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Short Communication

Fracture toughness of borides formed on boronized ductile iron

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Abstract

In this study, fracture toughness properties of boronized ductile iron were investigated. Boronizing was realized in a salt bath consisting of borax, boric acid and ferro-silicon. Boronizing heat treatment was carried out between 850 and 950 °C under the atmospheric pressure for 2–8 h. Borides e.g. FeB, Fe_2B formed on ductile iron was verified by X-ray diffraction (XRD) analysis, SEM and optical microscope. Experimental results revealed that longer boronizing time resulted in thicker boride layers. Optical microscope cross-sectional observation of borided layers showed dentricular morphology. Both microhardness and fracture toughness of borided surfaces were measured via Vickers indenter. The harnesses of borides formed on the ductile iron were in the range of 1160–2140 $HV_{0.1}$ and fracture toughness were in the range of 2.19–4.47 $MPa\,m^{1/2}$ depending on boronizing time and temperature.

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1. Introduction

Ductile cast iron, also known as nodular or spheroidal-graphite cast iron, is the one in which the graphite is present as tiny spheres. The relatively high strength and toughness of ductile iron give it some advantages over other cast iron and steel types in many structural applications. Ductile iron castings are used for many structural and industrial applications, particularly in those requiring strength and toughness combined with good machinability and low cost [1].

Boronizing processes are based on thermo-chemical reactions between the boron source and the respective base metal at temperatures 800–1000 °C [2]. In the boronizing process, boron atoms are introduced in to the metal lattice at the surface of the work piece due to their formation energy to form borides with atoms of the substrate. The formation of iron boride conversion coatings on ferrous substrates is attractive for a wide range of applications. Significant features are their high melting points (1540 °C for FeB and 1390 °C for Fe_2B), wear resistance, high hardness and potential low cost. Iron borides are very interesting compounds with properties typical of special ceramic materials (e.g. very high hardness) together with that of metals (e.g. high thermal and electrical conductivity, etc.) [3]. Industrial boriding can be carried out on most ferrous materials such as structural steels, cast steels, Armco iron, grey and ductile iron. Ductile and grey cast iron have been successfully boronized [4,5]. Because of the very good results achieved, boronizing is now regularly being used for cast ductile iron components of some textile machinery, sleeves and moulds [6]. In recent years, the use of hard ceramic coatings on the surfaces of various engineering components has dramatically increased. This trend reflects the ever increasing need for higher performance materials for use in extreme application conditions. Carbides, nitrides and borides that form on the transition metals have long been known to possess high potential for such applications because of their high hardness and excellent wear, friction and corrosion resistance [7]. Boronizing is therefore studied intensively

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throughout the world. Several different processes have been developed which can be classified into the following three groups: (i) solid state or pack boronizing, e.g. Ekabor; (ii) slurry coating, and; (iii) gas phase boronizing, e.g. ion boronizing with diborone; electrochemical boronizing, e.g. with $Na_2B_4O_7$ [8–10].

Despite a great deal of research on boronizing steels, studies about boronizing ductile irons appears to be relatively limited. However, there are some studies about fracture toughness of boronized steels [11–13].

In this study, fracture toughness properties of boride layer on boronized ductile iron were investigated. For this purpose, micro-hardness measurements and Vickers indentation fracture toughness tests were carried out. Finally, fracture toughness properties of the coating were determined in relation to the measured crack length of indentation marks and hardness of boride layer.

2. Experimental procedure

2.1. Materials and method

The workpiece material used in this study was a ductile iron containing 3.70 wt%C, 2.60 wt%Si, 0.95 wt%Cu, 0.40 wt%Mn, 0.065 wt%Cr and 0.052 wt%Mg. The boronized samples were rectangular plates of $10 \times 15 \times 10$ mm^3. In this work, the iron boride coatings were performed using molten salt bath boronizing technique. Boronizing bath consists of borax, boric acid, and ferro-silicon. Boronizing treatment was carried out in AISI 304 stainless steel crucible with the samples immersed into the molten salt bath. The process temperatures were 850 and 950 °C for a period of time varying between 2 and 8 h. After boronizing, borided ductile iron samples were removed from furnace and cooled in air.

2.2. Film characterization

The nature and type of borides formed on ductile iron were determined by optical microscopy, scanning electron microscopy-back scattered electron image analysis (SEM-BEI) and classical metallographic techniques. Boride layers were analyzed by an X-ray diffraction spectrometer with Co Kα radiation of the wave length of 1.7902 Å and between 20° and 100° 2θ values.

2.3. Thickness, hardness and fracture toughness

The depth of boride layers formed on ductile irons was measured by an optical micrometer attached to an Olympus B071 optical microscope. The hardness and fracture toughness of test materials were measured with a Vickers indenter under the loads of 100 and 300 g. The fracture toughness of a material is of critical importance in mechanical applications [14,15]. The use of the Vickers indentation method to asses fracture toughness of brittle materials has been developed particularly for glasses and ceramics [16]. The Vickers diamond indenter is a standard item used on a dedicated hardness tester or on a universal testing machine. In many instances, the crack length can be measured optically [17–19]. The equation used for calculating the fracture toughness is as follows;

$$K_c = X \cdot P/c^{3/2}, \tag{1}$$

where X is residual-indentation coefficient, P is the load and c is the half of the indentation crack length as defined in Fig. 1 [13]. Crack lengths were immediately measured by an optical micrometer attached to the optical microscope. Tests were repeated three times under the same conditions to ensure the reproducibility of the fracture toughness data.

X depends on the hardness-to-elasticity modulus ratio (H/E) of the boride layer. It equals to 0.064 $(E/H)^{1/2}$. The value of E is approximately 290 GPa [4].

3. Results and discussion

3.1. Film characterization

Whatever the process used, boronizing of ductile iron usually leads to the formation of two different iron boride phases; FeB and Fe_2B. Furthermore, it has been observed that there is a silicon-rich ferrite zone between the boride phases and the bases matrix. The morphologies of the cross sections of boride layers, which were examined by optical microscope and SEM-BEI, showed that boride layer on ductile iron surfaces are of denticular shape. At higher magnifications, it was detected that there were three distinct regions on the cross-sections of the borided ductile iron surfaces. The mor-

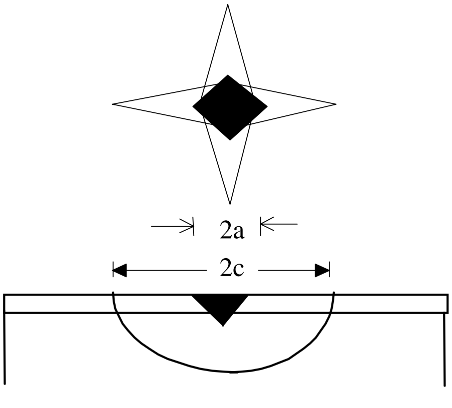

Fig. 1. Schematic view of indentation mark and crack length.

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