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Effects of surface alloying on microstructure and wear behavior of ductile iron

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In this research, the effect of austenitic stainless steel cladding on improving the wear behavior of ductile iron was studied. Samples made of ductile iron were coated with steel electrodes (E309L) by manual shielded metal arc welding. The effect of coated layer thickness on microstructure, hardness, and wear resistance of the surface were investigated. Wear resistance of the samples was measured using the pin-on-plate technique. Optical microscopy and scanning electron microscopy were used to investigate microstructure and wear mechanisms. The phases in the interface of both the coating and the substrate were studied by X-ray diffraction. The results showed that a film of white chromium-enriched iron formed at the interface between the substrate and coating which contained iron–chromium complex carbides. It was, therefore, concluded that enhanced properties would be obtained if the coating thickness and the carbides deposited on the surface were reduced. In samples with a thin coating, surface hardness rose to above 1150 HV (five times higher than that of the substrate) and wear resistance increased significantly.

1. Introduction

Ductile iron is regarded as a suitable replacement for steel having numerous applications in different industries because of its good combination of strength and toughness, high fatigue endurance, machinability, and relatively low cost [1]. Wear is one of the most commonly encountered problems in industry which requires frequent replacement of components [2]. One example is pipe components used in pneumatic conveying systems of powder materials in various fields of industry, where serious erosive wear may occur at the bends, elbows, valves, etc., and steel components usually exhibit short service life in such cases. Enhanced wear properties with desirable toughness should guarantee longer service life of the units and components.

The quality of the machine components prone to wear depends on their surface characteristics, which include surface roughness, microstructure, and surface hardness [3]. Surface modification is used to form wear resistant coatings on the surface of structural base materials [4]. Various techniques of depositing a hardened layer on ductile iron such as plasma spraying, thermal spraying, hardfacing, laser cladding, and chemical and physical vapor deposition processes [5–8] have been investigated.

Two major techniques, namely surface fusion and surface alloying, are relatively new trends in ductile iron hardening [9,10]. In surface fusion, a surface layer of the sample melts and, consequently, solidifies in a short time to form a fine ledeburite microstructure of high hardness on the surface, which is like white iron [11,12]. Normally, surface alloying is accomplished by adding the alloying elements before or simultaneously with surface fusion by a heat source via different techniques. Various materials such as chromium, tungsten, or tungsten–vanadium–cobalt–chromium are added to the weld pool. Among surface hardening alloys, iron alloys with a considerable amount of chromium have attracted more attention than others [13–15].

Surface alloying is usually accomplished by advanced techniques such as laser cladding due to significant advantages like faster processing speed, relative cleanliness, very high heating/cooling rates (105 K/s), and high solidification rates (up to a maximum of 30 m/s) [16]. However, there are simple and economically cheap methods like manual shielded metal arc welding (SMAW) in which enhanced surface and wear properties can be achieved by appropriate control of weld parameters. These processes, which have been in use since 1966, are the main methods of depositing commonly used in heavy industries [17]. The methods are effective and serve as techno-economic solutions to wear problems of materials. The cost of the coated material per unit area may be higher than that of uncoated material, but when applied only on critical areas of the components, the increase in cost may be insignificant as compared to the improvement achieved in performance. The advantages associated with these techniques include low cost of equipment, ease of deposition on complicated shapes of large or small dimensions and availability of wide range of materials, etc. In this research, SMAW with austenitic stainless steel electrodes

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(E309L) was investigated. The aim of the present work was to investigate the effect of coating thickness on microstructure, hardness, and wear behavior of ductile iron.

2. Materials and experimental details

2.1. Materials and cladding procedure

Samples of ductile iron with 70% nodular graphite were used. The mean hardness of samples was measured to be around 210 HV. In order to deposit on ductile iron, E309L stainless steel electrodes, 2.5 mm in diameter and 250 mm in length, were used. The weld metal consisted of austenite (γ) and about 15% delta ferrite (δ). The major characteristics of these electrodes are metal transfer by small droplets, cleanliness and uniformity of weld face, and simple slag separation [18]. The chemical composition of the stainless steel electrode used is given in Table 1. Before cladding, the surface was flattened thoroughly and all surface pollution was cleansed with acetone for the weld to be free of any defects. Finally, cladding was performed in a single layer using the SMAW method. During the welding process, a rectifier was used as a power source. Table 2 presents the conditions of the cladding process.

2.2. Sampling

Samples of ductile iron ($10 \times 10 \times 100$ mm) were coated by SMAW using austenitic stainless steel electrodes. After cladding in a single layer, the coating thickness was reduced to 1.3 and 0.4 mm thickness respectively by grinding for the wear study. Sample specifications and deposited layer thickness are listed in Table 3. An uncoated ductile iron sample was used as a reference.

2.3. Microstructure analysis and hardness measurement

For microstructural investigations, the samples were cross-sectioned and, after standard metallographic treatments, polished using 0.3 μm alumina polishing powder suspended in distilled water. Etching was performed using a 2% nital solution and the microstructure was investigated by an optical microscope (OM) OLYMPUSE-BX60M. The microstructure of the worn surfaces and wear debris were analyzed by a CANSCAN-MV2300 scanning electron microscope (SEM) to understand the wear mechanisms involved. Phases formed at the interface between the substrate and the layered coatings were characterized by X-ray diffraction (XRD) analysis. The microhardness of cross-sectioned welded layers was measured using a Vicker's microhardness tester under an applied load of 200 g.

Table 1
Chemical composition of the stainless steel electrode (wt.%).

C	Mn	Si	Cr	Ni	Fe
0.025	0.7	0.9	24	12	Balance

Table 2
SMAW parameters.

Welding voltage (V)	25–28
Welding current (A)	80
Welding speed (mm/s)	0.3–0.4
Electrode polarity	DCEP
Welding position	Horizontal-flat

Table 3
Test samples specifications.

Treatment	Treatment code	Coating thickness (mm)
Ductile iron	A	–
Ductile iron with thick cladding	B	1.3
Ductile iron with thin cladding	C	0.4

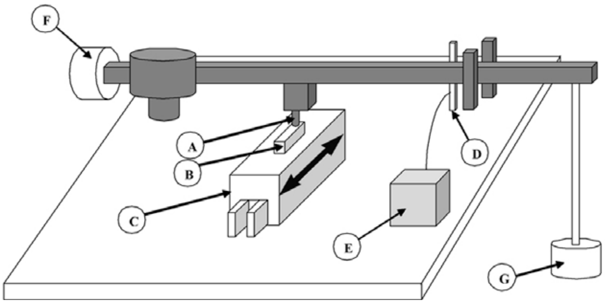

Fig. 1. The schematic view of the pin-on-plate apparatus used in this study: A, pin; B, plate (test specimen); C, reciprocating stage; D, strain gauge (friction force measurement); E, data logger; F, counter-balance weight; G, dead weight.

2.4. Wear test

Dry sliding wear tests were conducted on the specimens (coated and uncoated specimens) using a pin-on-plate reciprocating apparatus at room temperature (25 °C). A schematic diagram of the test apparatus is shown in Fig. 1. The counterpart material (pin) was a 52100 bearing steel. The steel pin was 6 mm in diameter and 12 mm in length with a spherical cap surface having an average hardness of HRC64. The tests were carried out at a constant sliding velocity of 0.5 m/s under applied loads of 90, 120, and 150 N using an incremental method [19]. Total sliding distance was 1000 m with an increment of 100 m. After each increment, the specimen was removed, cleaned by acetone and dried in hot air, then weighed and remounted in the wear apparatus at the same location. Weight losses were measured using an electronic balance with a sensitivity of 0.1 mg.

3. Results and discussion

3.1. Microstructure characterization

The arc between electrode and sample caused surface melting with inner surface remain cool which made melt to cool rapidly. Rapid solidification forms white iron in the surface layer [20]. Considering the iron–iron carbide phase diagram (Fig. 2) [21] and due to high carbon content of the substrate ductile iron (3.7%) and high rate of solidification, it can be deduced that white hypoeutectic iron should form at the interface between the ductile iron and the coating. Solidification in such irons begins by precipitation of an initial austenite phase which grows dendritically [22]. When temperature falls off, more austenite will form and the carbon content of the remaining liquid simultaneously rises up to the eutectic composition. At the eutectic composition, the melt transforms into a mixture of austenite and cementite, called ledeburite [20]. In Fig. 3, this microstructure can be observed in some regions of the interface.

The electrode consumed in cladding consisted of 24% chromium. On the other hand, the selected ductile iron contained 3.7% carbon. Due to heat of the arc, the temperature of interface rises, increasing possibility for diffusion of carbon atoms towards coating and diffusion of chromium atoms towards iron. As can be