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Microstructure evolution during laser-aided direct metal deposition of alloy tool steel

Guifang Sun,[a,b,*] Sudip Bhattacharya,[a] Guru P. Dinda,[c] Ashish Dasgupta[c] and Jyotirmoy Mazumder[a,*]

[a] *Center for Laser-Aided Intelligent Manufacturing, University of Michigan, Ann Arbor, MI 48109, USA*
[b] *School of Mechanical Engineering, Jiangsu University, Zhenjiang, Jiangsu 212013, People's Republic of China*
[c] *Center for Advanced Technologies, Focus: Hope, Detroit, MI 48238, USA*

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Laser-aided direct metal deposition has been used to form an alloy tool steel coating. The microstructure of the deposited material was analyzed by means of scanning electron microscopy and transmission electron microscopy. The formation relationships among martensite, ε-carbide, cementite and austenite in the coating are discussed. The effect of rapid solidification associated with direct metal deposition on lattice parameters is also reported.

Keywords: Laser deposition; Microstructure; Transmission electron microscopy; Phase transformations; Orientation relationships

Direct metal deposition (DMD) combines computer-aided design and manufacturing, laser cladding, and sensors. One important feature of this technique is that, as a result of layer overlap during build-up of a part, the deposited material undergoes consecutive thermal cycles leading to progressive modification of its microstructure and properties [1,2]. In the fields of rapid tooling and low volume production it can offer considerable commercial benefit by reducing the design to market time of a product, and in the die production industry it has the potential to drastically reduce operating costs [3]. However, the production rate by DMD is low compared with conventional manufacturing processes. Hence, DMD is especially suitable for repairing or fabricating high value parts at low production volumes [4,5].

AISI 4340 steel is widely used in industrial applications due to its toughness, high strength, and ability to retain good fatigue strength at elevated temperatures [6], e.g. in fatigue critical components [7,8], in nuclear power plant structures such as high pressure vessels and reactors, and in shafts [9]. DMD can be used to repair these components. To the best of our knowledge the relationship between formation of martensite (α), ε-carbide (ε), cementite (Fe_3C) and austenite (γ) in DMD processed steel have never been published. The aim of the present work was to investigate the microstructure and to determine the formation relationships among α, ε, Fe_3C and γ of laser deposited AISI 4340 steel.

The CO_2 laser used is built into a DMD 505 machine (developed by the POM Group, Auburn Hills, MI in collaboration with Trumpf Inc., Plymouth, MI). A coaxial nozzle with a feeding rate in the range 1–30 g min^{-1} was used to deliver the powders. The substrate material was AISI 4140 steel, whose chemical composition is Fe–0.38 C–1.04 Mn–0.026 P–0.014 S–0.23 Si–0.123 Ni–0.967 Cr–0.18 Mo (wt.%). AISI 4340 powder (Fe–0.4 C–0.75 Mn–0.017 P–0.009 S–0.18 Si–1.9 Ni–1.0 Cr–0.46 Mo (wt.%)) with a particle size of 45–109 μm was used as the feedstock material.

Before laser treatment the substrate was case hardened. Identical layers were scanned using unidirectional scan vectors and the tracks in the subsequent layer were located directly between two tracks in the previous layer. The overlap ratio between two tracks was 50%. The distance between the nozzle and the substrate was 20 mm. The flow rates of the delivery and shielding gas (argon) were 8 L min^{-1}. The laser beam with a transmission electron microscopy (TEM) 01^* (donut-shaped) mode was 2 mm in diameter. Processing parameters for the DMD

* Corresponding authors. Address: Center for Advanced Technologies, Focus: Hope, Detroit, MI 48238, USA (G. Sun); e-mail addresses: gfsun82@gmail.com; mazumder@umich.edu

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were laser power 1.4 kW, powder flow rate 22 g min^{-1}, and scanning speed 0.6 m min^{-1}. The DMD coating had five layers.

After laser treatment the specimens were prepared for scanning electron microscopy (SEM) (Philips FEI XL30FEG). Transmission electron microscopy (TEM) (JEOL 2010F) investigations were conducted at an accelerating voltage of 200 keV. After mechanical polishing to a thickness of 0.08 mm, discs 3 mm in diameter were punched from the coating. Punched disks were prepared with a Precision Ion Polishing System (Gatan Model 691).

The DMD coating cross-sectional morphology is shown in Figure 1. Unidirectional scan vectors are applied and the scanning pattern is identical for all layers. The layers are scanned from left to right and bright stripes between laser tracks in one layer can be observed. The deposition of subsequent tracks generates new thermal cycles and, as a consequence, materials at the boundary of the previously deposited tracks undergo additional phase transformations, resulting in the bright stripes. This microstructure, which is determined by the thermal history, controls the mechanical properties, so further investigation of the effect of this microstructure on the mechanical properties, such as tensile strength, lap shear and bending, needs to be done. The occurrence of those bright stripes allows us to estimate the actual intervals between adjacent tracks. The horizontal bands (bright stripes) in Figure 1a are approximately 1 mm apart (50% of the laser spot diameter) and, therefore, presumably result from the 50% overlap. Thus, the different tracks represent the different scan vectors. The \\\ pattern is caused by repetition of the scanning tracks. The laser beam is scanned from left to right and, hence, the tracks are slanted from left to right. This dependence suggests that the local heat transfer conditions, more specifically the heat conduction direction, plays a major role in determining the grain orientations. The average thicknesses of the five layers from the first to the fifth are 570, 736, 760, 753, and 1587 μm, respectively (Fig. 1b). As expected, due to dilution of the substrate, the first layer is the thinnest compared with the other layers. The second, third and fourth layers present similar thicknesses, approximately 750 μm, as a result of similar processing histories, i.e. metal powders deposited on the previous layer and then the deposited layer remelted by subsequent layer deposition. The fifth layer is the thickest, about twice the thickness of the middle layer, due to no remelting after deposition.

Figure 2a–d shows a plan view of the top surface, a cross-section of the fifth layer, a cross-section of the third layer and a cross-section of the heat affected zone (HAZ), respectively. The laser–material interaction generally consists of three steps: absorption of the laser energy by the material, redistribution of the absorbed energy within the target material, and melting or evaporation of the substrate depending on the power input [10]. As expected, due to the high temperature gradients that occur during the DMD process the resulting phase is a very fine acicular martensite with some retained austenite at the grain boundaries (indicated by black arrows). Different orientations between martensite cells, tempered martensite, and precipitated carbides due to the thermal effects of subsequent DMD processing can be observed in Figure 2b and c. The deposition of subsequent layers generates new thermal cycles and, as a consequence, the previously deposited material undergoes additional phase transformations. Precipitates can also be observed in the HAZ (Fig. 2d).

TEM investigations of the DMD coating are illustrated in Figure 3. The relationships among images, corresponding electron patterns and schematic drawings are indicated by arrows. The SAD patterns of Figure 3a and b are given in Figure 3d and e, respectively, which confirm the existence of martensite with zone axes [1 1 0] and [0 1 0], respectively. The martensite in Figure 3e also has a superlattice. In this figure the reciprocal lattice points denoted by large dots are fundamental while those denoted by small fixed dots are due to the superlattice. The SAD pattern (Fig. 3c) of the small white grain boundary region in Figure 3b is drawn schematically and indexed in Figure 3f. The orientation relationship between Fe_3C and ε is [1 0 0]Fe_3C//[0 1 1]ε, (0 1 0)Fe_3C//(2 1 1)ε and (0 0 1)Fe_3C//(1 1 1)ε. The SAD pattern and a schematic drawing of the region in Figure 3g are shown in Figure 3h and i, respectively. The martensite was intensely dislocated (Fig. 3g). The

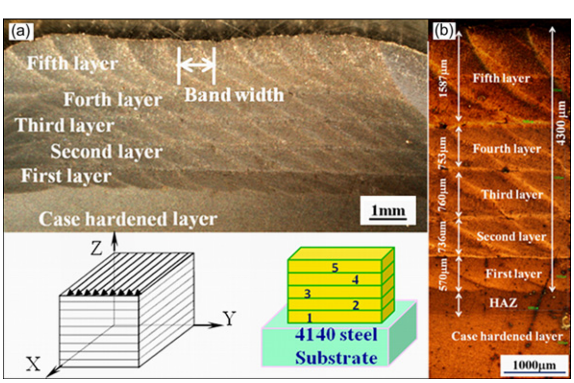

Figure 1. Morphology of the 4340 steel DMD coating: (a) micromorphology; (b) micromorphology.

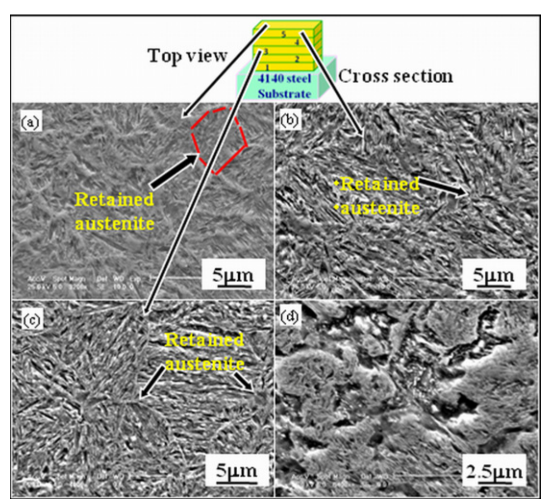

Figure 2. Microstructure of the 4340 steel DMD coating: (a and b) plan view and cross-section of the fifth layer; (c) cross-section of the third layer; (d) cross-section of the HAZ.