



The microstructure and properties of Cr alloying layer after surface alloying treatment induced by high current pulsed electron beam



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ABSTRACT

The Cr alloying layer was introduced on the steel substrate subjected to surface alloying treatment by combination of magnetron sputtering and high current pulsed electron beam. The microstructure of the Cr alloying layer was studied using SEM, XRD and TEM. The thickness of the remelted layer was about 5 μm after surface alloying treatment. The 2 μm thick Cr-rich layer containing Fe-Cr solid solution and a small amount of amorphous phase was observed at the top of remelted layer after irradiation. The remelted layer also contained columnar austenite grains and plate martensite. The microhardness of Cr alloying layer only dropped slightly comparing with the original steel substrate. However, the corrosion resistance of the specimen after surface alloying treatment was significantly improved and the Fe-Cr solid solution was believed to contribute to the formation of passive film to increase the corrosion resistance.

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1. Introduction

High speed steels are widely used in various industries for their high performance in mechanical properties [1,2]. However, the use of components in highly demanding applications requires new methods that are able to fulfil the increasing requirements in terms of high mechanical performance while simultaneously providing an adequate corrosion protection. Among the various methods available, high current pulsed electron beam (HCPEB) has been proved as a promising method for surface modification to meet these demands [3–7]. During irradiation, the beam energy (up to 20 J/cm²) transfers into surface layer within short time (~2 μs), followed by the fast (10⁸–10⁹ K/s) quenching process from liquid state which leads to the formation of remelted layer (up to 10 μm) in the surface layers [6,8–10]. After irradiation by HCPEB, the microstructure in the remelted layer contains super saturated solid solutions, nanocrystalline and amorphous structure [11–16]. Meanwhile, the ultra-rapid thermal cycles lead to the improvement of the mechanical properties and corrosion resistance [17–22].

It was observed that the corrosion resistance of samples with

surface alloying layer in different irradiated energy density was higher than that of unirradiated samples [23]. At the same time, the corrosion potentials of HCPEB treated samples shifted positively as compared with the initial sample and the higher pulses number contributed to the increase of corrosion potentials and resistance [24]. It was believed that the microstructure in depth of several micrometers was refined and uniformed along with a rather homogenous composition distribution which were favorable facts to the improvement of corrosion [24–26]. Some researchers also believed that the improvement of corrosion resistance irradiated by HCPEB was caused by the global increase of element concentration within the melted layer due to selective evaporation [27,28]. As the Cr-rich carbides and the distribution of alloying elements within the phases that essentially control the corrosion resistance [29,30], it is possible that adding Cr into the substrate using surface alloying treatment induced by HCPEB to improve the corrosion resistance. However, there is only limited content of the alloying elements dissolved from carbides in the original steel substrate after HCPEB and the improvement of the corrosion resistance is not significant.

It can be concluded from previous works that it is an effective way to increase the content of Cr element in the remelted layer to improve the corrosion resistance after HCPEB, while the solid solution formed in the remelted layer may still maintain relatively

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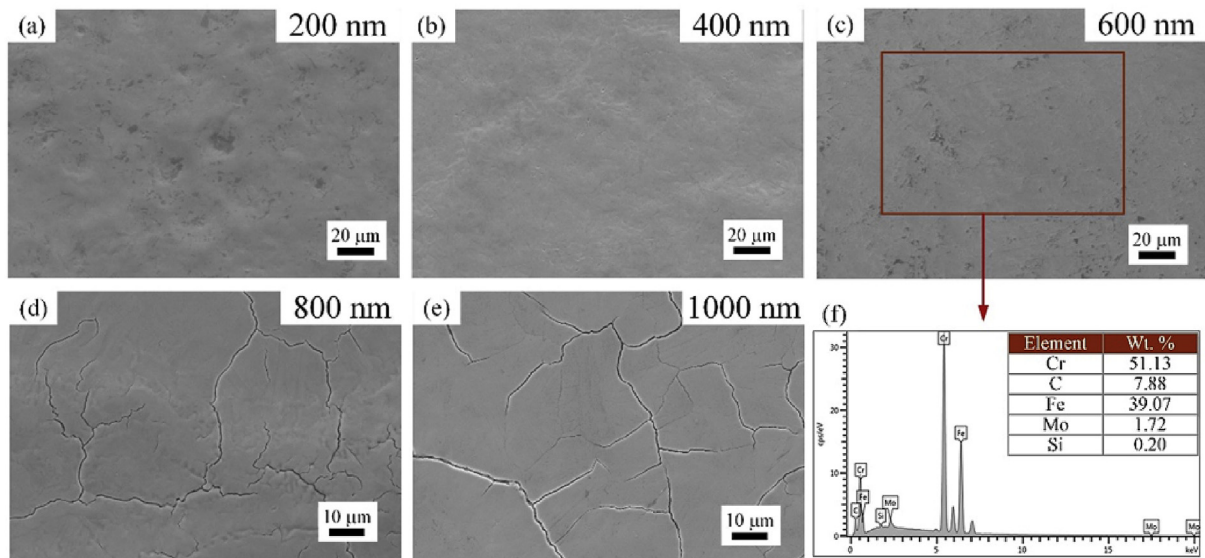


Fig. 1. The surface SEM images and EDS results of Cr alloying layer after HCPEB treatment with different thickness of pre-deposited Cr films. (a) 200 nm; (b) 400 nm; (c) 600 nm; (d) 800 nm; (e) 1000 nm; (f) EDS results of the red square in (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

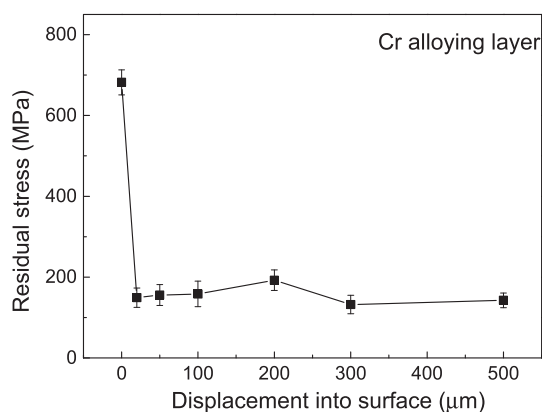


Fig. 2. The cross-sectional distribution of residual stress when the thickness of pre-deposited Cr film is 600 nm.

high strength. In this study, the novelty is that introducing surface alloying treatment by combination of magnetron sputtering and HCPEB to add Cr into steel substrate. In this process, the magnetron sputtering provides a feasible way to add alloying elements by film deposition before HCPEB. After surface alloying treatment, the higher content of Cr alloying layer may help to further increase the corrosion resistance of high speed steel as well as maintaining the surface microhardness. Therefore, the aim of this work is to shed light on the role of Cr as the alloying element in microstructure, mechanical and corrosion properties after surface alloying treatment irradiated by HCPEB.

2. Experimental

In this research, surface alloying treatment was achieved by combination of magnetron sputtering and HCPEB to add the Chromium into the surface layer of substrate. The substrate was tempered state high speed steel composed of C = 0.75–0.85%, Mn ≤ 0.35%, Si ≤ 0.35%, Cr = 3.75–4.25%, Mo = 4.00–4.50%, V = 0.90–1.10%, Ni ≤ 0.20% and Fe = balance (ASTM A600-T11350).

Before irradiation, the samples were polished with dimensions of $\Phi 25 \text{ mm} \times 3 \text{ mm}$. The high current pulsed electron beam was generated by electron gun and the detailed parameters about this equipment could be found in Refs. [31,32]. There were three steps during the surface alloying treatment. The first one was surface cleaning by irradiation with energy of 9 J/cm^2 and 100 pulses. The purpose of this step is to dissolve the carbides which may lead to the appearance of crater-like defects on the surface after irradiation [5,33]. After that, Cr film was deposited on steel substrate by DC magnetron sputtering and the thickness was varied from 200 nm to 1000 nm. The last step was surface alloying treatment with the irradiated energy density of 4.4 J/cm^2 and 100 pulses.

The surface and cross section morphology were observed by scanning electron microscope (Quanta 200FEG, FEI Instruments Co., Ltd., USA) equipped with energy-dispersive spectroscope (EDS). The phases of alloying layer were identified by Panalytical Empyrean X-ray diffraction (XRD) at 4° glancing angle. The scan step was 0.05° and the counting time was 0.4 s. The specimen for Transmission Electron Microscope (TEM) observation was prepared by Focused Ion Beam (FIB) in FEI HELIOS NanoLab 600i. The high resolution transmission electron microscope (HRTEM, Tecnai G2 F30, FEI Instruments Co., Ltd., USA) was employed for selected-area electron diffraction (SAED) analysis and microstructure observation with voltage of 300 kV.

The microhardness of the surface alloying layer was measured by MTS-Nano Indenter XP machine. Corrosion tests were carried out by using the conventional three-electrode cell containing the work electrode, a saturated calomel electrode (SCE) as the reference electrode and the graphite rod as the counter electrode. The standard potentiodynamic polarization test was performed in neutral NaCl solution (3.5 wt%), and all the experiments were conducted at room temperature. The potentiodynamic polarization was carried out at a scan rate of 0.5 mV/s. The salt-spray corrosion tests were performed according to GBT10125-2012 standard. The salt spray corrosion was tested in a cabinet and exposed to a $50 \pm 5 \text{ g/L}$ NaCl solution. At least three specimens were tested for each testing condition to verify the accuracy of the results. The air pressure of the atomized saline solution was maintained around $1.0 \pm 0.1 \text{ kgf/cm}^2$ and the temperature inside the cabinet was

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