Journal of Materials Processing Tech. 252 (2018) 217–224

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

Research Paper

Microstructure and wear resistance of laser-cladded Ni-based composite coatings on downhole tools

Yiyong Sui[a,*], Fan Yang[b], Guoliang Qin[b], Zhiyong Ao[b], Yong Liu[c], Yubao Wang[d]

[a] School of Petroleum Engineering, China University of Petroleum, Qingdao 266580, China
[b] Key Laboratory for Liquid-Solid Structural Evolution and Processing, Materials Ministry of Education, Shandong University, Jinan 250061, China
[c] CNPC Greatwall Drilling Company, Beijing 100101, China
[d] Shengli College, China University of Petroleum, Dongying 257061, China

ARTICLE INFO

Keywords:
Ni-based coatings
Original sialon powder
WC particles
Graded composite coatings
Wear resistance
Downhole tools

ABSTRACT

Single- and graded-composite coatings of Ni35 + tungsten carbide (WC), Ni35 + original sialon powders (OSP), and Ni35 + WC + OSP were prepared by laser cladding on 45 steel substrates, and their microstructures, hardness, and wear resistance were compared among different coatings. The high content of hard-phase WC, $CrFe_7C_{0.45}$, $Cr_4Ni_{15}W$, and $AlNi_3$ could effectively improve the hardness and wear resistance. The hardness and wear resistance of the graded coatings were better than that of the single-composite coatings except the Ni35 + WC + OSP composite coatings. The types of variation in the hardness of different coatings, such as the step increase and linear increase, were characterized by the distribution of hard phase. The maximum microhardness of the coatings reached 1118 $HV_{0.5}$, which was approximately 5.8 times that of the substrate. The wear loss of the Ni35 + WC graded coating showed much greater decrease, nearly double that of the substrate.

1. Introduction

The oil production mainly involves artificial lift, water flooding, and oil well stimulation in oil field development. The major downhole tools used in oil production include the sucker rod, plunger pump, and shock wave generator. The downhole tools work in corrosive media, and the pressure in the oil well can reach 10 MPa. Because of the severe working conditions, the downhole tools usually suffer from short lifetimes. Moreover, the wear loss is aggravated by increased sediment concentration, as well as the state of formation cementation change in the stage of oil-field exploitation. Zhang et al. (2012) suggested that the solid particles with large mass caused the block surface of the pump and the plunger pair wear. Abrasion reduces the service life of the sucker rod pump, and decreases oil production efficiency.

Surface modification techniques, such as plasma spraying and laser cladding, have been widely used to modify component surfaces, as described in Poate et al. (2013). Laser cladding is a promising technology in the field of surface modification processes. The composite coatings fabricated by laser cladding are different from the substrate in terms of composition, structure, and properties. There are three methods of the laser cladding process: pre-placed powder on substrates, feeding the material by wire, and blowing powder into the molten pool, as described in De Oliveira et al. (2005). The development of laser cladding offers distinctive advantages such as high hardness, a narrow heat affected zone (HAZ), good controllability, and high bonding strength, as described by Farahmand and Kovacevic (2014). More importantly, laser cladding has a low dilution rate. The typical dilution of laser cladding is approximately 1–2%, whereas the dilution rate of hardfacing is approximately 5–10%, as reported by St-Georges (2007).

Ni-based composite coatings have received extensive attention because of their high resistance to wear and corrosion at ambient and high temperatures, as reported by Conde et al. (2002). Hence, Ni-based composite coatings with self-lubrication are widely applied to components to prolong their lifetimes. A maximum microhardness of 520 $HV_{0.1}$ was found in Ni35 composite coatings as shown by Huang et al. (2011). Furthermore, the tungsten carbide (WC) phase is extensively used as the hard phase in surface engineering. The remanent WC_p, block or dendritic rich-tungsten carbides, and fine solid-solution dendrite were observed in WC_P/Ni composite coatings as described by Song-hua et al., (2006). Angelastro et al. (2013) recently reported that the microhardness of the WC/Co/Cr composite coatings was approximately 700–720 $HV_{0.3}$, which was approximately 3.5 times that of the stainless steel substrate (206 $HV_{0.3}$). Sialon is a kind of sintered ceramic with high hardness, high wearability, and corrosion resistance; it contains the elements silicon, aluminum, oxygen, and nitrogen. Recent studies by Nekouee and Khosroshahi (2016) showed that β-sialon/TiN

* Corresponding author at: School of Petroleum Engineering, Petroleum University of China, No. 66 Changjiang West Road, Qingdao 266580, China.
E-mail address: suiyy@upc.edu.cn (Y. Sui).

http://dx.doi.org/10.1016/j.jmatprotec.2017.09.028
Received 17 May 2017; Received in revised form 16 September 2017; Accepted 17 September 2017
Available online 19 September 2017

composites produced by the spark plasma sintering method had high hardness (14.6 GPa) and fracture toughness (6.3 MPa1/2). The study of Çelik et al., (2015) showed that sialon possessed higher hardness and abrasion resistance. Sialon materials could be prepared by reactive sintering or combustion synthesis, as shown by Liu et al. (2013).

In this work, the original sialon powder serving as the hard phase in Ni-based composite coatings was studied for the first time. The mixture of original sialon powders and other metallic powders was pre-placed on the surface of the substrate and then processed by laser. The behavior of original sialon powder under the instantaneous-concentration heat source differs from the sintering behavior. The microstructure, hardness, and wear resistance of coatings with different compositions were analyzed. Meanwhile, the performance of single-composite coatings and graded-composite coatings were compared.

2. Experimental procedure

2.1. Material

C45 steel is usually used to manufacture the piston for rod pumping. Therefore, carbon steel (C45 steel, Fe + 0.45 wt.% C) with pearlite and ferrite was used as the substrate (150 × 100 × 15 mm^3) in this study. The nickel-based self-fluxing alloy powder (Ni35), WC, and original sialon powder (OSP) (56%Si_3N_4 + 34%Al_2O_3 + 10%AlN) were used as the raw materials for the coatings. The chemical compositions of nickel-based self-fluxing alloy powder (Ni35) are shown in Table 1.

2.2. Experimental method

Prior to laser cladding, the substrates were abraded by an angle grinder and cleaned by acetone. A mixture of powders was placed on the substrate (the thickness of the powders was approximately 1 mm) and then dried at 150 °C in a vacuum oven for 30 min. The laser cladding was performed using a fiber laser (TruDisk12003) processing system with KUKA robotics (KUKA A60HA). The spot diameter was specified as 3 mm. The overlapping ratio was 50%. Three proportions of single-composite coatings and corresponding optimum parameters are shown in Table 2.

In the experiments, the previous layers were abraded by an angle grinder and cleaned by acetone after the workpiece had cooled to ambient temperature during the preparation of the graded-composite coatings. The mixture powders were placed on the top surface of the previous layers and dried at 150 °C in a vacuum oven for 30 min. The laser cladding was then performed. The proportions of graded coatings and the corresponding optimum parameters are listed in Table 3.

The cross section of the coatings was polished to a mirror by diamond paste. Then, the cross sections were etched in aqua regia for 15 s at ambient temperature. The coating microstructure was analyzed by means of an Olympus GX51 optical microscope (OM), Jeol-JSM-7001F scanning electron microscope (SEM) equipped with energy dispersive spectrometry (EDS), and PANalytical-EMPYREAN X-ray diffractometer (XRD, 40 kV, 40 mA Cu-Kα radiation: scanning within 2θ = 10°–20°).

The surface hardness of the coating was measured using Rockwell tests (HR150A). The hardness along the thickness direction of the coating was measured at a load of 4.9 N and dwell time of 15 s using a DHV-1000 Vickers microhardness tester. The wearing specimen was pre-ground at a load of 150 kn and low speed (200 rpm) for 1 min, and was cleaned by an ultrasonic cleaner. Then, the specimen was weighed with an analytical balance. The wear resistance tests were carried out by an M-2000 abrasion testing machine. The wear losses were calculated after grinding at high speed (400 rpm) for 100 min.

Table 1
Chemical compositions of nickel-based self-fluxing alloy powder (Ni35).

Element	C	Cr	Si	B	Fe	Ni
wt.%	0.15	10	2.8	2.1	≤14	Balance

Table 2
Three proportions of single-composite coatings and corresponding optimum parameters.

Number	Proportion	Thickness h/mm	Power, P/kW	Scanning speed v/mm s^{-1}
1-S	60% Ni35 + 40% WC	1	2.0	10
2-S	94% Ni35 + 6% OSP	1	1.6	10
3-S	54% Ni35 + 36% WC + 10% OSP	1	1.6	8

3. Results and discussion

3.1. Microstructure of Ni35 + WC powder coatings

The microstructure of the single laser-cladded Ni35 + WC coating is presented in Fig. 1(a). As seen, the thickness of the planar grains was approximately 5 μm (marked with A in Fig. 1(a)). During the initial period of laser cladding, the substrate attached to the bottom of the weld pool has high thermal conductivity. As reported by Gao et al. (2016), the ratio of temperature gradient (G) to solidification rate (R) at the coating/substrate interface was the key influencing factor on the microstructure. Because the temperature gradient of the interface was relatively higher and the solidification rate approached zero, $G/R \to \infty$. Therefore, the crystal grew towards the weld pool in the planar form. The planar grains were a good sign of excellent chemical and metallurgical bonding between substrate and coating, as reported by Zhang et al. (2015). Meanwhile, the diffusion of the iron element could be found at the coating/substrate interface, as shown in Fig. 2. Moreover, the hardness of the planar region (600 $HV_{0.5}$) with higher dilution rate was lower than that of the central area of the coating (753 $HV_{0.5}$) reinforced with WC particles.

As the planar grains grew up to the weld pool, the solidification rate increased and the temperature gradient gradually decreased with the release of the crystallizing latent heat. As a consequence, the grains should transform from planar to cellular. However, the growth of the cellular grains was inhibited owing to the higher density and high melting point (2870 °C) of the WC particles. Because the melting point of WC particles is higher than that of the Ni-based alloy (1020–1080 °C), the solid WC particles were deposited at the bottom of the weld pool under the vigorous convection caused by the laser beam, as marked with B in Fig. 1(a) by the black arrows. WC particles tend to sink toward the bottom of the melt pool because of the lower solidification rate and melting point of the Ni-based alloy, as described by Guo et al. (2011). Furthermore, grain refinement could be achieved because of the restrained grain growth by unmelted WC particles. Fig. 1(b) shows the dendritic carbides (marked with C in Fig. 1(b)), fish-bone like carbides (marked with D in Fig. 1(b)), and hexagonal petal-like carbides (marked with E in Fig. 1(b)) in the coatings. According to the XRD patterns of the single coating in Fig. 3, these carbides were determined as $W_6C_{2.54}$. Referring to the Fe-Ni-W-C phase diagram by Guillermet (1987), the melted WC particles reacted with the Ni-based alloy to form the carbides.

When the second laser cladding was made, this process served as the second heat input. The unmelted WC particles were further decomposed by the second thermal effect. Moreover, some cellular grains were developed at the coating/substrate interface as indicated by arrows in Fig. 1(c). The previously mentioned carbides were also found in the Ni35 + WC powder graded coating according to the XRD result in Fig. 3. As shown in Fig. 1(d), no obvious dividing line between the first layer and the second layer was observed, suggesting that the coatings had achieved chemical and metallurgical bonding. However, a large number of unmelted WC particles, which enhanced the hardness and