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Microstructure and mechanical properties of TiAl-based composites prepared by Stereolithography and gelcasting technologies

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ABSTRACT

TiAl intermetallic and SiC ceramic are two kinds of important high-temperature structural material, but it is difficult to fabricate complex high-performance composites of them by traditional methods. In the paper, it is a pioneer study to prepare their composites so as to fabricate turbine blade by the hybrid technology of Stereolithography and gelcasting. Impregnation and pyrolysis behaviors of polycarbosilane were explored for SiC ceramic preparation, and the microstructure evolution and mechanical properties of TiAl-based composites were mainly analyzed. The results showed that adding trace amount of nickel and aluminum could remarkably promote the sintering of gelcasting TiAl intermetallic samples, the micropores inside TiAl samples were connected after debinding, and the metallurgical structures were all intermetallic. After the porous TiAl samples impregnated with polycarbosilane were then pyrolyzed three times, the final metallurgical structures were TiAl-based composites of TiAl, NiAl, SiC, TiC and Ti_3SiC_2. Ti_3SiC_2 was the interface layer formed between TiAl intermetallic and SiC ceramic, and their high-temperature bending strength was between 82 MPa and 90 MPa at 1100 °C. Therefore, it was a promising method for the fabrication of complex high-performance TiAl-based parts such as turbine blade.

1. Introduction

TiAl intermetallic is considered as one of the most promising materials for aero-engine applications due to its low density, high specific strength, high specific modulus, good creep resistance and oxidation resistance [1,2]. Therefore, it is of great significance to study the fabrication of complex TiAl parts such as turbine blade [3,4]. However, the application of TiAl intermetallic is limited by its low formability [5]. TiAl intermetallic is mostly as-cast so that its microstructure is usually coarse dendrite, which makes it prone to loose and composition segregation [6,7]. In particular, its plasticity and fracture/creep resistance have the opposite relationship with its tensile strength [8,9]. Some ceramics such as SiC has good chemical stability, good oxidation resistance and corrosion resistance, low density and high strength [10–12], however it is hard to fabricate complex parts by traditional methods [13–15]. Therefore, TiAl intermetallic and SiC can play their respective advantages when the method of chemical transformation was developed to form TiAl-based composite materials [16–20].

Turbine blade is the key part of aero-engine and gas turbine, and a few manufacturing methods were put forward only for the fabrication of turbine blade of high-temperature alloy material. At present, with an increase of gas temperature of aero-engine turbine, the existing high-temperature alloy material has almost reached its upper limit bearing temperature [21–24]. In addition, more and more complex cooling structures of the hollow turbine blade is designed to achieve improved cooling efficiency [25], which brings big challenges to manufacturers. With the advancement of material science and manufacturing technology, new composite materials such as TiAl intermetallic and SiC ceramic are expected to be applied in the fabrication of hollow turbine blades [26].

In this paper, it is possible to fabricate complex TiAl-based parts such as turbine blade using the impregnation and pyrolysis of Polycarbosilane $[-SiH(CH_3)-CH_2-]_n$(PCS) based on Stereolithography (SL) and gelcasting technologies. The TiAl-based composite will be probably achieved by filling the pores of porous TiAl intermetallic with transformed SiC. The pyrolysis of PCS and transformation into SiC ceramic will be mainly studied, the microstructure of TiAl-based will be analyzed in the process of pyrolysis, and the relationship between microstructure and TiAl-based high-temperature strength will be discussed.

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2. Materials and methods

2.1. Materials

TiAl intermetallic powders (D_{50} = 40 μm and spherical), Al powders (D_{50} = 3 μm and spherical) and nano-Ni powders (D_{50} = 30 nm and spherical) were used in this experiment. Acrylamide [$C_2H_3CONH_2$] (AM) and N,N′-Methylenebisacrylamide [$(C_2H_3CONH)_2CH_2$] (MBAM) were used as the organic monomer and cross-linker, respectively, with a weight ratio of 24–1 [27].

2.2. Methods

(1) The fabrication procedures were shown in Fig. 1. Firstly, turbine blade mould was fabricated by SL device of SPS600 (Shanxi HengTong Corporation, China, the accuracy of manufacturing was 0.1%) using photosensitive resin (SPR 8981;Zhengbang Ltd., Zhu Hai, China), and the fabrication principle of SL was shown in Fig. 2. Then the gelcasting slurry (PH = 10–11) of TiAl/Al/Ni(mass ratios = 94:4:2) was prepared with the rotating speed of ball mill at 360 r/min and the milling time for 30 min, which was about 15% of organic matter concentration and 60% of solid phase volume concentration. Secondly, it was vacuum freeze dried by the LGJ-30F equipment (freeze temperature of −50 °C, drying temperature of 5 °C, vacuum degree <10 Pa). Thirdly, the heating rate during vacuum debinding (vacuum degree of 6×10^{-3} MPa) was 3 °C/min between room temperature and 220 °C; 0.5 °C/min between 220 °C and 440 °C; 1.5 °C/min between 440 °C and 600 °C; 5 °C/min between 600 °C and 1250 °C; finally, the samples were kept at 1250 °C for 2 h.

(2) Precursor Impregnation and Pyrolysis (PIP) processing.

The samples were vacuum impregnated in the liquid PCS three times at 110 °C for 30 min (vacuum vacuity 8×10^{-2} MPa), and then was kept at 150 °C for 10 h to completely crosslink PCS.

Then the pyrolysis experiment was conducted in tube furnace to fabricate TiAl–SiC. The heating rate with argon shield (flux 50 ml/min) was 5 °C/min between room-temperature and 200 °C; 2 °C/min between 200 °C and 600 °C; 5 °C/min 600 °C and 1300 °C; and then the samples were kept at 1300 °C for 1 h.

2.3. Measurements

The powders were observed by scanning electron microscope (SEM) of S-3000 N (Babcock Hitachi in Japan) and transmission electron microscopy (TEM) of JEM-2100F (JEOL in Japan) besides the microstructure of gelcasting and pyrolyzed samples. After the pyrolysis of PCS, the samples' phase composition and microstructures were analyzed by X-ray diffractometer (XRD) (Product Model: XRD-7000, Shimadzu in Japan). The infrared spectroscopy of PCS was measured every 100 °C from 100 °C to 800 °C using infrared spectrometer of EQUINOX 55 made in Germany (Product Model: SRS-3400, Brooke company). The high-temperature bending strength were obtained at 1100 °C by three-point bending strength measurement.

3. Results and discussion

Fig. 3 shows the SEM morphology of TiAl powders (Fig. 3a) and Al powders (Fig. 3c) besides nano-Ni TEM morphology (Fig. 3d). All of the powders were spherical, which was beneficial to obtain high solid loading of more than 50% in gelcasting, and Fig. 3b shows the energy spectrum analysis of TiAl powders, in which the molar ration between Ti and Al was about 1–1.

Fig. 4a shows that the Computed Tomography (CT) morphology of gelcasting samples of TiAl, in which the powders of different size were evenly distributed. Fig. 4b shows their SEM morphology, in which the large particles were evenly coated by the polymerization reaction of AM. Fig. 4c shows the backscattered electron image of gelcasting samples, and the net structure of polyacrylamide was integrated, in which the black area was monomer with network structure, and the white area was mainly TiAl intermetallic powders. TiAl-based prototype was formed and its strength was about 15 MPa. Fig. 4d shows the monomer's thermogravimetry curve in gelcasting samples. The thermal decomposition of monomer was very slow from room temperature to 220 °C, and the weight loss was about 15 wt%. Therefore, the heating rate was set as about 3 °C/min. But from 220 °C to 440 °C, the thermal decomposition of monomer was most violent, and the weight loss was about 50 wt%. Therefore, the heating rate was set as the minimum of 0.5 °C/min. Then from 220 °C to 440 °C, and the weight loss decreased to about 28 wt% so that the heating rate was reduced to 1.5 °C/min. After 600 °C to 1250 °C, the monomer was totally decomposed, and then the heating rate was increased again, which was set as the maximum of 5 °C/min.

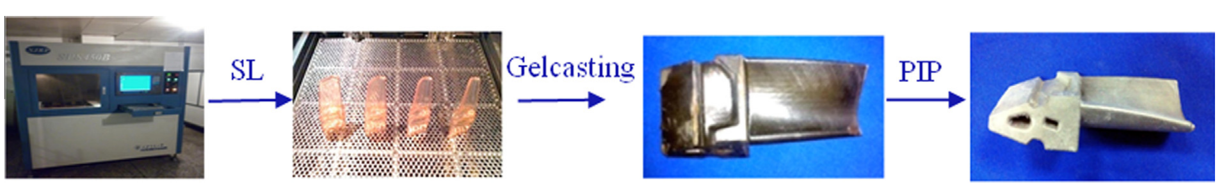

Fig. 1. The fabrication procedures.

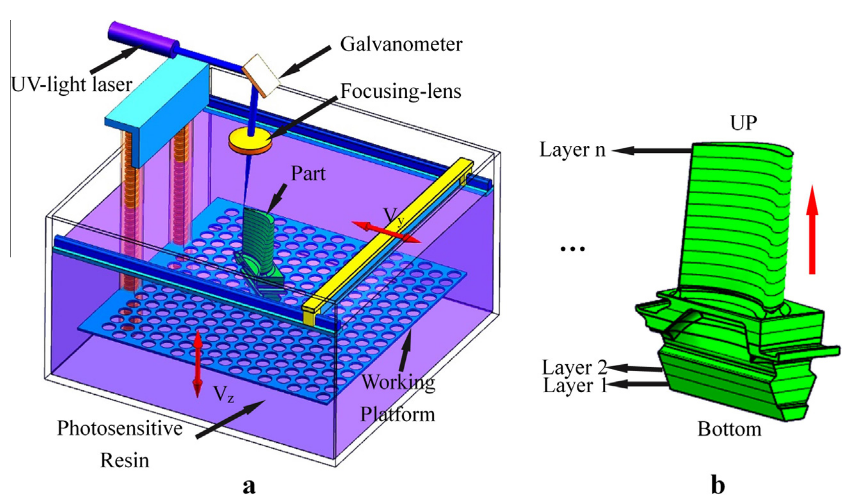

Fig. 2. The fabrication principle of SL.