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The influence of tantalum on the high temperature characteristics of lamellar gamma + alpha 2 titanium aluminide

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ABSTRACT

The high temperature behavior of as-cast Ti–46Al, Ti–45Al–7Nb and Ti–45Al–7Ta (in at.%) alloys at 800 °C was investigated in this work. The structure, hardness and bending strength of the as-cast alloys were characterized. During long-term (460 h) annealing of the alloys at 800 °C, the structural changes were examined, and the development of hardness was monitored. The creep behavior at 800 °C was studied in the three-point bending mode at bending stresses of 200, 400 and 600 MPa. The oxidation rate of the alloys in air at 800 °C was monitored by measuring the weight gain as a function of oxidation time. It was found that tantalum did not modify the lamellar $\gamma + \alpha_2$ structure of titanium aluminides, but it negatively influenced the bending strength at room temperature in comparison to niobium. The formation of metastable Ta-supersaturated γ and α_2 phases was also revealed to occur in the Ti–45Al–7Ta alloy. During annealing at 800 °C, the Ta-rich τ phase precipitated, which led to hardening of the Ti–45Al–7Ta alloy. The creep resistance of the Ti–45Al–7Ta alloy was shown to be the best of all the investigated materials, and the influence of Ta is discussed in relation to its diffusivity and creep mechanism.

1. Introduction

Titanium aluminide-based intermetallics show a good combination of high strength at elevated temperatures and low weight. These characteristics make them of interest for thermally and mechanically loaded components in the automotive, aerospace and power industries. Components like turbine blades, turbocharger rotors or exhaust valves are examples where Ti–Al intermetallics could potentially be used. Among processing technologies, precise casting is a promising and low cost process to produce complex shaped components of titanium aluminides. However, the coarse as-cast structure of castings results in low room temperature ductility and fracture toughness. To refine the structure of castings, two main approaches have been considered thus far: (1) application of minor additives like boron, which influence the solidification process and acting as inoculants for the primary beta titanium grains [1], (2) heat treatment leading to the formation and decomposition of the massive gamma phase. Titanium aluminides, when cooled at a sufficiently high rate from the alpha region, show the diffusionless massive transformation in which a highly faulted gamma phase is generated [2–6]. Subsequent annealing transforms the gamma phase to refined lamellar microstructures, showing improved mechanical properties. The main problem is that rapid cooling of complex shaped components causes the formation of excessive thermal stresses and cracks and is, therefore, unsuitable. Therefore, additives that reduce the critical cooling rates needed for the massive transformation to occur are beneficial. Among them, niobium and tantalum, which are slow diffusers in the Ti–Al phases, have recently been shown as very efficient because they significantly extend the cooling rate interval for the massive transformation [5,6].

The creep behavior of titanium aluminides at high temperatures has been studied severally in the past two decades. Pure titanium aluminides, i.e., γ-TiAl and α_2-Ti_3Al, show poor creep resistance at temperatures around 800 °C. Therefore, various alloying elements have been proposed to improve the high temperature creep resistance and strength. These include solid solution strengtheners, β-formers and slow diffusers in Ti–Al phases (W, Cr, V, Nb, Fe, Ta). Moreover, alloying with Si, B and C leads to the precipitation of silicides, borides and carbides, which also slow down the creep rate [7–15]. The positive effects of these elements are associated with hindering of the movement of dislocations and with slowing down of the recovery and dynamic recrystallization processes. The creep mechanisms of titanium aluminides were investigated by fitting the measured creep rates to the power law, which relates the minimum (secondary) creep rate $\dot{\varepsilon}$ to the applied stress σ and temperature T:

$$\dot{\varepsilon} = A \cdot \sigma^n \cdot \exp\left(\frac{-Q}{RT}\right) \quad (1)$$

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The stress exponents n and creep activation energies Q obtained suggested that the diffusion-assisted dislocation climb may be the dominating creep mechanism in Ti–Al intermetallics at around 800 °C [10,13,14]. Regarding the structure of titanium aluminides, many studies have revealed that the fully lamellar $\gamma + \alpha_2$ structure is beneficial for the improvement of creep resistance and that the minimum creep rate generally decreases with decreasing interlamellar spacing [10]. The reason is that the lamellar interfaces represent obstacles for the dislocation movement. It was also shown that interlocked lamellar grains with zigzag-shaped boundaries reduce the creep rate by preventing the grain boundary sliding [15]. As given above, both Nb and Ta positively influence the creep resistance of titanium aluminides. Despite the close positions of both elements in the Periodic Table, it was indicated by some authors that their effects are different. As an example, for the Ti–46Al–8Ta aluminide, the minimum creep rates at stresses of 200–400 MPa and at 750 °C were shown to be one order of magnitude lower than that for the Ti–46Al–8Nb one [16]. However, a detailed explanation of the influence of tantalum on the creep process is lacking.

Beside mechanical properties, high-temperature applications also require good resistance to high-temperature corrosion in oxidizing atmospheres. Pure Ti–Al alloys show poor oxidation resistance because unprotective mixtures of rutile and alumina are formed during the oxidation. In a number of studies, niobium has been shown to be very effective in improving the oxidation resistance due to the doping effect and the increase of aluminum activity and diffusivity [17–28]. The doping of the rutile lattice with niobium atoms reduces the oxygen vacancy concentration and, therefore, the oxygen diffusion rate through the rutile scales. The increase of Al-activity and diffusivity supports the formation of a protective alumina layer in the scales. Because of the similarity between the chemical behavior of Nb and Ta given by their positions in the Periodic Table, one may expect that tantalum would show an effect on high-temperature oxidation similar to that of niobium. To our knowledge, there are several studies concerned with the influence of Ta; however, these studies do not provide clear and generally accepted conclusions. On one hand, there are a few reports implying that Ta slows down the high-temperature oxidation similarly to Nb [20]; other works show that Ta retards the oxidation, but its effect is significantly weaker compared to that of Nb [18,19,24,25]. For this reason, Ta is sometimes also referred to as a neutral element in relation to the high-temperature oxidation, i.e., its influence is negligible [18]. However, in a recent work [29], it was shown that the positive effect of tantalum on the oxidation resistance at above 900 °C is stronger than that of niobium.

The strongly beneficial effects of tantalum on the refining process, mechanical properties, oxidation and creep resistance of Ti–Al based intermetallics has recently drawn attention to titanium aluminides containing this element [6,16,30,31]. However, detailed data on their high temperature behavior are still lacking. For this reason, this study is concerned with the characteristics of the as-cast Ti–45Al–7Ta aluminide at 800 °C, which is close to the operational temperatures of titanium aluminide components. The creep process was studied at this temperature along with the development of structure and hardness after long-term annealing at 800 °C. To better understand the effect of tantalum on the high temperature behavior, the material studied is compared to Ti–45Al–7Nb and Ti–46Al aluminides.

2. Experiment

In this work, three titanium aluminides with nominal compositions (in at.%) of Ti–46Al, Ti–45Al–7Nb and Ti–45Al–7Ta (see Table 1) were investigated. The experimental materials were prepared by arc melting of pure metals (99.99%) in a water cooled copper crystallizer under a high-purity helium atmosphere. Each melting was repeated seven times to ensure homogeneous chemical composition. Ingots of 20 mm × 10 mm × 80 mm in size were then cut by spark-machining into rectangular samples for structural and mechanical characterization and creep experiments.

Table 1
Chemical compositions of the investigated materials.

Alloy	Element (in at.%)			
	Ti	Al	Nb	Ta
Ti–46Al	53.4	46.6	–	–
Ti–45Al–7Nb	47.5	45.2	7.3	–
Ti–45Al–7Ta	48.6	44.8	–	6.6

Mechanical properties were characterized by three-point bending strength tests, Vickers hardness measurements with a loading of 10 kg and creep tests. Room temperature hardness was measured both in the as-cast state and after various annealing times at 800 °C in a flow of high-purity argon. The total annealing time was 460 h. For the bending mechanical testing at room temperature, samples of 5 mm × 50 mm × 1 mm in size were used, and the distance between both supports was 30 mm. Creep behavior in the three-point bending mode at 800 °C was studied with samples of the same dimensions by using a FPZ 100/1 loading machine equipped with a heated chamber. Creep tests were performed at three bending stresses of 200, 400 and 600 MPa, and the distance between supports was 34 mm.

Cross-sections of as-cast, annealed and crept samples were examined by various techniques including light microscopy (LM), scanning electron microscopy (SEM, HITACHI S 4700, regime of secondary electrons, acceleration voltage of 15 kV), energy-dispersion spectrometry (EDS), X-ray diffraction (XRD, X'Pert Philips, 30 mA, 40 kV, X-ray radiation Cu Kα) and X-ray fluorescence spectrometry (XRF, ARL 9400 spectrometer). To observe the structure with LM and SEM, samples were etched in a solution of 30 ml HF, 30 ml HNO_3 and 100 ml H_2O.

3. Results

3.1. Structures and mechanical properties of the as-cast materials

Optical micrographs of the as-cast alloys are shown in Fig. 1. All the investigated materials have almost fully lamellar structures consisting of relatively coarse grains of several hundreds of micrometers in size. As was also confirmed by XRD (not shown), there are alternating γ and α_2 lamellae in the grains. The average inter-lamellar spacing was a few micrometers for all the alloys. In some regions, a thin layer along grain boundaries is observed, and EDS microanalysis proves that this layer corresponds to the γ-TiAl phase that forms during cooling of prior α grains.

Mechanical properties were characterized by hardness testing and bending tests, and results are summarized in Table 2. During the three-point bending tests, the alloys did not exhibit any plastic deformation, and thus only the bending strength is given in this Table. The materials show slightly different hardness values of around 400 HV. The highest hardness is observed for the

Table 2
Vickers hardness and bending strength of the as-cast alloys at room temperature. The average of 10 and 5 measurements, respectively, are given.

Alloy	Vickers hardness	Bending strength (MPa)
Ti–46Al	399 ± 18	484 ± 33
Ti–45Al–7Nb	388 ± 30	837 ± 21
Ti–45Al–7Ta	418 ± 20	420 ± 27