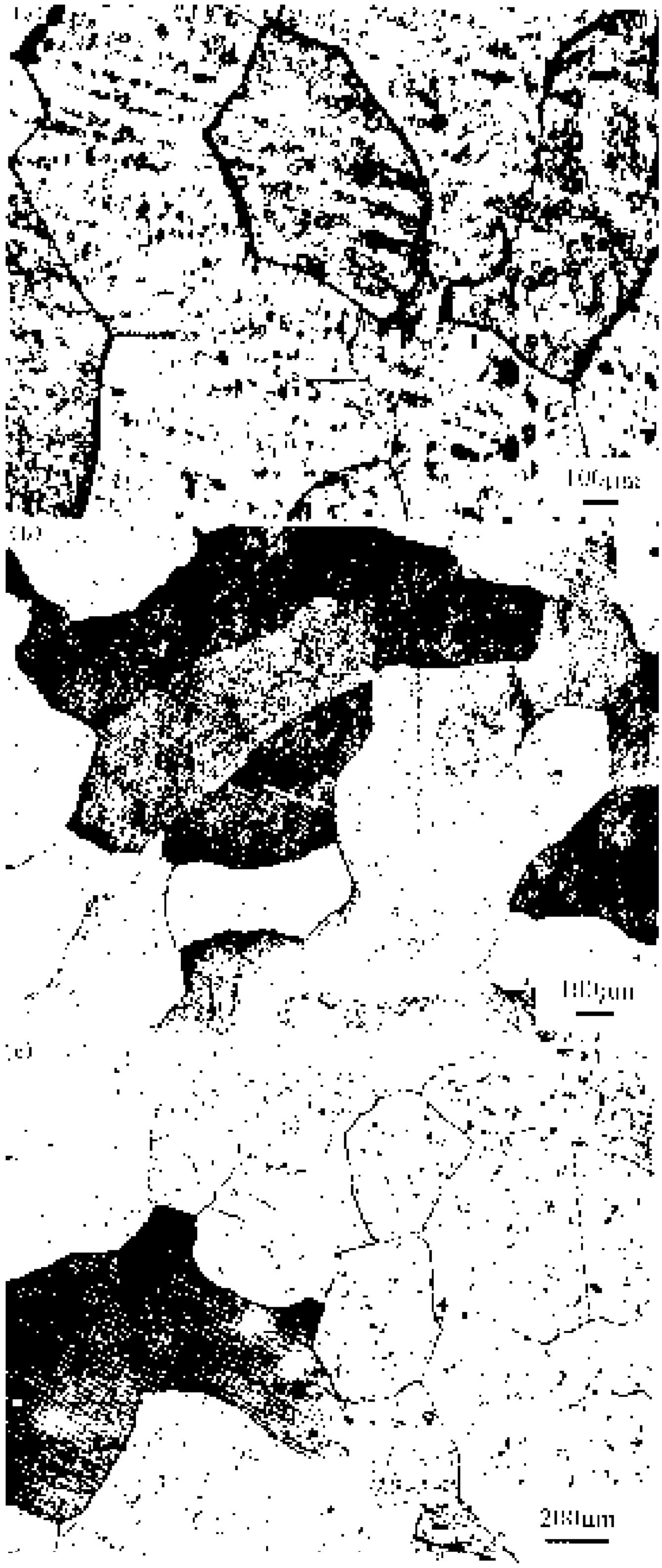

Fig. 3 Optical microstructure of FeAl alloys before deformation

(a) —Fe-36.5Al; (b) —Fe-36.5Al-1Ti; (c) —Fe-36.5Al-2Ti

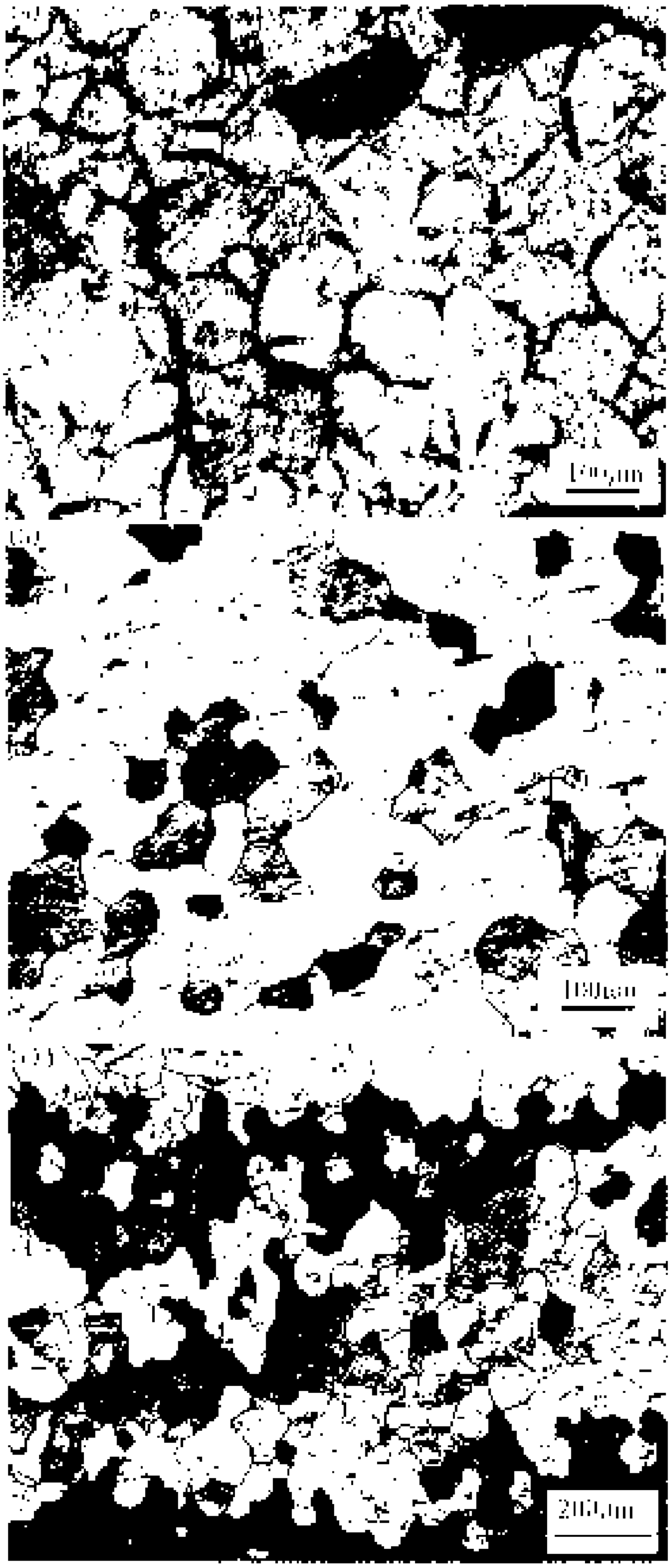

Fig. 4 Optical microstructure of FeAl alloys after elongation to fracture at 1 000 ℃

(a) —Fe-36. 5Al; (b) —Fe-36. 5Al-1Ti; (c) —Fe-36. 5Al-2Ti

Metallographic examinations show that the average grain size of binary FeAl alloy is much lager than that of FeAl alloys containing Ti and the average grain size decreases with increase in content of Ti addition. From the results it can be found that Ti addition can decrease the grain size of FeAl alloy. Because the finer size produces a beneficial effect on the deformation at high temperature, the effect of Ti addition on the grain size may play an important role in decreasing the activation energy of FeAl alloys during superplastic deformation.

4 CONCLUSIONS

In the temperature range from 875 ℃ to 1 000 ℃ in an initial strain rate range of 10^{-4} to 10^{-1} s^{-1}, the flow activation energy of FeAl based alloys is measured to be 370 kJ·mol^{-1} for Fe-36. 5A, 290 kJ·mol^{-1} for Fe-36. 5Al-1Ti and 260 kJ·mol^{-1} for Fe-36. 5Al-2Ti alloy. Ti addition can decrease the grain size and the activation energy of FeAl alloy.

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