EFFECT OF TUNGSTEN ADDITION ON MECHANICAL PROPERTIES OF Fe_3Al-BASED ALLOYS①

Xue Feng and Sun Yangshan
Department of Materials Science and Engineering, Southeast University, Nanjing 210096, P. R. China

ABSTRACT The microstructure and mechanical properties of Fe_3Al-based alloys containing tungsten were investigated. Tungsten added to Fe_3Al-based alloys results in significant increases of tensile strength and creep rupture life, but slight decrease of RT ductility. The addition of tungsten combined with niobium or molybdenum is more effective on improving creep resistance and yield strength at the high temperature of 600 ℃. Microstructure observations indicate that the addition of tungsten causes the microstructure refinement and formation of M_6C type precipitates which strengthen both the matrix and grain boundaries.

Key words Fe_3Al W mechanical properties

1 INTRODUCTION

Iron aluminides based on Fe_3Al offer excellent oxidation and sulfidation resistance, with a lower material cost and density than stainless steel. However, their potential use as structural material has been hindered by limited ductility at room temperature (RT), and low strength and poor creep resistance at temperatures above 600 ℃. Recent development efforts have indicated that adequate engineering ductility of 10 % ~ 20 % and tensile yield strength of 550 MPa at RT can be achieved through control of alloy composition and microstructure[1-3]. These improved tensile properties make Fe_3Al-based alloys more competitive against the ferritic steels. The elevated temperature strength and creep resistance have been improved by alloying processes[3,4] and molybdenum, niobium, tungsten have been found to be very effective on strengthening Fe_3Al based alloys at high temperatures[4-7]. The investigation reported here focuses on the effect of tungsten addition on tensile strength and creep resistance of the Fe-28Al-5Cr ternary alloy at RT and high temperature of 600 ℃.

2 EXPERIMENTAL PROCEDURES

Seven alloys whose compositions are listed in table 1 (all the compositions are reported in mole fraction, %) were prepared by vacuum induction melting using commercial melt stock which contained impurities such as C, Si, S and Cu, and the total amount of impurities was about 0.5 %. The composition of the base alloy (alloy 1) was Fe-28Al-5Cr and different amount of tungsten were added in alloys 2, 3 and 4, so that the effect of tungsten addition and variations in tungsten concentration on the microstructure and mechanical properties could be studied. Combined additions of tungsten with molybdenum, tungsten with niobium and molybdenum with niobium were used in alloys 5, 6 and 7, respectively, in order to optimize composition of Fe_3Al-based alloys for their structure applications at high temperatures.

The melt was normally held at 1 620 ~ 1 700 ℃ for 5 min and top-poured into graphite molds to make d 50.0 mm ingots. After homogenized for 10 h at 1 000 ℃, the ingots were hot forged at 1 000 ℃ to 12.0 mm thick sheet bars. The

① Project 715-005-0122 supported by the National Advanced Materials Committee of China
Received Jun. 23, 1998; accepted Oct. 5, 1998

Table 1 Compositions, mechanical properties and average grain size of alloys investigated

Alloy Code	Composition* / %(mole fraction)	RT Tensile			600 ℃ Tensile			Creep rupture*		Grain size/ μm
		σ_b/ MPa	$\sigma_{0.2}$/ MPa	δ/ %	σ_b/ MPa	$\sigma_{0.2}$/ MPa	δ/ %	L/ h	δ/ %	
1	Fe-28Al-5Cr	745	430	13.2	379	325	45.0	6.2	58	90
2	Fe-28Al-5Cr-0.5W	775	472	10.5	409	356	52.0	40	55	45
3	Fe-28Al-5Cr-0.8W	773	502	9.6	416	402	45.0	61	54	40
4	Fe-28Al-5Cr-1.0W	880	527	9.6	472	422	33.1	70	50	35
5	Fe-28Al-5Cr-0.5W-0.5Mo	914	567	11.7	497	430	54.1	404	56	30
6	Fe-28Al-5Cr-0.5W-0.5Nb	985	616	12.8	596	544	34.2	> 600	-	20
7	Fe-28Al-5Cr-0.5Mo-0.5Nb	901	571	11.5	538	500	46.0	116	47	30

Note: Alloy 5, 6 and 7 contain trace Zr, B, Ce, and the creep rupture properties are tested at 600 ℃, 200 MPa.

sheet bars were hot rolled to 4.0 mm thickness at 900 ℃, then worm rolled to 1.5 mm thick sheets at 700 ℃. Tensile specimens with a gage of 15.0 mm × 3.5 mm × 1.5 mm were cut by electric spark machine from rolled sheets. Before testing, all the specimens were annealed at 750 ℃ for one hour followed by oil quenching. For microstructure observation, some specimens were heated at 850 ℃ for 1 h (for recrystallization) and cooled in air. Microcharacterizations of deformation behavior and fracture mode were conducted on selected fracture specimens using various techniques including optical metallography, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Microcompositional analysis and determination of crystal structure of precipitates were performed on specimens of different alloys using analytical electron microscopy (AEM) and selected-area diffraction (SAD) technique, respectively.

3 RESULTS

3.1 Microstructure

The microstructures of the first three alloys were basically the same, consisting of the single phase of Fe_3Al as shown in Fig.1 (an optical micrograph of a recrystallized specimen of alloy 1). TEM observation revealed that some fine precipitates formed in both as-rolled and recrystallized specimens of alloy 4. The morphology of these

Fig.1 Optical micrograph of alloy 1

precipitates are shown in Fig.2. AEM analysis showed that these particles were tungsten-rich and contained a proportion (20 % ~ 30 %) of iron indicating the solubility of tungsten in Fe-28Al-5Cr ternary alloy was less then 1.0 %. Similar precipitates were also observed in alloy 5 and 6, but the composition of the particles in different alloys was not the same. The precipitates in alloy 5 contained molybdenum besides tungsten, and niobium was detected in precipitates in alloy 6. Electron diffraction analysis showed that these tungsten-rich precipitates have the same crystal structure. Fig.3 is the diffraction patterns taken from a specimen of alloy 5 along $[1\bar{1}0]$ prominent zones axes which can be indexed as arising from a cubic structure E93 (S. G. D_{6H}^3 - P63/ MCM) with lattice parameter a = 1.16 nm. This is consistent with the structure of M_6C type carbide (Fe_3W_3C)[11]. Niobium rich precipitates with dimensions of about 1 μm in diameter were observed in alloys 6 and 7. The morphology and composition of the niobium-rich precipitates were similar to that reported in the previous investigation[6].

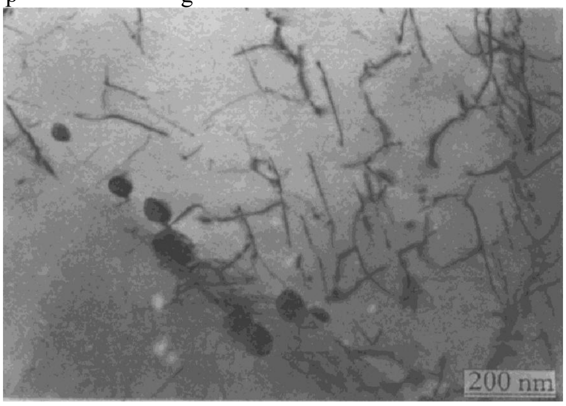

Fig.2 Precipitates in alloy 4

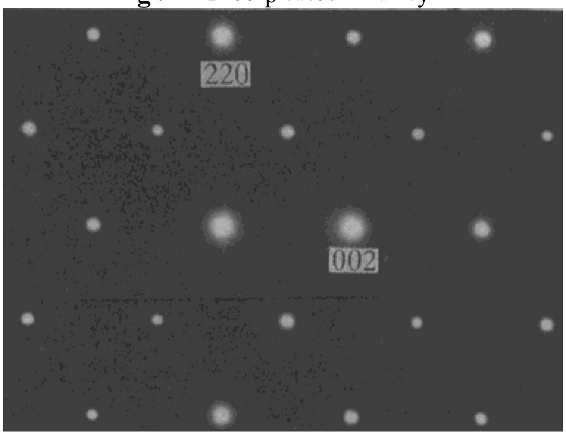

Fig.3 Electron diffraction patterns of precipitates in alloy 5 along $[1\bar{1}0]$

Another change in microstructure caused by tungsten addition was the reduction of the grain size which in the recrystallized specimen of the base alloy was about 90 μm in diameter. The tungsten addition of 0.5% mole fraction and 1.0% mole fraction to the ternary alloy of Fe-28Al-5Cr produced 45 μm and 35 μm grain, respectively. The average grain size in the recrystallized specimens of the Fe_3Al matrix in the alloys studied are listed in table 1, from which it can be seen that the addition of tungsten combined with niobium (alloy 6) was more effective on microstructural refinement than that of molybdenum combined with niobium (alloy 7).

3.2 Mechanical property

Table 1 lists the tensile and creep rupture data for all the alloys studied. From which it can be seen that tungsten addition to the Fe-28Al-5Cr ternary alloy resulted in significant influence on tensile properties and creep resistance. The yield strength increased while the ductility decreased with the increase of tungsten added at both RT and high temperature of 600 ℃. Remarkable improvement of tensile properties was achieved by combined addition of tungsten with niobium (alloy 6). The yield strength of alloy 6 reached as high as 616 MPa at RT and 544 MPa at 600 ℃, respectively, higher than those of the other alloys. In addition, the decrease of RT ductility caused by combined addition of tungsten with niobium was not notable. The elongation of alloy 6 slightly decreased to 12.8%, compared to 13.2% for the base alloy (alloy 1).

The most important result caused by tungsten addition was creep resistance. The creep rupture life increased rapidly when the tungsten added to the Fe-28Al-5Cr base alloy increased. The combined addition of tungsten with niobium or molybdenum resulted in more significant improvement of creep resistance. The longest creep rupture life was also observed on alloy 6, which exceeded 600 h (at 600 ℃, 200 MPa), two orders higher than that of the base alloy.

3.3 Microcharacterizations of dislocation structure

SEM observations showed that the fracture mode of the base alloy at RT was a mixture of transgranular cleavage and intergranular failure, it was consistent with the previous investigation[1]. With increase of tungsten content, the proportion of intergranular failure was reduced. Fig.4(a) is a SEM micrograph of the fracture surface of alloy 3, in which no intergranular failure can be observed. At 600 ℃, the fracture mode of all the alloys transferred to the ductile dimple, as shown in Fig.4(b), and tungsten additions did not cause any distinct changes in the fracture mode of the alloys.

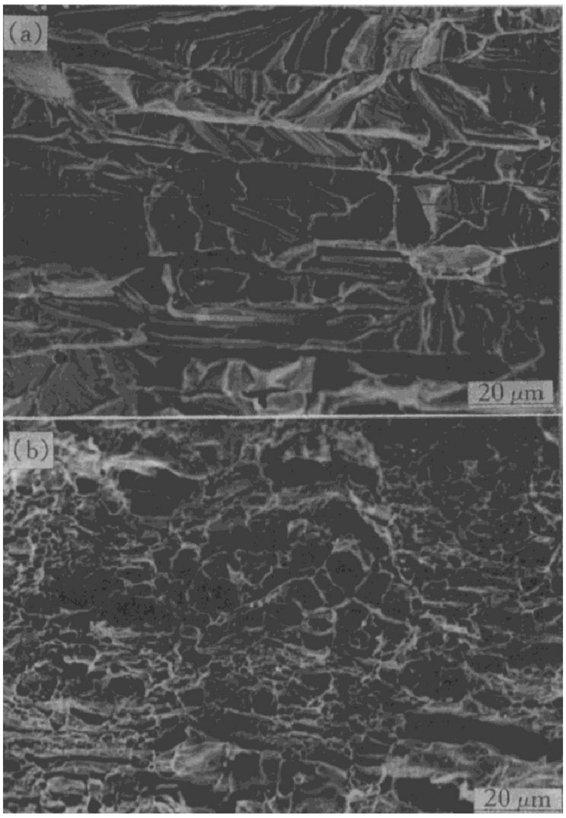

Fig.4 Tensile fracture mode of alloy 3 at RT (a) and 600 ℃ (b)

TEM observations performed on creep ruptured specimen of the base alloy (alloy 1) revealed a coarse structure of planar arrays of dislocation forming low-angle subgrain boundaries and no dislocation within high-angle grain boundaries was observed, as shown in Fig.5(a). However, in the creep ruptured specimens of alloys 4 ~ 7, the hindering of dislocation movement by precipitates and high concentration of dislocation tangle networks were observed, as shown in Fig.5(b).

4 DISCUSSION

The results of the present investigation show that the effect of tungsten additions on the microstructure of Fe_3Al-based alloys is similar to that of molybdenum reported in the previous investigation[4,5]. The formation of tungsten-rich M_6C precipitates in alloy 4 indicates that the solubility limit of tungsten in the matrix of Fe-28Al-5Cr ternary alloy is about 0.8% ~ 1.0% (mole fraction), which is close to that of molybdenum in the same alloy[5]. The same type of precipitate has also been observed in alloy 5 and 6 in which the tungsten concentration is only 0.5% (mole fraction) suggesting that niobium or molybdenum added to Fe_3Al-based alloys decreases the solubility of tungsten in the matrix. Both tungsten and molybdenum additions result in the reduction of grain size. However, tungsten seems more effective on the microstructure refinement for Fe_3Al-based alloys, especially when niobium combined with tungsten is added to the alloys.

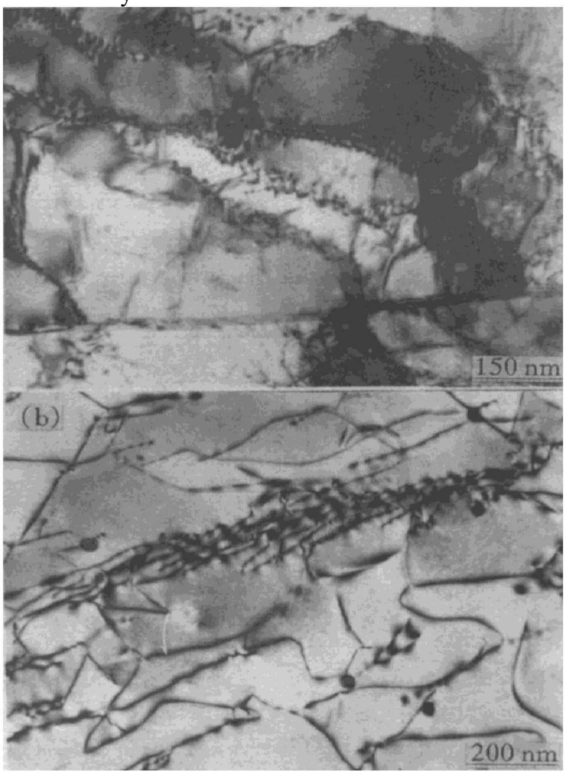

Fig.5 TEM micrographs of creep ruptured specimens
(a) —Alloy 1; (b) —Alloy 6

The addition of tungsten to the Fe-28Al-5Cr alloy causes the increase of the tensile strength at both RT and high temperature of 600 ℃. This is also similar to the effect of molybdenum or niobium additions. By the tensile data of alloys 2, 5 and 6 compared, in which the tungsten concentration is the same, it can be seen that the addition of tungsten combined with niobium or molybdenum is more effective on strengthening the Fe_3Al-based alloy and this can be accounted for by different strengthening mechanism. In alloy 2 the tungsten added goes into the solution and increases the yield strength is the result of the solid-solution strengthening. The combined addition of tungsten with niobium or molybdenum results in the formation of precipitation and both solid-solution strengthening and precipitation hardening make more significant increase of yield strength at both RT and high temperature.

In the previous work the combined addition of niobium and molybdenum to Fe-28Al-5Cr (alloy 1) has been considered to be an optimized composition for high temperature applications[5,8]. However, the combined additions of tungsten with niobium or molybdenum result in more notable improvement of creep resistance in the present work (compared the creep data of alloys 5, 6 and 7 in table 1). The poor creep resistance of the based alloy is due to weak high-angle grain boundaries combined with the reduced ability of dislocation to either interact and produce the strain-hardening or resist the recovery process. The formation of precipitates in alloys 5 ~ 7 strengthens the grain boundaries and precipitate-dislocation interaction strengthens the matrix so that the creep resistance is significantly improved. The differences of creep rupture lives are due to the different types of precipitates formed in these alloys with or without tungsten. The precipitates formed in Fe_3Al-based alloys containing molybdenum or niobium have reported to be Mo_2C (hexagonal, C_3-type) or NbC (FCC, B_1-type)[9,10], while the precipitates in alloy 5 and 6 studied are mainly tungsten-rich M_6C phase. TEM observations have revealed that the precipitates in the creep ruptured specimen of alloy 6 (after test at 600 ℃ for 600 h) are still very fine (about 50 ~ 100 nm in size) suggesting that the coarsening rate of the precipitates at 600 ℃ is very low. In addition, the high density of dislocation tangle observed in the creep rupture specimen of alloy 6 (see Fig.5(b)) indicates recovery of dislocations into subgrain boundaries is difficult at 600 ℃ because the fine precipitates are the effective obstacles to dislocation climb or recovery.

5 CONCLUSIONS

(1) The solubility limit of tungsten in the matrix of Fe-28Al-5Cr is estimated to be less than 1.0% (mole fraction). If the tungsten content exceeded this limit, a M_6C type particles can be found in the alloy.

(2) The addition of tungsten results in a decrease of grain size of Fe_3Al matrix.

(3) Addition of tungsten, especially when combined addition with niobium or molybdenum and trace Zr, B, Ce, to Fe_3Al based alloys results in significant improvement of tensile strength and creep rupture life.

(4) Tungsten addition increases creep resistance by forming precipitates and dislocation tangles which hinder dislocation movement.

REFERENCES

1 Mckamey C G, Horton J A and Liu C T. J Mater Res, 1989, (6): 1156.
2 Sikka V K. SAMPE, 1991, (2): 22.
3 Zhang Zhonghua and Sun Yangshan. Trans Nonferrous Met Soc China, 1997, 7(4): 57.
4 Mckamey C G and Horton J A. Metall Trans, 1989, (20A): 751.
5 Sun Yangshan, Xue Feng and Mei Jianping. Scr Metall Mater, 1995, (32): 1181.
6 Guo Jun and Xue Feng. The Chinese Journal of Nonferrous of Metals, (in Chinese), 1995, 5(Suppl 2): 113.
7 Xue Feng. Master's Thesis. Nanjing: Southeast University, 1996.
8 McKamey C G, DevanJ H, Tortorell P F *et al*. J Mater Res, 1991, (6): 1979.
9 McKamey C G, Maziasy P J and Jones J W. J Mater Res, 1992, (7): 1089.
10 Maziasy P J and McKamey C G. Mater Sci Eng, 1992, (A152): 322.
11 Huang Xiaoying. Transmission Electron Microscopy, (in Chinese). Shanghai: Shanghai Science and Technology Press, 1987: 582.

(Edited by Huang Jinsong)