Boriding Temperature Effect on Rapid Corrosion of Reinforcing Rebar

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Abstract

The corrosion of steel rebars affects the durability of reinforced concrete (RC) by decreasing the cross-section of the rebar (decreasing its load bearing capacity) and the adherence of the surrounding concrete. When there is a crack in concrete, corrosive species are able to reach directly the steel surface and accordingly the rebars corrosion can be followed more intensively. The durability of RC strongly depends on corrosion of rebars. In the present paper, investigations were carried out to study the corrosion behavior of protected low carbon ribbed reinforcing steel with boron in concrete. The ribbed steel bars were in size of Ø14, and they were coated with boron. The coating process was carried out at 800, 900 and 1000 ^{o}C for 2 h and 4 h, respectively. After boriding, the rebars were embedded into the concrete and exposed to rapid corrosion test. Weight loss method was used for estimation the corrosion rate in the current study. The results show that the corrosion rate and cross section loss of protected steel bars decreases when compared to unprotected rebars. According to findings, corrosion beginning time of borided rebars delayed about two times when compared to plain rebar. Boriding process supplies protection against reinforcement corrosion.

Keywords: Boron, coating, corrosion, protection, rebar.

1. Introduction

Surface treatments are an important method used to improve the tribological properties, oxidation and corrosion resistance of engineering materials subjected to aggressive environments and strong wear conditions, which need surfaces with a high hardness and good corrosion resistance. Abrasive and adhesive wear occur in many industrial applications, leading to reduced component durability and performance. Due to its small atomic size, boron can diffuse into a variety of materials, such as ferrous materials, nickel alloys, titanium alloys, copper, and sintered materials. In industry, boriding is generally applied to ferrous alloys to improve their hardness and wear resistance. The diffusion of boron in the crystal lattice of a ferrous alloy leads to the formation of FeB and Fe2B iron borides depending on process parameters including temperature, time, and the boron potential of the medium. The material alloy composition also plays an important role in the morphology and properties of the boride layer [1-3]. Corrosion-related maintenance and repairs for reinforced structure cost over $100 billion per annum in the world. As known, corrosion of steel rebars affects the durability of RC by decreasing the cross-section of the rebar (decreasing its load bearing capacity) and the adherence of the surrounding concrete. The corrosion products of iron have higher volume than the metal so that concrete cracking is caused by their formation. When there is a crack in concrete, corrosive species are able to reach directly the steel surface and accordingly the rebars corrosion can be followed more intensively. The durability of RC strongly depends on corrosion of rebars [4-6]. Many studies on the enhancing of mechanical properties of rebars have been carried out. Ding and Poursaee (2017) this investigation aimed to study the passivation and corrosion performance of sandblasted steel in a concrete environment. The surfaces of the steel specimens were modified using sandblasting method for three durations: 5, 10, and 15 min. The specimens were immersed in the chloride-free concrete pore solution for 14 days and then 3% by weight of chloride ions were added to the solution. The specimens were then kept in the chloride-contaminated pore solution for 60 days. Results from the electrochemical tests indicated that the passive layer formed on the surface on all specimens exposed to a simulated concrete pore solution were highly disordered n-type semi-conductors. In all specimens, except the 15 min sandblasted ones, the presence of chloride ions decreased the slope of the Mott-Schottky plots and increased the donor density which indicated formation of a thinner passive layer and corrosion. The results of electrochemical experiments on steel rebar exposed to chloride-contaminated pore solution showed significant improvement in corrosion resistance of the sandblasted specimens. This improvement was proportional to the increase in the sandblasting time. Song vd. (2014) this present work focused on investigating the influence of surface nanocrystallization on the surface-microstructure and corrosion resistance of a rebar processed by wire-brushing. 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. From these researches, it was found that the large improvement in surface properties can be achieved by applied surface treatment on engineering materials [7-9].

Boriding is a thermomechanical surface-hardening process, in which boron atoms are diffused into the surface of a workpiece to form borides with the base materials [10]. Thus, the boriding process enhances the corrosion and wear resistance of metallic and non-metallic surfaces covered with boride layers [11]. Thermal diffusion treatments of boron compounds used to form iron borides typically require process temperatures of 700-1000 °C [12]. In this study, the use of boriding coating as alternatively method to protect steel rebars embedded in concrete were investigated experimentally.

2. Experimental Details

2.1. Materials

Reinforcement rebar is made of mild steel, a low carbon steel usually used for structural applications. With too little carbon content (>0.2%) to thoroughly harden, it is weldable, which expands the possible applications. The experiments of this study were performed on ST-IIIa (S 420) ribbed reinforcement steel rebar specimens in size of Ø14. The characteristic properties of rebar were presented in Table 1.

Table 1. Characteristic properties of steel rebars

Properties	*Steel rebar, Ø14*		
Area (mm²)	*153.86*	*Tensile fore (N)*	*86269*
Initial length (mm)	*140*	*Yield stress (MPa)*	*447*
Last length (mm)	*172.06*	*Tensile stress (MPa)*	*560.7*
Yield force (N)	*68775*	*Elongation, %*	*22.9*

2.2. Coating of rebars

In the study, boriding layer was performed as coating on the steel rebar surface. Boriding heat treatment was carried out by using a solid boriding method with commercial Ekabor-II powders. All samples to be borided were packed in the powder mix and sealed in a stainless steel container. Boriding heat treatment was performed in an electrical resistance furnace under atmospheric pressure at 800ºC, 900 ºC and 1000 ºC for 2 h and 4 h followed by cooling in air. (Fig. 1)

Figure 1. Coating process of rebar by boriding

2.3. Sample Production and Corrosion Test

Two different aggregate sizes, 0/6 mm and 6/12 mm, were used in the production of concretes. The specific gravity of aggregates are 2.63 for 0/6 mm, and 2.69 for 6/12 mm. They were used in ratio of 50%-50%. In all mixtures, 350 kg of cement is used as binder. The workability values of the produced concrete have been tried to be kept constant, and the slump value has been decided to be around 20 cm. Concrete specimens were produced by using the cylindrical mould of size ø100x200 mm. The reinforcement rebar was held in position and concrete was poured into the mold. After 24 h, the reinforced concrete specimens were demolded and cured in a water pool until the time of test was reached. The specimen was allowed to cure for 28 days. The specimens were cast in constant strength classes such as C25 for corrosion test.

The test setup consists of a constant DC supply providing constant voltage of 50 V. The test was carried out in a 4% NaCl solution with an embedded reinforcement bar as a working electrode and a copper bar as a counter electrode. The variable parameter current was recorded at every 20 min interval in constant voltage study. The set up was kept for until cracking of concrete samples without disrupting the power supply. After cracking of concrete, the solution turned to reddish brown in color due to the formation of rust. Then the specimens were removed from the set up, dried in air, visually inspected and carefully split open to access the corroded steel bar. Simultaneously, the temperature of the solution was recorded together with the voltage value. The amount of corrosion in terms of mass loss of the reinforcing bar due to corrosion can be determined by the following equation (1):

$$\%W_c = [(W_0-W)/W_0]\times100 \quad (1)$$

Where, W_c is weight loss after corrosion test; W_o is the initial weight of rebar and W is weight of rebar after corrosion test.

3. Results and Discussions

The thickness of the boride layer formed on the rebar sample is shown in Figure 2. It has been observed that the boride layer thickness increases with the increase in the boriding temperature and time. The thickness of the boride layer increased with increasing boriding temperature and time. Since the boriding process is a thermochemical process, temperature and time provide diffusion of more boron atoms in rebar and cause the boride layers to grow [13-15]. Variation of the thickness of the boriding layer with time at different boriding temperatures in Figure 3 is given. The highest boriding layer was obtained in samples borided at 1000C for 4 hours. The lowest boride layer thickness was obtained in samples borided at 800C for 2 hours.

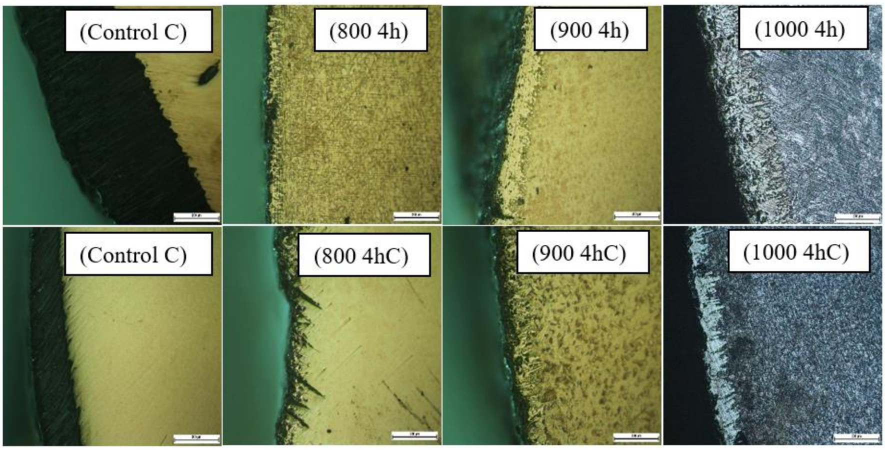


Figure 2. Microscope image of 4h borided rebar section before and after corrosion (C) depending on temperature for Ø14

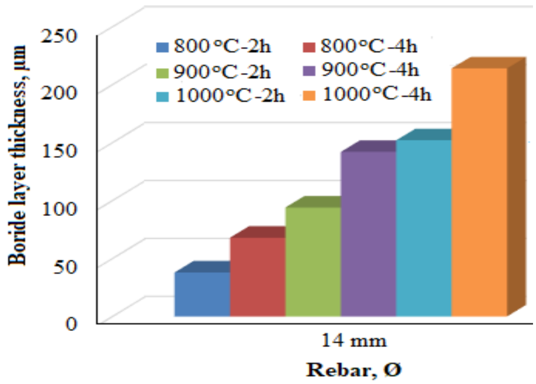
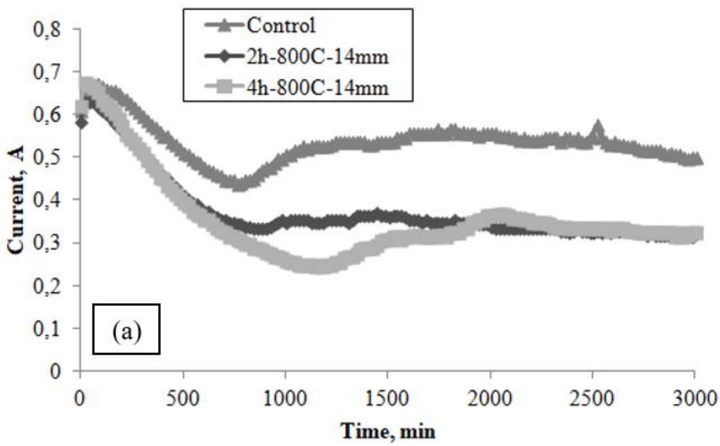
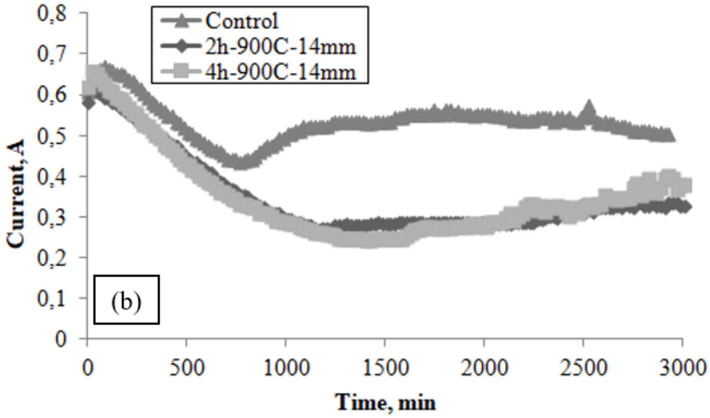


Figure 3. Variation of thickness of boriding layer with time at different boriding temperatures

Rapid corrosion tests are widely used by electrical stress method. When there is a difference in electrical potential along the steel reinforcement in concrete, electrochemical cell is setup. In the steel one part becomes anode and other part becomes cathode. They connected by electrolyte in the form of pore water in the hardened cement paste [16]. It is well known that steel rebars exposed to corrosion when ambient conditions are appropriate. Figure 4 shows the current values versus time during rapid corrosion test. When the voltage is applied firstly to the samples, the current values begin to decrease. After a while the current values reach the minimum value and become stable. It is understood that the corrosion process started when the current started to increase again. The current values start to decrease again after taking the maximum value. Here, corrosion time for the started to increase is an indicator of cracking of concrete samples. It can be clearly seen that borided reinforced concrete sample has lower current values than control sample. However, corrosion starting time is also longer for borided reinforced sample when compared to control sample. This is because of the boride layers mainly consist of intermetallic phases (FeB, Fe_2B and CrB) as a result of diffusion of boron atoms from the boriding compound to the metallic lattice with respect to the holding time. Thus, electron flowing from metal to solution carried out very slowly, and corrosion time increases by boriding of rebars.





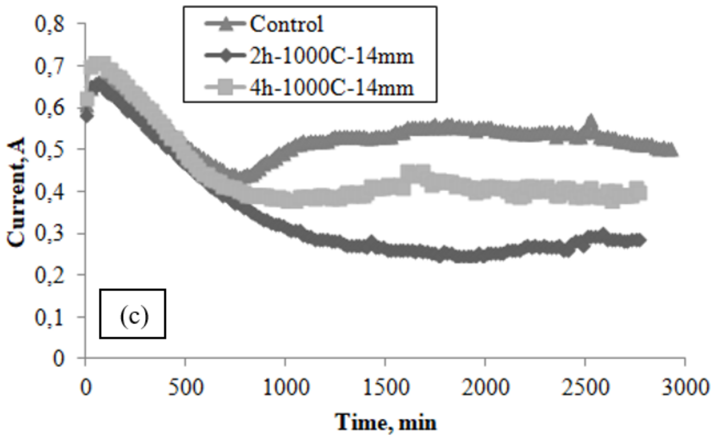


Figure 4. Comparison of current values for Ø14 borided reinforcement during corrosion test (a: 800 ^{o}C; b: 900 ^{o}C; c. 1000 ^{o}C)

Corrosion starting time plays an important role in the service life and rehabilitation of reinforced concrete structures. In order to see the effect of reinforcement surface boriding on corrosion initiation times, the corrosion starting time was determined on Figure 5. It is clearly seen that boriding on the surface of the reinforcement is very effective. For this one type of reinforced concretes, corrosion time of borided rebars about 2 times higher than non-coated steel rebars (Fig. 3). In other words, if the traditional reinforced structures with steel rebar exposed to corrosion after 10 years, same structures will be corroded after 20 years when borided rebar are used.

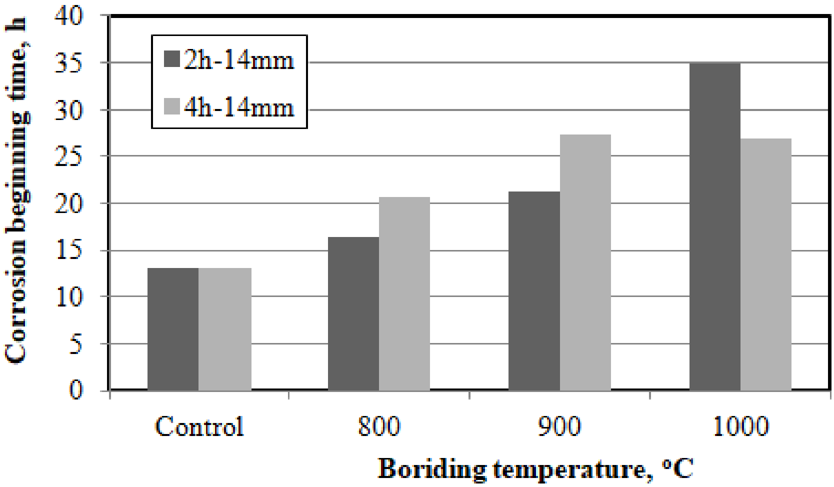


Figure 5. Corrosion initial time of control and borided reinforced concrete (for Ø14)

After corrosion test for the same duration, concrete samples were splitted and internal colour change were examined (Fig. 6). It is clearly seen that reinforcement with borided steel rebar has lower corrosion rust in the concrete than produced with steel rebar. About all the concrete side along the steel is rusty area. On the other hand, in the concretes produced with borided rebar, the rusty area is yet to reach the outer surface of the concrete. Rebars were removed from splitted concretes and weight loss were determined after cleaning. Figure 7 shows weight loss of rebars after corrosion experiment. The loss of weight of steel rebar in concrete is determined as 12%. By coating the rebar surface with boriding, the loss of weight is estimated as 3.9%.

Figure 6. Inner view of corroded Ø14 reinforced samples depending on boriding temperature

Figure 7 shows Weight loss of control and borided reinforced rebar. It decreased by 180% at 800°C, 653% at 900°C and 242% at 1000°C. Boriding process reduced the weight losses compared to unborided samples at very high rates and increased the lifetime of the steel reinforcement in concrete. The reason for this is that due to the increasing reinforcement diameter, the surface area where the rebar contacts with the concrete increases. As the diameter of the steel reinforcement increases, the surface contact area with the concrete increases. This means more corrosion contact area. As a result, as the surface contact of the steel reinforcement increases, weight loss increases. The surface roughness values of steels increase with increasing temperature and time of boriding. Gunes [17] has borided AISI 8620 steel in plasma environment with five different borax and B_2O_3 paste mixtures, and as a result, it has been determined that the surface roughness values of all samples have increased with the increase in boriding temperature and time.

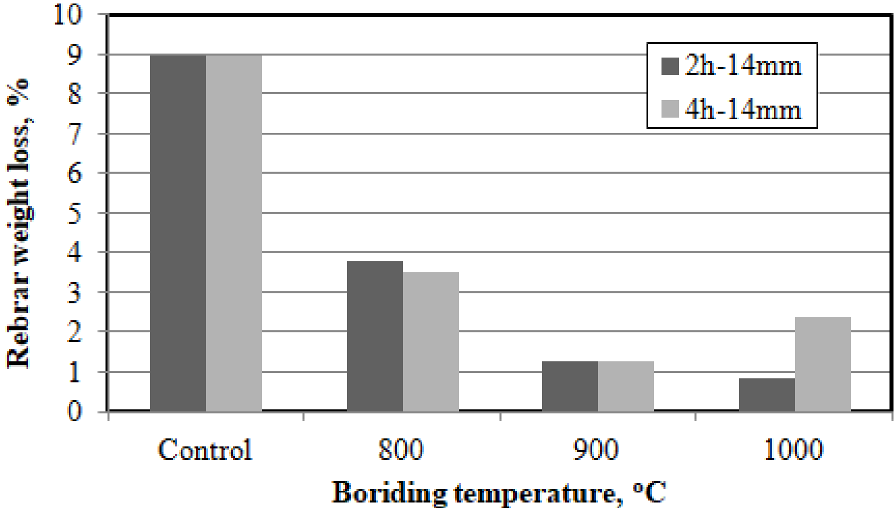


Figure 7. Weight loss of control and borided reinforced rebar (for Ø14)

Figure 8 show the percent cross-sectional losses of 14 mm diameter rebar. As the boriding temperature increased, the cross-sectional losses decreased the rebar. There are micro cracks and scratches on steel reinforcements that will result from production. There are micro cracks and scratches caused by production on steel reinforcements. As the boriding temperature increases, the voids, pores and scratches on the steel reinforcement are filled with the boride layer and become more resistant to corrosion. In addition, as the boriding temperature increases, the boride layer thickness on the reinforcement increases. By reducing the corrosion rates of steel reinforcements within the concrete, it will enable the building of longer-lasting buildings. Similar results were obtained with the 14 mm steel reinforcement (Figure 9). The corrosion rates of the boriding process on steel reinforcements for 4 hours at 1000C were slightly higher than the samples borided for 2 hours at 1000C. These results show us that the steel reinforcements, which are borided for more than 2 hours at 1000C, will not provide more corrosion resistance and this time should be accepted as the boundary boriding process time in boriding. Boriding of reinforcements 1000C-4h caused increased roughness values on the steel surface, increased surface contact area and increased the corrosion rate slightly. In addition, steels are not desired to be exposed to high temperatures and times for a very long time. Because this situation causes the growth of the grains in the steel and the decrease of their mechanical properties [18,19].

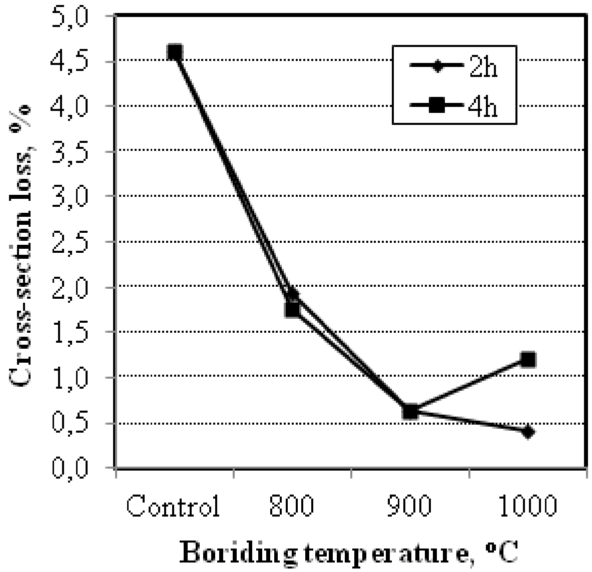


Figure 8. Cross-section loss of rebars in size of Ø14 versus boriding temperature

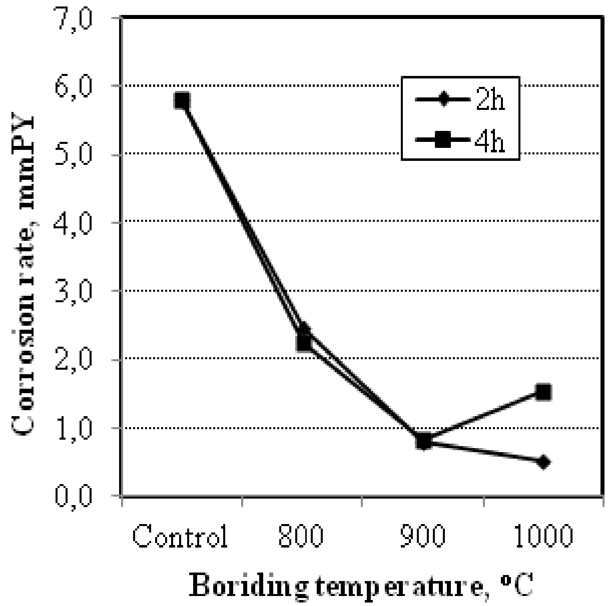


Figure 9. Cross-section loss of rebars in size of Ø14 versus boriding temperature

4. Conclusions

In the study, investigations were carried out to study the corrosion behavior of protected low carbon ribbed reinforcing steel with boron in concrete. Following results have appeared:

Reinforced concrete sample with borided steel rebar has lower current values than control sample. However, corrosion starting time is also longer for reinforced sample containing the borided rebar when compared to control sample.

Electron flowing from metal to solution carried out very slowly, and corrosion time increases by boriding of rebars.

Corrosion time of borided rebars about 2 times higher than non-coated steel rebars.

Reinforcement with borided steel rebar has lower corrosion rust in the concrete than produced with steel rebar.

The loss of weight of steel rebar in concrete is determined as 12%. By coating the rebar surface with boriding, the loss of weight is estimated as 3.9%.

Consequently, service life of reinforced structures which are under corrosion risk can be increased two times by protecting the steel rebars by boriding. Boriding technology can be used the alternatively to other rebar surface coatings.

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References

[1] Bindal, C., Ucisik, A. H., (1999). Characterization of borides formed on impurity-controlled chromium-based low alloy steels. Surf. Coat. Technol. 122, 208-213.

[2] Kulka, M., Makuch, N., Pertek, A., (2013). Microstructure and properties of laser-borided 41Cr4 steel, Optics & Laser Technology, 45, 308-318.

[3] Muhammad, W., (2014). Boriding of high carbon high chromium cold work tool steel, Materials Science and Engineering, IOP Conf. Ser.: 60-66.Chen Z.J., Effect of reinforcement corrosion on the serviceability of reinforced concrete structures, MSc thesis, Department of Civil Engineering, University of Dundee, Dundee, Scotland, 2004.

[4] Jaffer S.J., Hansson C.M., Chloride-induced corrosion products of steel in cracked-concrete subjected to different loading conditions, Cem. Concr. Res. 39 (2009) 116–125.

[5] Geetha, A., Perumal P., Chemical Reaction of Waterproofing Admixtures on the Corrosion Behaviour of Reinforced Cement Concrete, Asian Journal of Chemistry, 2011, 23(11), 5145-5148.

[6] Jamila HE, Shriria A, Boulifb R, Montemorc MF, Ferreirad MGS. Corrosion behaviour of reinforcing steel exposed to an amino alcohol based corrosion inhibitor. Cem Concr Compos 2005, 27(6):671

[7] Tang F, Chen G, Brow RK, Volz JS, Koenigstein ML. Corrosion resistance and mechanism of steel rebar coated with three types of enamel. Corr Sci 2012, 59:157–68.

[8] Varalakshmi R., Ramaswamy S.N., Effect of Anti Corrosive Coatings To Steel - A State of Art Report, International Journal of Scientific Research, 2016, 5(6), 302-306.

[9] Seneviratne AMG, Sergi G, Page CL. Performance characteristics of surface coatings applied to concrete for control of reinforcement corrosion. Constr Build Mater 2000,14:55–9.

[10] Uluköy, A., Can, A.Ç., Boronizing of steel, Journal of Engineering Sciences, 2006, 12(2), 189-198.

[11] Mohmmed, J.H., Wear Rate and Hardness of Boride Low Carbon Steel, Journal of Engineering, 2015, 10(21), 90-98.

[12] Pertek, A., Kulka, M. 2003. Two-step Treatment Carburizing Followed By Boriding on MediumCarbon Steel, Surface and Coatings Technology, V173, s. 309-314.

[13] Gunes, I., Investigation of Tribological Properties and Characterization of Borided AISI 420 and AISI 5120 Steels, Trans. Indian Inst. Met. 2014, 67, 359-365.

[14] Makuch, N., Kulka, M., Dziarski, P., S. Taktak, S., The influence of chemical composition of Ni-based alloys on microstructure and mechanical properties of plasma paste borided layers, Surface and Coatings Technology, 2019, 367, 187-202.

[15] Erdogan, M., Gunes, I., Dalar, A., Investigation of corrosion behavior of borided gear steels, Trans. Indian Inst. Met., 2014, 67, 291–297.

[16] Song, D., Ma, A., Sun, W., Jiang, J., Jiang, J., Yang, D., Guo, G. (2014). Improved corrosion resistance in simulated concrete pore solution of surface nanocrystallized rebar fabricated by wire-brushing. Corrosion Science, 82, 437–441.

[17] Gunes, I., 2013. Wear behaviour of plasma paste boronized of AISI 8620 steel with borax and B2O3 paste mixtures, J Mater Sci Technol, 2013, 29, 662-668.

[18] Huanting Zhou, Weiyong Wang, Kang Wang , Lei Xu, Mechanical properties deterioration of high strength steels after high temperature exposure, Construction and Building Materials, 2019, 199, 664-675.

[19] Yancheng Cai, Ben Young, Mechanical properties of thin sheet steel after exposure to high temperatures, Thin-Walled Structures, 2019, 142, 460-475.