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Short Communication

Improved corrosion resistance in simulated concrete pore solution of surface nanocrystallized rebar fabricated by wire-brushing

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ABSTRACT

Continuous surface nanocrystallization (SNC) of rebar was achieved through wire-brushing process. A uniform NC layer with thickness of 25 μm and average grain size of 50 nm was formed on the rebar surface. Due to the enhanced passivation performance of the NC layer, corrosion resistance of the SNC rebar was significantly improved in Cl^--containing saturated $Ca(OH)_2$ solution. High-energetic crystal defects of the nano-grains leads to the faster passivation and enhanced stability of the passive film of the SNC rebar.

1. Introduction

Rebar corrosion is the key factor leading to the deterioration of reinforced concrete structure (RCS), therefore, improving corrosion resistance of rebar is very important to extend the life of RCS [1–3]. Recent researches have confirmed that the rebar corrosion is mainly induced by chloride ion (Cl^-) erosion and alkalinity reduction of the concrete [4,5]. As the corrosion of the rebar initiates from the surface and gradually extends into the matrix, it is believed that the corrosion resistance of the surface material will significantly affect the service life of rebar, and anti-corrosion modification of the rebar surface is an effective method to enhance corrosion resistance of rebar. Surface nanocrystallization (SNC) can lead to formation of special surface microstructures of the material, which exhibits good mechanical properties, and its benefit to corrosion resistance of the passive materials through enhancing passive film performance can also be expected [6–9]. Until now, lots of methods have been developed to achieve NC layer of the materials, but most of them can only be used in small workpieces with regular surface shape [10,11]. Differently, the wire-brushing method has good shape adaptability [12], and can be used to achieve continuous SNC processing of a rebar with irregular surface shape.

The present work focused on investigating the influence of surface nanocrystallization on the surface-microstructure and corrosion resistance of a rebar processed by wire-brushing. Electrochemical experiments on the SNC rebar were carried out in the simulated concrete pore solutions. The results should be helpful for preparing corrosion-resistant rebar with enhanced passivation performance and corrosion resistance in concrete subjected to Cl^- contamination.

2. Experimental

The schematic illustration of SNC processing of a rebar through wire-brushing is shown in Fig. 1. The rebar was placed between two symmetrically arranged wire brushes, and the rotation of the wire brushes was driven by electric motor with adjustable rotation speed. The strength was loaded on the wire brushes to keep the wires contacting with the rebar surface appropriately during the processing. The feeding wheels were used to provide enough stiffness to the rebar and convey the rebar with appropriate speed. Rebar samples with diameter of 20 mm and length of 500 mm used for wire-brushing process were cut form a commercial hot-rolled carbon rebar, whose chemical composition was of Fe–0.22 wt% C–0.22 wt% Si–1.44 wt% Mn–0.02 wt% Cr–0.022 wt% S–0.025 wt% P–0.02 wt% Ni–0.01 wt% Cu–0.038 wt% V. All the rebar samples were SNC processed at room temperature with the feeding speed of 5 mm s^{-1} and the wire brush rotation speed of 8000 r min^{-1}. In order to obtain a uniform NC layer, each rebar was processed for two passes, and the rebar was rotated by 90° before the second-pass processing. After SNC processing, the microstructure

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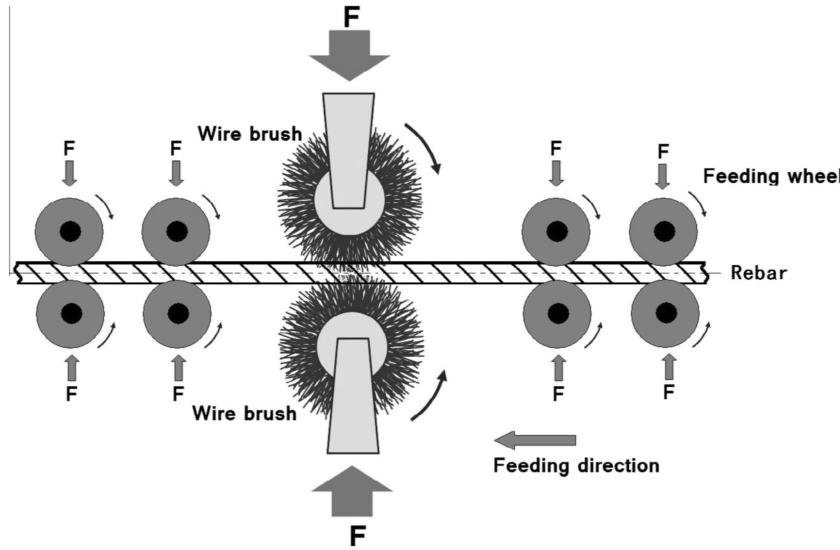

Fig. 1. Illustration of SNC processing of rebar through wire-brushing.

change of the rebar was observed by the optical microscope (OM, Olympus BX51M, Japan) and the scanning electric microscope (SEM, Hitachi S3400N, Japan). The microstructure characterization of the NC layer was also observed by the transmission electron microscopy (TEM, Tecnai G2, Holland). The passivation performance and corrosion resistance of the SNC rebar in simulated concrete pore solutions were studied via the Parstat 2273 advanced potentiostat (USA), comparing to the as-received rebar and scale-removed rebar (polished by emery papers up to 1000 level). Three-electrodes system was used, which included a saturated calomel reference electrode, a Pt counter electrode and a working electrode. Rebar samples with length of 10 mm were used as electrochemical testing samples, that the cylindrical surface of the rebar was exposed to the tested solutions and two cross-sections of the rebar sample were sealed by epoxy. Copper wire was linked to one of the cross-sections, and the rebar sample was connected as working electrode. For a good reproducibility, all the samples were cleaned with acetone and dired in warm air, and at least three replicates were run for each sample. Three kinds of electrochemical measurements, namely open circuit potential (OCP), electrochemical impendence spectroscopy (EIS) and potentiodynamic polarization (PDP), were applied. The rebar samples were immersed in the saturated $Ca(OH)_2$ solution with pH value of 12.6 for 5 days to obtain stable passivation, and then they were immersed in 0.05 M NaCl added saturated $Ca(OH)_2$ solution to be corroded by Cl^-. The frequency of EIS tests ranged from 10 kHz to 10 mHz, and the amplitude of the sinusoidal potential signal was 5 mV with respect to the open circuit potential.

3. Results and discussion

Fig. 2 shows the macro-morphology and microstructure of the as-received and SNC rebars, which demonstrates that the rebar scale has been removed completely after brushing repeatedly by high-speed rotating wires. The treated rebars presented bright metallic luster, and obvious plastic-processing waves can also be observed on the rebar surface. The cross-sectional microstructure of the treated rebar was observed by OM and SEM. Gradient microstructure was found according to the OM image of the treated rebar, where the rebar matrix was composed of initial coarse grains with ferrite and pearlite, and the surface grains of the rebar had been modified severely. The total thickness of the microstructure-modified layer was about 40 μm, presenting obvious gradient plastic flows. According to the intensity of the plastic flows, the modified surface layer can be divided into two parts, where the outer part of the layer was severely-deformed zone with thickness about 25 μm, and the inner part of the layer was lightly-deformed zone with thickness about 15 μm. According to the SEM image of the severely-deformed zone, the grains had been completely refined and deformed. Obvious plastic flows were formed in the severely-deformed zone, where it was difficult to distinguish the ferrite and pearlite. TEM was applied to observe the detailed microstructure characteristics of the severely-deformed zone and the results are shown in Fig. 3. Fig. 3a is the TEM image of the severely-deformed ferrite grains with low magnification, which clearly shows that the ferrite grains has been extremely refined into equiaxed grains with average grain size of 50 nm. Meanwhile, the selected electron diffraction pattern of the deformed ferrite grains shows the distinct ring, which infers to high-angle grain boundaries of the deformed ferrite nano-grains [13]. The high-angle grain boundary is non-equilibrium grain boundary, which stores a lot of internal energies. The severe strain also created lots of intragranular dislocations. As shown in Fig. 3b, mass of dislocations are stacked in the deformed ferrite nano-grains. So, according to the TEM observation, the severely-deformed zone of the modified layer can be defined as nanocrystalline (NC) layer. With the gradual reduced strains from surface to matrix, the deformation of the inner part of the modified layer was much lighter than that of the NC layer. The grains of ferrite and pearlite of this part were lightly deformed and elongated along with the plastic flows. This inner part of the modified surface layer can be regarded as a transition layer between the NC layer and matrix. Based on the systematical microstructure observation, the wire-brushing treated rebar can be defined as the SNC rebar.

OCP is the mixed electrode potential in the given corrosion environment, which is mainly determined by the surface state of the electrode. When rebar is immersed in saturated $Ca(OH)_2$ solution, continuous passivation will be processed. With the effect of alkalinity and dissolved oxygen of saturated $Ca(OH)_2$ solution, passive film will be formed on the rebar surface [14,15]. OCP has close relationship with the integrity and density of the rebar's passive film, the nobler OCP value, the better passivation state of the rebar with more complete and denser passive film. Fig. 4 shows continuous OCP evolution of the rebars passivated in saturated $Ca(OH)_2$ solution for 5 days. All kinds of rebars were obtained effective passivation during the whole immersion period in saturated