Effects and mechanisms of an alternating current field on pack boriding

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ABSTRACT

An alternating current field (ACF) was applied to AISI 1045 steel samples and boriding media for enhancing pack boriding. Effects of the ACF on temperature changes of treated samples, reaction extents of boriding media, as well as on boride layers' growth and hardness distribution, were investigated for revealing mechanisms for the enhancement. A temperature rise caused by the ACF is detected, and it increases with increasing ACF current and decreases with increasing furnace soaking temperature. Reactions of boriding media are proved being intensified by the ACF. Pack boriding, in terms of boride layer thickness, is enhanced by the ACF, and the enhancement is increased with increasing the ACF current. The Vickers' hardness distribution along the boride layers depth to the substrate can be optimized by applying ACF. It is shown that the temperature rise caused by the ACF is not the main reason for enhancing boride growth and modifying layers' phases. Mechanisms for the ACF's effects are given by concerning the ACF's thermal and non-thermal functions. The non-thermal effect is more effective than the thermal effect in intensifying reactions and diffusions in pack boriding.

1. Introduction

The requirements for enhancing properties such as fatigue and wear resistance in engineering components have led to extensive studies on the most convenient and least expensive techniques by surface hardening steels. Surface hardening techniques include thermal methods such as flame hardening and induction hardening, and thermochemical methods such as carburizing, nitriding and boriding [1]. Very hard and wear-resistant boride layers can be formed on most metals and engineering alloys by diffusing boron into and combining it with the metal substrate [2]. Boriding can be carried out in solid, liquid or gaseous medium. Of the several techniques available, pack boriding is the most widely favoured technique for commercial applications owing to its economics, simplicity and safety [1,2]. The boride layers of steels are generally composed of either single phase Fe_2B or dual phase FeB plus Fe_2B. Because of the discrepancies in thermal expansion coefficient of Fe_2B (2.9×10^{-8} K^{-1}), FeB (8.7×10^{-8} K^{-1}) and iron (5.7×10^{-8} K^{-1}), the formation of crack is often observed in the region of the FeB/Fe_2B interface, especially when the component with the dual phase layer is subjected to thermal and/or mechanical shock [2]. Therefore, layers with single phase Fe_2B is preferred for many industrial applications [3,4].

Many new boriding techniques have been investigated in recent years for improving the efficiency and quality of pack boriding. It was found that the kinetics of boron diffusion was increased by employing surface plastic deformation before pack boriding. The increase of boride layer thickness is believed to be a result of the surface plastic deformation caused fine grains, nanocrystalline structure with high free energy, and high density dislocations in the treated sample [5,6]. Applying superplastic deformation during boriding is another approach to accelerate pack boriding. Unlike conventional pack boriding producing acicular boride grains, the technique can produce equiaxed boride grains which have better mechanical properties, such as fracture strength, toughness and the maximum flexure, than acicular grains [7]. The spark plasma sintering (SPS) pack-boriding uses spark plasma to activate boron atoms, and electrical field to promote boron's diffusion into the workpiece. It has been shown that the activation energy of the SPS boriding can be greatly reduced. As a result, the boriding temperature is decreased and the boriding process is accelerated [8].

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Employing direct current field (DCF) properly during pack boriding can greatly promote pack boriding of samples taken as or attached to a cathode [9–11]. The obtained layers are composed of FeB and Fe_2B. If the sample is attached to the anode, single phase Fe_2B layer can be produced but its thickness is similar to that by conventional pack boriding (CPB) [10]. Preliminary work shows that thick single phase Fe_2B layers can be easily produced by alternating current field enhanced pack boriding (ACFEPB) technique [12]. Kinetics studies further prove the ACF's enhancing to pack boriding [13]. However, discussions about mechanisms of the ACF on pack boriding were preliminary, mainly based on the boriding layers' growth and lacking enough experimental evidences.

In this paper, more experiments were designed and carried out for revealing the ACF on temperature change of borided samples, reaction levels among boriding media, boride layers growing characteristics and hardness distribution. Based on experimental investigations, comprehensive mechanisms for the ACF's effects are proposed. A better foundation is laid before applying the technique ACFEPB to engineering.

2. Experimental details

The substrate used for present investigation was normalized AISI 1045 steel, with a carbon content of ~0.45 wt-%. The test pieces had a disc shape, with nominal dimensions of 15 mm in diameter and 5 mm in thickness. Two flat faces on each of the samples were ground using 1000 grid emery papers to get a clean surface finish before pack boriding.

The alternating current field enhanced pack boriding was carried out by an apparatus shown schematically in Fig. 1. The container, conducting wire and electrodes were made of heat-resistant steels. The distance between parallel electrodes was around 25 mm. The treated sample was set at the center of the electric field. A thermal couple was embedded in a simulating sample for measuring temperature change in the sample caused by the ACF. The boriding powder contained 10 wt-% ferroboron as the main source of boron, 5 wt-% KBF_4 as an activator, 2 wt-% charcoals as a sintering retarder and 83 wt-% SiC as inert diluents. The container was sealed to prevent a leakage of the reaction gas and the entry of air. After the sealing, the container was moved into a chamber electrical resistance furnace for heating from room temperature. Once the soaking temperature was reached, a 50 Hz ACF with a designated current (1, 2, 4 and 6 A, respectively) and a

voltage of 30–40 V was applied to electrodes for 4 h, followed by turning off power and cooling in the furnace to the room temperature. The ACF frequency and boriding time are not taken as variables in the present study. A series of CPB using the same boriding powder as that for the ACFEPB was conducted for comparison. The CPB was carried out in a sealed container similar to the one shown in Fig. 1 except with no electrodes and the simulating sample.

A series of experiment was carried out for revealing the effect of the ACF on the extent of reactions in boriding media for producing active boron atoms or boron-containing species. Three sets of powder boriding media named as BM-ACF, BM-TRC and BM-C, respectively, were prepared. The original composition of these three boriding media was same, as given in the last paragraph. The media underwent a series of treating. First, the BM-ACF went through ACFEPB at 800 °C for 4 h with a 6 A ACF in an apparatus shown by Fig. 2. The BM-TR went through CPB at 800 °C+ΔT6 for 4 h, where ΔT6 stands for temperature rise caused by the 6 A ACF, in the same apparatus. And the BM-C went through CPB at 800 °C for 4 h, also in the same apparatus. No ACF was applied during the later two treatments. The outer container was sealed with clay. The inner container shown in Fig. 2 was covered with a lid without clay sealing. The powder charcoal in the outer container was for absorbing gases leaking from the inner container during treating. No sample was employed for these three treatments. Then those three treated BM-ACF, BM-TR and BM-C boriding media, after being added with 5 wt-% KBF_4 for each, were re-used respectively for CPB at 800 °C for 4 h in a normal container sealed with clay. Samples were employed for later three treatments. The boriding abilities of previously treated BM-ACF, BM-TR and BM-C were assessed by comparing the boride layer thickness and structure of those treated samples.

Borided samples were cross-sectioned for metallographic preparation and characterized using an optical microscope (OM). The layer thickness was measured by means of optical microscopy at the center part of the sample in order to eliminate "corner effects" (i.e., layer growth by inward diffusion of boron from more than one side). The layer phases formed on the surface of the samples were revealed with X-ray diffraction (XRD, Cu Kα radiation, 100 mA and 40 kV). Microhardness profiles across boride layers were obtained with cross-sectional indentation by a Vickers' micro-hardness testing machine using a load of 50 g.
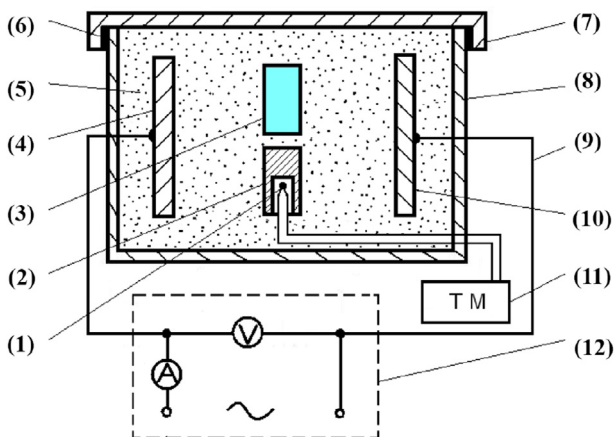
Fig. 1. Schematic of the apparatus for the ACFEPB (1: thermal couple; 2: simulating sample; 3: sample; 4, 10: electrode; 5: powder boriding media; 6: clay sealing; 7: lid; 8: container; 9: conducting wire; 11: temperature monitor; 12: adjustable AC supplier).
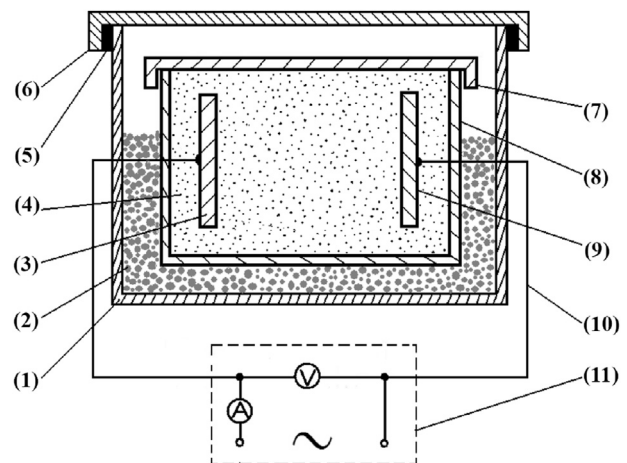
Fig. 2. Schematic of the apparatus for assessing the effect of ACF on boriding media (1: outer container; 2: powder charcoal; 3, 9: electrodes; 4: powder boriding media; 5: clay sealing; 6, 7: lids; 8: inner container; 10: conducting wire; 11: adjustable AC supplier).