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EVALUATION OF CREEP BEHAVIOR OF TI-6AL-4V ALLOY WITH THERMAL BARRIER COATING DEPOSITED BY AIR PLASMA SPRAY

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Abstract

Titanium alloys have attractive properties for application in aeronautical components submitted to high temperature. Yttria-stabilized zirconia (YSZ) of thermal barrier coating systems (TBC) have become an alternative to increase the operational lifetime of turbine blades. The aim of this work was to evaluate the creep behavior of Ti-6Al-4V with TBC deposited by air plasma spray. Constant load creep tests were conducted in air on equiaxed Ti-6Al-4V (uncoated) and Ti-6Al-4V with TBC and the experimental parameters related to secondary creep were determined. All the coated samples showed a reduction of secondary creep rate values and, thereafter, higher creep resistance, which could be associated with oxidation protection and thermal insulation provided by the coating. Creep rate analysis suggests that the dominant creep mechanisms in all cases is the dislocation climb.
Keywords: Ti-6Al-4V; Creep behavior; TBC.

AVALIAÇÃO DO COMPORTAMENTO EM FLUÊNCIA DA LIGA TI-6AL-4V COM RECOBRIMENTO COMO FORMA DE BARREIRA TÉRMICA DEPOSITADO POR ASPERSÃO TÉRMICA

Resumo

Ligas de titânio possuem propriedades atrativas para aplicação em componentes aeronáuticos submetidos a altas temperaturas. O revestimento de barreira térmica (TBC) de zircônia estabilizada com ítria (YSZ) tem se tornado uma alternativa para aumentar a vida operacional das palhetas de turbina. O objetivo deste trabalho foi avaliar o comportamento em fluência da liga Ti-6Al-4V com recobrimento TBC depositado por aspersão térmica. Os ensaios foram conduzidos em carga constante e ao ar em amostras de Ti-6Al-4V com estrutura equiaxial com e sem recobrimento TBC e foram determinados os parâmetros experimentais relacionados à fluência secundária. Todas as amostras revestidas mostraram uma redução dos valores da taxa de fluência secundária e, consequentemente, maior resistência à fluência, que pode ser associada à proteção contra oxidação e à barreira térmica fornecida pelo revestimento. A análise da taxa de fluência sugere que o mecanismo de fluência dominante em todos os casos é a escalagem de discordâncias.
Palavras-chave: Ti-6Al-4V; Comportamento em fluência; TBC.

1 INTRODUCTION

High temperature applications, such as aeronautical turbines, have been benefited for decades by new materials development, which has allowed an increase of materials operation temperature [1,2]. This creep phenomenon is an important industrial problem due to the increasing level of exigency of industries equipment operation conditions, such as power generation plants, chemical installations and aerospace industries [3,4].

Ti-6Al-4V alloy has been widely used in aeronautical and aerospace industries, particularly for applications requiring high temperature resistance, because its very attractive properties, such as high strength-to-weight

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ratio and metallurgical stability [5-9]. A limiting factor for titanium alloys is the oxygen absorption and consequent oxide formation when exposed to temperatures above 500 °C, reducing its resistance at high temperatures [10].

Thermal Barrier Coatings (TBC) provide oxidation resistance for substrate alloys, reducing the temperature under heat flow conditions and are suitable for use in titanium alloys for long periods at high temperatures [11,12]. The TBC system consists of a metallic bond coating (BC) on the substrate, generally MCrAlY type (M = Ni, Co, Fe or combinations thereof); a thermally grown oxide (TGO) formed on the MCrAlY by a oxygen diffusion process during the exposure at high temperatures, and an yttria-stabilised zirconia (YSZ) top coating (TC), of low thermal conductivity, bonded to the metallic layer [12-14].

Air Plasma Spray (APS) is a technique for coatings deposition where materials in shape of powder, wire or rod are fed into a torch or gun and heated near their melting point. The droplets are projected towards the substrate surface to be coated. Upon impact, they become thin lamellar particles which adhere to the surface, overlap and then solidify [15].

The lifetime of stationary gas turbine blades has been significantly increased with use of coatings as a way of alloys protection applied in the manufacture of these components [16]. In addition, studies have been carried out in Ti-6Al-4V alloy with several types of coatings and surface treatments with the aim of improving mechanical properties at high temperatures and oxidation resistance [17-20].

The aim of this work was to evaluate the creep behavior of Ti-6Al-4V alloy with thermal barrier coating deposited by air plasma spray. This study is part of an innovative area of evaluation of creep behavior, showing an important issue in the technological scenario due to the need of Ti-6Al-4V alloy improvement properties at high temperatures and aggressive environment.

2 MATERIALS AND METHODS

A commercial Ti-6Al-4V alloy with 12.7 mm diameter rod in hot-forged condition was used for creep test samples. The alloy chemical composition of the elements are conform to ASTM B265 specification [21] and the creep test samples were made according to ASTM E139 standard [22].

The creep specimens were prepared by air plasma spray. Firstly, NiCrAlY (Bond Coat Amdry 962) metal layer was applied, forming a layer of 140 ± 40 μm on the substrate. Then, yttria-stabilized zirconia (8% YSZ - Top Coat Metco 204NS-G) was applied, forming a ceramic layer of 290 ± 40 μm on the metallic layer. This APS process was performed by the equipment: Sulzer Metco 9M pistol, Sulzer Metco 9MP powder feeder and Praxair PC-100 gas controller. Figure 1 shows the specimen with TBC.

Constant load creep tests were conducted on a standard creep machine in air performed according to ASTM E139 standard [22]. Table 1 shows the creep tests conditions of equiaxed Ti-6Al-4V (uncoated) and Ti-6Al-4V with TBC samples.

3 RESULTS AND DISCUSSION

Figure 2 displays representative creep curves of strain (ε) versus time at 500 to 700 °C at 125 to 319 MPa, where T is the test temperature and σ is the applied stress. Typical creep curves are observed in all conditions with most of the creep life dominated by a constant creep rate, that can be associated with a stable dislocation configuration due to recovery and hardening process.

The results from creep tests are summarized in Table 2, where $\dot{\varepsilon}_s$ is steady-state creep rate (or secondary creep rate), t_p is the primary creep time, t_r is the time to rupture and ε_f is the strain at fracture.

The results of Table 2 show that with the stress rise on temperature at 600 °C, there is an increase in steady-state creep rate, a decrease in the primary creep time and a reduction of the time to rupture. The same was occurred with the temperature on stress at 125 MPa, considering the conditions evaluated in this work.

The creep resistance is determined, mainly, by the steady-state creep rate. Regarding the uncoated samples, the secondary creep rate of TBC Ti-6Al-4V had a reduction of 33% at 500 °C condition, approximately 60% at 600 °C condition and 80% at 700 °C condition. It is observed that at higher working temperature, the greater is the ceramic coating efficiency under the test conditions. In addition, a higher creep resistance of Ti-6Al-4V alloy with TBC can be associated with thermal barrier improvement and oxidation protection provided by the coating.

The power-law creep equation (Equation 1) is a relationship to describe creep behavior [23]:

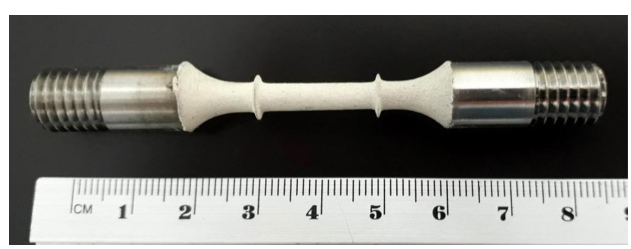

Figure 1. Creep test sample with Thermal Barrier Coating.

Table 1. Creep tests conditions of equiaxed Ti-6Al-4V with and without TBC

Temperature (°C)	Stress (MPa)
500	125
600	125
	250
	319
700	125

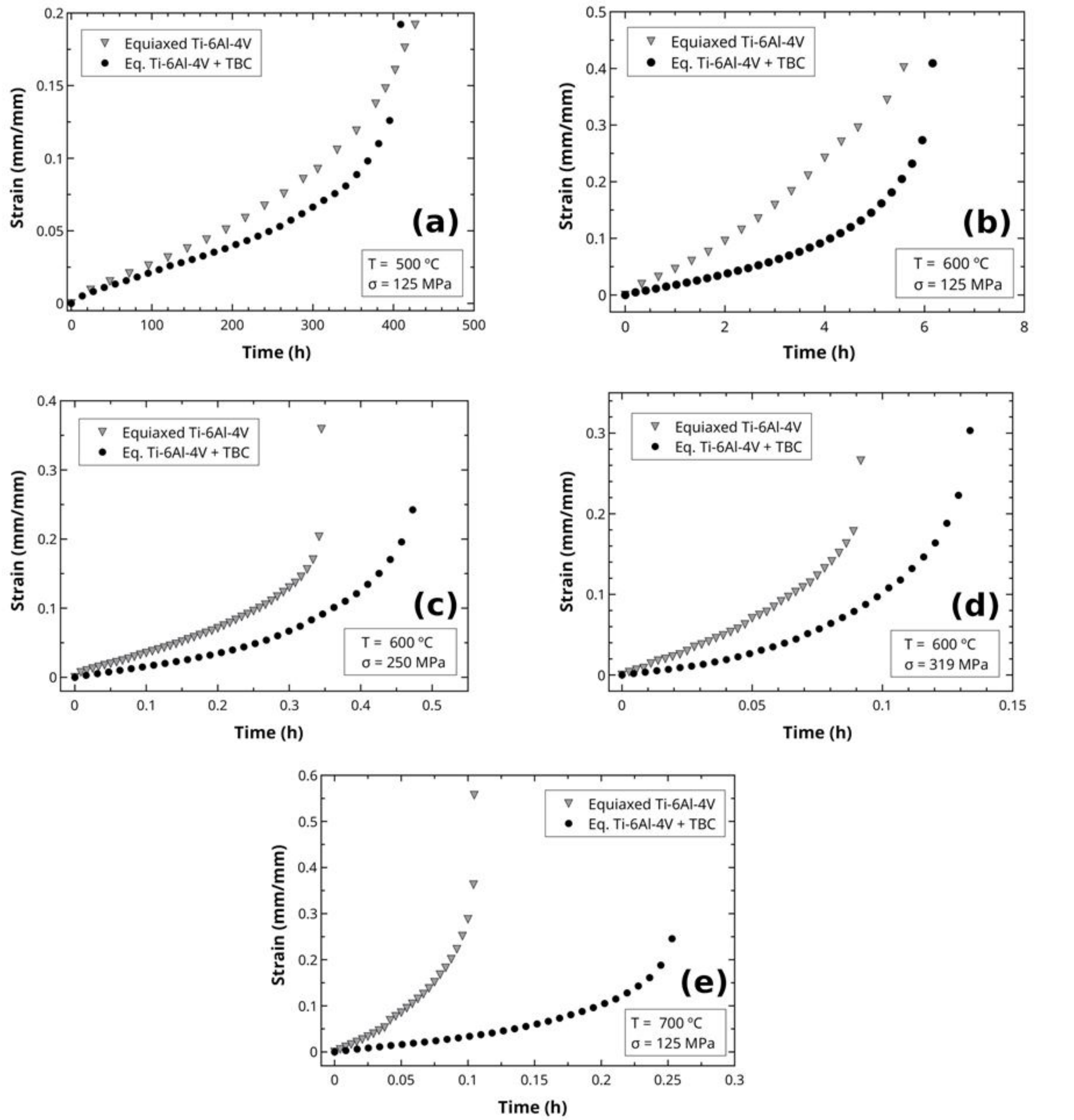

Figure 2. Creep curves of equiaxed Ti-6Al-4V and Ti-6Al-4V with TBC at a) 500 °C and 125 MPa; b) 600 °C and 125 MPa; c) 600 °C and 250 MPa; d) 600 °C and 319 MPa; e) 700 °C and 125 MPa.

$$\dot{\varepsilon}_s = B\,\sigma^n \quad (1)$$

where B is structure-dependent constant and n is the creep stress exponent.

Figure 3 shows the steady-state creep rate dependence (at 600 °C) to obtain the stress exponent (n) of equiaxed Ti-6Al-4V with and without TBC. The stress exponent found for equiaxed Ti-6Al-4V alloy was 3.59 and for Ti-6Al-4V with TBC was 3.29.

As the creep deformation is a thermally activated process, power-law creep equation can be modified to a temperature dependence, represented by an Arrhenius equation 2 [23]:

$$\dot{\varepsilon}_s = B_0\,\sigma^n \exp(-Q_c/RT) \quad (2)$$

where Q_c is the activation energy for creep, B_0 is a constant that depends on the microstructure, temperature and applied stress (σ), n is the stress exponent, R is the universal gas constant and T absolute temperature. The combination of n and Q_c values indicates the main creep mechanism [23].

The dependence of the steady-state creep rate on temperature at 125 MPa is presented in Figure 4. The activation

Table 2. Creep data of equiaxed Ti-6Al-4V (uncoated) and Ti-6Al-4V with TBC

Treatment	T (°C)	σ (MPa)	t_p (h)	$\dot{\varepsilon}_s$ (h^{-1})	t_f (h)	ε_f (mm/mm)
Equiaxed Ti-6Al-4V	500	125	16.0	0.0003	427	0.1918
	600	125	0.67	0.0410	5.58	0.4017
		250	0.05	0.4030	0.35	0.3590
		319	0.02	1.2703	0.09	0.2658
	700	125	0.01	1.5084	0.11	0.5569
Ti-6Al-4V with TBC	500	125	27.3	0.0002	409	0.1922
	600	125	0.21	0.0187	6.16	0.4092
		250	0.03	0.1580	0.47	0.2423
		319	0.01	0.4290	0.13	0.3032
	700	125	0.01	0.3050	0.25	0.2458

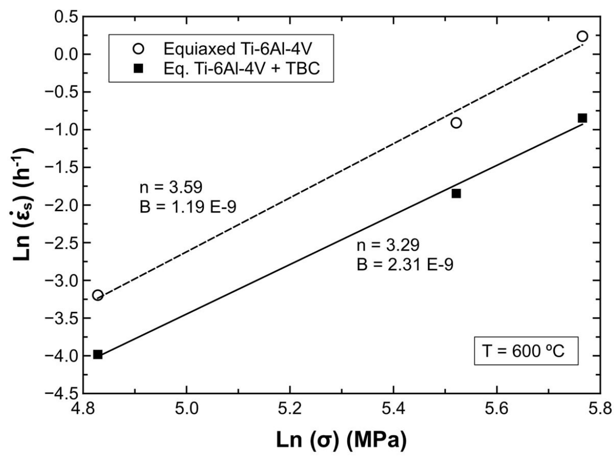

Figure 3. Dependence of steady-state rate on applied stress at 600 °C for equiaxed Ti-6Al-4V and Ti-6Al-4V with TBC.

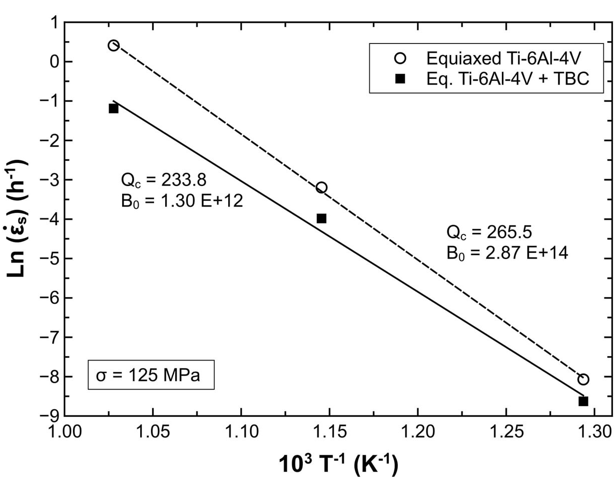

Figure 4. Dependence of steady-state rate on temperature at 125 MPa for equiaxed Ti-6Al-4V and Ti-6Al-4V with TBC.

energy for creep found for equiaxed Ti-6Al-4V and Ti-6Al-4V with TBC was, respectively, 265,5 kJ/mol and 233,8 kJ/mol.

Reis et al. [17] analyzed the creep rates for equiaxed Ti-6Al-4V with and without TBC and suggests that the creep mechanism at 500 and 600 °C is consistent with the lattice diffusion-controlled dislocation climb process in α-Ti. Warren et al. [24] reported that the stress exponent is n = 3.80 and the activation energy is Qc = 240.0 kJ/mol for Ti-6Al-4V without treatment at 600-680 °C. For the same alloy, Reis et al. [25] found values of n = 4.25 at the temperature of 600 °C and Qc = 218.0 kJ/mol for the range of 500 to 700 °C.

According to Evans and Wilshire [23], n> 3 and activation energy values close to the material self-diffusion energy indicate the mechanism of low temperature dislocation creep. The self-diffusion activation energy for Ti-α is in the range of 242 to 293 kJ/mol [26]. Based on these data, it is concluded that the analysis of stress exponent and activation energy values in conditions presented in this work suggest that the dominant creep mechanism for all cases is primarily controlled by high temperature dislocation climb.

4 CONCLUSION

The Ti-6Al-4V with TBC samples presented lower steady-state creep rate and, therefore, higher creep resistance than the uncoated samples. These results reflect the improvement of oxidation resistance and the thermal barrier (lower thermal conductivity) offered to the coated alloy.

For all test conditions, the steady-state creep rate could be described by the Norton law equations, where the values found for the stress exponent were 3.59 and 3.29 and the activation energy for creep were 265.5 and 233.8 kJ/mol for the uncoated and Ti-6Al-4V with TBC samples, respectively. Analysis of these values suggests that the dominant creep mechanism is primarily controlled by dislocation climb in all cases.

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