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Effect of Fe and Mo additions on microstructure and mechanical properties of TiAl intermetallics

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Abstract: The ductility of TiAl intermetallics can be improved through stabilizing the ductile β phase. New β-stabilized Ti−45Al−xFe−yMo (x, y=1, 2, 3, 4) alloys were designed through adding the β stabilizing elements Fe and Mo. The microstructural evolution and deformation behavior of the Ti−45Al−xFe−yMo alloys were investigated. The results show that the amount of β(B2) phase is increased with the increase of alloying elements. Mo shows a higher capability for stabilizing the β phase than Fe. In the optimized Ti−45Al−3Fe−2Mo alloy, the grains are significantly refined to about 12 μm, and this alloy shows a very good hot ductility at the elevated temperature.

Key words: TiAl intermetallics; Fe; Mo; β phase; grain refinement

1 Introduction

To develop a high temperature structural material, γ-based TiAl intermetallics are very promising due to their low density, high specific strength and relatively good resistance to oxidation at service circumstance. However, one of main drawbacks of the γ-TiAl intermetallics is the limited ductility at ambient temperature, which influences its practical applications. Property optimization of these alloys can be achieved by alloying and appropriate thermal or thermo-mechanical treatment. For instance, the ductility can be improved by introducing the ductile β phase into the alloy. Several studies [1−4] reported that adding the elements Nb, Cr, Si, V, Zr, Mo and Fe into binary γ-TiAl alloys can stabilize the β phase and develop the $\alpha/\gamma+\beta$ ternary γ-TiAl alloys.

Among the alloying metals, Mo [5] is well known to be a strong β stabilizing element so that a modest amount addition of Mo can promote the formation of β-containing microstructure in γ-TiAl alloys. Fe addition into the TiAl alloy is restricted to selected isothermal sections of the ternary phase diagram. Several cubic ternary and quasi-binary phases are present in Al−Ti−Fe system [6]. These additional phases [7−9], which can contribute to the increase of yield stress in TiAl alloys, are the hexagonal Ti_3Al with $D0_{19}$ structure, the cubic FeTi with B2 structure which is dissolved Al corresponding to (Fe,Al)Ti, and the ternary τ_2 phase with the complex cubic $D8_a$ structure which is approximately described by $(Ti,Al)_3Fe$. For these reasons, efforts should be made to develop a TiAl alloy with optimized microstructure and ductility through the alloying of Fe and Mo. The objective of the present work is to study the effect of alloying with Fe and Mo on the microstructure and mechanical properties of TiAl alloys.

2 Experimental

TiAl ingots with the nominal compositions of Ti−45Al−xFe (x=1, 2, 3, 4, mole fraction, %), Ti−45Al−xMo (x=1, 2, 3, 4), and Ti−45Al−xFe−yMo (x=2, 3) alloys were prepared by vacuum electrode arc melting method. The raw materials were high-purity (99.99%) Ti, Al, Fe, and Mo powders. The ingots were re-melted five times to ensure the composition uniformity. Then, the ingots were homogenized at 1150 °C for 24 h. Tensile samples with gauge dimensions of 8 mm×3 mm×2 mm were cut from the homogenized ingots. High temperature tensile experiments were carried out on a CSS−44100 testing machine at a strain rate of 2×10^{-3} $s^{-1}$and ambient

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temperature of 790 °C. X-ray diffraction measurements were performed on a X-ray diffractometer (XRD) using Cu K_α radiation. The microstructures were observed in a Quanta 600 environmental scanning electron microscope (SEM) and an energy-dispersive spectrometer (EDS).

3 Results

3.1 Microstructures

The results from a series of microstructural investigations were combined for evaluation of the relevant composition and mechanism in the Ti−Al−Fe−Mo alloys. The microstructures of Ti−45Al−*x*Fe (*x*=1, 2, 3 and 4) alloys in as-cast and as-annealed conditions are shown in Fig. 1 and Fig. 2, respectively. β(B2) phase can be clearly observed in the Fe-modified TiAl alloys, and the volume fraction of β(B2) phase (white phase) increases from about 0.5% to about 18% as the Fe content increases from 1% to 4%. The grain size in the 4% Fe-containing alloy is about 30 μm, which is much finer than that in the Fe-free condition. Molybdenum is also a strong β stabilizer, and a great deal of stabilized β phase can also be found in the Mo-modified TiAl alloys, as shown in Figs. 3 and 4. The cast Mo-modified TiAl alloys exhibit a coarse lamellae microstructure and the average colony size is about 0.5 μm wide (Fig. 3). After annealing treatment, the grains in the 2%−3% Mo-containing TiAl alloys are refined to about 18 μm, and the volume fraction of β phase increases to 15%−20% (Fig. 4). Therefore, the above results suggest that the addition of Fe and Mo not only stabilizes the β phase but also refines the microstructure. Specially, the even and refined microstructure of TiAl alloys can be acquired by the addition of Fe or Mo while the content is 2%−3%. So, the further research on Ti−45Al−*x*Fe−*y*Mo (*x*, *y*=2, 3) alloys will be taken.

Figures 5 and 6 show the microstructures of Ti−45Al alloys with Fe and Mo additions in the as-cast and as-annealed conditions, respectively. These microstructures consist of three phases (Fig. 7): the dark γ phase, the gray α_2-Ti_3Al phase, and the dendritic white β(B2) phase, which are homogeneously distributed in the dark γ matrix. Element Fe mainly distributes in gray α phases and element Mo distributes mainly in white β phase, and in dark γ phases. The ratio of Ti/Al is about 1:1 (Fig. 8). The size of matrix γ grains in the Ti−45Al−3Fe−2Mo alloy is about 12 μm, which is the finest in the three annealed alloys. Therefore, this alloy was selected for further study of the mechanical behaviors.

3.2 Mechanical behaviors

Figure 9 shows the tensile true stress—strain curve of the annealed Ti−45Al−3Fe−2Mo alloy tested at

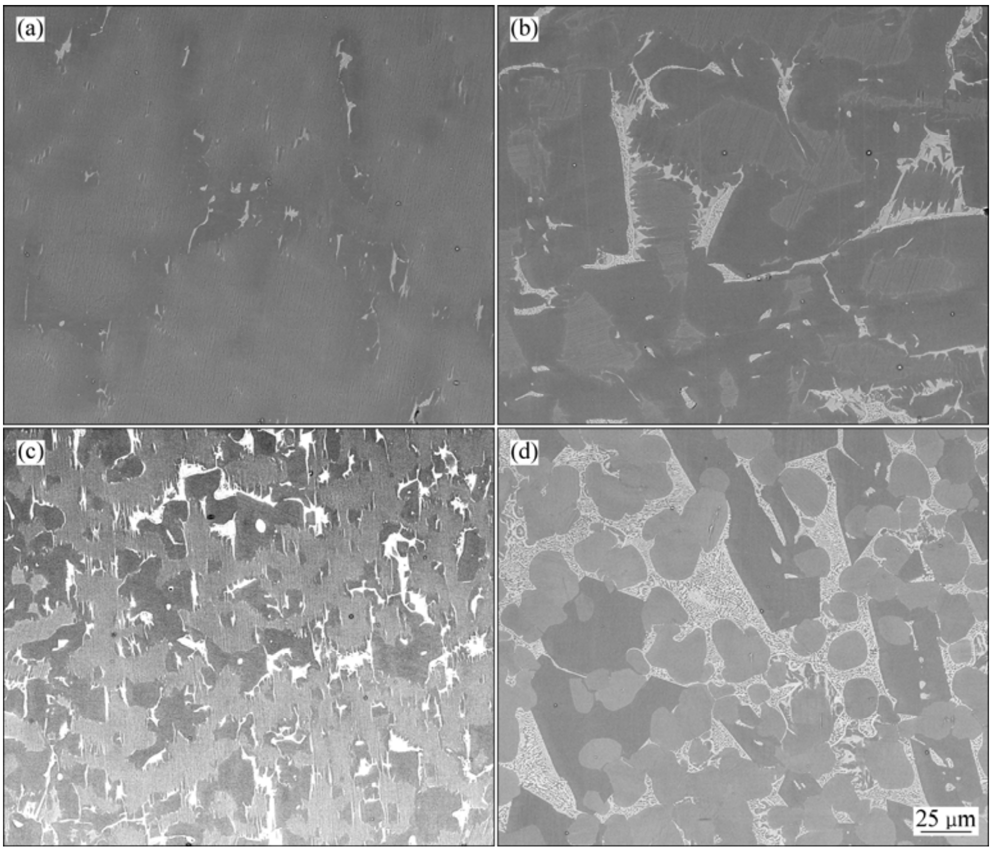

Fig. 1 As-cast microstructures of Ti−45Al−*x*Fe: (a) *x*=1; (b) *x*=2; (c) *x*=3; (d) *x*=4

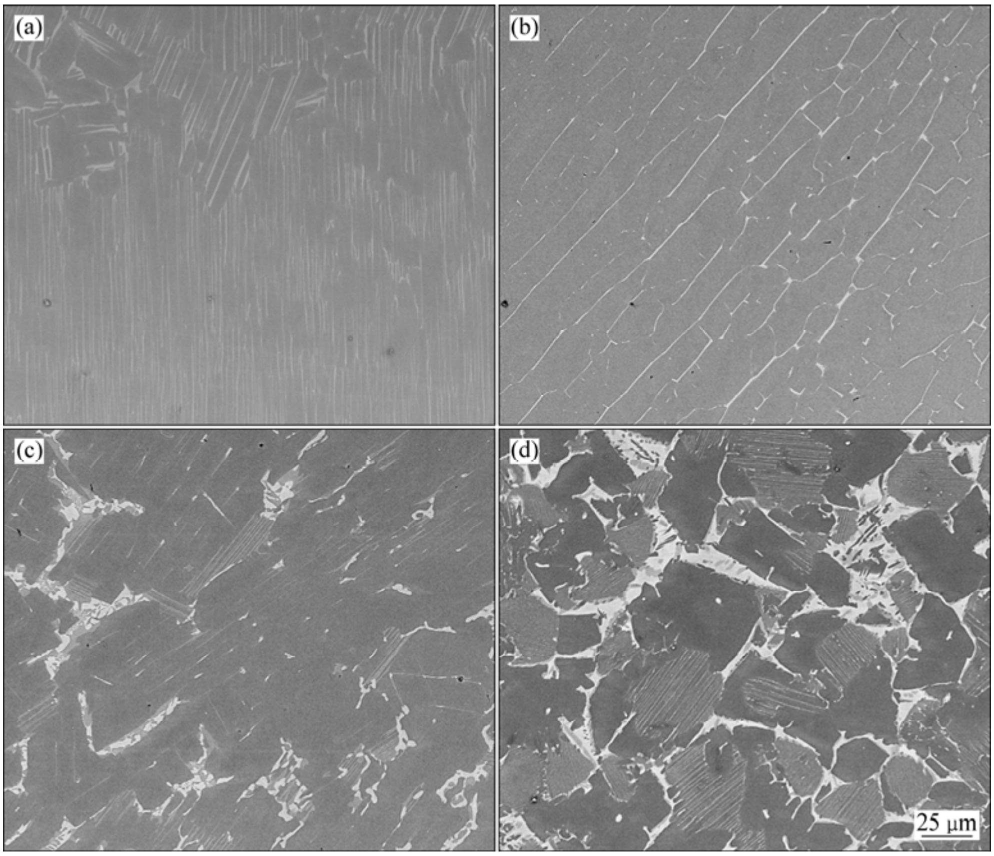

Fig. 2 As-annealed microstructures of Ti−45Al−xFe: (a) x=1; (b) x=2; (c) x=3; (d) x=4

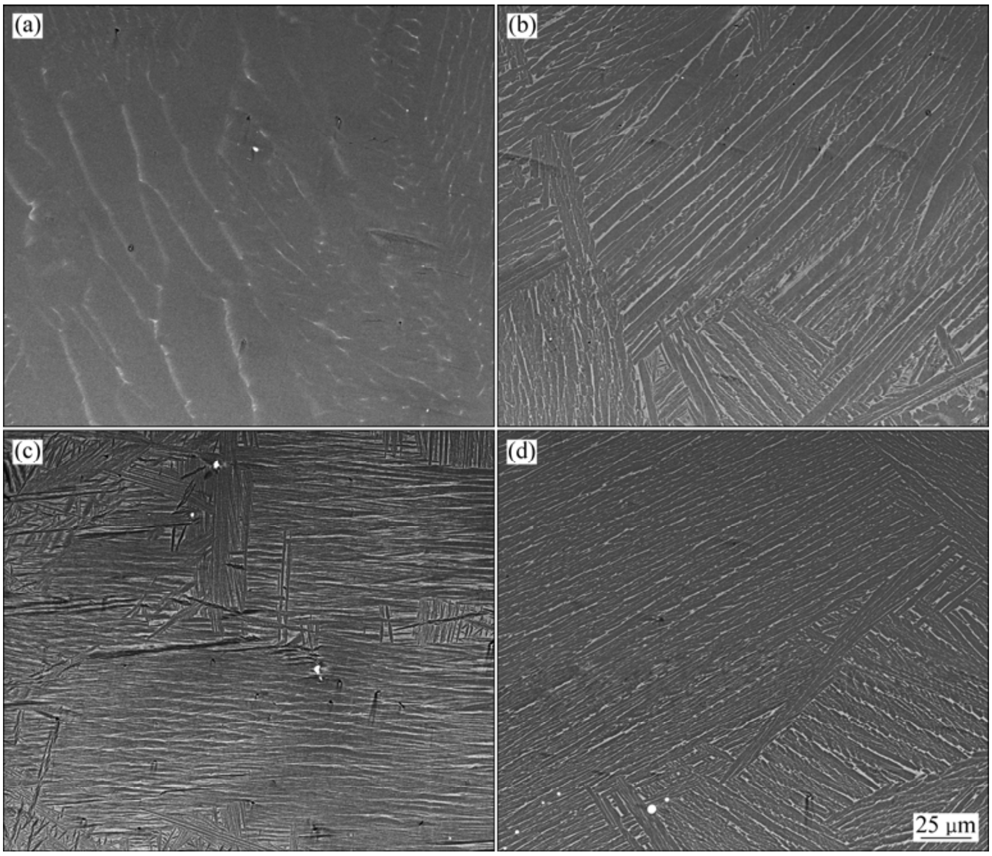

Fig. 3 As-cast microstructures of Ti−45Al−xMo: (a) x=1; (b) x=2; (c) x=3; (d) x=4

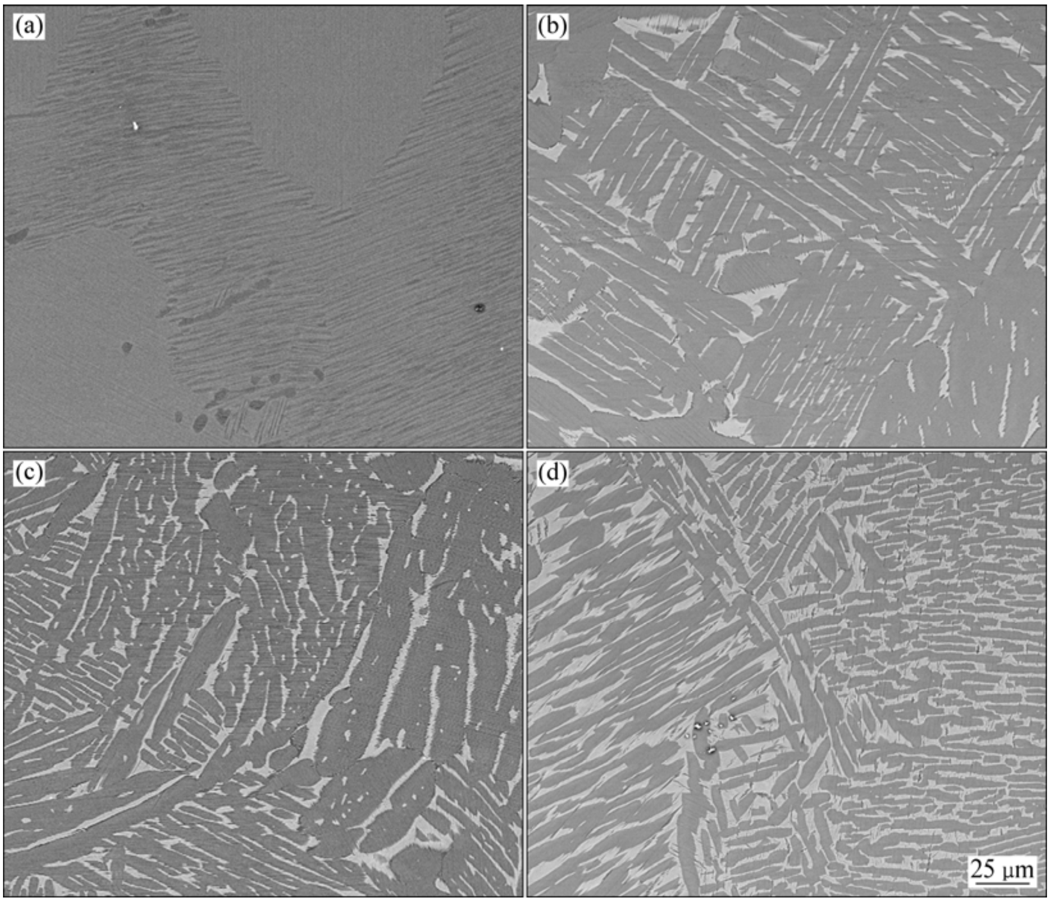

Fig. 4 As-annealed microstructures of Ti−45Al−xMo: (a) x=1; (b) x=2; (c) x=3; (d) x=4

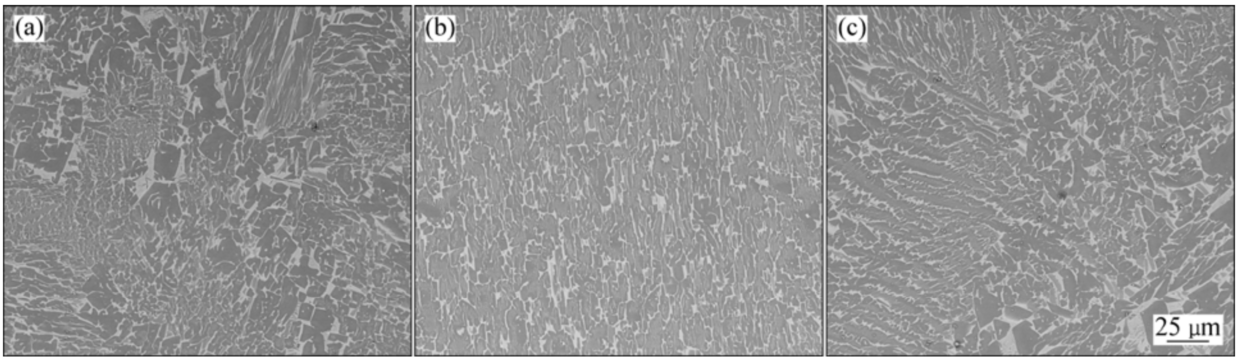

Fig. 5 As-cast microstructures of Ti−45Al alloys with additions of 2Fe+2Mo (a), 3Fe+2Mo (b), and 3Fe+3Mo (c)

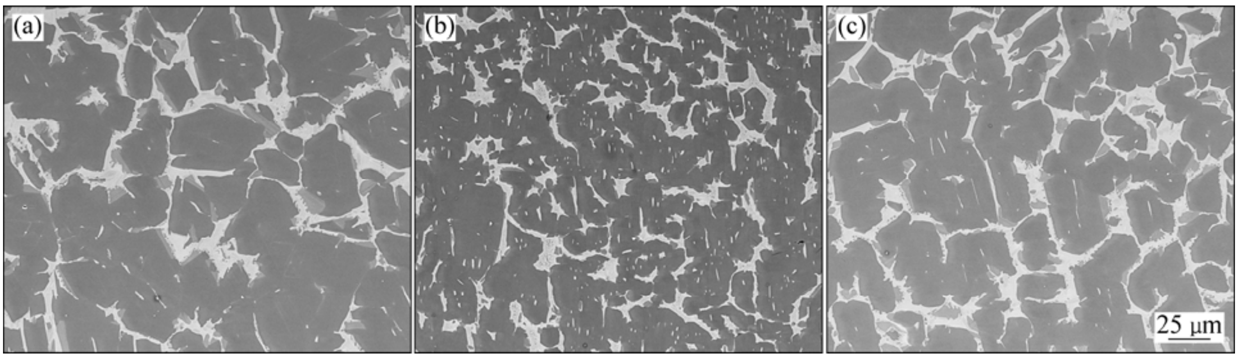

Fig. 6 As-annealed microstructures of Ti−45Al alloys with additions of 2Fe+2Mo (a), 3Fe+2Mo (b), and 3Fe+3Mo (c)

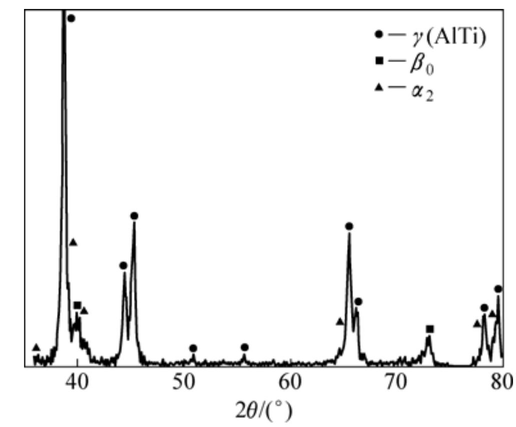

Fig. 7 XRD pattern of Ti−45Al−3Fe−2Mo alloy

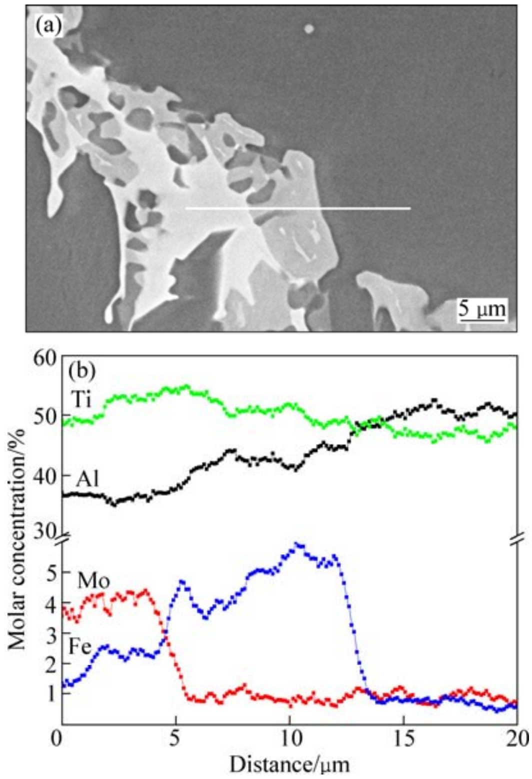

Fig. 8 TEM microstructure (a) and cross-sectional element profile (b) (white line in Fig. 8(a)) of Ti45Al−3Fe−2Mo alloy

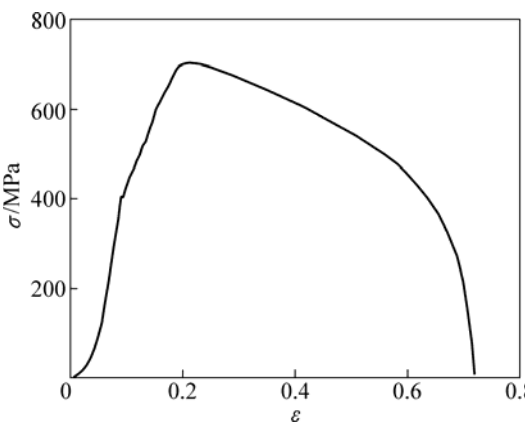

Fig. 9 Flow curve of annealed Ti−45Al−3Fe−2Mo alloy at strain rate of 2×10^{-3} s^{-1} and 790 °C

790 °C and strain rate of 2×10^{-3} s^{-1}. The ultimate tensile strength (σ_b) is about 702 MPa and the ultimate strain (ε) is about 0.72. It is apparently shown that this alloy has a good hot ductility at elevated temperature. Figure 10 shows the tensile fractograph of the tensile sample, where some fine ductile dimples can be clearly seen, which suggests that the tensile fracture mode is ductile.

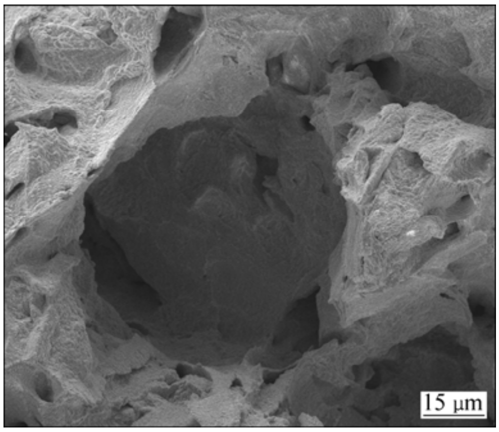

Fig. 10 SEM morphology of fracture surface of Ti−45Al−3Fe−2Mo alloy

4 Discussion

The B2 phase has been used to improve the workability of TiAl alloys. For obtaining a reasonable microstructure and good hot-workability, it has been highly desirable to introduce the B2 phases in TiAl intermetallics.

Ti−45Al−*x*Fe−*y*Fe alloy is a near *γ*-TiAl alloy. An important phase transformation in this alloy is the phase transformation from high temperature *α* phase to equilibrium *β*+*γ* phases at lower temperatures. YI [5] studied the phase transformation in Ti−Al−Mo system and reported that some *β* phases can be stabilized, which was attributed to the selective microstructural evolution paths that are determined mainly by the cooling rate and the composition. ZHANG et al [10] indicated that, in the *β*-stabilized TiAl alloy, the high temperature *α* phase will transform to *α*+*γ* lamellar colonies when passing through the *α*+*β*+*γ* three-phase field with slow cooling rate. IMAYEV et al [3] also observed a bimodel microstructure with *β*+*γ* lamellar colonies and *γ* grains in the as-cast Mo-containing TiAl alloy. According to the above discussions and the phase diagram of Ti−Al−Mo system [5], the possible phase transformation paths for the present Mo-modified alloy during cooling are as follows: $L\rightarrow L+\beta\rightarrow\beta+\alpha\rightarrow\alpha\rightarrow\alpha'+\gamma\rightarrow\alpha'+\beta'+\gamma\rightarrow\alpha_2+\text{B2}+\gamma$.

Similar to the effect of Mo, Fe also works as the *β* stabilizer in TiAl alloy [9]. By the addition of Fe to improve castability, the fine grains of *γ* phase, surrounding with *β*(B2) grains, are present in as-cast

TiAl alloys. The B2 phase could be stable at room temperatures or after following heat-treatment.

On the other side, JIN et al [11] pointed out that fine-grained cast TiAl alloys can be produced by utilizing the refining effect of *β* solidification. Obviously, the microstructural scale of these *β*-containing TiAl alloys tends to be significantly smaller than that of conventional *γ*-TiAl alloys. During annealing, the grain coarsening is controlled by grain boundary diffusion, since the *β* phase exists along the grain boundaries of *γ* matrix grain. The kinetics for the coarsening process can be classically expressed by the following equation [12]:

$$\frac{T}{t}(r_t^3 - r_0^3) = \frac{8(D_{\sigma\upsilon}\sigma_{\gamma\beta}\sigma_{\gamma\alpha}C_\upsilon V_m)}{9R}\exp(-\frac{Q_v}{RT})$$

where D and Q are the pre-exponential factor and the activation energy for volume diffusion of the rate controlling species within the matrix, respectively; C and V are the solubility in the matrix and the molar volume of the rate controlling species within the matrix, respectively. Since the annealing temperature (T) is relatively high (1150 °C>(2/3)T_m), the rate difference between volume diffusion and diffusion along the grain boundaries would not be remarkable [5]. The flux due to volume diffusion can be dominant. The *β* phase is stable with respect to the interfacial ratio in the *β*-containing microstructure by alloying a certain mount of Fe and Mo. The elements Fe and Mo, which mainly distribute in the *α* and *β* phase, may be considered in the diffusion and coarsening process. The *γ* matrix grain size of Ti−45Al−3Fe−2Mo alloy is less than 20 μm even after annealing treatment, and a significant effect of quadrijunction [13] in retarding grain growth rate of *β*-containing microstructure is evident.

Furthermore, recent studies [2,14,15] revealed that the good hot-working behavior in the *β*-containing TiAl alloys is attributed to the development of a fine-grained microstructure with metastable *β* grains. In the present study, the Ti−45Al−3Fe−2Mo alloy has a very fine microstructure (c.a. 12 μm) with high proportion of *β* phase. Therefore, it is reasonable to believe that plastic deformation of Ti−45Al−3Fe−2Mo alloy may take place at 790 °C.

5 Conclusions

1) Iron and molybdenum are *β* stabilizers in TiAl alloy. For the present Ti−45Al−3Fe−2Mo alloy, the possible paths for the phase transformation during cooling are as follows: $L\rightarrow L+\beta\rightarrow\beta+\alpha\rightarrow\alpha\rightarrow\alpha'+\gamma\rightarrow\alpha'+\beta'+\gamma\rightarrow\alpha_2$+B2+$\gamma$.

2) The stabilized B2 phase refines the *γ* matrix through retarding grain growth rate. A significant effect of grain refinement is evident by alloying Fe and Mo elements.

3) The Ti−45Al−3Fe−2Mo alloy shows a good hot ductility at elevated temperatures, which is believed to be derived from the effect of fine microstructure and retained B2 phase.

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Fe 和 Mo 元素对 TiAl 金属间化合物显微组织和性能的影响

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摘　要：β 相可以提高 TiAl 金属间化合物的塑性。通过显微组织分析和变形行为的评估研究 β 稳定性元素 Fe 和 Mo 对 Ti−45Al−xFe−yMo(x, y=1, 2, 3, 4)合金的影响。结果表明：合金中的 B2 (β)相随着 Fe 和 Mo 元素含量的增加而增多，Mo 表现出强的 β 稳定性。加入 3%Fe 和 2%Mo 后，合金的晶粒得到细化，其尺寸达到 12 μm。由于具有一定量的 β 相，细化后的 Ti−45Al−3Fe−2Mo 合金在 790 °C 具有良好的塑性。

关键词：TiAl 金属间化合物；Fe; Mo；β 相；晶粒细化

(Edited by YUAN Sai-qian)