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Original Research

Improving thermal insulation of TC4 using YSZ-based coating and SiO_2 aerogel

Lei Jin[a,*], Peizhong Li[b], Haibin Zhou[a], Wei Zhang[a], Guodong Zhou[a], Chun Wang[a]

[a]Science and Technology on Power Beam Process Laboratory, Beijing Aeronautical Manufacturing Technology Research Institute, Chaoyang District, Beijing 100024, China
[b]Inner Mongolia Baotou Steel Rare-earth (Group) Hi-Tech Co., Ltd. Baotou 014030, China

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Abstract

In this paper, air plasmas spray (APS) was used to prepare YSZ and Sc_2O_3–YSZ (ScYSZ) coating in order to improve the thermal insulation ability of TC4 alloy. SiO_2 aerogel was also synthesized and affixed on TC4 titanium alloy to inhabit thermal flow. The microstructures, phase compositions and thermal insulation performance of three coatings were analyzed in detail. The results of thermal diffusivity test by a laser flash method showed that the thermal diffusivities of YSZ, Sc_2O_3–YSZ and SiO_2 aerogel are 0.553, 0.539 and 0.2097×10^{-6} m^2/s, respectively. Then, the thermal insulation performances of three kinds of coating were investigated from 20 °C to 400 °C using high infrared radiation heat flux technology. The experimental results indicated that the corresponding temperature difference between the top TC4 alloy (400 °C) and the bottom surface of YSZ is 41.5 °C for 0.6 mm thickness coating. For 1 mm thickness coating, the corresponding temperature difference between the top TC4 alloys (400 °C) and the bottom surface of YSZ, ScYSZ, SiO_2 aerogel three specimens is 54, 54.6 and 208 °C, respectively. The coating thickness and species were found to influence the heat insulation ability. In these materials, YSZ and ScYSZ exhibited a little difference for heat insulation behavior. However, SiO_2 aerogel was the best one among them and it can be taken as protection material on TC4 alloys. In outer space, SiO_2 aerogel can meet the need of thermal insulation of TC4 of high-speed aircraft.

Keywords: YSZ coating; ScYSZ coating; SiO_2 aerogel; Thermal insulation properties

1. Introduction

Ti–6Al–4V (named as TC4 in China) alloy is the most widely used titanium alloy and it occupies 80% in titanium industry due to its high strength, low density, and good corrosion resistance [1–3]. However, the application of titanium alloys under severe thermal and friction conditions is severely restricted. Some skins of high-speed aircraft are composed by TC4 titanium alloys. When an aircraft is flying from ground to outer space at 4–6 mach high speed, TC4 alloy is quickly near to its limited serve temperature (400 °C) within 5 min. Simultaneously, the inner space of high-speed aircraft (such as missile) is heated rapidly. As a result, electrical equipment (their operation temperature is lower 130 °C) in the interior of high-speed aircraft are interfered and may lost their normal functions.

In order to solve the problems mentioned above, numerous surface treatment techniques have been used to improve thermal insulation properties of titanium alloys, such as physical vapor deposition (PVD) [4] and chemical vapor deposition (CVD) [5]. It is remarkable that coatings prepared by air plasmas spray (APS) show lamellar microstructure and exhibit strong thermal insulation ability [6–9]. Thermal barrier coatings (TBCs) possess the potential to protect underlying metallic substrate from hot gas oxidation and corrosion in gas turbines, leading to significant gains in the efficiency of engines as well as the operating lifetime of components. The typical low thermal conductivity material is yttrium-stabilized zirconia (YSZ), which

*Corresponding author. Tel.: +86 10 85701575.
E-mail address: yugongyishanjin@126.com (L. Jin).
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is widely commercialized and can service for long time in high temperature [10,11].

Silica aerogels are known as unique porous materials with highly cross-linked network structure having large specific surface area, high porosity, low density and very low thermal conductivity. Due to these prominent properties, silica aerogels in recent years have been used in various advanced applications such as thermal insulators, catalysts, sensors, oil absorbent and drug delivery systems. Specifically, lightweight materials-silica aerogel composite are used in high-speed aircraft for thermal protection according to our knowledge because the materials are the best existing thermal insulators for continuous applications between room temperature and 650 °C [12,13].

With the above background, all of the YSZ, Sc_2O_3–YSZ and SiO_2 aerogel are adopted in our studies in order to seek suitable thermal insulation materials on TC4.

2. Experimental procedures

2.1. Preparation of APS coatings

The substrates were cut into coupons with a dimension of 100 mm × 100 mm × 1 mm from a wrought sheet of TC4 titanium alloy with nominal composition (wt%) of Al 5.5–6.8, V 3.4–4.5, Fe ≤ 0.3, C ≤ 0.1, N ≤ 0.05, H ≤ 0.015, O ≤ 0.2 (Bal, Ti). These coupons were grit-blasted using 250 μm alumina grit to obtain a roughness average of 4–5 μm sharp-peaked surface to improve the adherence of the coatings.

The average size of YSZ, Sc_2O_3 and bond coat (NiCoCrAlY) particle is 60 μm, 50 μm and 65 μm, respectively. Such as particle size can be directly sprayed using APS technology.

The thickness of bond coat is 100 μm, and the thickness of ceramic coat is 0.6 and 1 mm, respectively. Air plasma spraying parameters for bond and top coat are presented in Table 1.

2.2. Preparation of SiO_2 aerogel composite materials

SiO_2 fibers and SiO_2 micro powder were selected as raw materials. The weight percent of SiO_2 micro powder in the composites was 20%. The mean size of powders was 8–20 μm. The diameter of SiO_2 fibers was 0.5 μm, and the length of fibers was cut into 1 mm. The raw materials were mixed together, and pressed into the dimensions of 100 mm × 100 mm × 1 mm under 2 MPa. The similar procedure of pore structure of silicon dioxide through sol–gel processing can be found in other references [14]. And then silica aerogel composite material is adhesive to TC4 alloy using organic glue.

Table 1
Plasma spray parameters for bond coating and top coating.

	NiCoCrAlY	Ceramic coating
Primary gas Ar (L/min)	40	44
Secondary gas H_2 (L/min)	7	10
Carrier gas Ar (L/min)	6	9
Gun current (A)	500	560
Gun voltage (V)	63	67
Spray distance (mm)	16	14
Powder feed rate (g/min)	49	41

2.3. Microstructure and phase analysis

The phase structures of three coatings were identified with a D/max 2200 pc X-ray diffractometer (Rigaku, Tokyo, Japan). The microstructures were determined using Quanta-FEG 250 SEM (FEI Company, America). Porosity of the coatings is estimated by quantitative image analysis (IA) using a picture analysis system in scanning electron microscopy.

2.4. Thermal diffusivity measurement

The coating was sprayed on the TC4 substrate (without bond coat) and then it is detached from substrate by water-quenching after APS. The thermal diffusivities of standalone YSZ, Sc_2O_3–YSZ coating and SiO_2 aerogel were determined by the laser flash technique (LFA427, NET-ZSCH). In order to completely absorb the laser-flash at the sample surface, the coatings samples were coated with a carbon film before measurement. The thermal diffusivity measurement of the specimen was carried out three times at each temperature.

2.5. Heat-resistant test

Heat-resistant coating materials mentioned above were tested by high infrared radiation heat flux, as shown in Fig. 1.

Since the thermal couple directly detects the surface temperature of the test sample rather than the ambient air temperature, the applied thermal loading is more accurate and stable. By adjusting the input electric power, the temperature of the test sample surface can be accurately controlled within 0.1 °C. Compared with conventional high-temperature furnace, the transient aero dynamic heating simulation device offers a capability of rapid heating speed with high accuracy.

Two Pt–Rh thermocouples were used as sensors. One was located on the surface of TC4 alloys (TC4 alloys surface temperatures, $T0$) and the other was sealed on specimen backsides to monitor coating temperatures ($T1$). The thermocouples were linked to the X–Y function recorders respectively to record the heating temperature curves ($T0$ and $T1$) in the range of 0–350 s. The temperature of TC4 surface was heated up to 400 °C in 15 s and then the temperature ($T0$) kept at 400 °C from 16 s to 400 s. Meanwhile, the temperature of coating surface was recorded. The value of thermal insulation capability was calculated using $\Delta T = T0 - T1$ when $T0$ and $T1$ are stable.

3. Results and discussions

3.1. Microstructure of coatings and silica aerogel

Fig. 2 presents the surface macro morphology for the investigated three coatings. The colors of Fig. 2(a)–(c) are