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Competitive failure analysis on tensile fracture of laser-deposited material for martensitic stainless steel

Shaopeng Wei [a,b], Gang Wang [a,b,*], Jianchao Yu [a], Yiming Rong [b,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

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ABSTRACT

Sufficient mechanical properties of deposited materials are needed in remanufacturing applications to guarantee the functionality and reliability of repaired parts. The present paper described the tensile fracture behavior of laser-deposited FV520B martensitic stainless steel comprehensively based on evolution of the microstructure and mechanical property. The samples were fabricated by laser hot-wire deposition. The fracture behavior of the deposited samples was characterized using a specially designed uniaxial tension testing approach and investigated on the grain size, microhardness profile, residual stresses and precipitate distribution. The results show that the tensile fracture occurred at the position with high fluctuating microhardness caused by the multi-layer laser heating. Three tensile fracture patterns of deposited material were found: interfacial fracture, heat affected zone (HAZ) fracture and HAZ/interface hybrid fracture. They result from the competitive failure between microvoid coalescence in the heat affected zone and interfacial cracking in the clad layer/HAZ interface. Grain refinement and dissolution of precipitates occurred in heat affected zone, leading to a decrease of strength and increase of toughness.

1. Introduction

Laser hot-wire deposition combined with computer-aided design (CAD), laser cladding, and a rapid prototyping technique is a novel additive manufacturing technology for fabricating components with complex geometries and high performance [1–3]. It has become a popular manufacturing technique for industrial applications due to its distinct advantages, such as high energy density, high material deposition rates, low dilution and negligible distortion [4–5]. During the laser hot-wire deposition process, the motion of the high-powered laser beam is controlled by a CNC system developed from the CAD model for a desired geometry. Metal wire is preheated up to near the melting temperature by resistance before being fed into the molten pool. The external preheating can reduce the required laser power, leading to a narrow heat influence and small heat damage to the substrate. Wire deposition can result in almost 100% material utilization efficiency [6]. Deposited metal is then formed in a track-by-track and layer-by-layer way to produce the near-net desired shape with full density.

The present investigation centered on martensitic precipitation hardening stainless steel FV520B, which is widely used to produce compressor components due to its outstanding resistance against corrosion, wear and fracture [7–8]. It is reported that the compressor components are easily damaged because of the severe working conditions (2000–10,000 r/min [9], dynamic loading [10], and an H_2S atmosphere [11]). Laser hot-wire deposition provides an effective remanufacturing technique for repairing damaged components [12–13]. Compared with producing a new component, laser repairing can reduce the down-time and economic cost. High forming precision and sufficient mechanical properties are required for the remanufacturing applications.

Most researchers have focused on the mechanical properties of deposited materials [14–15]. Previous studies have shown that good formation quality and sufficient mechanical properties of deposited material can be achieved using laser hot-wire deposition [16]. However, a softening effect in the heat affected zone (HAZ) and great residual stress in the clad layer/HAZ interface and are often reported as accompanying the laser deposition process [17]. The rapid heating and cooling process of the material (heating rate: $10^{4-}10^9$ K/s; cooling rate: 10^6 K/s) results in a great residual stress in the clad layer/HAZ interface and microstructural change in the HAZ. Additionally, clad layer/HAZ interfaces of laser-deposited material are usually associated with an abrupt transition in the microstructure and associated mechanical properties. The clad layer/HAZ interface and HAZ become the potential weak link exposed to external service loads. Consequently, it is essential to investigate the tensile properties and fracture behavior of the deposited material in order to guarantee the functionality of the repaired parts.

Subjected to large centrifugal force, the common failure mode of a remanufactured compressor is tension fracture under the tensile stress

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

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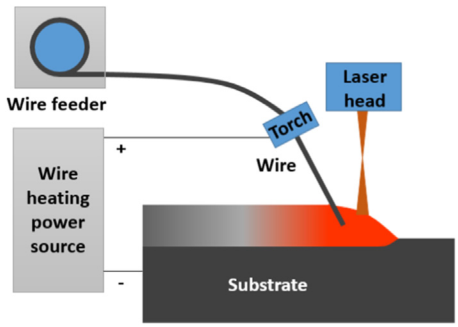

Fig. 1. Schematic of laser hot-wire deposition

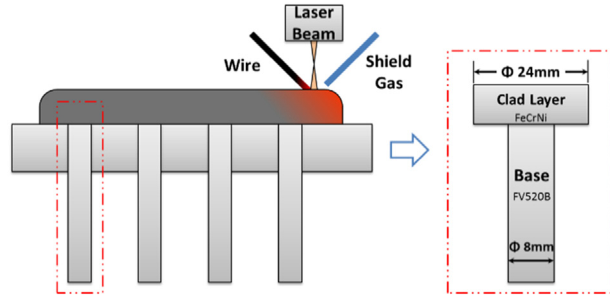

Fig. 2. Sample preparation procedure.

state. Sufficient tensile strength is needed for the repaired components. Interfacial adhesion is a critical parameter governing the mechanical behavior and reliability of the deposited material [18]. Strong interfacial adhesion can improve load transfer, increasing the yield strength and stiffness. Additionally, HAZ softening has been responsible for premature failures due to reduction in local strength leading to modified mechanical properties after laser processing [19]. Few works have addressed the mechanical properties of the interface and HAZ. The interfacial property and HAZ softening effect is always examined by hardness measurements and nanoindentation testing [20–21], which cannot obtain the fracture behavior of the overall deposited material system. This paper concentrates on a specially designed specimen to allow a uniaxial tension test on the laser-deposited samples.

The aim of this study was to address the fracture failure mechanism of laser-deposited FV520B material using a uniaxial tensile test. In the present study, a fiber laser was used to deposit multi-layer overlapped cladding on an FV520B steel substrate using laser hot-wire deposition. Specially designed T-shaped samples were fabricated. The uniaxial tension of the T-shaped samples was applied to investigate the tensile properties of laser direct deposited FV50B steel. The tensile fracture morphology was investigated with an optical microscope and a Scanning Electron Microscope (SEM). The microstructure, microhardness profiles and residual stresses in the deposited sample were obtained to investigate the fracture behavior. The effect of multi-layer laser heating on the tensile properties and fracture behavior were also discussed.

2. Experimental methods

2.1. Laser hot-wire deposition

Fig. 1 shows the schematic of laser hot-wire deposition. The deposition experiment was conducted using a 2KW fiber laser (IPG YLS-2000) with the wave length of 1.07 μm and a wire heating power supply (Panasonic YC-400TX). The laser beam was focused onto the base metal to create a molten pool. The filler wire was preheated by resistance and then fed into the molten pool. FV520B steel plates with dimensions of 200 × 98 × 10 mm^3 containing uniform cylindrical holes and assembled with several rods were used as the substrate. The base metal has been normalized by heating up to 1050 °C, followed by solution treatment at 850 °C, and finally ageing at 470 °C for 4 h. The filler wire with diameter size of 1.2 mm was made of FeCrNi steel. The chemical compositions of the base metal and FeCrNi steel wire used in this study are given in Table. 1. The deposition process was protected by argon shielding gas (purity of 99.9%).

Single-track cladding experiments were carried out to obtain the optimized process parameters. Then, five-layered cladding material was deposited on the substrate, as shown in Fig. 2. Each deposited layer consisted of 22 overlapped cladding tracks. The processing parameters were set as follows: laser power 1810 W, scanning speed 0.5 m/min, wire feed rate 1.5 m/min, wire current 58 A, an overlap ratio of 30%, a wire angle of 60° and shielding gas flow rate of 20 L/min. After the material deposition experiment, T-shaped samples were machined from the laser-deposited material. The clad layer/HAZ interface was made at the structural transition of the T-shaped samples. In addition, twelve control samples made of substrate material were prepared as a contrast.

2.2. Tensile test design and microstructure characterization

As shown in Fig. 3, the tensile experiments of T-shaped samples were conducted on a universal testing machine (WDW-100/E) with a fixture. The fixture system was developed to fix the testing samples. The displacement rate of the tensile test was 0.05 mm/s. Load and displacement during the test were recorded by a computer data-acquisition system.

The test sample was cross-sectioned, polished with emery papers of grain number ranging from #400 to #2000 and finished up by buffing with diamond powder of 1 μm grain diameter. Then metallographic sample was etched by a solution of 5 ml of hydrochloric acid, 1 g picric acid and 100 ml of ethanol. The optical microscope (Olympus BX-51), scanning electron microscopy (SEM, Quanta FEG 450), electron backscatter diffraction (EBSD, JEOL JSM-7001F) and transmission electron microscope (TEM, JEOL 2100F) were applied to examine the microstructure and fracture morphology of the test sample. Chemical composition analysis was carried out by SEM-energy dispersive spectroscopy (EDS, Quanta FEG 450, EDX-OXFORD). The phase structures were examined by X-ray diffractometer (XRD, Bruker D8) in the range of glancing angles 20–100° with Cu-Kα radiation.

The microhardness profile along the cross section was measured using a Vickers hardness tester (Instron MH-3) with a load of 0.1 kgf. Each microhardness was calculated from three measurements executed at the same position along the deposited direction. The depth profiles of residual stress were obtained by XSTRESS3000 stress measuring instrument. The samples were prepared by using iterative electrolytic removal of surface layers and the tested interference peaks were evaluated based on the $sin^2\varphi$ method [22]. The residual stresses of the tested area were the average values of the measurements.

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

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