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Wear and corrosion performance of laser-clad low-carbon high-molybdenum Stellite alloys

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ABSTRACT

Low-carbon Stellite alloys such as Stellite 21 exhibit good high-temperature and corrosion properties but need improved wear resistance in some applications. In this research, two low-carbon Stellite alloys with highly increased molybdenum content are produced via laser cladding. The microstructures of the laser cladding hardfacings are studied using scanning electron microscopy (SEM) with an energy dispersive X-ray (EDS) spectroscopy, and X-ray diffraction. The wear resistance of the hardfacings is evaluated using a pin-on-disc tribometer. The corrosion performance of the hardfacings is investigated under electrochemical tests in 3.5 wt.% sodium chloride (NaCl) solution and in Green Death solution. The experimental results show that the presence of Mo-rich intermetallic compounds enhances the wear resistance of the alloy hardfacings significantly. Since Stellite alloys are all able to form protective oxide films due to high chromium content against corrosion of the substrates, the bonding strength and repair ability of the oxide films dominate the corrosion resistance of the hardfacings in the corrosive environments. Stellite 21 hardfacing is also studied under the same testing conditions for comparison.

1. Introduction

Stellite alloys are a group of superalloy, which are cobalt (Co) based and contain a high level (20–30 wt.%) of chromium (Cr), a moderate amount (4–18 wt.%) of tungsten (W) or molybdenum (Mo) and a certain amount (0.25–3 wt.%) of carbon (C), strengthened by the precipitation of carbides embedded in the cobalt solid solution matrix [1]. These carbides provide Stellite alloys excellent wear resistance. Among Stellite alloys, Stellite 21 contains the least carbon content (0.25 wt.%) with many unique features, including high mechanical strength at high temperatures and good corrosion resistance [2–4], which render this alloy a wide range of application mainly involving high temperature and corrosion, for instance, forging or hot stamping dies, valve trims for high pressure steam, oil and petrochemical processes. Owing to the ideal compatibility with human body environments and better wear resistance than stainless steels, it is also a popular biomaterial for various medical implants and prosthetics [5,6].

In addition to making components, Stellite 21 has been reported to deposit on stainless steels as hardfacing to strengthen surfaces for wear resistance. Laser cladding (or laser additive manufacturing) technique, owing to many advantages over other coating deposition techniques, including minimal dilution due to low heat output, controllable energy supply, high heating and cooling rates for better microstructure, has been widely applied to produce hardfacings. Some recent studies in Stellite alloy laser claddings have been reported [7–18]. For example, Ganesh et al. [7]. investigated the relationship between microstructure and mechanical properties of laser-clad joint of Stellite 21 on AISI 316L stainless steel, focusing on direct deposition of Stellite 21 and gradient in chemical composition across the substrate/clad interface. They found that in both the specimens inter-dendritic carbides provided low energy fracture path in the laser claddings, and both the specimens exhibited superior fatigue strength to the AISI 316L substrate, but the instrumented impact tests showed distinct difference in the mode of crack propagation across the direct and the graded clad specimens. The Stellite 21 hardfacings produced with off-axis and high-power diode laser (HPDL) multi-feeder cladding techniques, respectively, were compared with main concern on the size of the heat-affected zone (HAZ), dilution, microstructure, micro-hardness and powder catchment efficiency, in the research of Tuominen et al. [10]. The fatigue properties of Stellite 21 cladding on S355 structural steel substrate were investigated in four-point bending and torsion fatigue tests. The results showed that with the Stellite 21 cladding the fatigue life of S355 structural steel decreased at all the applied loads [11]. The fatigue failure mechanism of Stellite 21 laser clad-

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ding deposited on heat-resistant steel due to Fe dilution was studied by Wang et al. [14]. They found that Fe dilution occurred significantly in the Stellite 21 cladding layer during the laser processing, resulting in a thin Fe-rich layer in the coating close to the fusion line, which caused fatigue fracture of the Stellite 21 cladding due to intergranular rupture. Recent investigation by Wu et al. [18] in the formation mechanism and phase evolution of in-situ synthesizing TiC-reinforced 316L stainless steel matrix composites using laser melting deposition technique was reported. It focused on the α-Fe phase, which was precipitated out of the γ-Fe matrix with the addition of Cr_3C_2 and Ti powders, and the volume fraction and the size of the in situ synthesized TiC, which were found to affect grain texture of the γ-Fe matrix.

However, in some applications where enhanced wear resistance is required while good corrosion resistance has to be maintained, Stellite 21 displays deficiency due to small amount of carbides present. Increasing carbon content in Stellite 21 may deteriorate anticorrosion properties, because the carbides in Stellite 21 are Cr-rich. The more the carbides in Stellite 21, the less the Cr in the solid solution is, which causes Cr depletion in the region near the carbides. Therefore, a modified Stellite 21 alloy with increased Mo content (from 5.5 to 11 wt.%), designated as Stellite 22, has been proposed and created [3,19]. This special chemical composition results in large amounts of Co_3Mo intermetallic compound precipitated in the alloy, which increases hardness and wear resistance as carbides do in Stellite alloys. Molybdenum in Stellite alloys serves to provide additional strength to the solid solution matrix; it does so by virtue of its large atomic size, that is, it impedes dislocation flow when present as a solute atom [1]. On the other hand, when added to low-carbon Stellite alloys in large quantities, molybdenum participates in the formation of intermetallic compounds (Co_3Mo or/and Co_7Mo_6) [3].

Because of the advantages and wide application of laser technologies in Stellite alloy hardfacing or additive manufacturing, in the present research, Stellite 22 was deposited on stainless steel 316 via laser cladding. Furthermore, a new low-carbon (0.35 wt%) high-molybdenum (11 wt.%) Stellite alloy, designated as Stellite 728, which was designed by Kennametal Stellite Inc., was also prepared under the same laser processing conditions. In this new alloy, additional element niobium (Nb) was added to create niobium carbide so that chromium carbide can be suppressed [19]. The carbide phases in Stellite 21 with addition of Nb were studied by Youdelis and Kwon [20]. In their work, it was found that very fine NbC could be formed which substituted coarse $Cr_{23}C_6$ when a small quantity of Nb (1.5 at.%) was added in Stellite 21. The fine NbC can improve the strength of the alloy. Stellite 21 hardfacing was also prepared via laser cladding for comparison in this research.

The microstructures of laser claddings of Stellite 21, Stellite 22 and Stellite 728 were analyzed using SEM/EDS and X-ray diffraction. The sliding wear resistance of these hardfacings was evaluated on a ball-on-disc tribometer in dry-sliding mode. The corrosion behavior of the hardfacings in 3.5% sodium chloride (NaCl) aqueous solution and in Green Death solution, which are standard media to test the corrosion resistance of materials in industry, was investigated using electrochemical tests. These experimental results will guide the applications of Stellite 21, Stellite 22 and Stellite 728 hardfacings in different operation conditions and environments.

2. Experiments and methods

2.1. Materials and hardfacing fabrication

The Stellite 21, Stellite 22, and Stellite 728 powders used in this research were all supplied by Kennametal Stellite Inc. The morphologies of these powders were examined with SEM, showing a shape close to sphere. The powder sizes were generally uniform, but varied in a range of 45–150 µm. The morphology and particle size distribution of the three Stellite powders are shown in Fig. 1. The chemical compositions of these powders are given in Table 1. The Stellite 22 and Stellite 21 powders have similar chemical compositions except that the former has double Mo content than the latter. The Stellite 728 powder has a slightly higher C content than the Stellite 21 powder and it also has 2.07 wt.% Nb content, which the Stellite 22 and Stellite 21 powders do not have. The substrate was a stainless steel 316 plate with the dimensions of 100 × 60 × 10 mm. The substrate surface was grit-blasted using 24 mesh alumina and ultrasonically cleaned in absolute ethyl alcohol before the hardfacing was applied.

The Stellite 21, Stellite 22, and Stellite 728 hardfacings were prepared using a LDF400-2000 high power flexible fiber coupled diode laser. The output wavelength of the laser was 900–1070 nm, the highest output power was 2 kW, and the motion device was the IRB2400/16 robot with six degrees of freedom. The Stellite alloy powders were fed through a feeder (GTV-PF-Twin2/2) supplied by GTV, GmbH, Germany. The cladding process was performed under shielding using argon gas with the process parameters: laser power 1800 W, laser spot size 4 mm in diameter, laser energy density 75 J/mm^2, laser scanning rate 6 mm/s, and powder feeding rate 13 g/min. The single-track cladding specimens, before multiple scanning, prepared with different process parameters were laid to observe physical appearance and were also examined under SEM for porosity, cracking and slag estimations in order to choose optimal process parameters. Laser tracks were laid at ~50% overlapping to obtain a uniform clad thickness (about 2.5 mm). The powder aligning with the laser beam was focused on the surface of the specimen by using a co-axial cladding head. The obtained hardfacings are photographically shown in Fig. 2, with color indication for cracking from the liquid penetrant tests. It is obvious that the three Stellite alloy hardfacings do not have visible cracks, because there would be color liquid penetration in the cladding layer if there are cracks present.

2.2. Microstructural analysis

The laser cladding specimens were cut using the line-cutting method. Metallographic samples were prepared following the mechanical polishing procedures and the polished surfaces were then etched with Marble's corrosive (a mixture of 10 g $CuSO_4$, 50 ml deionized water and 50 ml hydrochloric acid) to reveal the microstructures. The microstructural analyses of the hardfacings were performed on a Hitachi Model S-570 scanning electron microscope (SEM) with the energy dispersive spectrometer (EDS). The phases in the microstructures of the hardfacings were analyzed using XRD (X'Pert PRO) with scan angles of 30–100° at a scanning speed of 1°/min. The carbides and intermetallic compounds in each hardfacing were quantified in volume fraction using the system software of SEM.

2.3. Hardness and wear tests

The hardness of the hardfacings was evaluated using a Rockwell hardness tester (HR-150DT type, load capacity 1471 N, loading time 5 s). The test was conducted on the surface layer of the hardfacings at a constant interval of 10 mm. Ten measurements were made on each hardfacing and the average hardness value of the ten measurements was taken for each hardfacing.

Ball-on-disk wear test was conducted on the hardfacings in dry-sliding mode at room temperature, according to ASTM G99 – 17 [21], Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. The pin was a Si_3N_4 ceramic ball 5 mm in diameter