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Evaluation of defect density, microstructure, residual stress, elastic modulus, hardness and strength of laser-deposited AISI 4340 steel

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Abstract—Laser-aided direct metal deposition (DMD) was used to form a AISI 4340 steel coating on an AISI 4140 steel substrate. Stress in the coating was relieved before mechanical testing. The defect density and microstructural property of the DMD coating were analyzed. The thermal analysis, continuous cooling transformation (CCT), residual stress, micro-hardness, nano-hardness and elastic modulus of the DMD coating before and after stress relief were studied. Tensile testing, lap shear testing and bend testing were done on the stress-relieved DMD coatings. Finally, evaluation of the effect of porosity on fracture behavior was characterized. A porosity and residual stress-based fracture mechanism was proposed. A better deposition strategy is needed to improve the microstructure (decrease porosity), and the mechanical properties of DMD could be tailored through appropriate heat treatments.

Keywords: Laser deposition; Microstructure; Thermal analysis; Nanoindentation; Fracture

1. Introduction

AISI 4340 steel is widely used in industrial applications because of its toughness, high strength and ability to retain good fatigue strength at elevated temperatures [1], e.g. in fatigue-critical components, such as the rotor hubs and connecting links of helicopters [2,3], in nuclear power plant structures, high-pressure vessels and reactors and shafts [4], and it is regarded as one of the most popular spring materials for typical force transducer applications [5]. These components often fail. Laser-aided direct metal deposition (DMD®) can be used to repair these metal components with a complex geometry.

DMD is a solid free-form fabrication developed at the University of Michigan. It is one of the rapid prototyping technologies, which has the ability to fabricate and to repair a wide range of metal components with a complex geometry, starting from metal powders. It combines computer-aided design, computer-aided manufacturing, laser cladding and sensors [6,7]. In the fields of rapid tooling and small batch production, DMD can afford considerable commercial benefit by reducing the design-to-market time of a product, and in the die production industry in particular it has the potential to drastically reduce operating costs, and repair or fabricate high-value parts with low production volume [8–10]. Various laboratories have developed similar processes with different names, such as direct light fabrication (DLF) at Los Alamos National Laboratory, Los Alamos, NM [11,12], and laser-engineered net shaping (LENS) at Sandia National Laboratory, Albuquerque, NM [12–14]. The main difference between DMD, DLF and LENS is the closed-loop controlled, though all three use pneumatically delivered powder. Another group selected melting of powders in a powder bed, e.g. selective laser powder remelting or selective laser melting at Fraunhofer ILT, Aachen [15], and selective laser sintering (SLS®) at the University of Texas, Austin (commercialized by the Desktop Manufacturing Corporation) [16]. The basic principles of these pneumatically delivered powder technologies are similar, in that they use a high-power focused laser beam to create a melt pool on the substrate, to which metallic powder is delivered to create a metal cladding. A robot or a computer numerical control system is used to control the motion of the laser beam as per the tool path generated

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from the computer-aided design model of an object to create a three-dimensional component layer-by-layer [17]. Accurate control of parameters such as laser power, spot diameter, scanning speed and powder mass flow rate is fundamental to obtaining the required geometric dimensions and material property.

Extensive work has been done so far by various research groups to develop novel coatings with high performance by various laser technologies [18–24]. However, a large proportion of the research attention in this field is focused towards the characterization of microstructures, determination of micro-hardness and the evaluation of wear or corrosion behavior of the fabricated coatings.

First, porosity and discontinuities are two important problems in DMD or SLS. Their nucleation, growth and coalescence greatly affect the stiffness, fracture and fatigue resistance of the components [25–28]. All the defects, such as de-bonding, micro-voids, inclusions, pores and weak grain boundary films can cause rupture. The effects on the structural performance of porosity and bonding defects in the DMD coating need to be clarified. Second, induced residual stress of the laser-treated coating is dependent on the elastic modulus, which is one of the important properties that determine the mechanical strength of the coating [29]. Therefore, it is necessary to investigate the relationship between residual stress and elastic modulus and their effects on the mechanical properties of the DMD coating. Third, what is the effect of the stress-relieving treatment on the residual stress, nano-hardness and elastic modulus of each layer of the DMD coating? These aspects are, of course, of utmost importance for the use of DMD manufactured parts when used in actual working conditions, but to the best of the authors' knowledge, none of the studies available so far in open literature has addressed this topic.

Therefore, the current study aims to shed light on the effects of stress-relieving treatment on the microstructure, the full width at half maximum (FWHM) of the presented peaks, the residual stress, nano-hardness and elastic modulus of each layer in the DMD, and on the relationships between strength, fracture, residual stress, porosity and microstructure of the DMD-processed material. A thorough testing procedure combining microstructure, phases and mechanical tests was carried out. The microstructure, FWHM of the presented peaks of the as-deposited and stress-relieved DMD AISI 4340 steel were observed by scanning electron microscopy (SEM) and X-ray diffractometry (XRD). The phase transformation and martensite transformation starting temperature were analyzed by differential scanning calorimetry (DSC) and continuous cooling transformation (CCT) curves. The residual stress, nano-hardness and elastic modulus were investigated by analyzing the residual stress change and indentation load–displacement curves resulting from the nano-indentation test. Furthermore, evaluation of the effect of process-induced porosity on the strength and fracture behavior of stress-relieved DMD AISI 4340 steel was carried out by tensile, lap shear and three-point bend testing. These fracture surfaces were characterized. A fracture mechanics-based mechanism was proposed to illustrate the failure mechanism.

2. Experimental procedures

2.1. Powder material

The substrate material was AISI 4140 steel with chemical composition Fe–0.38C–1.04Mn–0.026P–0.014S–0.23Si–0.123Ni–0.967Cr–0.18Mo (wt.%). Gas atomized pre-alloyed AISI 4340 steel powders (Fe–0.4C–0.75Mn–0.017P–0.009S–0.18Si–1.9Ni–1.0Cr–0.46Mo (mass%)) with size range 45–109 μm were used as the feedstock material. The powders were manufactured by Carpenter Powder Products (PA, USA). Fig. 1 shows the as-received powder particle morphology. The particles are mainly spherical, with an average particle size of 75 μm and 85% of the particles within the 60–109 μm range. Powder was also mounted in epoxy, ground and polished to examine the powder particle cross sections, using SEM, for particle morphology, size and porosity measurements. A cross section of the as-received powder particles is shown in Fig. 1(b). Approximately 100 particles per micrograph were selected for measurement, and always the largest diameter and the diameter in the direction perpendicular to the long axis were measured. The average powder particle porosity was found to be ~0.45%.

2.2. DMD process

Fig. 2 shows a schematic of the DMD process. The DMD system consisted primarily of a laser generation system, a powder delivery system, a feedback control system and the CNC motion stage [30]. The DMD process could be performed either in air or under a controlled atmosphere. DMD samples for this investigation were prepared at Focus, HOPE, using a 1 kW fiber coupled diode laser (Laserline GmbH, Germany) POM DMD 105D system. The authors have investigated the laser processing

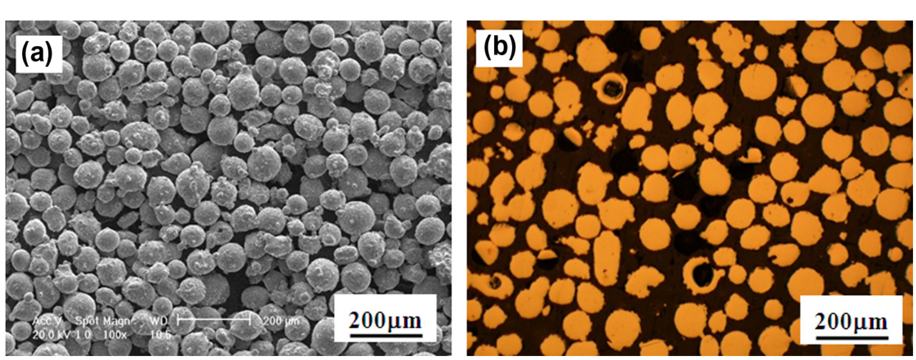

Fig. 1. SEM micrograph of AISI 4340 powders: (a) morphology; (b) cross section.