Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 27(2017) 2043−2054
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Residual stress distribution in different depths of TiNi/Ti_2Ni-based laser clad coating prepared at different environmental temperatures

Yang-feng TAO, Jun LI, Ying-hao LÜ, Lie-feng HU

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

Received 5 June 2016; accepted 9 October 2016

Abstract: This study aimed to effectively reduce the cracking susceptibility of the laser clad coating by enhancing the environmental temperature during laser cladding, and reveal the residual stress distribution in different depths of the coating. The TiNi/Ti_2Ni-based coatings were prepared on Ti6Al4V by laser cladding at different environmental temperatures of 25, 400, 600 and 800 °C. The changes in residual stress along the depth of the coatings were investigated in detail by the nanoindentation method. Results showed that the average residual stress of 2.90 GPa in the coating prepared at 25 °C was largest. With the increase in environmental temperature, the average residual stress was reduced to 1.34 GPa (400 °C), 0.70 GPa (600 °C) and 0 GPa (800 °C). For all the coatings, the residual stress was increased with increasing the distance from the coating surface. Enhancing the environmental temperature can effectively reduce the cracking susceptibility of the coatings.

Key words: laser cladding; coating; microstructure; environmental temperature; cracking susceptibility; residual stress; nanoindentation

1 Introduction

Titanium alloys are widely used as high-performance materials in the aerospace, petro-chemical, medical, and aircraft industries due to their low density, high specific strength, exceptional corrosion resistance and high-temperature mechanical properties. However, the application of these alloys in other industrial fields is restricted due to their poor tribological properties and low hardness [1]. Thus, some surface-modification techniques are used to improve the surface structures and properties of titanium alloys by changing their surface compositions [2,3]. Among these techniques, laser cladding is regarded as an excellent technology to fully optimize the properties of mechanical components, such as limited heat-affected zone, minimal stress deformation and good metallurgical bonding between the coating and the substrate [4,5].

Although laser cladding has many advantages, high residual stress usually generates in the coating because of its rapid heating and cooling characteristics. Consequently, the coating fabricated by laser cladding possesses very high cracking susceptibility, which is a critical shortcoming that vastly limits the industrial application of this technique. Thus, it is very necessary to reduce the cracking susceptibility of the laser clad coating. Several methods have been used to reduce the cracking susceptibility, including designing the cladding-material compositions, optimizing the processing parameters and preheating the substrate. WANG et al [6] prepared the coatings on 45# steel by laser cladding the NiCrBSiC alloy powders doped with V_2O_5. They found that the number of cracks was significantly decreased with the increase in content of V_2O_5. Furthermore, no cracks generated in the coatings when the content of V_2O_5 was increased to 4%−5% (mass fraction). WENG et al [7] fabricated the coatings on Ti6Al4V substrates by laser cladding the mixtures of Co42 self-fluxing alloy, TiN and Y_2O_3. The coating with 1.0% Y_2O_3 (mass fraction) addition showed good metallurgical bonding with the substrate and was free of pores and cracks.

RIQUELME et al [8] produced the SiC-reinforced Al matrix coatings on ZE41 magnesium alloy using a high-power diode laser (HPLD). The results showed that

Foundation item: Project (51471105) supported by the National Natural Science Foundation of China; Project (12SG44) supported by the "Shu Guang" Project of Shanghai Municipal Education Commission and Shanghai Education Development Foundation, China; Project (15KY0504) supported by the "Graduate Innovation" Project of Shanghai University of Engineering Science, China
Corresponding author: Jun LI; Tel: +86-13524458254; E-mail: jacob_lijun@sina.com
DOI: 10.1016/S1003-6326(17)60229-2

the optimal parameters for laser cladding were 650 W of laser output power and 17 mm/s of laser scanning speed, in which the coating with few interface pores and cracks had excellent microstructure and mechanical properties. ZHOU et al [9] prepared the Ni-based composite coatings on A3 mild steel at different processing parameters. The results indicated that cracking susceptibility was increased with increasing the laser output power and laser scanning speed. There were few cracks in the coating when the laser scanning speed was 480 mm/min and the laser output power was 2.5 kW.

The two methods mentioned above can effectively decrease the cracking susceptibility of the laser clad coating. However, the selected compositions or parameters may be only suitable to the specific combination of the coating and the substrate, and may have to be adjusted when the coating or the substrate changes. Compared with the above two methods, preheating the substrate is more universal as it can markedly reduce the residual stress in the coating due to the reduction in temperature change between the coating and the substrate. As a result, the cracking susceptibility of the coating is reduced or even eliminated. FALLAH et al [10] prevented the crack initiation in the coating by preheating the substrate prior to laser cladding of the hardfacing alloy stellite 1 on AISI-SAE 4340 steel. LESTAN et al [11] investigated the deposition of the Metco 15 E powders on cast iron by the laser-engineered net shaping (LENS™) technology. The number of cracks in the coatings was significantly decreased by preheating the substrates.

The cracking susceptibility of the coating is usually evaluated by crack number [12], fracture toughness [13] and residual stress [14] in the coating. The number of cracks cannot be used to evaluate the crack-free coating and to quantitatively evaluate the cracking susceptibility of the coating. Fracture toughness of the coating is usually measured by the Vickers indentation method. This method had been used to evaluate fracture toughness of the laser clad coating in previous studies [15,16]. Fracture toughness of the coating can be calculated with the following equation [16]:

$$K_{\mathrm{IC}} = 0.079\frac{P}{a^{3/2}}\ \lg(4.5\frac{a}{c}),\ 0.6 \le \frac{c}{a} \le 4.5 \tag{1}$$

where K_{IC} is fracture toughness (MPa·m$^{1/2}$), P is the applied load (N), a is the half-length of the diagonal line in an indentation (m), and c is the half-length of cracks (m).

However, the method presents the very low precision because of the two reasons. On one hand, based on different models, different equations are derived and applied to calculating fracture toughness, which leads to different calculations. On the other hand, it is very difficult to precisely measure the crack length due to the irregular and asymmetric cracks produced in the four corners of the indentation. The cracking susceptibility of the coating is increased with the increase in residual stress of the coating. Thus, it can be evaluated by the residual stress in the coating. The residual stress can be calculated by several methods such as X-ray diffraction, hole-drilling and nanoindentation method. However, the X-ray diffraction method has a very strict requirement for the surface of the coating and is inapplicable to the material composed of complicated phases [17]. The residual stress measured by the hole-drilling method may be affected by the equipment operators. Other than that, it is difficult to punch onto the materials with high hardness. Due to its depth-sensing capability, the nanoindentation method as an effective tool can be used to determine the residual stress in the coating. The nanoindentation method had been adopted to accurately measure the residual stress in the coating by DEAN et al [18], ZHU et al [19], WANG et al [20] and KHAN et al [21].

In this work, the TiNi/Ti_2Ni-based coatings were prepared on Ti6Al4V alloy by laser cladding at different environmental temperatures. The residual stress in the zones with different depths of the coatings was calculated by the nanoindentation method. Moreover, the effects of the environmental temperature on the cracking susceptibility of the coatings were investigated in detail.

2 Experimental

2.1 Pre-placed layer preparation

Ti6Al4V alloys (composition in mass fraction, 6.5% Al, 4.26% V, 0.1% C and balanced Ti) were used as the substrate and cut into the samples with dimensions of 30 mm × 20 mm × 10 mm. They were ground with 150-grit SiC abrasive papers and ultrasonically cleaned in ethanol for 15 min. The cladding materials were composed of 10% B_4C and 90% F102 Ni-based alloy with the compositions (mass fraction) of 75% Ni, 1% C, 16% Cr, 3.5% B, and 4.5% Si. The binder (4% polyvinyl alcohol) was placed on the surface of the substrate with a brush, and then it was placed into a model (30.2 mm in length, 20.2 mm in width, and 10.8 mm in height). The mixed powder was filled into the empty space with 0.8 mm in height above the surface of the substrate in the model. The powder was compacted with a tablet machine at 30 MPa for 3 min to obtain the pre-placed layer with about 0.8 mm in thickness.

2.2 Laser cladding

Before laser cladding, the samples were preheated to 400, 600 and 800 °C in the resistance furnace. Laser cladding was performed using a YLS−5000 fiber laser