Journal of Chemical Technology and Metallurgy, 60, 3, 2025, 413-418

RESISTANCE TO CORROSION OF BIMETAL REINFORCING RODS RECEIVED BY EXPLOSION WELDING

Sylwester Sawicki

Czestochowa University of Technology
Faculty of Production Engineering and Materials Technology
Department of Materials Engineering, 19 Al. Armii Krajowej St.,
42-200 Czestochowa, Poland, sylwester.sawicki@pcz.pl

Received 14 March 2024
Accepted 04 May 2024
DOI: 10.59957/jctm.v60.i3.2025.5

ABSTRACT

The manuscript shows the result of corrosion tests of reinforcing bimetallic rods, the core of which was made of C45 carbon steel, and the cladding layer was made of 304L steel. Bimetallic reinforcing rods were obtained by explosive welding and then subjected to hot plastic working. The corrosion tests of the rods consisted of acidified salt spray tests and polarization measurements in sulphate solutions containing chloride ions. Potentiodynamic tests confirmed the correctness of choosing 304L steel for the plating layer. To determine the influence of the production process of bimetallic reinforcing rods on the microstructure of the cladding steel and the quality of the connection between the core and the cladding layer, a microscopic analysis of cross-sections of reinforcing bimetallic rods was carried out.

*Keywords**:** bimetallic reinforcing rods, electrochemical corrosion, microstructure.*

INTRODUCTION

Reinforced concrete products, thanks to their valuable properties, such as resistance to static and dynamic loads, fire resistance or corrosion resistance, are construction materials that have a wide range of applications. The time of reliable use of reinforced concrete products depends on the quality of the concrete used. A layer of properly made concrete cover will effectively protect the steel against corrosive effects such as, for example, moisture or some electrolytes [1 - 10]. There is a belief that in an environment of clean air and water, the process of corrosion degradation of reinforcing rods in concrete may occur only after a period of 40 - 50 years [2]. This is because in a strongly alkaline environment, characteristic of concrete (pH ~ 12.6), steel is covered with a passive layer of 20 to 200 μm thick, which effectively protects the substrate against further corrosion. Even in the event of mechanical damage to its continuity, the passive layer can spontaneously regenerate in an alkaline environment [2, 5, 6]. Over time, because of concrete binding carbon dioxide from the atmosphere (carbonation) and the penetration of ions (e.g. chloride), the pH of concrete gradually decreases and the aggressiveness of its pore liquid towards the reinforcement material increases [2, 6]. After the concrete reaches pH = 8 - 9, the steel depassivates at the interface between the reinforcement and the concrete phase and the process of intense steel corrosion begins. The presence of chloride ions in concrete leads to local corrosion of reinforcing rods [5, 6]. As a result of corrosion, ferrous chloride is locally formed on the steel surface, which hydrolyses and leads to local acidification of the environment (even to pH = 3) and accelerated pitting corrosion [2]. The formation and precipitation of corrosion products on reinforcing rods leads to stresses in the surrounding concrete and, as a result, to cracking and debonding of the concrete cover [2, 5]. Typically, steels with high carbon content are used to make reinforced concrete structures, obtained through hot or cold rolling and drawing processes. The advantage of carbon steels, apart from their low price, is also significant mechanical strength, while the disadvantage is low corrosion resistance. The use of reinforcing rods made of alloy steel, despite high corrosion resistance, would be unfavourable due to the high price of the resulting reinforced concrete, as well as due to worse mechanical properties compared to carbon steel. In order to ensure good mechanical properties of the reinforcement while significantly reducing corrosion, it is worth considering plating carbon steel with chrome-nickel steel [2, 7, 9]. When choosing a method for producing bimetal rods, it is necessary to consider the necessity of ensuring the product with optimal plastic and strength properties, electrical and thermal conductivity, and corrosion resistance [8 - 10]. In this work, a two-layer insert was used to produce bimetal reinforcing rods, initially explosively welded and then hot-rolled in blanks. The main advantage of explosion welding is that this method allows for joining different metals (e.g. steel-copper or steel-steel) and can thus produce multilayer materials with a wide range of thicknesses. Very good mechanical and technological properties of connections are also obtained [6 - 10].

To ensure adequate durability of the connection between steel reinforcement and concrete, reinforcing rods are used in reinforced concrete structures. As a result of rolling, in addition to the change in shape, which most often involves elongation of the material with a simultaneous reduction in its cross-section, there is also a change in the structure of the material, its mechanical and physico-chemical properties, a change in the surface condition and internal stresses. An unfavourable phenomenon during the hot rolling process is the formation of a layer of scale on the surface of the processed strip. Scale is a brittle material that does not deform plastically and must be removed for further stages of the technological process [2, 7, 10].

The aim of this work is to assess the suitability of explosive cladding of carbon steel with chromium-nickel steel to obtain reinforcing rods with very high corrosion resistance in the concrete environment, and to determine the role of the degree of carbonation of concrete and the presence of chloride ions in it on corrosion resistance.

EXPERIMENTAL

Two steel grades were used for the tests: 304L and C45, the chemical composition of which is presented in Table 1.

Sets were prepared for explosive welding, consisting of pipes made of corrosion-resistant 304L steel and internal rods made of C45 steel. The use of 304L steel as the cladding layer was to ensure high corrosion resistance, while the use of carbon steel for the core - good mechanical strength.

Ammonal (2 wt.%) was used to explosively weld corrosion-resistant steel pipes to steel rods, which consisted of ammonium nitrate and aluminium flake dust. The explosive material was in the form of a loose, fine-grained powder, thanks to which, despite the small distances between the container wall and the steel pipe, it was easily poured into the explosive sets. The detonation velocity was approximately 1600 ms^{-1}. After explosive welding, an elongated, cylindrical bimetallic charge was obtained with a permanent connection between the layers and their entire length and circumference. The produced bimetal charge was then hot rolled in two passes in a laboratory rolling mill. Before rolling, the bimetal charge was heated to a temperature of 1100^{o}C in an induction furnace. A rolling speed of 0.5 ms^{-1} was used. After the rolling process, the rod was cooled in air. As a result of rolling, bimetal reinforcing rods with a diameter of 18 mm and an angle of inclination of the side edges of the rib $\beta = 60^{o}$ were obtained.

Electrochemical tests were carried out using the CHI 660 measuring station (CH Instruments 660, USA) in a three-electrode system, in which the auxiliary electrode was a platinum electrode, and the reference electrode was a silver chloride electrode. The working electrodes were samples made of C45 and 304L steel. The geometric area of the working electrode was 0.2 cm^2.

Table 1. Chemical composition of steels, wt. %.

Steel	C	Mn	Si	P	S	Cr	Ni	Mo	N	Al	Cu	Sn
C45	0.45	0.64	0.21	0.015	0.031	0.13	0.14	0.04	-	0.004	0.25	0.015
304L	0.03	2.00	0.24	0.045	0.03	19.00	10.00	0.75	0.10	-	-	-

Potentiodynamic curves were made at a potential change rate of 10 mV s^{-1} using potential scanning from the value E_{start} = -0.8 V to E_{end} = 1.6 V. Polarization curves were measured in an aqueous solution of 0.25 mol mol L^{-1} Na_2SO_4 + 0.5 mol L^{-1} NaCl. To reproduce conditions similar to real ones, some tests were carried out using a solution with pH = 10, imitating the pore liquid of partially carbonated concrete. Since the tests were accelerated tests, solutions with pH = 2 and 4, which were more aggressive, were also used.

Corrosion resistance tests against acidified salt mist were carried out using a Braive Instruments salt chamber. The samples were exposed to salt mist prepared from a solution of 5 % NaCl in 0.1M CH_3COOH at a temperature of 35°C continuously for 6 h, in accordance with the PN-76/H-0464 standard. The intersection surfaces of the rods were insulated with epidian. The samples were visually inspected after each exposure cycle. The appearance of the samples was assessed in accordance with the PN-EN ISO 10289:2002 standard.

Microscopic observations were carried out using an Axiovert microscope on samples etched in the core area with nital, and in the area of the plating layer - with a reagent with the composition (% by volume): 30 HNO_3 (conc.), 15 HCl (conc.), 10 HF (conc.) and 45 H_2O.

Reagents of pure p.a. grade were used to prepare the solutions and deionized water.

RESULTS AND DISCUSSION

To compare the corrosion properties of C45 steel and 304L steel, polarization curves were measured at a potential change rate of 10 mVs^{-1} in an electrolyte environment consisting of 0.25 mol L^{-1} Na_2SO_4 + 0.5 mol L^{-1} NaCl (at three different pH values). The course of the obtained polarization curves is shown in Fig. 1.

The data presented in Fig. 1 shows that C45 steel

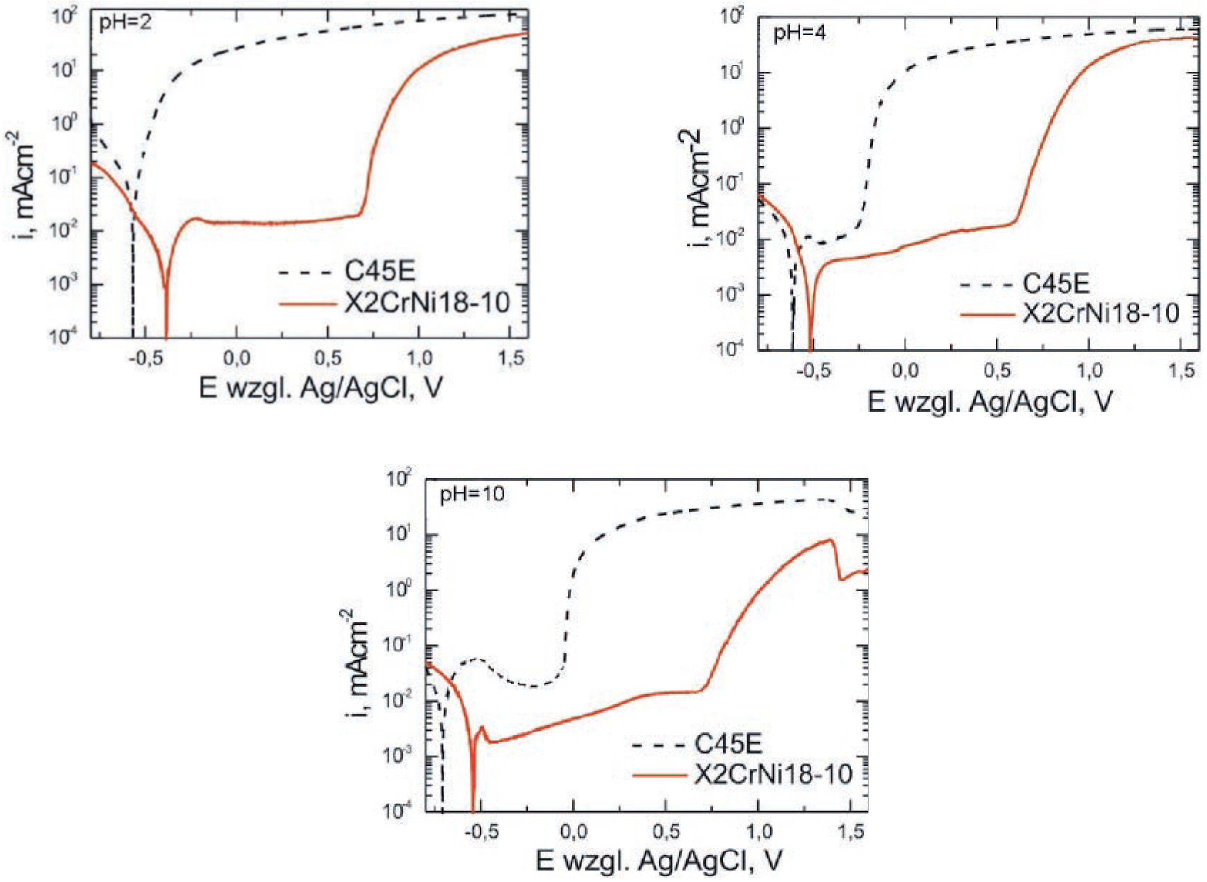

Fig. 1. Potentiodynamic curve in the solution 0.25M Na_2SO_4 + 0.5M NaCl (different values of pH) for C45 mild steel (dashed line) and 304L stainless steel (solid line): (a) pH = 2; (b) pH = 4; (c) pH=10. Scan rate 10 mVs^{-1}, the solution in contact with air, without mechanically mix, 20°C.

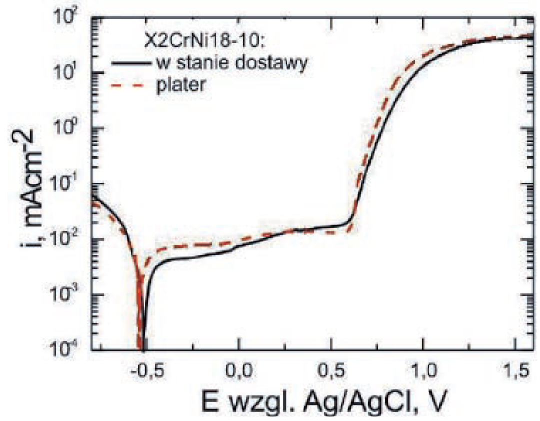

Fig. 2. Potentiodynamic curve for 304L as received (solid line) and as clad (dashed line). Electrolyte: 0.25M Na_2SO_4 + 0.5M NaCl, pH = 4. Scan rate 10 mV s^{-1}, the solution in contact with air, without mechanically mix, 20°C.

in solutions with pH = 4 and 10 undergoes passivation even despite the presence of chloride ions. However, even in a slightly alkaline environment (pH = 10), the passive layer created on this steel is easily destroyed (punctured), and the steel undergoes local active dissolution. However, in a solution with pH = 2, the tested carbon steel does not passivate in the presence of chloride ions.

Austenitic 304L steel is characterized by much lower values of corrosion current density and more positive values of corrosion potential compared to carbon steel. Regardless of the pH of the solution, 304L steel undergoes passivation even in the presence of chloride ions. The passive state occurs in a wide range of potentials, which proves the good protective properties of the passive layer. Regardless of the pH of the corrosion solution, the breakdown of the passive layer occurs at a potential close to 0.7 V, and when it is exceeded, the current density increases, illustrating the development of pitting corrosion. Formally speaking, an increase in the anodic current density of austenitic steel above 0.7 V could also be attributed to the transpassive dissolution of the steel or the evolution of oxygen. It should be noted, however, that at low pH values (i.e. 2 or 4) both processes start at much higher potentials, moreover, the corresponding equilibrium potentials should decrease significantly with increasing pH. However, it cannot be ruled out that for an environment with pH = 10, for E > 0.7 V, transpassive etching of chromium (in the form of CrO_4^{2-}) begins.

Potentiodynamic tests confirmed the correctness of choosing 304L steel for the plating layer. To check whether the plating process itself does not lead to unfavourable changes in the cladding material, which would result in deterioration of its corrosion characteristics, a comparison was made of the potentiodynamic curves of the initial 304L steel (as delivered) and the same steel after its explosive deposition on the substrate. C45 core. The appropriate potentiodynamic curves are shown in Fig. 2. The analysis of both curves indicates that the plating process (within the measurement error) does not affect the polarization curves of the tested chrome-nickel steel. Therefore, it can be assumed that plating carbon steel 304L is an effective method of improving the corrosion resistance of reinforcing rods.

Corrosion tests in acidified salt fog allow for an accelerated assessment of the corrosion resistance of metals, as well as metal or non-metal coatings on metals. Fig. 3 shows the appearance of the tested samples before and after the salt spray test.

Traces of brown corrosion products were observed after the first measurement cycle (after 6 h of exposure), however, the tests were continued (up to cycle 17, for a total exposure time of 102 h) to assess the possible progress of corrosion changes. However, subsequent cycles did not lead to any changes in the appearance or weight of the samples. It was observed that the mentioned corrosion products occur in places close to the base of the rib, while the smooth spaces do not change during exposure.

To determine the cause of the described corrosion changes, the structure of the plating layer and the quality of the connection formed between the core and the plating layer were analysed. There was a suspicion that the appearance of brown deposits was a consequence of possible cracks in the clad in the ribs.

Fig. 4 shows microscopic photos of 304L steel as delivered and after the process of producing a bimetal reinforcing rod (after explosion welding and hot rolling). Both photos show the cellular structure typical of austenitic steel with numerous twin boundaries. Non-metallic inclusions are visible in the structure. In Fig. 4a, you can see slip bands inclined to each

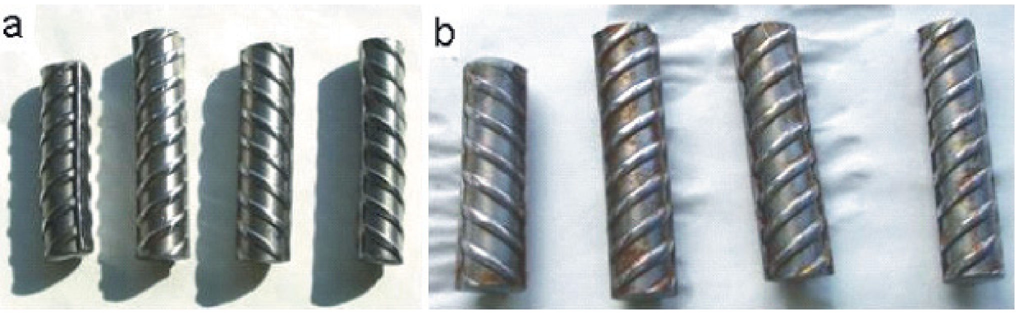

Fig. 3. The bimetallic reinforcing rods (a) before and (b) after exposition in salts spray.

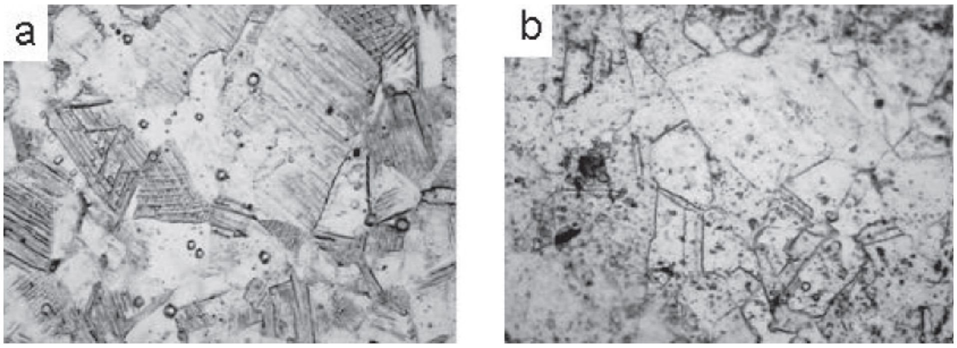

Fig. 4. Photomicrographs of: (a) 304L austenitic steel as received and (b) after the process of obtained bimetallic reinforcing rods, magnification x 500.

other at an angle of 60°, formed in the cold plastic working process (characteristic of austenitic steel in the delivered condition). However, in Fig. 4b, no slip bands are observed, which results from the explosive welding and hot rolling processes carried out. It should be emphasized that both the results obtained for the steel as delivered and after the rolling process did not reveal any cracks or other defects in the austenite structure. Hence, it can be concluded that the processes carried out for producing the bimetal reinforcing rod do not negatively affect the steel structure of the plating layer.

To determine the quality of the connection between the core and the cladding layer, an analysis of microstructural changes was carried out on the cross-section of a bimetal reinforcing rod.

Based on the data in Fig. 5, it can be concluded that the connection area of the core and the cladding layer was uniform, without oxide phases and frays. Everything indicates that the rust-like deposits observed in the first exposure cycles, mainly at the base of the ribs, are not corrosion products, but only technological contamination of the rolling process.

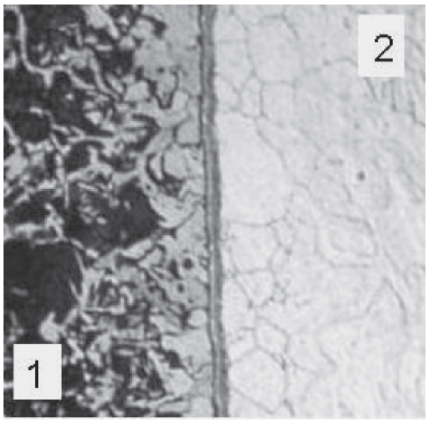

Fig. 5. Microstructure of the bimetallic reinforcing rods in area of the joint the core (1) and clad layer (2). Magnification x500.

CONCLUSIONS

The test results presented in this paper confirm the correctness of choosing 304L austenitic steel as the cladding layer for C45 steel used for concrete reinforcement. The clad layer provides high corrosion resistance to the reinforcement and at the same time practically does not lead to a deterioration of its mechanical properties. Microscopic observations indicate that because of explosive welding of C45 and 304L steels and subsequent hot rolling, bimetal reinforcing rods with a good connection between the plating layer and the core are obtained. The processes performed do not change the structure of the austenitic plating layer and therefore do not deteriorate the protective properties of the reinforcing element.

Accelerated tests in a salt spray chamber showed that despite the occurrence of trace corrosion changes (visible at the base of the rod's ribs), the plating layer provides good protection for the rod's core and thus extends its durability under operating conditions. Clad rods also demonstrate satisfactory durability in environments that are much more aggressive than those of carbonated concrete.

Authors' contribution*: The publication presents my own research on the production of bimetallic charge and the production of target bimetallic rods. Corrosion tests were performed in the laboratory of the Czestochowa University of Technology and photos of the microstructure were taken after corrosion tests. My contribution to the publication is 75 %, 25 % are tests performed in the laboratory of the University of Technology.*

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