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Effects of high temperature treatment on microstructure and mechanical properties of laser-clad NiCrBSi/WC coatings on titanium alloy substrate

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ABSTRACT

Laser-clad composite coatings on the Ti6Al4V substrate were heat-treated at 700, 800, and 900 °C for 1 h. The effects of post-heat treatment on the microstructure, microhardness, and fracture toughness of the coatings were investigated by scanning electron microscopy, X-ray diffractometry, energy dispersive spectroscopy, and optical microscopy. The wear resistance of the coatings was evaluated under dry reciprocating sliding friction at room temperature. The coatings mainly comprised some coarse gray blocky (W,Ti)C particles accompanied by the fine white WC particles, a large number of black TiC cellular/dendrites, and the matrix composed of NiTi and Ni_3Ti; some unknown rich Ni- and Ti-rich particles with sizes ranging from 10 nm to 50 nm were precipitated and uniformly distributed in the Ni_3Ti phase to form a thin granular layer after heat treatment at 700 °C. The granular layer spread from the edge toward the center of the Ni_3Ti phase with increasing temperature. A large number of fine equiaxed $Cr_{23}C_6$ particles with 0.2–0.5 μm sizes were observed around the edges of the NiTi supersaturated solid solution when the temperature was further increased to 900 °C. The microhardness and fracture toughness of the coatings were improved with increased temperature due to the dispersion-strengthening effect of the precipitates. Dominant wear mechanisms for all the coatings included abrasive and delamination wear. The post-heat treatment not only reduced wear volume and friction coefficient, but also decreased cracking susceptibility during sliding friction. Comparatively speaking, the heat-treated coating at 900 °C presented the most excellent wear resistance.

1. Introduction

Titanium alloys are widely applied in the aircraft, automobile, and biological industries due to their high-temperature strength, high strength-to-weight ratio, and excellent corrosion resistance [1–3]. However, further industrial applications of these alloys can be limited by their relatively low surface hardness and poor wear resistance. The surface properties of titanium alloys can be feasibly improved by surface modification technologies, such as plasma spraying [4], physical vapor deposition [5], chemical vapor deposition [6], and nitriding and carburizing [7,8]. However, these techniques bring some advantages, meanwhile with some new problems, i.e., low bonding strength and some defects at the interface.

Laser cladding is a surface modification technology that has elicited a significant number of researcher's attention because of its unique advantages, such as ability to form metallurgical bonds between coating and substrate, limited heat-affected zones, highly refined microstructure, and improved thickness controllability [9–11]. However, non-equilibrium supersaturated solid solutions and metastable phases are often formed because of the high cooling rate of approximately 10^5 °C/s that occurs during laser cladding [12,13].

Although the strengthening effect of solid solutions can be enhanced, phase transformations may occur and structure instability can affect the service properties of the coating upon application in special environments, such as high temperature. Therefore, microstructural stability of the coatings must be improved by appropriate methods. Moreover, cracks occur in the coatings during or after laser cladding, thereby restricting their industrial applications. Generation of cracks is mainly attributed to high residual stresses caused by rapid melting and solidification [14]. The cracking susceptibility of the coatings has been reduced by optimization of the processing parameters [15], addition of a transition zone [16], and substrate preheating [17].

Post-heat treatment is a traditional method widely used to acquire the desired properties in coatings and bulk materials by improving their microstructure and relieving residual stresses [18]. However, few studies have focused on the effects of post-heat treatment on laser-clad coatings. Chen et al. [19] investigated the influence of post-heat treatment on the residual stress of laser-clad AISI P20 tool steel on pre-hardened and wrought P20 substrates. They found that heat treatment significantly affects the magnitude and sign of residual stress. Chen et al. [20] analyzed the effect of stress relief on laser-clad IN-625, Stellite 6, and CPM 10 V and revealed that high-temperature annealing

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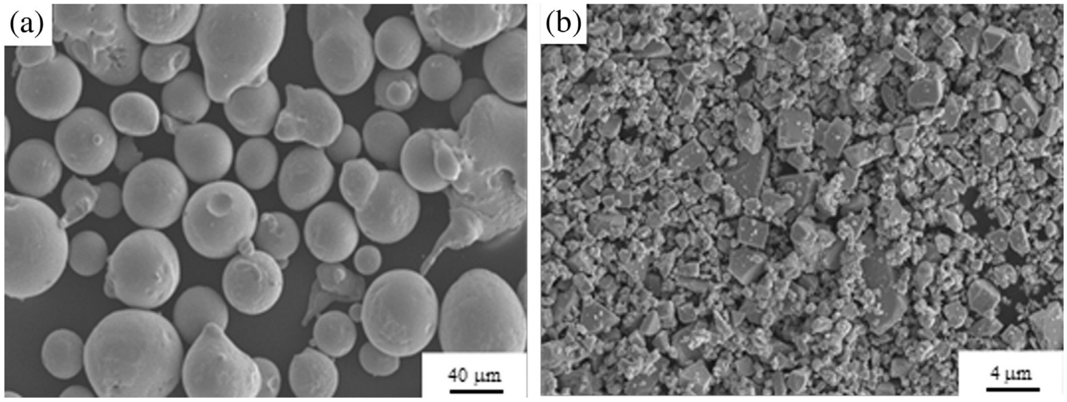

Fig. 1. Morphologies of the cladding materials: (a) NiCrBSi alloy powder and (b) WC powder.

can alleviate the intensities of residual stress through thermal relaxation. Wu and Chen [21] studied the phase evolution of laser-clad Fe–Cr–W–Ni–C coatings during tempering at 963 K and observed that high-temperature tempering promotes the precipitation of various carbides from non-equilibrium austenite. Huang et al. [22] found that new stable phases are formed when TiVCrAlSi high-entropy alloy coatings are vacuum annealed at 800 °C for 24 h. Despite these interesting findings, studies on the combined effects of post-heat treatment on the microstructure and mechanical properties of laser-clad coatings are limited.

In the present study, the effects of post-heat treatment on the microstructure of laser-clad coatings fabricated on titanium alloy substrates are analyzed and the effects of post-heat treatment on microhardness, fracture toughness, and wear resistance are investigated.

2. Experimental procedures

Ti6Al4V cylindrical samples with 50 mm in diameter and 10 mm in height were used as substrates. Before the coatings were prepared, the substrates were ground with emery papers to remove the oxide layer and then ultrasonically rinsed with acetone. The cladding material consisted of a mixture of commercially available NiCrBSi (70%) and pure WC (30%) powders. The NiCrBSi powder comprised the following elements with the corresponding mass fractions (wt.%): 16.0Cr, 4.0B, 4.0Si, and balance Ni. Fig. 1 shows the morphologies of the powders. The NiCrBSi and pure WC powders were respectively characterized by spherical (size, 50–100 μm) and irregular block particles (size, 0.5–5 μm). The fully mixed in a ball mill and dried powder blend was uniformly preplaced on the Ti6Al4V substrate using an organic binder and was compressed with a press force of 5000 N by a hydraulic press instrument to form a dense preplaced layer with the thickness of approximately 1 mm.

Single-track laser cladding was carried out by a HL-5000 type CO_2 laser source with a power output of 2.5 kW, a beam diameter of 4 mm, and a scanning speed of 5 mm/s. The melted pool was shielded to prevent the reactions between the molten pool and air by blowing high pure argon gas over the surface during laser treatment. The specimens were subsequently heat-treated at 700, 800, and 900 °C for 1 h in a muffle furnace and cooled in air.

Microstructure was observed by means of a JSM6460 scanning electron microscope (SEM) equipped with EDAX GENESIS energy dispersive spectroscopy (EDS). Microhardness along the depth of the cross-section was measured by using an HXD-1000TM micro-hardness tester. The load used was 100 g and loading time was set at 15 s.

The cracking susceptibility of the single track coatings was evaluated from their fracture toughness via the Vickers indentation method. Vickers indentations were prepared on coating cross-sections by a HV-120 Vickers hardness tester with 10 kg load. The indentations were immediately observed and measured using the VHX-600 K optical microscope (OM). The schematic of the cracks around the Vickers indentations is shown in Fig. 2. The fracture toughness K_{IC} ($MPa \cdot m^{1/2}$) of the coatings was calculated as follows [23]:

$$K_{IC} = 0.079\left(\frac{P}{a^{3/2}}\right)\log\left(4.5\frac{a}{c}\right) \tag{1}$$

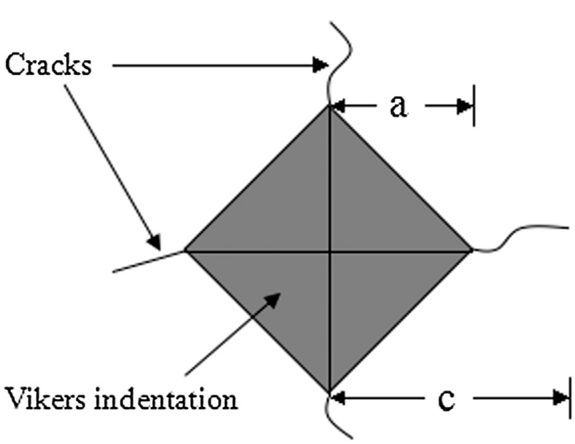

Fig. 2. Schematic drawing of the cracks around the Vickers indentation.

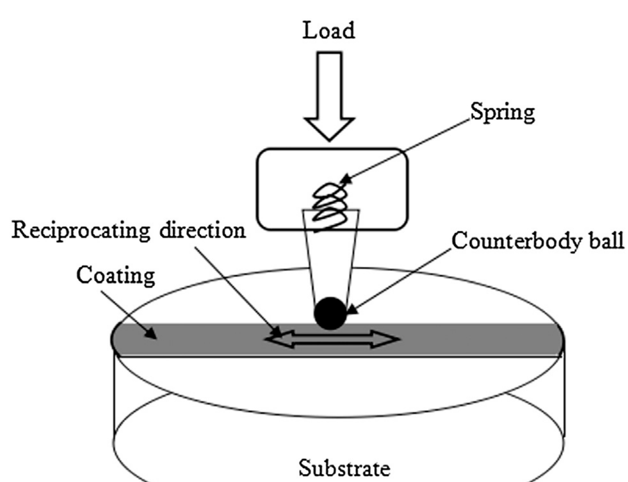

Fig. 3. Schematic drawing of dry sliding reciprocating wear test.