

## Influence of cold rolling on the corrosion resistance of austenitic steel

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### Properties

#### ABSTRACT

**Purpose:** The paper analyzes the effects of plastic deformation in cold working process on the corrosion resistance, micro-hardness and mechanical properties of austenitic stainless steel X5CrNi18-10.

**Design/methodology/approach:** Corrosion resistance of X5CrNi18-10 steel was examined using weight and potentiodynamic methods. In the weight method, the specimens were immersed in the prepared solution for 87 days. The evaluation of the corrosion behaviour of investigated steel in the potentiodynamic method was realized by registering of anodic polarization curves. The VoltaLab® PGP 201 system for electrochemical tests was applied. The tests were carried out at room temperature in electrolyte simulating artificial sea water (3.5% NaCl). Registering of anodic polarization curves was conducted at the potential rate equal to 1 mV/s. As the reference electrode the saturated calomel electrode (SCE) was applied, the auxiliary electrode was platinum electrode. Mechanical properties were evaluated on the basis of the static tensile and Vickers micro-hardness test. The observations of the surface morphology after corrosive tests were carried out using Scanning Electron Microscope SUPRA™25.

**Findings:** According to the results of potentiodynamic analyses it was found that plastic deformation in a cold working of austenitic steel grade X5CrNi18-10 affected to lower its corrosion resistance in 3.5% NaCl solution, what has an essential meaning in industrial applications of this group of materials.

**Research limitations/implications:** The microscope observations of the surface samples subjected to corrosion resistance test in 3.5% NaCl solution permitted to evaluate types and the rate of corrosion damages.

**Practical implications:** The obtained results can be used for searching the appropriate way of improving the corrosion resistance of a special group of steels.

**Originality/value:** The corrosion behaviour in chloride solution of a Cr-Ni austenitic stainless steel was investigated.

**Keywords:** Corrosion resistance; Cr-Ni steel; Plastic deformation; Potentiodynamic test; NaCl solution

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## 1. Introduction

The existing demand for materials with high functional properties, a definite geometrical shape, a high resistance to the destructive effect of a aggressive environments, produced in compliances with a valid ecological standards, motivates the manufacturers to a continuous improvement in the engineering process, in particular the steelmaking and plastic forming processes. Stainless steels fulfil enough above requirements and characterized excellent corrosion resistance combined with high mechanical and plastic properties. The most common stainless alloys are austenitic steels, well-known as 18/8 types and usually contain between 16 and 18% wt. Cr, 6-8% wt. Ni and 0.03-0.1% wt. C [1, 2].

Stainless steels are iron alloys that have thin, transparent and durable chrome oxide passive layers on the surface. The stability of the passive film and the corrosion resistance of the steel increase with increasing chrome content in the alloy. Although the costs of the stainless steel are higher than those with similar mechanical characteristics, the primary justification for its common usage is improved corrosion resistance. Stainless steels have a large range of applications. Over 1/3 of produced stainless steels are used in structural applications for chemistry and power engineering industries. These applications include nuclear reactor canals, heat converters, tubes that are used in oil industries, chemistry applications, paper industries components, and as the pieces of boilers and furnaces that are used in nuclear reactors [3, 4].

Corrosion resistance of stainless steels depends on various metallurgical and processing variables [5]. The austenitic grade is considered to be most resistant to industrial atmospheres including aggressive aqueous and non-aqueous acid media [6].

However, as conditions become more severe, addition of several alloying elements is useful in promoting corrosion resistance and hence is desirable. Chromium >12%wt., for instance, improves the passivity of iron alloys, and molybdenum (>2% wt.) promotes resistance to pitting corrosion [7].

Similarly, sensitization that occurs in stainless steels in the temperature range 500 to 870°C leading to intergranular corrosion can be improved by lowering carbon <0.03%wt. or by addition carbide formers, e.g. titanium and niobium. The degree of susceptibility after heating in this range as a function of time, temperature, and composition [8-10].

Some grades of austenitic stainless steels, such as X5CrNi18-10 and X5CrNiMo17-12-2 steels, are metastable in ambient temperature. Martensite will appear in these steels under the proper conditions, such as in plastic deformation, cathodic hydrogen charging, and cooling after welding. Cold working and welding are inevitable processing methods for stainless steel parts, so the martensite in such steel parts is common. The appearance of martensite changes the single-phase state of the steels, so the physical and chemical properties of the steels also change. Since martensite and austenite have different corrosion potentials, it is easy for them to become the anode and cathode, respectively, of a corrosion battery. According to this theory, the corrosion resistance of metastable austenite stainless steel will decrease when martensite appears [11-14].

Literature data show, that the cold plastic deformation of steel worsens its corrosion resistance. It can be explains for several ways. The delivering to material additional energy in result of induction of external tensions is generally accepted as a one of

causes of the lowering of corrosion resistance. It leads in consequences to decreases of the thermodynamical durability of the material [15, 16]. Second reason is connected with that the crystallographic structure of plastic deformed material marks deformity and shows the characteristic orientation of grains (texture). The thin oxygen layers created on metal in cases of structure compatibility with the base material structure. This leads to advancing conclusion, that in the result of disorder of crystalline lattice the changes of crystallographic structure of created oxide and passive oxygen layers with decreases protective properties are possible [17-19].

Thus, the aim of the investigations is to determine the influence of cold rolling on the corrosion resistance, structure and mechanical properties forming in the X5CrNi10-10 steel.

## 2. Experimental procedure

Experiments were carried out on three melts of austenitic stainless steel grade X5CrNi18-10, according to PN-EN 10088-1:2007 [20], with the chemical composition presented in Table 1. The investigated material was supplied in the form of sheet-cutting steel with dimension about 700×40×2 mm, as a result of industrial smelting from the UGINE&ALZ (Poland). The material was cold-rolled within the range 10-70% and samples for researches of the corrosion resistance, mechanical properties, for microhardness measurements and metallographic observations were cut. The rolling was conducted at room temperature keeping a constant direction and side of the rolled strip. Small unitary draft was applied with a different number of roll passes to ensure a summary draft for every single strip.

The microhardness measurements of the investigated cold reduced sheets from steel X5CrNi18-10 were carried out by a micro-hardness tester PMT-3, according to the standard PN-EN ISO 6507-1:2007 [21]. Researches were made by Vickers's method on metallographic samples with a load of 50 g.

Evaluation of the mechanical properties was made on the basis of measurements of statically tensile tests on the testing machine ZWICK 100N5A. Dimensions of test samples were determined on the basis of PN-EN 10002-1+AC1:2004 [22] standard and cut from the steel sheet in parallel to the rolling direction.

Corrosion resistance of investigated steel was examined using weight and potentiodynamic methods.

The weight method was conducted according to the standard EN ISO 7384:2001 [23] and EN ISO 7539-1:1995 [24]. Corrosion tests were carried out in 3.5% NaCl solution on samples with dimensions about 20×15 mm. The specimens were cut along to rolling direction from steel sheet-metals in its delivery state and after cold rolling with a draft of 10-70%. Before starting the analysis the samples were cleaned in 95.6% ethanol and weighed on analytical balance. The corrosion test was realized at room temperature, whereas the time of the test was equal 87 days. Value of corrosion loss was calculated using the following dependence (1):

$$V_c = \frac{\Delta G}{A \cdot t} \left[ \frac{g}{m^2 \cdot day} \right] \quad (1)$$

where:  $\Delta G$  - mass loss of a sample [g],  $A$  - surface of a sample [ $m^2$ ],  $t$  - time of the measurement [day].

Table 1.  
Chemical composition of the investigated steels

Steel heat X5CrNi18-10	Type of analysis	Chemical composition in mass %										
		C	Mn	Si	P	S	Cr	Ni	N	Mo	Cu	Fe
A	ladle analysis	0.030	1.31	0.39	0.030	0.004	18.07	8.00	0.044	0.25	-	bal.
B		0.033	1.32	0.41	0.026	0.002	18.08	9.03	0.026	0.23	-	bal.
C		0.047	1.12	0.42	0.028	0.006	18.35	8.06	0.060	0.28	0.36	bal.
Standard steel grade X5CrNi18-10	by PN-EN 10088-1 :2007	Chemical composition in mass %, according to standard										
		≤0.07	≤2.0	≤1.0	≤0.045	≤0.015	17-19	8-11	≤0.11	-	-	bal.

Linear corrosion rate was determined basing on the dependence (2):

$$V_p = V_c \cdot k \left[ \frac{mm}{year} \right] \quad (2)$$

where:  $V_c$  - value of corrosion loss  $\left[ \frac{g}{m^2 \cdot day} \right]$ ,  $k$  - ratio including

mass loss of a sample and linear corrosion rate calculated by the formula:  $k = \frac{365}{1000 \cdot \rho}$  where  $\rho$  - density of material  $\left[ \frac{g}{cm^3} \right]$ .

The corrosion resistance test was realized by recording the anodic polarization curves with the use the potentiodynamic method. The VoltaLab® PGP 201 system for electrochemical tests was applied (Fig. 1). The tests were carried out at room temperature in electrolyte simulating artificial sea water (3.5% NaCl) on specimens of size 30×20mm with an exposed samples area of about 1 cm<sup>2</sup>.

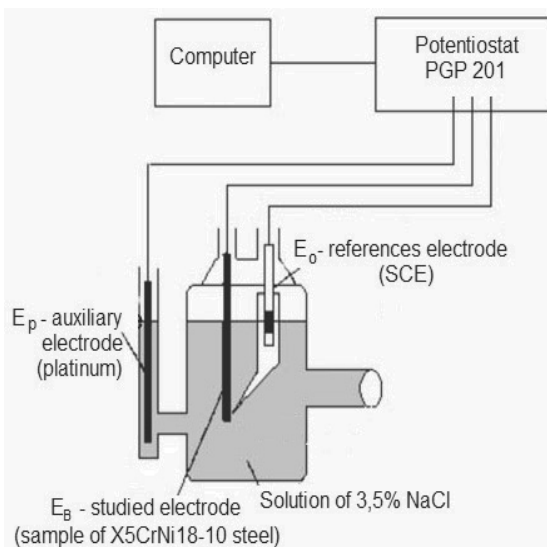


Fig. 1. Diagram of the corrosion resistance set

Registering of anodic polarization curves was conducted at the potential rate equal to 1 mV/s. The measurement of corrosion potential was realized in time of 60 min. The Saturated Calomel Electrode (SCE) was applied as the reference electrode, the auxiliary electrode was platinum electrode.

According to registered curves the corrosion potential ( $E_{cor}$ ), polarization resistance ( $R_p$ ) and corrosion current density ( $i_{cor}$ ) were determined.

In order to calculate the corrosion current, the Stern-Geary equation was used [25]:

$$R_p = \frac{b_k \cdot b_a}{2.3 \cdot i_{cor} (b_a + b_k)} \left[ k\Omega \cdot cm^2 \right] \quad (3)$$

where:  $b_k$  - the slope coefficient of the cathodic Tafel line,  $b_a$  - the slope coefficient of the anodic Tafel line,  $i_{cor}$  - the corrosion current density [ $\mu A/cm^2$ ],  $R_p$  - the polarization resistance [ $k\Omega \cdot cm^2$ ].

Microscopic examinations of the structure of austenitic X5CrNi18-10 stainless steels were performed on longitudinal polished microsections and chemically etched in the reagent Mi17Fe heated to a temperature of about 40°C, according to standard PN-61/H-04503 [26]. Metallographic observations of the structure and non-metallic inclusions were performed in a light microscope LEICA MEF4A, equipped with a Leica Qwin image analyzer with a magnification of 500-1000x.

Examinations of the surface morphology after corrosive tests in 3.5% NaCl solution were executed in the electron scanning microscope SUPRA™25 produced by ZEISS with the accelerating voltage 20 kV, applying the magnification of 500-5000x.

### 3. Results and discussion

The metallographic investigations permit to assess the steel structure grade X5CrNi18-10 in the delivery state and to define the influence of the degree of plastic deformation on its cold rolled structure with a draft from 10 to 70%.

The results of metallographic observations are presented on microphotographs (Figs. 2-3).

It was found that structure of three steel grades A, B and C in the delivery (Fig. 2) state shows typical equiaxed austenite grains with micro-hardness amount about 162 HV<sub>0.05</sub> (for steel A), 183 HV<sub>0.05</sub> (for steel B), 155 HV<sub>0.05</sub> (for steel C) and the presence of annealing twins. It also exhibits a few non-metallic inclusions probably of oxides, carbonitrides and sulphides.

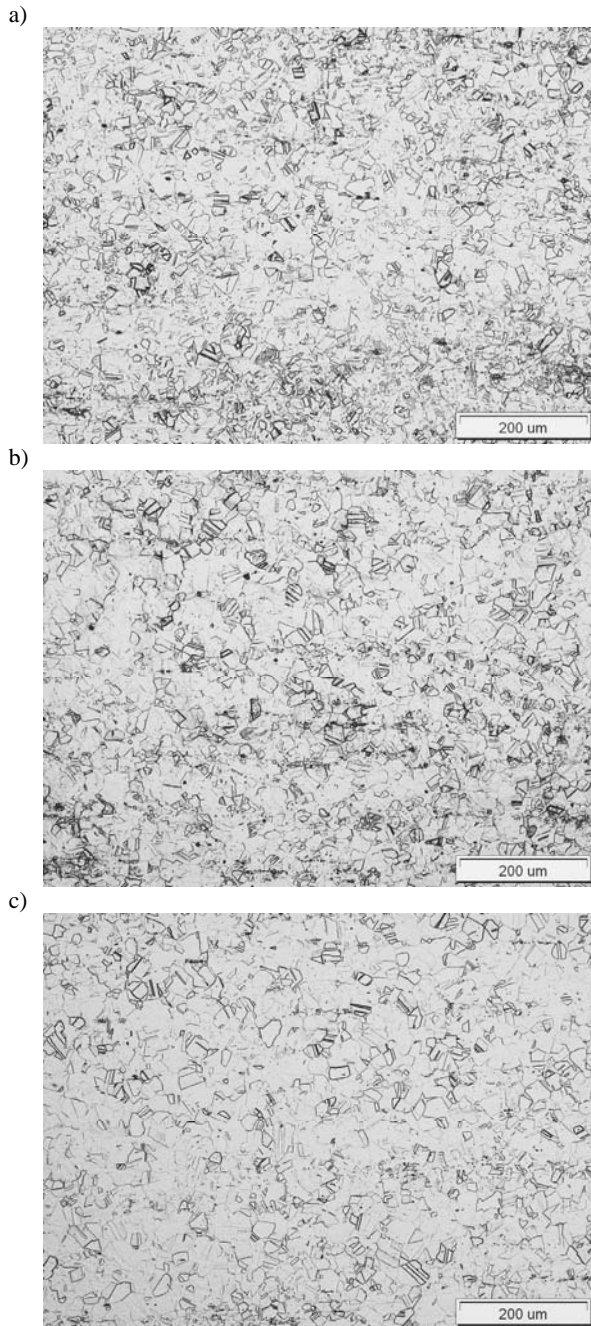


Fig. 2. Microstructure of the investigated steel grade X5CrNi18-10 in the delivered state; a), b), c) microstructure of steel A, B and C, respectively; Etching-Mi17Fe

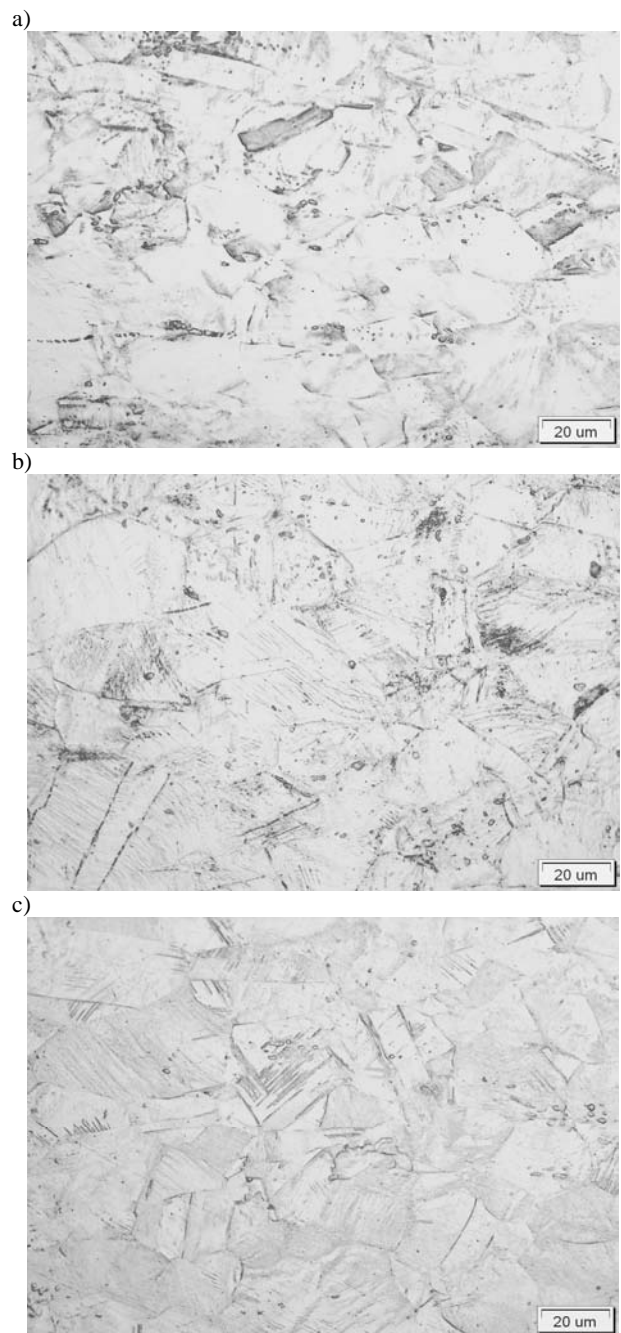


Fig. 3. Structure of the investigated steel type X5CrNi18-10 after deformation with a draft of 30%; a), b), c) microstructure of steel A, B and C, respectively; Etching - Mi17Fe

Sparse non-metallic inclusions indicate a large metallurgical purity of the all examined steel melts. The quality assessment of a non-metallic inclusion was carried out in accordance with a standard PN-EN 10247:2007 [27]. Additionally, in structure of C steels, the agglomerations of copper precipitations were affirmed, that proves the incomplete introduction of this element

to the  $\gamma$  solution. Therefore this element does not slow down the form of martensitic  $\alpha'$  phase in steel X5CrNi18-10 deformed with small drafts degree.

The microstructures of the studied A, B, C melts of the X5CrNi18-10 steel after cold rolling with a drafts of about 10% are characterized by austenite grains with slip bands and deformation twins. Deformation with a larger draft causes in the steel structure elongated  $\gamma$  grains in the rolling direction. The micro-hardness of the cold rolled samples amounts to 227 HV<sub>0.05</sub> for steel A, 279 HV<sub>0.05</sub> for steel B and 234 HV<sub>0.05</sub> for steel C.

After plastic deformation with a draft of 20 to 30% in all melts next to austenite grains, slip bands and deformation twins a few areas of parallel plates characteristic for martensite  $\alpha'$  were observed (Fig. 3). During rolling in applied reduction the micro-hardness of steel A increase from about 288 HV<sub>0.05</sub> to about 321 HV<sub>0.05</sub>, from about 316 HV<sub>0.05</sub> to about 405 HV<sub>0.05</sub> for steel B and from about 287 HV<sub>0.05</sub> to about 295 HV<sub>0.05</sub>.

Metallographic observations of A, B and C steel structure deformed at a degree from about 40 to 70% show the large areas of elongated austenite with small parallel lines of martensitic  $\alpha'$  phase. With the increasing deformation within the above ranges the micro-hardness of melts A, B and C increases from about 331 HV<sub>0.05</sub> to about 400 HV<sub>0.05</sub>, from about 425 HV<sub>0.05</sub> to about 554 HV<sub>0.05</sub>, from about 331 HV<sub>0.05</sub> to 415 HV<sub>0.05</sub>, respectively. It was affirmed that after maximum cold reduction the steel B is the hardest of all investigated melts of X5CrNi18-10 steel.

It is already known that in metastable austenitic stainless steel during plastic deformation the ( $\gamma \rightarrow \alpha'$ ) phase transformation takes place [28]. Increase in hardness in this type of transformation can either be due to increase in dislocation density within the austenitic matrix which provides better conditions for transformation of austenite to martensite or increase in twin boundaries. In addition, by increasing the amount of deformation, the hardness of the matrix increases because of higher formation of dislocation and their interaction with each other, but this cause higher stability of austenite which in turn causes a lower rate of martensitic transformation. So, at higher amounts of strain it is expected that the rate of increasing of hardness reduces as a result of the reduction in the rate of martensite formation [29].

The static tensile test shows that in delivery state steel A characterized by the highest yield point  $R_{p0.2}$  displays about 330 MPa, while steel C shows  $R_{p0.2}$  about 302 MPa and steel B only 300 MPa. Similarly in the case of tensile strength  $R_m$ , the highest strength has steel A about 647 MPa, steel C about 630 MPa and the lowest tensile strength has steel B, about 624 MPa. The elongation A is almost on the same level for these three steels and amounts to about 53%. Steel A, B and C have a considerable different reduction of area Z. Steel C is distinguished by the highest value of Z about 66%, followed by steel B with Z about 54% and steel A with the lowest reduction of area amounting to about 48%.

Cold rolling within the range of 10-50% cause that the mechanical properties of all investigated melts of X5CrNi18-10 steel increase, while the plasticity decreases. It was observed that

the yield point of steel A increases from about 586 MPa to about 969 MPa, the tensile strength from about 784 MPa to about 1257 MPa, while the elongation decreases from about 32% to about 1% and the reduction of area from about 45% to about 15%. In these same conditions steel B is characterized by similar mechanical and plastic indices. It's  $R_{p0.2}$  increases from about 542 MPa to about 1059 MPa, the  $R_m$  from about 783 MPa to

about 1228 MPa, while the A decreases from about 35% to about 2% and the Z from about 50% to about 13%. During plastic deformation with the same degree the yield point of steel C increasing from about 535 MPa to about 1198 MPa, the tensile strength from about 763 MPa to about 1295 MPa, while the value of elongation decreasing from about 37% to about 2% and the reduction of area from about 58% to about 29%.

It was affirmed that after maximum degree of deformation, about 70% steel C is characterized by the highest values of  $R_{p0.2}$  about 1259 MPa, while steel A and B show a little lower value of  $R_{p0.2}$ , amounting to about 1161 MPa (steel A) and 1148 MPa (steel B). At the same reduction level the highest value of tensile strength demonstrate steel A, while steels B and C shows a similar value of  $R_m$ , about 1452 MPa and about 1433 MPa, respectively.

After 70% of deformation the plasticity of all investigated steel melts received very low value. For steel B and C the elongation is at the same level, amounts about 1%, while steel A show a little lower value of elongation- about 0.68%. The same effect was observed in case reduction of area. It was affirmed that after maximum deformation steel C is characterized by values of the reduction of area Z by about 23%, while steel A shows about 11% and steel B only 10%

On the basis of researches of the mechanical properties it was found that with the increasing deformation of the X5CrNi18-10 steel the strength properties increases, while the plastic properties decrease proportionally to the degree of deformation during the cold rolling.

The conducted corrosive investigations with gravimetric method permit to determine the influence of a degree of plastic deformation on unitary mass lost ( $V_c$ ) and the linear corrosion rate ( $V_p$ ) of cold rolled samples from austenitic steel type X5CrNi18-10 immersed in 3.5 % NaCl solution. The mass lost of a samples ( $V_c$ ) was counted with dependence (1), whereas the linear corrosion rate ( $V_p$ ) was determined using the formula (2). The ratio binding mass loss of a sample with linear corrosion rate (k) carries out about 0.0462 for all investigated steel grade X5CrNi18-10.

On the basis of the carried out corrosion test in 3.5% NaCl solution it was found that for all investigated steel grades in their delivery state the value of the linear corrosion rate ( $V_p$ ) was lower than 0.001 mm/year, what proves of about total corrosion of those materials.

The results of the corrosion test samples after plastic deformation within the range from 10 to 70% show that the average linear corrosion rate of steel A amounts about 0.008 mm/year, while steel C and B shows a little lower value of  $V_p$ , 0.004 mm/year and 0.002 mm/year, respectively. On the basis of calculation values of  $V_p$  and according to the standard EN ISO 7539-1:1995 steel A is characterized by the second degree of corrosion resistances, while steel B and C demonstrate third degree of corrosion resistance. It was found that cold rolled samples shows a little lower resistance on corrosion in artificial sea water than material in delivery condition.

Fractographic analyses of sample surface put to corrosion tests allowed to evaluate the type and the degree of corrosion damages.

Metallographic observations of sample surface after corrosion test using weight method showed numerous corrosion damages. The view of sample surface after corrosion tests in 3.5% NaCl solution carried out for 87 days is presented in Fig. 4.

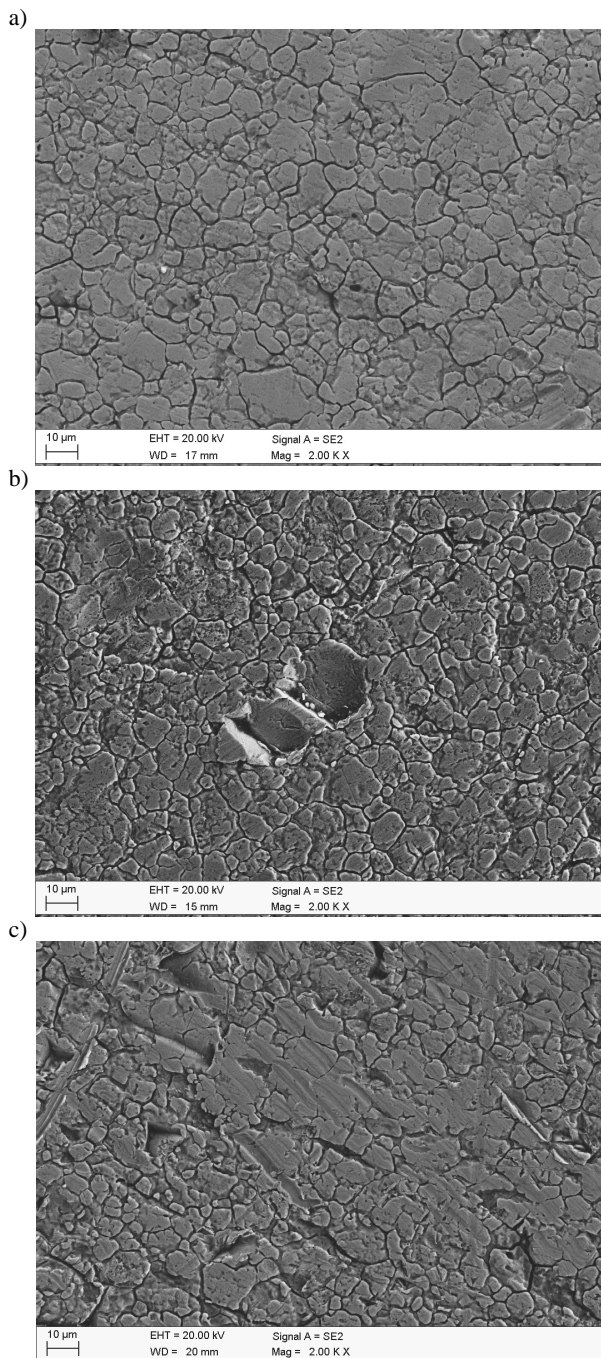


Fig. 4. Surface of specimens of the investigated steel grade X5CrNi18-10 after immersion tests in the 3.5% NaCl; steel in delivery state; a), b), c) microstructure of steel A, B and C, respectively

The morphology observations of surface samples of steel A in delivery state disclose local damages assume shape of cracks, fissure and pits. On the surface of investigated samples some non-metallic inclusions, micropores as well as linear arranged corrosion failure were observed (Fig. 4a).

In the same state on surface sample of B steel, the damage in figure of craters, the cracked passive layer and symptoms of intercrystalline corrosion running by the borders of grains were disclosed (Fig. 4b). The occurrence of intercrystalline corrossions is connected with releases of chrome carbides ( $M_{23}C_6$ ) on grain borders as well as with impoverishment border areas of grains in chrome. Additionally, on surface of B samples the effect of cold rolling was observed.

Pointwise pits as well as cracked passive layer probably are results of quick penetration of corrosion environment in deep of investigated samples of steel C (Fig. 4c).

The surfaces of the studied A, B, C melts of the X5CrNi18-10 steel after cold rolling with a drafts of about 10 to 70% and immersed in 3.5% NaCl solution for 87 days the numerous pits and micropores with diversified size were revealed (Figs. 5a, b, c), however the pits present on the surface of samples coming from deformed state were characterized by bigger sizes in relation to the pits observed on samples in delivery condition. Damaging of a superficial layer occurred around the pits (Fig. 5b). Cracked passive layer was also observed, what could be a result of rapid penetration of corrosive medium into interior of investigated specimens. On all investigated surface samples, the traces of intercrystalline corrosion running by the borders of grains and numerous pits with designate effects of cold rolling were observed (Fig. 5). The microscopic observations also disclosed the occurrence of spares non-metallic inclusions on surfaces specimens after corrosion tests in artificial sea water.

The metallographic investigations of samples after corrosion tests permit to define that degree of plastic deformation have significant influences on intensive and character of corrosion changes. On the basis of investigations it was stated as for increase of deformation within the range of 10-70 % the quantity, size and depth of pits increases. Conducted observations indicate on the fact that the pits surfaces fulfil a function of anode a local corrosion cell where proceeds metal digestion.

The potentiodynamic examinations of the samples A, B, C made of investigated X5CrNi18-10 metastable steel showed diverse corrosion resistance in 3.5% NaCl solution (Figs. 6, 7, 8).

The corrosion potential value of steel A contain in the range  $E_{corr} = -10.6 - -7.5$  mV. The recorded anodic polarization curves indicate the existence of passive range. The values of breakdown potential equal to  $E_{np} = +104 - +440$  mV. When the current density reached  $3 \text{ mA/cm}^2$  the direction of anodic polarization of samples was changed. The change of the polarization direction caused increase of the current density.

Additional parameters describing the corrosion resistance of investigated samples were determined by the Stern-Geary equation: polarization resistance  $R_p$  and corrosion current density  $i_{corr}$ .

The values of the corrosion parameters for sample A were in the range  $R_p = 103.7 - 526.7 \text{ k}\Omega\text{cm}^2$ ,  $i_{cor} = 0.017 - 1.1806 \text{ }\mu\text{A/cm}^2$  (Fig. 6a).

Next researches were carried out on the B melts of steel X5CrNi18-10. It was found that the corrosion potential value was in the range  $E_{corr} = -91.4 - -48.5$  mV. The values of breakdown potential equal to  $E_{np} = +245 - +360$  mV. When the current density reached  $3 \text{ mA/cm}^2$  the direction of anodic polarization of samples was changed. The other parameters describing the corrosion resistance of investigated B samples were determined using the Stern-Geary equation were in the range:  $R_p = 462.1 - 871.6 \text{ k}\Omega\text{cm}^2$ ,  $i_{cor} = 0.010 - 1.16 \text{ }\mu\text{A/cm}^2$  (Fig. 6b).

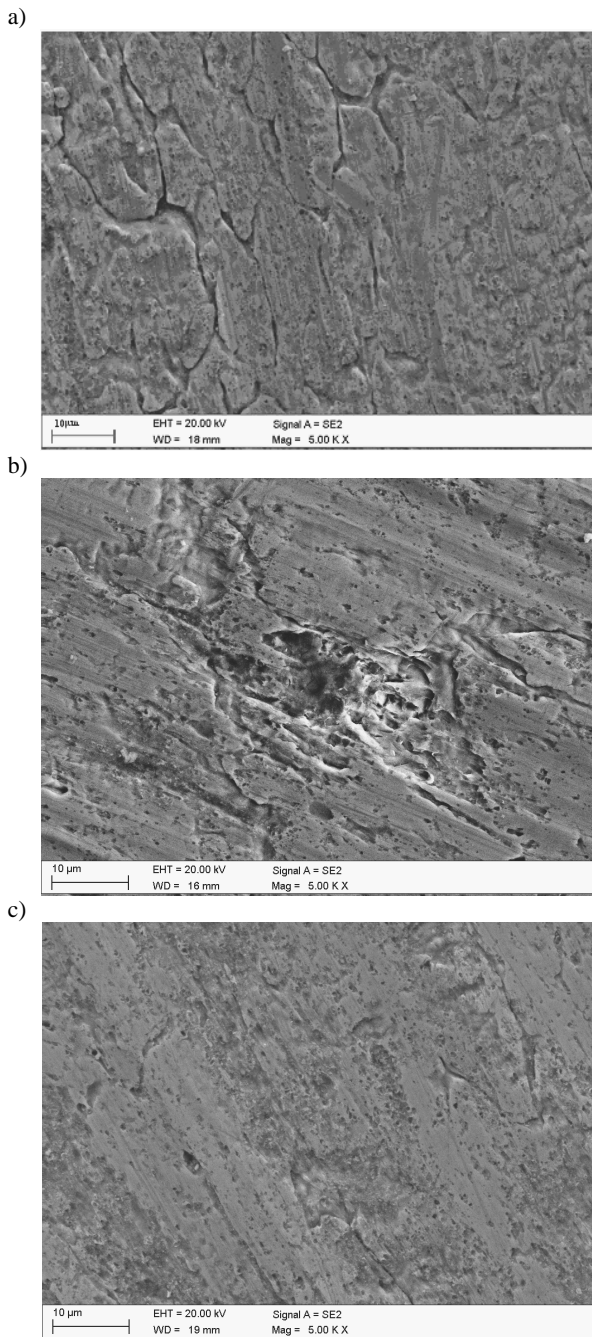


Fig. 5. Surface of samples of investigated steel grade X5CrNi18-10 after immersion tests in the 3.5% NaCl; steel after deformation with a draft of about 70%; a), b), c) microstructure of steel A, B and C, respectively

Further investigations were carried out on the C samples. The course of changes of current density in a function of potential for the sample investigated in 3.5% NaCl solution is presented in Fig. 6c. The value of corrosion potential for C melts were on the level  $E_{cor} = -282.6 - -3.9$  mV, polarization resistance  $R_p = 114.0 - 469.0$

$k\Omega cm^2$  and the density of corrosion current determined basing on the Stern-Geary equation was equal to  $i_{cor} = 0.029 - 0.058 \mu A/cm^2$ .

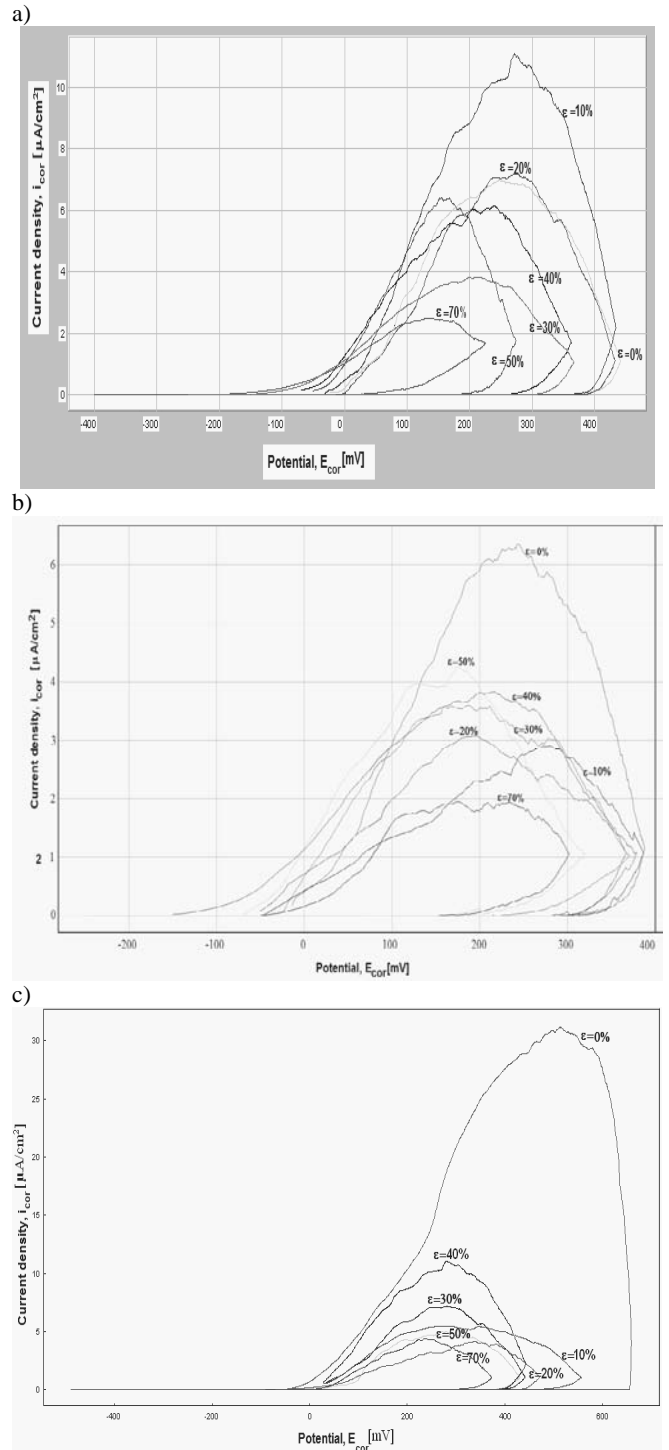


Fig. 6. Anodic polarization curves of the investigated cold rolled steel grade X5CrNi18-10; a) A steel, b) B steel, c) C steel

When the current density reached  $3 \text{ mA/cm}^2$  the direction of anodic polarization of samples was changed.

Performed electrochemical analysis in solution, which simulated artificial sea water revealed that steel B in its delivery state is characterized by the highest corrosion resistance of all investigated melts of X5CrNi18-10 (the density of corrosion current  $i_{\text{corr}}$  is on the level  $0.010 \text{ } \mu\text{A/cm}^2$ ). A little lower corrosion resistance in the delivery state shows steel A, which corrosion current density carries out about  $0.017 \text{ } \mu\text{A/cm}^2$ . The results of corrosion researches suggested that the lowest corrosion resistance was observed for non-deformed C steel for with corrosion current density was about  $0.029 \text{ } \mu\text{A/cm}^2$ .

With the corrosion current values of A, B and C investigated steels correlated the results of the polarization resistance  $R_p$ . Evaluated polarization resistance of B samples indicate on the fact, that this steel shows the best corrosion behaviour in examined solution ( $R_p = 871 \text{ k}\Omega\text{cm}^2$ ). Steel A is characterized by average value of polarization resistant amounts about  $R_p = 526 \text{ k}\Omega\text{cm}^2$ . In the case of C steel it was stated the significant decrease of polarization resistance value ( $R_p = 469 \text{ k}\Omega\text{cm}^2$ ).

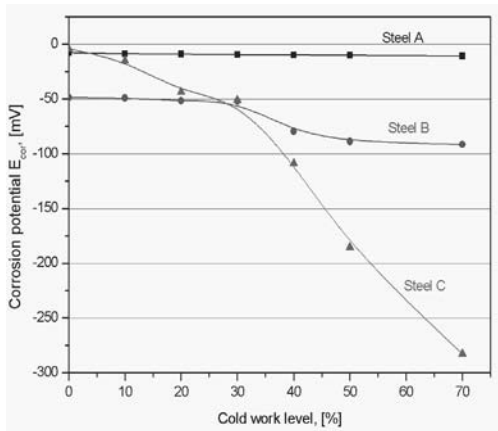


Fig. 7. Changes of the corrosion potential of investigated cold rolled steel A, B and C depending on a degree of deformation

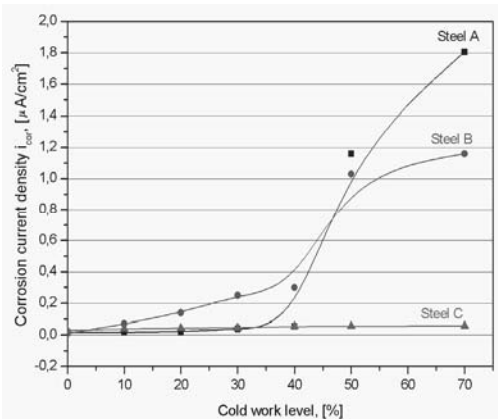


Fig. 8. Changes of the corrosion current density of investigated cold rolled steel A, B and C depending on degree of deformation

On the basis of the carried out examinations it was found that at the increase of a degree of plastic deformation within the range of 10 - 70 % samples of A, B, C steel after corrosion test are characterized by the lower values of corrosion potential (Fig. 7), as well as higher values of corrosion current density (Fig. 8), what proves that the material rapidly corrode.

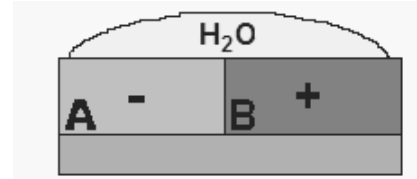


Fig. 9. Scheme of corrosion behaviour of material at a homogeneous degree of deformation

Additionally it was found that in results of local plastic deformation in X5CrNi18-10 austenitic steel the homogeneous microstructure was formed that leads to the local decrease of corrosive resistance of this material. Fig. 9. shows the corrosion behaviour of homogeneous material formed during such plastic working. In place A, characterized by a higher draft degree, the material will be demonstrated lower value of corrosion potential in relationship to the B area. In the results of that this area will show the anodal character regarding to the rest of the material.

#### 4. Conclusions

Metallographic investigations of samples A, B, C in their delivery state showed that the steel X5CrNi18-10 has a single-phase austenitic microstructure with numerous annealing twins as well as non-metallic inclusions. After plastic deformation in the range from 10 to 70% the martensite  $\alpha'$  phase and slip bands were revealed in the microstructure of metastable austenitic steel.

Plastic deformation of steel A, B, C in cold rolling process causes the increase of the mechanical properties ( $R_m$ ,  $R_{p0.2}$ ,  $HV_{0.05}$ ) and decreasing of plasticity (A, Z).

Metallographic observations of surface of samples A, B, C after corrosion tests showed corrosion damages diversity. After investigations in 3.5% NaCl solution numerous corrosion pits were revealed. The same corrosion effects were observed on samples deriving from the immersion tests and after potentiodynamic analyses.

Corrosion tests carried out using weight method revealed that for all investigated steel grades in their delivery state the value of the linear corrosion rate ( $V_p$ ) was lower than  $0.001 \text{ mm/year}$ , what proves of about total corrosion of those materials. Samples after plastic deformation within the range from 10 to 70% are characterized by an average linear corrosion rate of steel A amounts about  $0.008 \text{ mm/year}$ , while steel C and B show a little lower value of  $V_p$ ,  $0.004 \text{ mm/year}$  and  $0.002 \text{ mm/year}$ , respectively. On the basis of calculation values of  $V_p$  and according to the standard EN ISO 7539-1:1995 steel A is characterized by the second degree of corrosion resistances, while steel B and C demonstrate third degree of corrosion resistance. It was found that cold rolled samples shows a little lower resistance on corrosion in artificial sea water than material in delivery state.



Performed electrochemical analysis in solution, which simulated artificial sea water revealed that steel B in its delivery state is characterized by the highest corrosion resistance of all investigated melts of X5CrNi18-10 (the density of corrosion current  $i_{\text{corr}}$  is on the level  $0.010 \mu\text{A}/\text{cm}^2$ ).

With the increasing of degree of plastic deformation within the range of 10 - 70 % samples of A, B, C steel after corrosion test are characterized by the lower values of corrosion potential, as well as higher values of corrosion current density, what proves that the materials rapidly corrode. The corrosion resistance in 3.5% NaCl solution of cold rolled austenitic steel grade X5CrNi18-10 has an essential meaning in industrial applications in this group of materials.

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