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Preparation of ultra-fine grain Ni−Al−WC coating with interlocking bonding on austenitic stainless steel by laser clad and friction stir processing

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Abstract: The ultra-fine structured Ni−Al−WC layer with interlocking bonding was fabricated on austenitic stainless steel by combination of laser clad and friction stir processing (FSP). Laser was initially applied to Ni−Al elemental powder preplaced on the austenitic stainless steel substrate to produce a coating for further processing. The as-received coating was subjected to FSP treatment, processed by a rotary tool rod made of WC−Co alloy, to obtain sample for inspection. Microstructure, phase constitutions, hardness and wear property were investigated by methods of scanning electronic microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDX) microanalysis, and X-ray diffraction (XRD), hardness test alongside with dry sliding wear test. The results show that the severe deformation effect exerted on the specimen resulted in an ultra-fine grain layer of about 100 μm in thickness and grain size of 1−2 μm. Synergy between introduction of WC particles to the deformation layer and deformation strengthening contributes greatly to the increase in hardness and friction resistance. An interlocking bonding between the coating and matrix which significantly improves bonding strength was formed due to the severe deformation effect.

Key words: laser clad; friction stir processing; Ni−Al−WC coating; ultra-fine grain; interlocking bonding

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1 Introduction

Ultra-fine grain materials exhibit significantly excellent performance over the traditional one with coarse grain. Most of the failure during the service of materials occurs on the surface of work pieces. For this reason, preparation of ultra-fine grain coating is necessary to improve the performance of substrate. Laser cladding is a surface treatment technique which employs laser beam as heat source to form metallurgical bonding between the matrix and coatings. Some researchers have covered the study of laser cladding coating on surface treatment [1−5]. There are two major concerns in the research of laser clad coating on austenitic stainless steel: one is how to refine the grain of coating from coarse size to the fine-grain and even to the nano-scale [6−11], thus a more desirable performance can be obtained; the other is what can be done to improve the bonding condition between the matrix and surface material, hence, to avoid distinct transition section or thermo-match degeneration in materials which may lead to crack formation and short life span.

To overcome the disadvantages of laser cladding, friction stir processing (FSP) becomes a superb choice amongst others. FSP is a thermomechanical treatment during which the workpiece undergoes severe plastic deformation at high temperatures. Materials can reach the ultra-fine even to the nano scale after the treatment of FSP with enhanced mechanical performance. Currently, FSP has mainly focused on the microstructural refinement of soft metals, for instance, Mg alloys [12,13] and Al alloys [9,10,14−16]. Some FSP works focused on high-strength materials such as stainless steel [17,18],

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tool steel [7,19], coating [7,20,21]. Therefore, FSP is an ideal way for microstructural refinement and forming interlocking bonding of coating.

In this work, we concentrate on preparation of Ni−Al coating with ultra-fine grain and interlocking bonding with substrate by laser clad and friction stir processing. In the meantime, by using a WC−Co FSP tool, we try to introduce a certain amount of WC particles into the coating, which act as a dispersoid hard phase so as to obtain better wear resistance. The microstructural evolution of as-received Ni−Al−WC coating and matrix was investigated. Mechanical properties and tribology characteristics were also characterized.

2 Experimental

The stainless steel substrate (100 mm × 60 mm × 10 mm) for laser cladding was acquired from cutting off a continuous plate. The substrate was machined on the surface and blasted with sand to remove impurities and oxide before laser cladding. The nominal chemical composition of Ni−Al alloy powder is 80% Ni and 20% Al (mass fraction). The 304 stainless steel used in the experiment consists of 0.06% C, 0.48% Si, 1.54% Mn, 18.47% Cr, 8.3% Ni, 0.37% Cu, 0.027% Nb, 0.30% Mo (mass fraction) and Fe in balance.

In laser surface cladding (LSC) experiments, the heat source is a pulsed Nd:YAG laser with maximum output power of 400 W. Computer aided multiaxis positioning system and worktable cooperate with the laser. A rectangular pulse was applied to obtaining steady square wave pulse. A focus lens with a focal distance of 100 mm focused the spot size of laser beam to approximately 1.5 mm. Uniform powder beds were applied to increasing the laser energy absorptivity of 304 stainless steel surface.

After laser cladding experiments, FSP was applied to the laser-clad Ni−Al coating. The FSP tool rod was made of WC−Co hard metal in a columnar shape with the diameter of 10 mm without a probe. The adopted rotation speed was 1000 r/min with travel speed of 50 mm/min. Optical microscopy observation proved that there were no detectable cracks on the surface after FSP.

After FSP, transverse cross sections were obtained from the specimens for microstructure and microhardness examination. The cross section of FSP samples was observed by scanning electron microscope (SEM, JEOL JSM−6700) equipped with an energy-dispersive spectroscope (EDS). The phases before and after FSP were inspected by X-ray diffraction (XRD) with Cu K_α radiation.

Surface layer microhardness test was carried out by a micro-Vickers hardness tester with an applied load of 300 g for 10 s. Wear resistances of Ni−Al based coatings before and after FSP were conducted on the UMT-2MT tribo-meter with ball-on-disk configuration without lubrication. The ball material was quenched chromium steel with a Rockwell hardness of 60−63 and a diameter of 9.5 mm. The disk was vertically fixed while the ball can reciprocally slide on the disk. The tests were conducted at room temperature with a fixed load of 5 N. The morphology of the as-received sample was characterized by SEM.

3 Results and discussion

3.1 Characterization of ultra-fine grain surface layer

Figure 1 shows the XRD patterns of laser clad Ni−Al−WC coating before and after the FSP. The strong diffraction peaks presenting the $Al_{0.9}Ni_{1.1}$ can be observed evidently in both curves. Moreover, there are diffraction peaks of $AlNi_3$. However, there are two new phases, tungsten carbide (WC) and Fe−Ni, appearing after friction stir processing. It was reasonable to conclude that WC was incorporated in Ni−Al coating during friction stir processing since the FSP tool was made by WC−Co. Both the rotary tool rod and the Ni−Al coating were subjected to high temperature and intense stress during the FSP treatment. As the tool rod, made of WC cemented with Co, would inevitably wear off in this process, the abrasive dust consisting of WC and Co subsequently entered the coating layer. Under the influence of high temperature and severe deformation, the particles of WC entered the surface of the coating and blended into coating layer. These dispersed WC particles resulted in a dispersion strengthening effect, which helps to improve the strength and hardness of the coating, thus prolongs the service life of the whole workpiece. As for the Fe−Ni diffraction pattern, the severe friction exerted by the rotary rod affected not only the coating itself, but

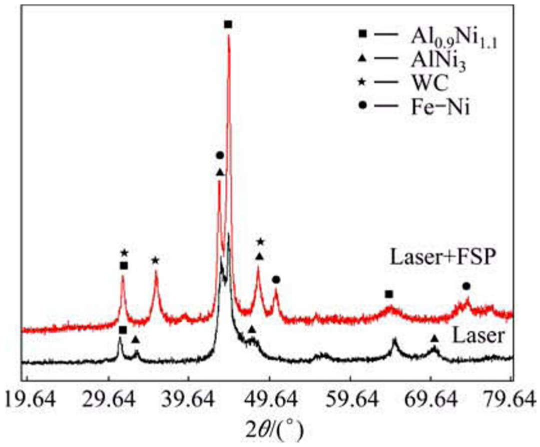

Fig. 1 XRD patterns obtained from unattended laser cladding and FSP-treated coating