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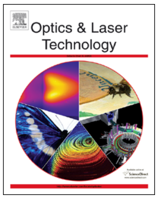

# Effects of post-heat treatment on microstructure and properties of laser cladded composite coatings on titanium alloy substrate

G.J. Li, J. Li*, X. Luo

*School of Materials Engineering, Shanghai University of Engineering Science, Shanghai 201620, China*

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ABSTRACT

The composite coatings were produced on the Ti6Al4V alloy substrate by laser cladding. Subsequently, the coatings were heated at 500 °C for 1 h and 2 h and then cooled in air. Effects of post-heat treatment on microstructure, microhardness and fracture toughness of the coatings were investigated by scanning electron microscopy (SEM), X-ray diffraction (XRD), energy dispersive spectroscopy (EDS), optical microscopy (OM). Wear resistance of the coatings was evaluated under the dry sliding reciprocating friction condition at room temperature. The results indicated that the coatings mainly consist of a certain amount of coarse white equiaxed WC particles surrounded by the white-bright $W_2C$, a great deal of fine dark spherical TiC particles and the matrix composed of the $\alpha$(Ti), $Ti_2Ni$ and TiNi phases. Effects of the post-heat treatment on phase constituents and microstructure of the coatings were almost negligible due to the low temperature. However, the post-heat treatment could decrease the residual stress and increase fracture toughness of the coatings, and fracture toughness of the coatings was improved from 2.77 MPa $m^{1/2}$ to 3.80 MPa $m^{1/2}$ and 4.43 MPa $m^{1/2}$ with the heat treatment for 1 h and 2 h, respectively. The mutual role would contribute to the reduction in cracking susceptibility. Accompanied with the increase in fracture toughness, microhardness of the coatings was reduced slightly. The dominant wear mechanism for all the coatings was abrasive wear, characterized by micro-cutting or micro-plowing. The heat treatment could significantly decrease the average friction coefficient and reduce the fluctuation of the friction coefficient with the change in sliding time. The appropriate heat treatment time (approximately 1 h) had a minimal effect on wear mass loss and volume loss. Moreover, the improvement in fracture toughness will also be beneficial to wear resistance of the coatings under the long service.

## 1. Introduction

Titanium and its alloys are widely used in chemical industries, aerospace and medical applications owing to their excellent corrosion resistance, high toughness and exceptional strength-to-weight ratio. However, the low surface hardness and poor wear resistance of titanium alloys limited severely their further application in many industry fields [1,2]. Therefore, it is essential to improve the wear resistance of titanium alloys using surface modification techniques, for instances, physical or chemical vapor deposition and plasma spraying [3–5]. Nevertheless, these methods have their limitations, such as the poor bonding strength between coating and substrate. As a promising surface modification technology, laser cladding has unique properties on wear resistance, corrosion resistance, and metallurgical bonding between the coating and the substrate compared with these conventional surface modification technologies [6]. Over the past few years, laser cladding composite coating onto pure titanium or titanium alloy substrate has attracted extensive attention owing to the higher efficiency, excellent metallurgical bonding in the interface and easy-controlled process and the excellent wear properties of the coatings [7]. Kulka et al. [8] obtained composite boride layers composed of laser-borided re-melted zone (TiB, $TiB_2$ and $Ti_{\alpha'}$-phase), heat affected zone ($Ti_{\alpha'}$-phase) and the substrate ($Ti_{\alpha}$-phase) using laser-boriding with boron on cylindrical surface of commercially pure titanium substrate, the composite layers present excellent wear resistance in comparison with commercially pure titanium. Savalani et al. [9] produced TiC reinforced Ti matrix composite layers on pure titanium substrate by laser cladding mixed powders of Ti and carbon-nanotube of different contents, and found that the coatings with higher carbon-nanotube content had better wear resistance. Li et al. [10] obtained in situ synthesized TiN and TiB particulate-reinforced metal matrix composite coating with hardness of 800 HV–1200 HV by laser cladding with a Ti/h–BN powder mixture, and the composite coating present better wear

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* Corresponding author. Tel.: +86 21 67791198; fax: +86 21 67791377.
*E-mail address:* jacob_lijun@sina.com (J. Li).

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resistance. Our research team [11–13] fabricated titanium-based composite coating reinforced by in situ synthesized TiB whiskers and TiC particles on Ti6Al4V by laser cladding. The above studies mainly focused on the Ti matrix composite coating, some works regarding Ni matrix composite coating on titanium substrate were also carried out. Guo et al. [14] produced NiCrBSi and NiCrBSi/WC–Ni composite coatings on pure Ti substrates by laser cladding and investigated the friction and wear behavior at elevated temperatures of 300 °C and 500 °C, and found the wear rate of the NiCrBSi/WC–Ni composite coating was approximately 24–47 times lower than that of the pure Ti substrate in the same case. A process of laser cladding NiCoCrAlY coating on Ti6Al4V substrate with pre-placed NiCoCrAlY powder was studied by Meng et al. [15], the average microhardness of the coating was 800 HV–1000 HV, which was two times higher than that of Ti6Al4V substrate. The above researches indicate that laser cladding can improve significantly hardness and wear resistance of titanium alloys.

However, laser cladding composite coating also has some disadvantages, e.g. high cracking susceptibility, which critically restricts its extensive applications in industry. Cracks may occur in the coating during or after laser cladding, caused by high thermal stress and microstructural stress occurred during rapid heating and rapid solidification [16]. Once cracks have been generated, crack propagation will be difficult to deal with in the subsequent application process, even resulting in the sample's failing. Therefore, cracks have a great influence on the quality of the laser cladded coating. How to reduce the cracking susceptibility of the coating has attracted extensive and continuous attention [16–18].

The generation of cracks can be attributed to the presence of the residual stress in the cladded coating. Based on this, many researchers have proposed many creative methods to reduce cracking susceptibility of the coating, such as preheating the substrate [19], adding rare elements and alloying elements to the clad powder [16,20,21], optimizing the processing parameters [22], etc. Besides, considering many important components by preheating the substrate are often subjected to the damage, Zhou et al. [23] put forward laser induction hybrid rapid cladding (LIHRC), and obtained the composite coatings which were free of cracks and had a good metallurgical bonding with substrate. Based on the principle of crack generation and expansion during laser cladding, Wang et al. [24] proposed adding 316 stainless steel net with low yield strength and good plasticity in the coatings, and crack density was significantly reduced. The former researches were mostly focused on preventing from producing of cracks in laser cladding process. However, post-treatment after laser cladding, aims to adjust microstructure and relieve residual stress generated in laser cladding process to avoid cracking in the subsequent application process [25]. In previous reports, post-heat treatment was widely used to improve the required properties of the bulk materials by refining crystal, relieving residual stresses and even changing the microstructure [26]. A few investigations reported the effect of the heat treatment on the laser cladded composite coating. Chen et al. [27] investigated the influence of post-cladding stress-relieving treatments on the residual stresses in laser clad AISI P20 tool steel on the pre-hardened wrought P20 substrate, and the results indicated that the heat treatment significantly influenced the magnitude and sign of the residual stress by changing the volume fraction of retained austenite in the coating. Liu et al. [28] investigated the effect of tempering treatment on the corrosion resistance and microhardness of the Ni60CuMoW composite coatings on 45 steel surfaces, and the results showed that the tempering treatment could improve microhardness and the maximum self-corrosion potential and reduce corrosion current density significantly. Previous studies mainly focused on the effects of the heat treatment on residual stress, microstructure and corrosion resistance. However, very few studies reported the combined influence of post-heat treatment on cracking susceptibility and wear resistance of the laser cladded coating.

Hence, in this study, the authors attempted to explore and discuss the effects of the post-heat treatment on microstructure and properties of the laser cladding coating on titanium alloy substrate, especially focused on hardness and fracture toughness. On this basis, the effect of the post-heat treatment on wear resistance was further studied.

## 2. Experimental procedures

Ti6Al4V cylindrical samples with 50 mm in diameter and 10 mm in height were used as the substrate. Before laser cladding, in order to ensure good surface finish, all the samples were ground with emery papers and ultrasonically cleaned in acetone. Commercial powder blends of pure Ni and pure WC in nominal chemical constituents (mass fraction, %) of 70Ni–30WC were selected as the cladding materials. The powder blends after fully mixed and drying treatment were pre-placed on the Ti6Al4V substrate with the thickness of approximately 1 mm and were compressed with a press force of 50000 N by a hydraulic press instrument in order to make the preplaced blends more dense. Then single track laser cladding was carried out by an HL-5000 type $CO_2$ laser source with a power of 2.5 kW, a beam diameter of 4 mm and a scanning speed of 5 mm/s. Fig. 1 shows the schematic drawing of laser cladding.

After laser cladding, the specimens were divided into three groups. One group was not disposed and remained the original status as cladding; others were heated respectively at 500 °C for 1 h and for 2 h in the muffle furnace, and cooled in air.

Microstructure was observed by means of 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 microhardness tester. The load used was 100 g and loading time was set at 15 s.

Fracture toughness, representing the cracking susceptibility of the coating, was measured by the Vickers indentation method. Vickers indentations were prepared on the cross-sections of the coatings using an HV-120 Vickers-hardness with the load of 20 N. Morphologies of the indentations were observed immediately using the VHX-600K optical microscope (OM). Fig. 2 shows the schematic drawing of cracks around the Vickers indentation. Fracture toughness of the coatings was calculated by the following

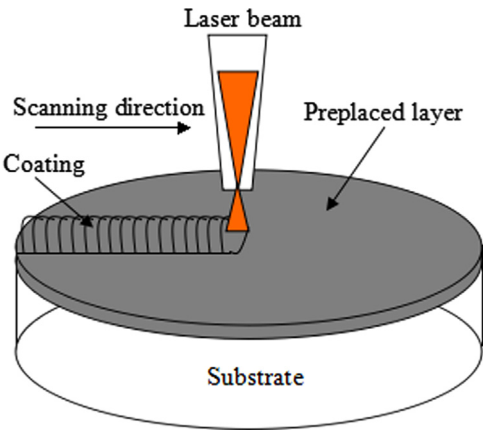

**Fig. 1.** The schematic drawing of laser cladding.