HIGH-TEMPERATURE BEHAVIOUR OF Ti-Al-Nb-Ta INTERMETALLICS

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Abstract

Ti-Al intermetallics have gained significant attention as possible replacements of nickel superalloys in high-temperature applications in automotive, aerospace and energetic industry. The favourable properties of Ti-Al intermetallics are improved by alloying; keeping their low density these materials gain high strength, good structural stability, high-temperature oxidation and creep resistance. One of the common alloying elements used in this application is niobium. It improves the high-temperature properties especially the oxidation resistance. In present time the tantalum is studied as well with same or even better results.

This work compares the influence of Nb and Ta on the properties of Ti-Al intermetallics. In particular, we studied the alloys of the compositions Ti-46Al, Ti-46Al-8Nb and Ti-46Al-8Ta (at. %). We evaluated the transverse strength and the hardness of as-cast samples and described their microstructure as well. Finally we inspected the high-temperature properties such as oxidation, creep and structural changes.

Keywords

titanium aluminide, high-temperature materials, creep, transverse strength, structural stability

1. INTRODUCTION

The alloys based on titanium aluminides have became the attractive candidates for application in the automotive, aerospace and energetic industry (valves, blades in turbines). These materials exhibit outstanding properties which consist in combination of low density (3.9 – 4.2 g.cm\(^{-3}\)) and good mechanical and chemical properties even at elevated temperature. The 3\(^{\text{rd}}\) generation [1] of TiAl alloys contains Nb (4 – 8 at. %) which improves oxidation resistance and high-temperature mechanical properties and strengthens the solid state solution as well. The beneficial effect of niobium to oxidation resistance consists in increase of the activity of aluminium and therefore support of the formation of compact protective layer of Al\(_2\)O\(_3\). The alumina is a very effective barrier against oxygen penetration because of its very low diffusion coefficient in this oxide [2]. Niobium also possesses a so-called doping effect which consists in replacing of Ti\(^{4+}\) ions in TiO\(_2\) lattice with ions of higher valence, such as Nb\(^{5+}\), which leads to reduction of oxygen vacancy responsible for oxygen diffusion [2]. As said before, the presence of Nb is also beneficial to the mechanical properties even at high temperatures because its relatively big atoms induce stresses in titanium lattice and therefore limit the movement of dislocations. Because its chemical similarity given by position in Periodic Table, tantalum has the positive effect on high-temperature properties of TiAl-alloys as well [3]. The influence of tantalum on high-temperature properties of TiAl-based intermetallics has been tested and, in our recent study, we have proved tantalum has greater positive effect on high-temperature oxidation of the concerned intermetallics than niobium [4]. However, some studies did not evaluate the influence of tantalum more positive than the influence of niobium and found it similar or even lower [3, 5].

The difference between tantalum and niobium as a ternary alloying element to TiAl-based intermetallics is not only in their oxidation behaviour. Depending on these two alloying elements also the structure of these
intermetallics differs. This is very important fact because the structure significantly affects the mechanical properties of the majority of alloys which is also the case of TiAl-based intermetallics.

Our aim is to compare the influence of tantalum and niobium on high-temperature properties of TiAl-based intermetallics including oxidation behaviour, mechanical properties and structural stability.

2. EXPERIMENTAL

The ingots of alloys with chemical composition in at. % Ti-46Al (hereafter denoted as TiAl), Ti-46Al-8Nb (denoted as TiAlNb) and Ti-46Al-8Ta (denoted as TiAlTa) were prepared by arc melting of pure metals (99.99%) in a water cooled copper crystallizer under high-purity helium atmosphere. Ingots were then cut by spark-machining into rectangular samples with dimensions of 15x15x5 mm for oxidation experiments and structural stability evaluation and into elongated samples with dimensions of 50x8x2 mm for transverse strength tests and for creep tests. Prior to oxidation, surface of samples was ground on SiC papers, then polished by a 1 µm diamond paste and finally washed and dried. Cyclic oxidation in air was conducted in a resistance furnace at 800 °C. The total oxidation time was 305 hours. Oxidation kinetics was measured as weight gain versus oxidation time. For evaluation of microstructure the samples were ground on SiC papers, polished by a 0.7 µm diamond paste, etched by a Kroll’s reagent (in wt. % H₂O 85%, HNO₃ 5%, HF 10%) and observed by a light microscope Olympus PME3. The samples for creep tests were ground on SiC up to SiC grain size approx. 15 µm from all sides. The creep tests were carried out in a laboratory furnace for determination of modulus of rupture at elevated temperatures with attached computer which writes down the bending strain of the sample in dependence on time. The transverse strength tests at laboratory temperature were carried out on the similarly treated samples on universal tensile machine Heckert FPZ100/1. The structural stability tests ran in cyclical annealing regime at 800 °C in laboratory furnace under argon atmosphere. The total time of these tests was 460 hours. The microstructure and hardness of annealed samples were observed every 48 hours.
3. RESULTS AND DISCUSSION

As it is shown (Fig. 1.), the microstructure of as-cast TiAlNb alloy is fully lamellar $\alpha_2 + \gamma$. The TiAlTa alloy is composed of lamellar grains ($\alpha_2 + \gamma$) and massive $\gamma$ regions. Massive $\gamma$ is created during massive transformation which occurs usually at high cooling rates. It is well known that some alloying elements can make massive transformation possible even at low cooling rates what is also the case of tantalum [6]. Moreover the lamellar grains ($\alpha_2 + \gamma$) are surrounded by another phase in Ta alloy. We believe this phase is $\gamma$-TiAl as tantalum is a gama-stabilizer. The microstructure of binary TiAl alloy is composed of very fine lamellae of $\alpha_2 + \gamma$ (thickness in $\mu$m)

The values of transverse strengths of the tested alloys at laboratory temperature are shown hereby (Fig. 2.). The highest transverse strength was measured on Nb-alloy and was approximately two times higher than for other two alloys. It is given by the presence of relatively big niobium atoms which induce stresses in the titanium lattice and therefore limit the movement of dislocations. Surprisingly the lowest transverse strength was observed in the case of the Ta-alloy, although there should be the same effect of tantalum atoms on titanium lattice as it is in the case of niobium. As one can see from the picture (Fig. 1.) the microstructure of TiAlTa significantly differs from the two other alloys. The presence of $\gamma$ phase on the grain boundaries is probably the cause of their lower adhesion which leads to lower values of transverse strength of the alloy.

Conversely, the Ta-alloy had the highest resistance against high-temperature creep. This fact can be seen from the plots (Fig. 3.) showing the dependence of samples deflection on the exposure time at all three loads. Slow creep rate having the exponential dependence was observed at load of 200 MPa for all three alloys. None of these alloys was broken after exposure for 80 hours. The slope of the interpolation line and thus the creep rate is significantly lower for the TiAlTa alloys in comparison with the binary alloy and the alloy containing niobium. The TiAl alloy failed under load of 400 MPa after approximately 30 hours. Neither Ta nor Nb containing alloy failed under this load after 80 hours. The load of 600 MPa caused the failure of

Fig. 2. The values of transverse strength for investigated alloys.

Fig. 3. Creep curves for alloys exposed at 800 °C under constant loads of a) 200 MPa, b) 400 MPa and c) 600 MPa.
TiAl immediately as it was higher than the transverse strength of this alloy (see Fig. 2.). One can see from the plot (Fig. 3.c) that the TiAlNb alloy had significantly higher creep rate than the TiAlTa alloy. The difference between creep resistance of binary and ternary alloys is given by lower diffusion rate caused by presence of slow diffusers Ta and Nb [6]. The fact that tantalum slows down the diffusion more than niobium [6] causes the difference of creep rate between the two ternary alloys. This difference is probably supported by the presence of the γ phase on the grain boundaries in TiAlTa alloy. As one can see from the plot in Fig. 3.c, the TiAlTa can withstand the load of 600 MPa at 800 °C (the load was applied after the specimens were completely heated at 800 °C) although its transverse strength at laboratory temperature is significantly lower. Thus it seems that the mechanical properties of TiAlTa are better at high temperatures.

The difference of high-temperature behaviour of TiAlTa in comparison with other two alloys was also observed during cyclical annealing of the specimens at 800 °C. The pictures (Fig. 4.) show the microstructure of the studied alloys annealed for 460 hours. Meanwhile the microstructure of TiAl and TiAlNb alloys does not significantly differ from their as-cast state, the precipitation of a new phase occurred in the microstructure of the annealed TiAlTa alloy (Fig. 4.c). As it was found out by means of X-ray diffraction (not shown) the new phase could be the τ phase of composition in at. % Ti-38Al-13Ta which has been also mentioned in literature [7]. This phase induces the hardening of the material which was also observed during the hardness test (not shown). It is also one of the causes of high creep properties of TiAlTa alloy.

Oxidation kinetics of investigated alloys at 800 °C expressed as weight gain vs. oxidation time is plotted in Fig. 5. There can be seen that the weight of the TiAl alloy rapidly reduces during the oxidation due to the intensive oxide spallation. The weight gain of this alloy was nearly six times larger than for the Nb- and Ta-alloy. One can see that the impact of cyclical oxidation on these ternary alloys is minimal what is given by the presence of niobium and tantalum which have both very positive effect on oxidation resistance of TiAl-based intermetallics.

Fig. 4. Microstructures of the a) TiAl, b) TiAlNb, c) TiAlTa after annealing at 800 °C for 460 hours.
4. CONCLUSION

This work concerned the alloys based on TiAl-intermetallics. The structure of as-cast Ti-46Al and Ti-46Al-8Nb alloys was identified as fully lamellar $\alpha_2 + \gamma$. Only the lamellae thickness differs. The as-cast Ti-46Al-8Ta alloy is composed also from lamellar regions $\alpha_2 + \gamma$ but also the regions of massive $\gamma$ phase are present in the structure.

The main purpose of this work was to find out how Nb or Ta influence the high-temperature properties of TiAl-based intermetallics. The creep behaviour of investigated alloys was better in the case of Ta-alloy in comparison with the Nb one whereas the creep behaviour of TiAl alloys was not satisfactory. The high creep characteristics of the Ta-alloy are probably supported by its structural instability (precipitation of the $\tau$ phase in the structure). On the other hand the Ta-alloy showed very poor mechanical properties. Its value of transverse strength was even lower than for the binary alloy.

The positive effect of Nb and Ta was also observed during cyclical oxidation of TiAl-based intermetallics. The presence of these two alloying metals significantly reduces the weight gain of the alloy (nearly six times in comparison with unalloyed TiAl).

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