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Characteristics of microstructure and stresses and their effects on interfacial fracture behavior for laser-deposited maraging steel

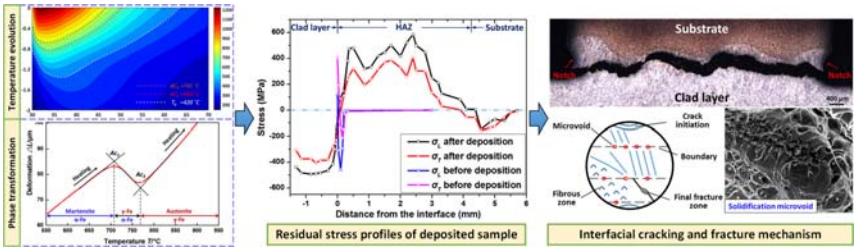
Shaopeng Wei [a,b], Gang Wang [a,b,*], Liping Wang [a,b], Yiming Rong [c]

[a] State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China
[b] Beijing Key Lab of Precision/Ultra-precision Manufacturing Equipments and Control, Tsinghua University, Beijing 100084, China
[c] Mechanical and Energy Engineering Department, South University of Science and Technology of China, Shenzhen 518055, China

HIGHLIGHTS

- Compressive stress existed in clad layer, and tensile in HAZ with a depth of 4 mm.
- Stress profile resulted from interaction between thermal shrinkage and martensitic expansion.
- Fracture morphology presents recognizable boundaries along laser scanning direction.
- Solidification voids and steep stress gradient facilitated interfacial crack propagation.

GRAPHICAL ABSTRACT



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ABSTRACT

Laser cladding is one of the most attractive ways to repair or remanufacture high-added-value engineering components. The present paper describes the effect of microstructure and residual stresses on the interfacial fracture behavior of laser-deposited maraging steel. The multi-layer overlapped cladding material was deposited on maraging steel substrates using laser hot-wire deposition. Residual stress profile was measured by X-ray diffraction. Temperature evolution and the induced phase transformation during the process were investigated to reveal the generation mechanism of residual stresses. A novel testing method was developed to analyze the interfacial fracture behavior and evaluate the bonding strength with specially designed T-shaped samples. The compressive stresses derived from martensitic expansion was presented in the clad layer, and tensile stresses in the heat affected zone up to a depth of 4 mm, which was caused by thermal shrinkage. Both the solidification micro-voids and steep stress gradient appearing in the interface contributed to the propagation of interfacial crack that will critically affect the mechanical properties of laser deposited material.

1. Introduction

The martensitic precipitation-hardening stainless steel, FV520B steel, has been widely used to produce compressor components because of its outstanding resistance to corrosion, wear, and fracture [1]. However, under severe working conditions (e.g., 2000–4000 rpm in an H_2S atmosphere), the compressor components are easily subjected to damage accompanied by material loss [2–3]. In recent years, laser direct deposition has provided an effective remanufacturing technique to repair damaged parts with many different geometries, while retaining high performance [4]. It produces an extremely dense and crack-free structure with an excellent metallurgical bond to the base metal [5].

During the laser deposition process, a high-power laser beam is focused onto the surface of the damaged region to create a molten pool at a high temperature above the melting point of its constituent

* Corresponding author at: Tsinghua University, Beijing 100084, China.
E-mail address: gwang@tsinghua.edu.cn (G. Wang).

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materials. The material is heated repeatedly beyond the phase transition temperature, and the uneven temperature distribution leads to the formation of a gradient microstructure across the coating/substrate interface. Additionally, the high thermal gradients involved in the process inevitably result in the generation of residual stresses. Cracking caused by the high residual stress may occur during the deposition or subsequent service process. The residual stress will affect the mechanical properties of the repaired parts, such as fatigue, creep, and brittle fracture behavior. To achieve production goals and reliable service performance, it is essential to obtain the desired distribution of microstructure and residual stress with minimum distortion. A comprehensive understanding of residual stress evolution in the deposited material and their controllability will be beneficial to the development of the laser deposition process and the improvement of in-service mechanical performance.

Previous studies have shown that well-formed deposited material with adequate mechanical properties can be achieved by laser hot-wire deposition [6–7]. However, a very large residual stress in the coating/substrate interface has often been reported to accompany the laser deposition process. As a metallurgical transition zone, the coating/substrate interface is a potential weak link when exposed to external loading; thus, interfacial adhesion is a critical property governing the mechanical behavior and reliability of the repaired parts [8]. It is essential to assess the interfacial strength to guarantee the functionality and service life of the repaired parts.

There have been a number of methods proposed to determine the interfacial strength, such as the tensile test [9–10], shear test [11], bend test [12–13], peeling test [14], scratch test [15], indentation test [16–17], and laser spallation test [18]. The testing methods for evaluating the interfacial bonding strength of thin films are well-developed. The test standards such as the tensile adhesion test (ASTM C633-79, DIN 50160 and JIS-H8664), shear test (ASTM F1044-05, GB/T 13222-91) and scratch test (ASTM C1624-05, JB/T 8554) are generally applied to test the interfacial strength of thin films with a low bonding strength (<100 MPa). However, these tests are of limited applicability due to the high strength of the metallurgical interface, the tensile state of stress and the lack of repeatability. None of them can assess the interfacial tensile strength of the thick coatings with high bond strength that emerge from the laser deposition process.

The aim of this study was to address the residual stress and interfacial bonding strength of laser-deposited FV520B material. In the present study, a fiber laser was used to deposit multi-layer overlapped cladding on FV520B steel substrates using laser hot-wire deposition. The depth profiles of residual stress before and after laser deposition process were studied by X-ray measurements. In order to have a comprehensive understanding of residual stress generation, the temperature history during the laser deposition and dilatometric curves of FV520B steel were obtained. An effective method was developed to evaluate the interfacial bonding strength of laser deposited material with a high bonding strength. Specially designed T-shaped samples were fabricated, and the interfacial strength was tested using a quasi-static tension method. The fracture behavior was investigated, and microstructural analysis was performed to provide better understanding of the fracture mechanism.

2. Experimental procedure

2.1. Material preparation

The substrate metal was martensitic precipitation-hardening stainless steel FV520B that had been normalized by heating up to 1050 °C, followed by solution heat treatment at 850 °C, and finally aging at 470 °C. The original microstructure of the substrate was composed of martensite laths and dispersed precipitation phases. The filler wire was FeCrNi steel with a diameter of 1.2 mm. The composition of the FeCrNi wire also conforms to the specification of FV520B steel. The chemical compositions of the FV520B substrate and FeCrNi wire are given in Table 1.

Developing a quantitative understanding of phase transformation behavior under rapid heating and cooling conditions during deposition is necessary. In order to investigate the effect of heating rate on the phase transformation behavior, the dilatometric curves of FV520B steel subjected to different heating rates were obtained by the dilatometer (DIL 805L). Samples with dimensions of ϕ 4 × 10 mm were heated to 1050 °C at heating rates of 0.25, 1, 5, 30, 80, and 100 °C/s, followed by soaking for 10 min, and finally cooled to room temperature at a cooling rate of 5 °C/s. The deformations and temperature histories during the experiment are shown in Fig. 1.

2.2. Sample fabrication using laser hot-wire deposition

An IPG YLS-2000 fiber laser with a wave length of 1.07 μm was applied to deposit a multi-layer overlapped cladding on the FV520B steel substrates. The filler wire was preheated by a Panasonic YC-400TX power source and then injected into the molten pool at an angle of 30° normal to the surface, as shown in Fig. 2. A single-track cladding experiment was conducted to obtain the optimized process parameters. The main optimized parameters were then set as: laser power 1810 W, scanning speed 0.5 m/min, wire feed rate 1.5 m/min, overlap ratio 30%, and wire current 58 A. Then, three layers of cladding material were deposited on the substrate using the optimized parameters.

The temperature history during the single-track deposition process was captured by K-type thermocouples and a data acquisition system (Graphtec GL7000). Sixteen thermocouples were installed at different positions on the substrate, as shown in Fig. 3. The thermocouples were classified as A_i, B_i, C_i, and D_i, corresponding to the depths of 0.5, 1.0, 1.5, and 2.0 mm, respectively. Since the scanning speed is known, the temperature curves captured by thermocouples along the X direction for a given value of Y (Y = 0, 1, 2, 3 mm) were extracted and the temperatures at the same positions with different depths can be concluded. Then the uneven temperature distribution of the heat affected zone (HAZ) was obtained based on interpolation of sixteen temperature-evolution curves. Additionally, the temperature history during the three-layer and six-track deposition process was measured to analyze the characteristics of rapid cyclic temperature change.

2.3. Microstructure and residual stress characterization

The samples were cut along the cross section, then grounded with emery papers ranging from #400 to #2000, and finally polished with diamond powder having a 1-μm grain diameter. The as-polished samples were etched by a mixed solution of 5 ml of hydrochloric acid, 1 g picric acid and 100 ml of ethanol. Microstructural examinations were characterized using an optical microscope (Olympus BX-51) and a scanning electron microscope (SEM, Quanta FEG 450) equipped with the energy dispersive spectroscopy (EDS) system. Microscopic studies were performed to reveal the effect of the laser heating on microstructure of deposited material.

The stress-measuring instrument (XSTRESS3000, Stresstech Oy) was used to measure the residual stress profiles of laser-deposited

Table 1
Chemical composition of FV520B steel substrate and FeCrNi wire (wt%).

	C	Cr	Ni	Mn	Si	Cu	Mo	P	S	Nb	Fe
FV520B substrate	0.034	13.34	5.7	0.55	0.21	1.42	1.49	0.024	<0.025	0.25–0.45	Bal
FeCrNi wire	0.029	14.02	6.2	0.54	0.32	0.33	1.15	0.014	0.009	0.33	Bal