TENSILE AND CREEP PROPERTIES OF Fe_3Al-BASED ALLOY WITH DIFFERENT GRAIN SIZES[①]

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ABSTRACT The tensile and creep properties of Fe_3Al rolling sheets with the same composition but different grain sizes are investigated, and the results show a complex effect of grain size on the tensile and creep properties of Fe_3Al-based sheets. At RT, both strength and ductility increase with the decrease of grain size. For the recrystallized specimen, the improvement of the RT tensile properties is caused by microstructural refinement if the specimen tested is oil quenched. However, the ductility enhancement for the unrecrystallized specimen is a result of minimizing the transverse grain boundaries. At 600 ℃ for the thicker sheets, both the tensile strength and creep resistance of the specimens corresponding to larger grain size are higher than those with fine microstructure.

key words Fe_3Al mechanical properties microstructure

1 INTRODUCTION

Iron aluminides based on the ordered Fe_3Al have long been stimulating the interests of material scientists because of their excellent oxidation and sulfidation resistance. However, the major drawbacks to the use of these materials in structural applications have been low room-temperature (RT) ductility and a rapid drop in strength at temperatures above 600 ℃[1, 2]. Considerable efforts have been devoted to improve mechanical properties of Fe_3Al-based alloys and recent developments have shown that adequate engineering ductility of 10% ~ 20% can be achieved by means of thermomechanical treatment and alloying processing[3, 4], and the high-temperature tensile and creep strengths have been increased by the additions of Nb and Mo[4]. While there is a growing data base on the properties of alloys with different compositions, little work has been done on the mechanical properties of alloys with the same composition but different microstructures.

In this paper, the tensile and creep properties of Fe_3Al rolling sheets with the same composition but different grain sizes are investigated. The alloy studied is designated with a composition tailored for having relatively good RT ductility and high-temperature strength[5]. The results show the effect of microstructures on the tensile and creep properties.

2 EXPERIMENTAL

The alloy studied was prepared in a vacuum-induction furnace and cast into a 7 kg round ingot with dimension of d40 mm × 600 mm. The composition of the alloy studied was Fe-28Al-5Cr-0.5Nb-0.5Mo-0.05Zr-0.01Ce (mole fraction, %). The ingot was first held at 1 100 ℃ for 24 h for homogenizing and then hot forged to 30 mm × 800 mm sheet bars. The sheet bars were hot rolled at 1 000 ℃ to 8 mm thickness. Finish rolling was conducted at 700 ℃, and four

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sheets of different thickness were produced, they were 4, 3, 2 and 1 mm thick, respectively.

Tensile specimens with gage sections of 15 mm × 3.5 mm × (1~ 4) mm were cut by electric spark erosion from rolled sheets. Before testing, some specimens were stress-relieved at 700 ℃ for 1 h followed by oil quenching. As the annealing was performed below the recrystallization temperature, these specimens remained the as-rolled microstructure. The other specimens were heated for 1 h at 850 ℃ (for recrystallization) plus 1 h at 700 ℃ followed by oil quenching. Tensile tests were conducted at RT and 600 ℃ at strain rates of 5×10^{-2} %/s and 5×10^{-3} %/s, respectively. Creep tests were completed at 600 ℃ and 200 MPa using dead-weight loading.

Microcharacterizations of deformation behavior and fracture mode were conducted on selected fracture specimens using optical and scanning electron microscopy (SEM).

3 RESULTS

By comparing the microstructures of recrystallized specimens from sheets of different thickness, it can be seen that more deformation of rolling resulted in the refinement of the microstructure, and the grain size of the specimen decreased with the increase of deformation (see Table 1). Fig. 1a and Fig. 1b show the microstructures of recrystallized specimens with the thickness of 3 mm and 1 mm, respectively. Apparently, the grain size in the 3 mm sheet is larger than that in the 1 mm sheet. In the as-rolled specimens, the grain of the Fe_3Al matrix is elongated, as shown in Fig. 2, and the grain width is correlated with that of recrystallized specimen, which decreases with the increase of strain caused by rolling processing.

Table 1 Grain sizes of recrystallized sheets

Sheet thickness/ mm	1.0	2.0	3.0	4.0
Grain size/ μm	20	40	70	95

The results of RT tensile tests are shown in Fig. 3 and Fig. 4, from which it can be seen that the RT ductility and strength increase with the decrease of grain size (which refers to the average diameter of the grains in recrystallized specimens and the average width of the elongated grains in stress relieved specimens) for both stress-relieved and recrystallized specimens. However, the increase of ductility is more remarkable than that of strength. At the temperature of 600 ℃, the contrary effect of grain sizes on the strength is observed. As shown in Fig. 5, both the yield and ultimate strength decrease with the reduction of grain sizes, and drop to 345 MPa and 380 MPa respectively for the recrystallized 1 mm thick specimens which have the finest grain structures, and are reduced by nearly 20% as compared with the 4 mm thick specimens.

Another important result related to grain size is creep resistance. The creep rupture life

Fig. 1 Recrystallized microstructures of sheets
(a) —3 mm thick sheet; (b) —1 mm thick sheet

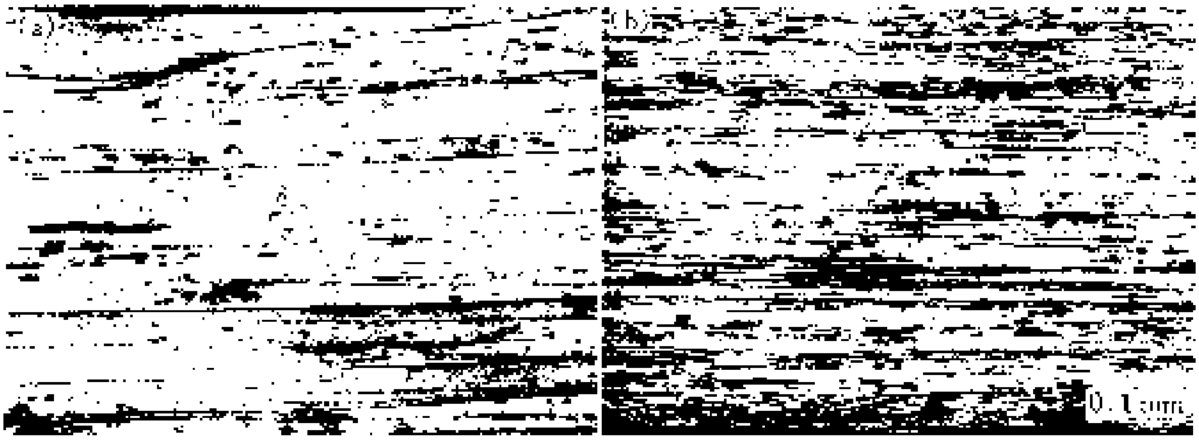

Fig. 2 As-relieved microstructures of sheets

(a) —3 mm thick sheet; (b) —1 mm thick sheet

decreases remarkably with the decrease of grain size, as shown in Fig. 6. The highest creep rupture life (180 h) was obtained from the stress-relieved 4mm thick specimen which has the most coarse microstructure. The creep curves of the stress-relieved sheets are shown in Fig. 7, from which it can be seen that the steady-state creep rate increases significantly with the reduction of grain size. The creep rate of the 1 mm thick specimens increases to 1.6×10^{-3}%/s compared

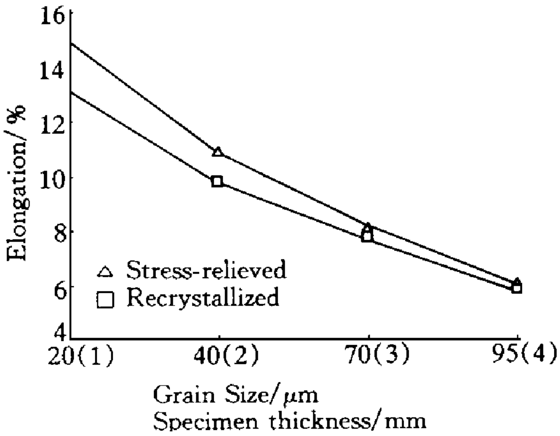

Fig. 3 RT elongation vs grain size

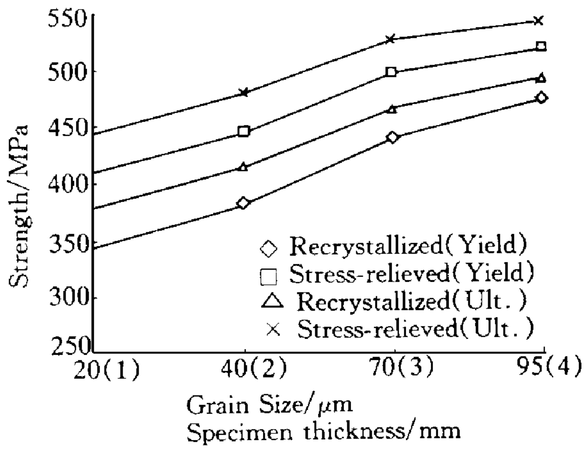

Fig. 5 600 ℃ tensile strength vs grain size

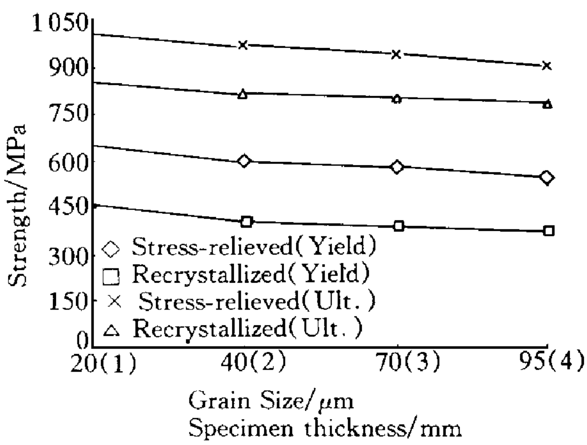

Fig. 4 RT tensile strength vs grain size

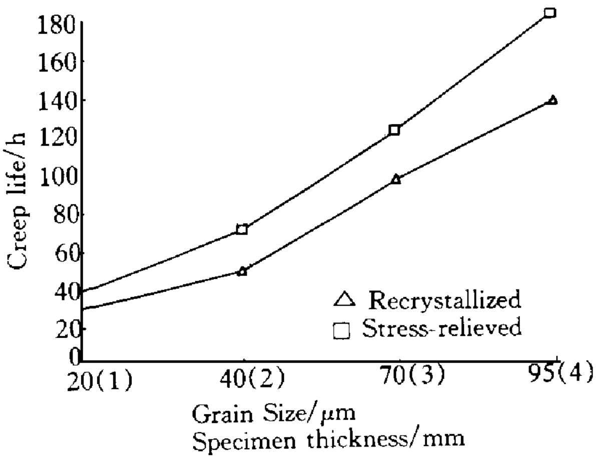

Fig. 6 Creep rupture life vs grain size

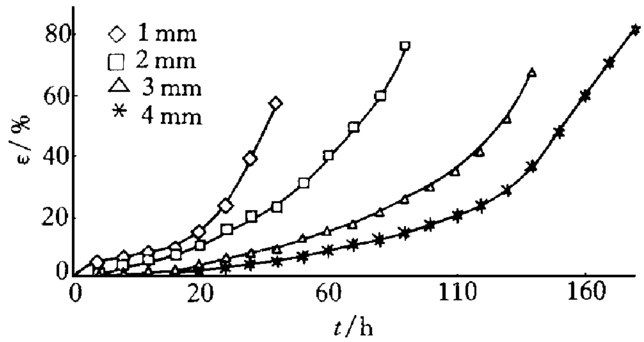

Fig. 7 Creep curves of stress-relieved sheets

to 1.8×10^{-5}%/s for the 4 mm thick specimen.

For the specimens with the same thickness (through the same rolling processing), the two different heat treatments used in the present investigation resulted in significant differences of tensile and creep properties, which can also be seen clearly from Figs. 3~7. First, the RT ductility of the recrystallized specimens is slightly lower than that of the stress-relieved specimens and the margin of the ductility difference increases with the reduction of grain size. Second, the yield and ultimate strength of the stress-relieved specimens at both RT and 600 ℃ are higher than those of the recrystallized specimens. Third, the stress-relieved specimens have longer creep rupture life and lower steady-state creep rate than that of the recrystallized specimens at 200 MPa and 600 ℃.

The RT fracture modes of all the specimens tested are transgranular cleavage with the characteristic of cleavage crack (Fig. 8), suggesting that there appears to be no correlation between the fracture mode and the grain size.

Fig. 8 RT tensile rupture surface of 2 mm thick sheet

4 DISCUSSION

The poor ductility of Fe_3Al intermetallics commonly observed at RT is ascribed to environmental embrittlement involving hydrogen generated from the reaction of aluminum atoms with water vapor in the air[6, 7]. The efforts devoted to improve RT mechanical properties have been focused on alloying and thermo-mechanical treatment. The additions of chromium and cerium[5, 6] result in a change in the nature of the protective oxide layer on the specimen surface, which provides rapid passivation of reaction between moisture and aluminum atoms in the specimens, so that the environmental embrittlement is minimized and the RT ductility is enhanced. The improvement in RT ductility achieved by thermomechanical processing and oil-quenched treatment is believed to be the result of minimizing the number of transverse grain boundaries and obtaining an oil barrier for interaction of metal surface with moisture, which slows hydrogen diffusion into the specimen interior[3, 8]. Gieseke *et al* have proposed that the decreased RT ductility observed in the thicker plates is attributed to less plastic deformation of the microstructure during fabrication and, hence, the presence of more retained grain boundaries for rapid hydrogen diffusion into the material[9]. In the present investigation, the results of tensile tests obtained on the stress-relieved sheet are consistent with the previous work, the increase of the RT ductility with the decrease of grain size may be accounted for by the decrease of transverse grain boundaries in the specimen. This is also the reason why the RT ductility of recrystallized specimen is lower than that of stress-relieved specimen. For the recrystallized sheets tested in the present work, however, the increase of the RT ductility with microstructural refinement is apparently in contradiction with the previous studies[6, 9], since the amount of grain boundaries is significantly increased with microstructural refinement resulted from more rolling deformation and treatment of recrystallization. The specimens tested in the present work are oil quenched. The oil quenching of specimens from the temperature of 700 ℃ puts a protective barrier between the aluminum atoms and the moisture in air[8], hence, the significant enhancement of strength and ductility at RT caused by the reduction of grain size indicates that Hall-Petch equation is also applicable and microstructural refinement is also a way to improve the RT ductility for Fe_3Al-based alloys if the environmental embrittlement is minimized.

At the temperature of 600 ℃, the creep data shows that the thicker specimens have a better tensile strength and creep resistance than the thinner materials. It is well documented that, in general, a large-grain microstructure will resist creep better than an equivalent fine microstructure. Hence, it is no surprise that the sheets with larger grain size have better creep resistance.

5 CONCLUSIONS

The current study shows a complex effect of grain size on the tensile and creep properties of Fe_3Al-based sheets. At RT, both strength and ductility increase with the decrease of grain size. For the recrystallized specimen, the improvement of the RT tensile properties is caused by microstructural refinement if the specimen tested is oil quenched. However, the ductility enhancement for the unrecrystallized specimen is a result of minimizing the transverse grain boundaries. At 600 ℃ for the thicker sheets, both the tensile strength and creep resistance of the specimens corresponding to larger grain size are higher than those with fine microstructures.

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