DETERMINATION OF THE EXPERIMENTAL PARAMETERS RELATED TO THE PRIMARY AND SECONDARY CREEP STAGES OF THE Ti-6Al-4V ALLOY WITH ATMOSPHERE CONTROLLING

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Abstract. *The objective of this work was to evaluate the creep behavior of the Ti-6Al-4V alloy focusing on the determination of the experimental parameters related to the primary and secondary creep stages. Yttria (8 wt.%) stabilized zirconia (YSZ) with a CoNiCrAlY bond coat was atmospherically plasma sprayed on Ti-6Al-4V substrates. Constant load creep tests were conducted with Ti-6Al-4V alloy in air for coated and uncoated samples and in nitrogen atmosphere for uncoated samples at 500 and 700°C to evaluate the oxidation protection on creep of the Ti-6Al-4V alloy. Results indicated the creep resistance of the coated alloy was greater than uncoated in air, but nitrogen atmosphere was more efficient in oxidation protection.*

Keywords: *Ti-6Al-4V, oxidation, plasma-sprayed coatings, creep*

1. Introduction

The affinity of titanium for oxygen is one of the main factors that limit the application of titanium alloys as structural materials at high temperatures. Oxidation results in the loss of material by oxide scale growth and embrittlement of the alloy by dissolved oxygen [1, 2]. The high solid solubility of oxygen in titanium results in material loss and in the formation of hard and brittle layer during elevated temperature air exposure [3]. Advances have been observed in the development of titanium alloys with the objective of improving the creep properties, although the surface oxidation limits the use of these alloys in temperatures up to 600°C. The development of titanium alloys with the objective of improving the creep properties have been observed, although the surface oxidation limits the use of these alloys in temperatures up to 600°C [4].

A substantial part of the creep research has been devoted to Ti-6Al-4V due to its industrial and technological importance. Its creep properties in air have been well documented. However, its creep behavior in nitrogen atmosphere and plasma-sprayed coatings for oxidation protection has only rarely been investigated.

Improvements in aero gas turbine performance in terms of power, efficiency and weight have necessitated the use of high specific-strength low-density materials. Titanium alloys, in general, readily absorb oxygen leading to oxidation and alpha case formation when exposed to high temperatures (>500°C), in air. This is known to severely limit the high temperature capability of alloys in terms of their mechanical properties. In order for titanium alloys to be utilized more effectively at higher temperatures, the ingress of oxygen must be reduced, if not prevented completely [5].

Plasma spraying is an established technique for the deposition of coatings. Applications include ceramic thermal barrier coatings for gas turbine engine components and the reclamation of worn parts. Plasma spray processing also lends itself nicely to the fabrication of ceramic matrix composites. It is applicable to wide range of materials. The only requirement is that the material to be sprayed does not decompose, sublime, or otherwise react in the plasma flame [6].

Thermal barrier coatings (TBCs) have been widely studied over the past 20 years because they increase the durability and efficiency of gas turbine engines by allowing an increase in turbine inlet temperature and by reducing the amount of cooling air required by the hot-section components. It has been reported that applications of such coatings throughout the combustion chamber and early stages of the turbine would save an operator around 1-2% of fuel cost [7]. Thermal barrier coating (TBC) systems, consisting of yttria partially stabilized zirconia (YSZ), thermally grown oxide (TGO) and a metallic bond coat, are finding applications for thermal protection of hot-section parts in gas turbine engines. The insulating characteristic of the YSZ ceramic coatings and the oxidation / corrosion resistance of the metallic bond coats provide improvement in performance and efficiency for these engines [8].

Plasma sprayed yttria stabilized zirconia (YSZ) coatings are used as isolative and corrosion resistant layers in high temperature applications such as gas turbine and diesel engines to enable higher working temperatures. Plasma sprayed YSZ coatings, often referred to as thermal barrier coatings (TBCs), with their porous microstructure and ceramic nature provide good heat insulation to the main metal component. A NiCrAlY bond coat layer is applied to enhance adhesion strength between the metal component and YSZ coating. In addition, this NiCrAlY bond coat provides oxidation resistance to the main metal component at high temperatures [9].

The aim of the present paper was estimate the influence of the plasma-sprayed coatings for oxidation protection on creep of the Ti-6Al-4V alloy, focusing on the determination of the experimental parameters related to the creep stages.

2. Experimental procedure

The material chosen for the present study was hot-forged 12.7 mm diameter rod of commercial Ti-6Al-4V alloy with the same specifications as published by ASTM [10]. The microstructure (Figure 1) consists of equiaxed α grains with average size about 10 μm. The β phase is present in the α grain boundaries. Tensile testing was performed at 500 and 700°C in air according to ASTM standard E 21 specification [11]. The tensile properties are summarized in Table 1 namely, 0.2% yield stress (*YS*), ultimate tensile stress (*UTS*), elongation (*EL*) and reduction of area (*RA*).

Yttria (8 wt.%) stabilized zirconia (YSZ) (Metco 204B-NS) with a CoNiCrAlY bond coat (AMDRY 995C) was atmospherically plasma sprayed on Ti-6Al-4V substrates by Sulzer Metco Type 9 MB. The Ti-6Al-4V coated sample is shown in Figure 2. The initial creep stress levels were determined from the elevated temperature tensile properties given in Table 1. Constant load creep tests were conducted on a standard creep machine in air and nitrogen atmospheres in uncoated samples and in air in coated samples, at stress level of 520 MPa at 500ºC; and at stress levels of 56 MPa at 700ºC. Samples with a gauge length of 18.5 mm and a diameter of 3.0 mm were used for all tests. The creep tests were performed according to ASTM E139 standard [12].

Table 1. Tensile properties of Ti-6Al-4V alloy.

T (ºC)	*YS* (MPa)	*UTS* (MPa)	*EL* (%)	*RA* (%)
500	521	638	30	73.6
700	73	193	58.3	88.2

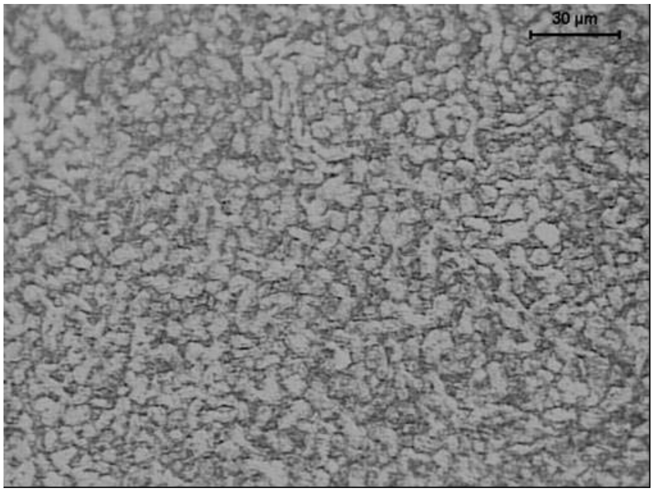

Fig. 1. Micrograph of Ti-6Al-4V alloy as-received.

Fig. 2. Ti-6Al-4V coated sample.

3. Results and discussion

Representative creep curves of Ti-6Al-4V are displayed in Figure 3 and 4 in air and nitrogen atmospheres in coated and uncoated samples at 500°C and 520 MPa and 700°C and 56 MPa, respectively. Ti-6Al-4V alloy exhibits a normal creep curve consisting well-defined primary and secondary stages. There is a relatively short initial period of decreasing primary creep rate that is associated with hardening due to the accumulation of dislocations. However, most of the creep life is dominated by a constant creep rate that is thought to be associated with a stable dislocation configuration due to recovery and hardening process [13, 14]. The double logarithm plot of true strain against time for the several test conditions is illustrated in Figure 5 and 6. The higher creep resistance of Ti-6Al-4V is observed in uncoated samples in nitrogen atmosphere and coated samples in air.

Results from the creep tests at 500 and 700°C are summarized in Table 2 and 3, respectively, which show the values of primary creep time (t_p) defined as time to the onset of secondary creep and secondary creep rate ($\dot{\varepsilon}_s$).

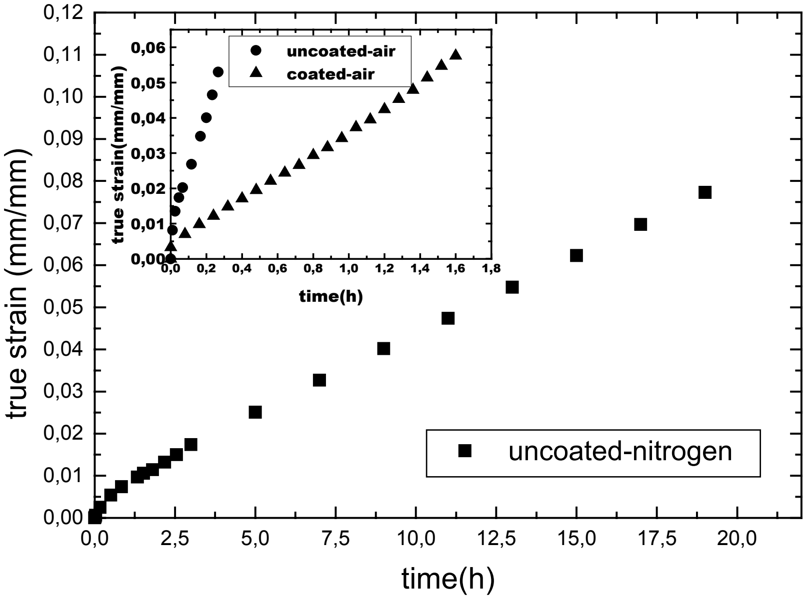

Fig. 3. Typical creep curves of Ti-6Al-4V at 500ºC / 520 MPa.

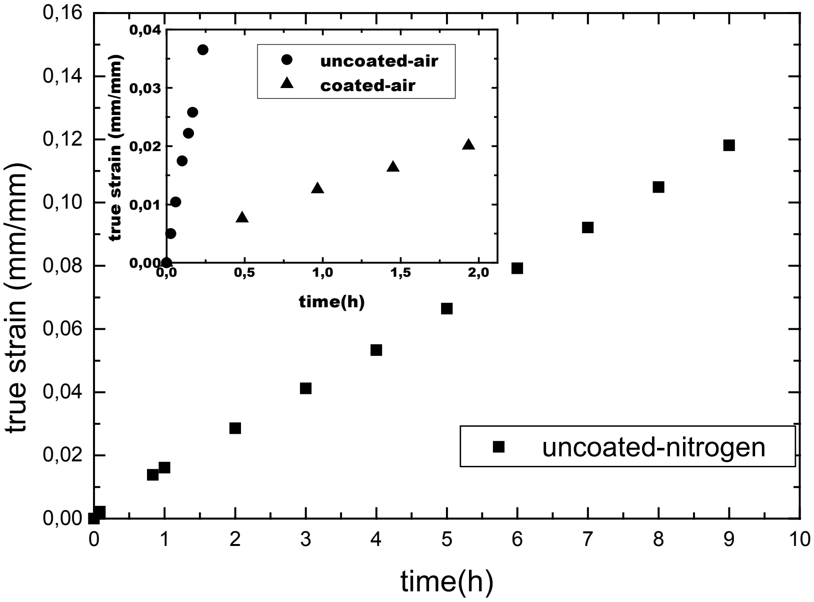

Fig. 4. Typical creep curves of Ti-6Al-4V at 700ºC / 56 MPa.

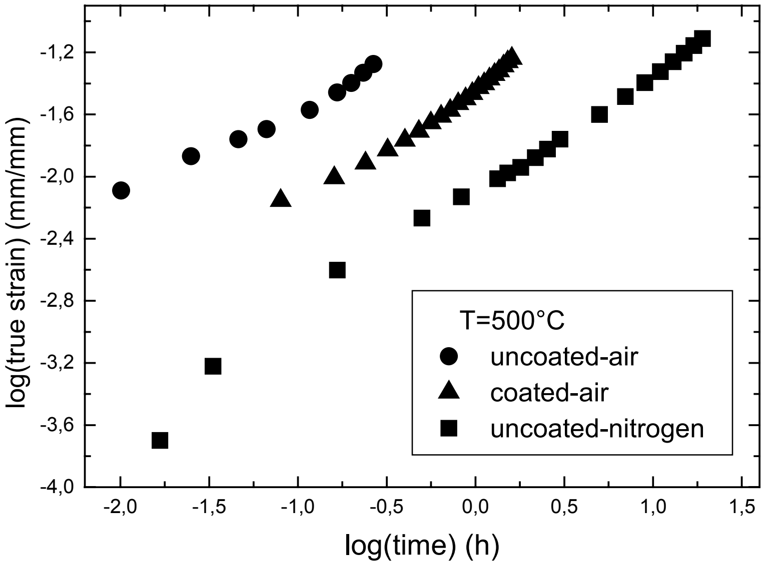

Fig. 5. The double logarithm plot of true strain against time for Ti-6Al-4V at 500°C.

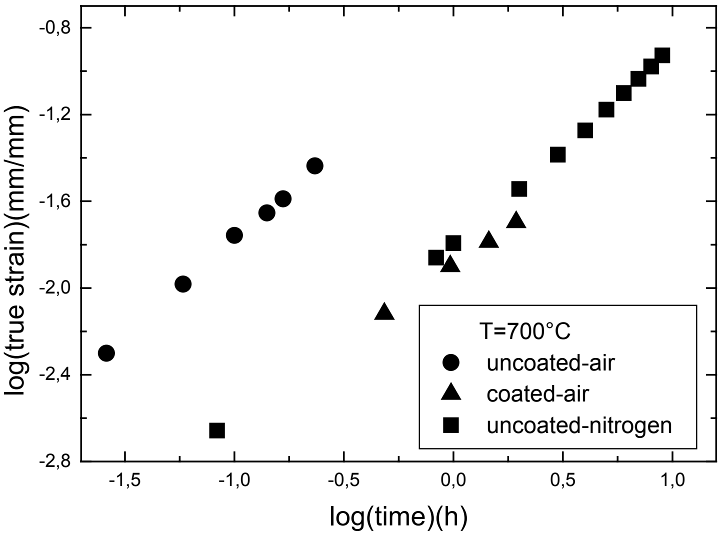

Fig. 6. The double logarithm plot of true strain against time for Ti-6Al-4V at 700°C.

Table 2. Creep data at 500°C.

Atmosphere	**Coating**	**σ (MPa)**	**t_p (h)**	**$\dot{\varepsilon}_s$ (1/h)**
nitrogen	no	520	1.801	0.00377
air	no	520	0.0462	0.1596
	yes	520	0.56	0.0304

Table 3. Creep data at 700°C.

Atmosphere	**Coating**	**σ (MPa)**	**t_p (h)**	**$\dot{\varepsilon}_s$ (1/h)**
nitrogen	no	56	2.00	0.0128
air	no	56	0.141	0.15656
	yes	56	0.967	0.00775

The results presented in Table 2 and 3 suggest that strain hardening during primary creep is dependent on the test temperature. The highest values of t_p and the reduction of the steady-state creep rate demonstrate that the higher creep resistance of Ti-6Al-4V is observed in uncoated samples in nitrogen atmosphere and coated samples in air. This fact is related to the hard and thin nitride surface layer formed during creep tests [15] and the oxidation protection on creep that the plasma-sprayed coatings offer to the Ti-6Al-4V alloy.

A comparison of the steady-state creep rates and primary creep times at 500°C and 520 MPa and 700°C and 56 MPa is shown in Table 4. As can be seen, coated samples have higher creep resistance than the uncoated samples. The steady-state creep rates are smaller for coated samples and this fact demonstrates the efficiency of the coating during the primary and secondary stages.

Table 4. Comparison of the secondary creep rates and of primary creep times for conditions investigated.

Temperature (°C)	**σ (MPa)**	**$t_{pcoating} / t_{pair}$**	**$t_{pcoating} / t_{pnitrogen}$**	**$\dot{\varepsilon}_{s\ air} / \dot{\varepsilon}_{s\ coating}$**	**$\dot{\varepsilon}_{s\ nitrogen} / \dot{\varepsilon}_{s\ coating}$**
500	520	12.12	0.31	5.25	0.12
700	56	6.86	0.48	20.20	1.65

3. Conclusions

The creep properties of Ti-6Al-4V alloy in air in coated and uncoated samples and in nitrogen atmosphere in uncoated samples at 500 and 700°C. High temperature exposure in a nitrogen atmosphere increases the creep resistance of the alloy at 500°C and 520 MPa and 700°C and 56 MPa. The highest values of t_p and the reduction of the steady-state creep rate demonstrate that the higher creep resistance of Ti-6Al-4V is observed in uncoated samples in nitrogen atmosphere and coated samples in air. The coated samples have higher creep resistance than the uncoated samples. The steady-state creep rates are smaller for coated samples and this fact demonstrates the efficiency of the coating during the primary and secondary stages.

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