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Microstructure and corrosion behavior of laser surface-melted high-speed steels

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Abstract

Three high-speed steels (HSSs) M2, ASP23, ASP30 were surface-melted by a CW 2.5-kW Nd:YAG laser. The microstructure of the laser surface-melted HSSs was investigated by optical microscopy, scanning electron microscopy and X-ray diffractometry, and the hardness profiles of the laser surface-melted layers were determined by a Vickers hardness tester. The corrosion behavior in 0.6 M NaCl and 0.5 M $NaHCO_3$ solutions at 25 °C was studied by potentiodynamic polarization technique. Metallographical as well as electrochemical corrosion studies illustrated the beneficial effects of laser surface melting (LSM) in refining the microstructure and in enhancing the corrosion resistance of the HSSs. The large carbide particles of annealed HSSs were dissolved after LSM and ultrafine dendrites of austenite and martensite with submicroscopic carbide precipitation were formed in the melt zones of the laser surface-melted HSSs. LSM of M2, ASP23 and ASP30 produced surface layers of hardness 615, 580 and 665 Hv, respectively. The hardness of the laser surface-melted ASP23 and ASP30 reached about 0.75 to 0.80 that of the conventionally hardened ones, while the hardness of laser-melted M2 was comparable to that of conventionally hardened M2. The corrosion resistance of all laser surface-melted HSSs in both solutions was significantly improved, as evidenced by a noble shift of the corrosion potential and a reduction in the corrosion current density. Among the HSSs, laser surface-melted ASP23 possessed the highest corrosion resistance in both solutions. The presence of cobalt in ASP30 has no beneficial effect on enhancing its corrosion resistance. The enhancement in the corrosion resistance of the laser surface-melted HSSs is attributable to the combined effects of dissociation and refinement of large carbides and the increase of the passivating alloying elements such as Cr, Mo and W in solid solution.

Keywords: Laser surface melting; Corrosion; Hardness; Microstructure; High-speed steels

1. Introduction

High-speed steels (HSSs) are iron-based alloys of the Fe–C–X multi-component system where X represents Cr, W, Mo, V or Co. HSSs are better than high-carbon steels because they can be hardened by air cooling from austenitizing temperature while most other steels require water quenching for hardening. The addition of Co in HSSs can further increase their red hardness. HSSs have been widely used in cutting tools, forging and punching dies, automotives, space vehicles, IC packaging molds and substrates for thin-film deposition. However, the high alloy contents in HSSs inherently give rise to carbide segregation at grain boundaries and a coarse-grained microstructure by conventional processing such as casting, hot working, and cooling [1]. This could reduce toughness, with the consequent risk of premature failure by chipping or breakage of tools under high-stress conditions [1]. In recent years, advanced rapid solidification technologies such as surface melting employing laser-beam [2–11], electron-beam [12] and ion-beam [13,14] have been reported to be feasible routes for enhancing the surface properties of the HSSs and have gained increasing technological interest. Among these surfacing techniques, laser surface melting (LSM) is the simplest and most economical treatment method because no vacuum environment is required. After surface melting, the ensuing self-quenching (with cooling rates of the orders of 10^3 to 10^6 °C/s) is rapid enough to eliminate the need for external quenching to produce a wide range of intriguing microstructure while the bulk properties of the alloys

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can be preserved. LSM does not involve change in the overall chemical compositions and no additional precious materials are needed. Another advantage of LSM over conventional heat treatment is its capability in the localized treatment of a selected part of a surface, leaving the other parts unaffected. This could be of practical value in the case of HSSs used as tools. Owing to the high cooling rates in LSM, classical transformations are often inhibited, and instead the melt pool undergoes a non-equilibrium solidification process and new metastable phases may appear. In particular, LSM of HSSs leads to the dissolution of large brittle carbides, resulting in the formation of homogeneous and ultrafine microstructure. These desirable features lead to enhanced surface properties.

While the hardness of HSSs is an important property in applications, corrosion resistance is another because failure of HSS parts may also be caused or accelerated by corrosion. Besides the metallurgical factors, the corrosion behavior of an alloy is essentially determined by the composition of the electrolyte in contact with the alloy. Chloride ions and bicarbonate ions are commonly present in natural environments, with the former abundant in marine environments and the latter in soil [15], concrete pore solution [16], and rivers in China [17,18]. Chloride ions are aggressive and would aggravate corrosion attack on HSSs whereas bicarbonate ions promote passivation. Studies on the electrochemical behavior and passivation properties of conventionally heat-treated M2 in both chloride and bicarbonate solutions have been reported [19–21]. However, the corrosion behavior of laser surface melted HSSs is scarcely reported in the literature. It is the aim of the present study to investigate the effect of LSM on the microstructure and corrosion behavior of three common HSSs, namely, M2, ASP23 and ASP30.

2. Experimental details

Three as-received HSSs (M2, ASP23 and ASP30), without and with Co, in soft annealed condition (designated as AR-M2, AR-ASP23 and AR-ASP30 respectively) were selected in the present study. The nominal chemical compositions of the HSSs in weight % are given in Table 1. They were received in the form of round bars of diameter 12.7 mm. The bars were then cut into discs of 5 mm thick. Conventionally hardened specimens (designated as HD-M2, HD-ASP23 and HD-ASP30) were prepared by heat treatment in a furnace for comparison. They were preheated to, and kept at, 560 °C for 60 min and then heat-treated through the austenitizing temperature (1100 °C) for 30 min, followed by air cooling. Then the specimens were subjected to three tempering cycles at 560 °C for 60 min, followed by air cooling.

Table 1
Nominal chemical compositions of the high-speed steels

Composition (in wt.%)									
Specimen	Fe	C	Cr	Mo	W	V	Co	Total of alloying elements (in wt.%)	Density ρ (g cm^{-3})
M2	Bal.	0.88	4.2	5.0	6.4	1.9	–	17.5	8.16
ASP23	Bal.	1.28	4.2	5.0	6.4	3.1	–	18.7	8.05
ASP30	Bal.	1.28	4.2	5.0	6.4	3.1	8.5	27.2	8.05

The surface of the as-received HSSs for LSM was sand-blasted in order to reduce reflectivity to the 2.5-kW CW Nd:YAG laser. Argon flowing at 15 l/min was used as shielding gas. Successive melt tracks were overlapped at 50% track width interval to achieve treatment over a surface. Preliminary trials on the laser processing parameters (laser power P, laser scanning speed v, and laser spot size D) were carried out to select the proper processing conditions. These parameters were varied to yield different laser fluence $F=P/vD$. The laser spot size D was set at 6 mm as a compromise between homogeneity of power density and melt track width. Having set the value for D, the power and scanning speed were varied to determine the minimum fluence that would effect surface melting. The minimum value for F was about 5 J/mm^2. For fluence above this minimum, the parameters P and v were varied, aiming at obtaining a crackless surface layer with high hardness because high hardness is one of the most important requirements of HSS. After these preliminary trials, LSM was performed with a laser power of 900 W, at a beam scanning speed of 25 mm/s, as the hardness achieved was the highest using this set of parameters.

The surface and cross-section of the laser surface-melted specimens were polished to a constant roughness with 1-μm diamond paste and then cleaned, degreased and dried. The surface was then etched with acidified ferric chloride solution and the microstructure was investigated by optical microscopy (OM) and scanning electron microscopy (SEM, Leica Stereoscan 440). The average chemical compositions of the specimens taken from various locations were analyzed by energy dispersive spectrometry (EDS, Oxford EDX System). The standard used for quantification was Co. The phases present in the specimens were identified by X-ray diffractometry (XRD, Philips PW3710). The radiation source used in XRD was Cu Kα with nickel filter and generated at 40 kV and 35 mA. The scanning range was $40° \le 2\theta \le 100°$ and the scan rate was 1.5°/min.

To investigate the electrochemical corrosion behavior, as-received, conventionally hardened, and laser surface-melted specimens were embedded in cold-curing epoxy resin, exposing a surface area of 1 cm^2. Potentiodynamic polarization tests in both 0.6 M (3.5 wt.%) NaCl solution (pH=7) and 0.5 M $NaHCO_3$ solution (pH=8.6), open to air at 25±1 °C, were performed using an EG&G PARC 273 potentiostat according to ASTM Standard G5-92 [22] or G61-86 [23]. The corrosion potential (E_{corr}) and corrosion current density (I_{corr}) were extracted using the Tafel extrapolation method with the aid of a commercial software (Model 352 SoftCorr II). All potentials were measured with respect to a saturated calomel electrode (SCE, 0.244 V versus SHE at 25 °C) as the reference electrode. Two parallel graphite rods served as the counter electrode for current measurement. After an initially delay of 30 min, the potential was increased at a rate of 0.167 mV s^{-1}, starting from 200 mV below the open-circuit potential. In cyclic polarization tests, the scan was reversed at a current density of 5 mA/cm^2. The corroded surface of the specimens after the polarization test was studied by SEM.