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Corrosion Behavior of Cr Micro-alloyed Corrosion-resistant Rebar in Neutral Cl^--containing Environment

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Abstract: A new low-cost corrosion-resistant rebar (HRB400R) was designed and fabricated by Cr micro-alloying. The HRB400R rebar had uniform distribution of Cr element in ferrite grains. The corrosion behavior of the rebar in the neutral Cl^--containing environment was studied systematically, and the improved corrosion resistance of the HRB400R rebar was revealed. According to the corrosion-morphology observation and electrochemical monitoring during the constant immersion corrosion in the 3.5 mass% NaCl solution, the HRB400R rebar presented alleviated corrosion damage, nobler E_{corr}, lower I_{corr}, and larger R_t values, and these phenomena were more remarkable in the initial corrosion period. The elevated electrode potential of the rebar, caused by the solid-solution of Cr micro-alloying in the ferrite grains, was the key to the corrosion-resistance improvement. The HRB400R rebar also presented much lower mass-loss rate in the salt spray corrosion test. Besides the elevated corrosion resistance of the matrix, the doping and enrichment of Cr element in the rust layer was another factor for the higher corrosion resistance, which retarded the penetration of aggressive medium through the rust layer.

Key words: corrosion-resistant rebar; corrosion behavior; Cr micro-alloying; Cr-rich rust layer

Rebar corrosion is the key factor for the deterioration of reinforced concrete structure (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]. Therefore, improving corrosion resistance of rebar is very important to extend the service life of RCS[6]. Several corrosion-resistant rebars have already been developed and used in the RCS serviced in the aggressive environment, in which epoxy-coated rebar and stainless steel rebar are the most popular corrosion-resistant rebars[7-10]. However, due to the high production and construction cost, those corrosion-resistant rebars are still only used in the extremely severe aggressive environment. Considering the project cost, they may not be acceptable in the RCS projects serviced in mild aggressive environment, such as non-critical parts of the offshore constructions.

Micro-alloyed rebar may be qualified in the mild aggressive environment. With the addition of one or several anti-corrosive alloying elements, such as Cr, Ni, Mo and Cu, the micro-alloyed rebar can be endowed with improved corrosion resistance[11,12]. Meanwhile, due to the low total amount of alloying elements, the production cost can be controlled at a relatively low level. The equivalent carbon contained in the micro-alloyed rebar is also suitable for welding. Therefore, these kinds of micro-alloyed rebar will have great potential to be used as a substitute of the common carbon steel rebar in the mild aggres-

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sive environment with much longer service life.

In this work, a Cr micro-alloyed corrosion-resistant rebar was designed and fabricated. The corrosion behavior and anti-corrosion mechanism of this rebar in the neutral Cl^--containing environment were systematically studied, which provides the basis to the research of corrosion behavior of the corrosion-resistant rebar in the concrete under Cl^--contamination.

1 Materials and Experimental Procedure

In this paper, the 400 MPa grade rebar with and without Cr micro-alloying were named as HRB400R and HRB400, respectively. The target rebar was fabricated by Cr micro-alloying in Shagang Group of China, using the existing production equipment and technology of the common 400 MPa grade rebar.

The chemical composition of the HRB400R rebar was analyzed by the photoelectric emission spectrograph (Shimadzu PDA-700, Japan). The microstructures of the rebar were observed by the microscope (Olympus BX51M, Japan). The distribution of Cr element in the rebar matrix was obtained by the electron probe micro-analyzer (EPMA, Shimadzu 1610, Japan).

The constant immersion test was conducted according to the ASTM standard G31-72, and the corrosion morphology was observed by a KH-7700 digital microscope (Hirox, USA). Electrochemical corrosion tests were conducted in 3.5 mass% NaCl solution via a Parstat 2273 advanced potentiostat. Open circuit potential (OCP) test, potentiodynamic polarization (PDP) test and electrochemical impendence spectroscopy (EIS) test were carried out. The PDP test was carried out at a scan rate of 1 $mV \cdot s^{-1}$. The frequency of EIS test ranged from 10 mHz to 100 kHz, whereas the amplitude of the sinusoidal potential signal was 5 mV with respect to the OCP. The salt spray test was conducted according to the ASTM standard G85-09. A 5 mass% NaCl solution was used to create an artificial NaCl salt mist environment by a salt spray test chamber (KC-60, China). After testing for each interval, the corrosion product was cleaned and the mass loss was measured to evaluate the average corrosion rate (unit: $mg \cdot cm^{-2} \cdot d^{-1}$). Meanwhile, corrosion morphologies with and without corrosion product were observed by a KH-7700 digital microscope. Electron microprobe analysis technology was applied to observe the rust layer structure and analyze the alloying element distribution in the rust layer.

Corrosion products formed in salt spray test of the both rebars were identified by X-ray diffraction (XRD, D8 DISCOVER, Germany). The XRD test was set at a scanning angle of 10°—90°, and a scanning speed of 2(°)/min with a copper target radiation under 40 kV to 300 mA with a scanning step of 0.02°. Two kinds of rust samples were prepared and tested. One is the rust powder, which was scratched from rebar rust surface and ground into rust powder mechanically. This rust powder was detected as outer rust layer. The other is the bulk rust sample, which was obtained from the salt spray tested rebar sample after scratching of rust layer surface. This kind of sample was covered by the rust layer combining with the rebar matrix closely, and it was detected as inner rust layer.

2 Results and Discussion

2.1 Chemical compositions and microstructures of the rebars

Table 1 lists the chemical compositions of the studied rebar. Compared to the HRB400 rebar, the HRB400R rebar contains slightly lower C, lower Mn but higher Cr. According to the carbon equivalent empirical formula recommended by the International Institute of Welding (IIW):

$$CE(IIW) = [C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15] \times 100\% \quad (1)$$

Table 1 Chemical compositions of HRB400 and HRB400R rebars mass%

Sample	C	Si	Mn	S	P	Cr	V	Fe
HRB400	0.23	0.51	1.41	0.007	0.026	0.09	0.029	Balance
HRB400R	0.20	0.65	0.71	0.003	0.025	0.86	0.032	Balance

The carbon equivalent of the HRB400R (0.497) is similar to that of the HRB400 rebar (0.488), which indicates the good weldability of the two rebars.

Fig. 1 shows the optical microstructures of HRB400 and HRB400R rebars, presenting the typical ferrite (the white phase) and pearlite (the black phase). The average ferrite grain size of the HRB400R rebar (10.7 μm) is slightly larger than that of the HRB400 rebar (8.2 μm). Meanwhile, the proportion of the pearlite in the HRB400R rebar (58%) is slightly less