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Influence of plastic deformation of S235JR steel rods on their mechanical properties and corrosion behavior in NaCl solution

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Abstract. Studies show that although commonly used steels are standardized, some of their mechanical properties (such as tensile strength) vary widely and knowledge of their corrosion behavior is insufficient. Additional treatments, such as plastic deformation, alter the structure of carbon steels and affect their properties. This article explores one of the most widely used materials in mechanical and civil engineering – steel S235. Two types of rods, 6 mm in diameter, from hot-rolled non-alloy structural steel (S235JR, BDS EN 10025-2: 2005) and bright cold drawn steel (S235JRC, BDS EN 10277-2: 2008) have been tested. Tensile tests have been carried out, stress-strain curves are constructed and compared, the main mechanical properties such as yield strength, tensile strength and modulus of elasticity are determined. The typical consequences of plastic deformation such as increased yield strength have been identified. The assessment of corrosion behavior was done by means of the weight loss method in a 3,5% NaCl water solution for 5 weeks. It was found out that in the studied period the two types of rod exhibit close corrosion resistance, with the tendency for the cold drawn steel to have a higher uniform corrosion rate over a longer period.

1 Introduction

Low-cost carbon steels are used as the preferred construction material across industries and are considered to be a more economical option than the costly corrosion-resistant alloys [1]. Carbon steels typically contain less than 1,5% of carbon (C). Depending on the carbon content they are divided into 3 groups – low carbon steels (<0,25% C), medium carbon steels (0,25-0,70% C) and high carbon steels (0,70-1,05% C). The different carbon content leads to different mechanical properties of steel such as strength, ductility, hardness, etc., which determines their application. Thus, for example, steel with a content of about 0,08 wt% C is good to form and has good ductility, steel with 0,18 wt% C is useful for general application and good for welding, etc.

Carbon steels are used in a wide range of applications, such as structural components, industrial pipes, pipelines that supply gas and oil, construction and others. In general, they are susceptible to corrosion under the conditions of industrial operations.

An important consequence of steel corrosion is the deterioration of its mechanical properties. Change in steel behavior can lead to unexpected problems and even to the undesired brittle failure due to a reduced cross section [2-4]. That is why it is of great importance to study the impact of corrosion on the mechanical properties in order to be able to make a correct assessment of the corroded steel structures. This allows for the building of models for adequate forecasting and evaluation of the behavior and safety of these constructions.

It has been found out that mechanical treatment impacts the corrosion resistance of steel. Deformation conditions, such as hot rolling and cold rolling parameters affect texture development in steel. Rolling schedule, rolling temperature, reheating time and temperature, etc., are some of the important parameters to consider for texture development, which can cause significant changes to material properties. Surface texture (also referred to as preferred orientations), is one of the important parameters related to corrosion. Other parameters such as microstructure, chemical composition, defects and surface energy of crystal planes, also affect the corrosion properties of steel [1].

Hot plastic deformation is carried out in temperature-rate conditions, which lead to full recrystallization during the process, and does not cause work strengthening of metals and alloys. Cold plastic deformation takes place in temperature-rate conditions, which do not allow for recrystallization to occur. This leads to significant work strengthening of metals and alloys [5].

The purpose of this paper is to study the mechanical characteristics and corrosion behaviour of two varieties of one of the most widely used non-alloy structural steel – S235. The steel is formed into rods with a diameter of 6 mm. In one variety the rods are hot rolled, and the material has the standard designation S235JR, BDS EN 10025-2: 2005. In the other variety the rods are cold drawn, and the material has the standard designation S235JRC, BDS EN 10277-2: 2008. The mechanical characteristics are determined before the beginning of the corrosion process. Corrosion behaviour is studied in a model corrosion

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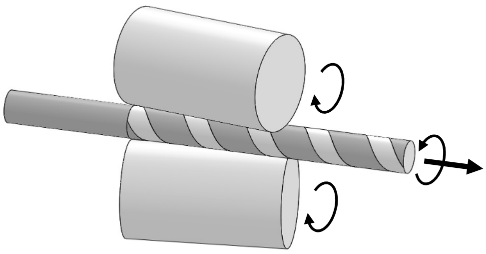
solution – 3,5% water solution of NaCl. The results presented here belong to the initial stage of a comprehensive study of the impact of corrosion on the mechanical properties of steel S235JR and S0235JRC rods.

2 Specific features of hot rolling and cold drawing

Hot rolling is a process, which removes defects from previous technological operations in manufacturing the workpiece and achieves the required form and quality of the surface. In hot screw rolling (Fig. 1*a*) the workpiece passes through crossed rolls, which rotate in the same direction and give it a rotary and progressive motion. The process of deformation leaves a spiral trace on the workpiece as can be seen in the picture of the rod in Fig.1*b*.

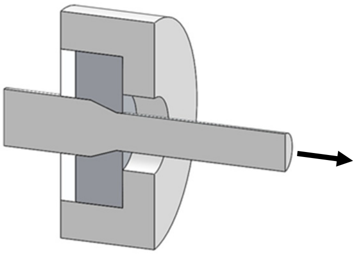


a)

b)

Fig. 1. Hot screw rolling. *a*) Basic schematic view of the process; *b*) Picture of the surface of the rod, from which the tested test pieces have been made.

Drawing through a nozzle is a technological process of metal working using plastic deformation, where workpieces are deformed by compulsory passing them through an opening under tensile force [5], Fig. 2*a*. An exact form and size of the cross section of the workpieces is achieved as well as clean and smooth surface. Fig. 2*b* shows a picture of the surface of cold drawn steel.



a)

b)

Fig. 2. Cold drawing. *a*) Schematic view of the process of drawing through a nozzle; *b*) Picture of the surface of the rod, from which the tested test pieces are made.

In order for the process of drawing to take place the stress created by the drawing force in the already drawn part of the workpiece must not reach the yield limit. That condition can be satisfied only if plastic deformation goes together with work hardening. This means that the process of drawing through a nozzle cannot take place in the conditions of hot plastic deformation. Plastic deformation and work hardening in cold drawing considerably change the stress-strain curve of material and its strength-deformation characteristics. The changed structure and surface impact its corrosion behaviour.

3 Chemical composition

The chemical composition of the tested test pieces is given in Table 1. The table compares them with the standard values too. As can be seen, the chemical composition as a whole corresponds to the stipulations in the standard. There are differences between the two steels, however. In cold drawn steel S235JRC, the content of C and Mn is considerably lower than the limit value, but on the other hand small quantities of Si and Cr have been added. The composition of the test pieces of S235JRC is better than that of the hot rolled steel S235JR in its content of sulphur and phosphorus – apart from the fact that the content of these elements is lower in the cold drawn material, it is considerably lower than the limit value set in the standard. Obviously, the chemical composition has been changed in order to improve deformability, which is very important for cold drawing. Variations in the chemical composition, which are permitted in the respective standards, however, inevitably affect the mechanical properties and the corrosion behaviour. Table 1 shows that with the commonly used types of steel, even when they fully meet the standards, it is necessary to test each batch if their properties are to be defined exactly.

Table 1. Chemical composition of the test pieces and standard values.

Element	Hot rolled steel S235JR		Cold drawn steel S235JRC	
	Test pieces	EN10025-2: 2005, max	Test pieces	EN10277-2: 2008, max
C, %	0,17	0,17	0,08	0,17
Si, %	-	-	0,2	-
Mn, %	1,4	1,4	0,08	1,4
P, %	0,035	0,035	0,027	0,04
S, %	0,035	0,035	0,027	0,04
Cr, %	-	-	0,1	-
Cu, %	0,5	0,55	-	0,55
N, %	0,012	0,012	-	0,012

4 Mechanical tests

In order to determine the mechanical properties of the studied steel we have conducted tensile tests on a modernized tensile testing machine ZD10 with screw loading mechanism, which through digital control allows for precise loading (Fig. 3), in accordance with BS EN ISO 6892-1:2016. The results of these tests are needed to compare the two grades of steel, as well as a starting point for determining the change in the mechanical properties when corrosion develops.

Three test pieces of each of the studied steels were tested. In order to measure the test piece extension we have used self-supporting extensometer SCHENCK with a gauge length of 25 mm. The test pieces are subjected to pure tension and the tensile force and longitudinal elongation (extension) are recorded. The set testing speed is 1050 kg/min.

Fig. 3. Modernized mechanical tensile testing machine ZD10. The force is measured with precise 100 kN load cell, the extension with a longitudinal extensometer. The signals are recorded in a computer with special software.

Fig. 4 shows the stress-percentage extension curves of the studied steels. The damage of the test pieces has occurred in the gauge length of the extensometer. Table 2 presents the values of the following parameters determined in Fig. 4:

- Tensile strength R_m – the stress corresponding to the maximum force, which the test piece can bear during testing;
- Upper yield strength R_{eH} – the value of stress when the first decrease in the force is observed. It is determined for hot rolled steel, in which there is physical yielding;
- Proof strength, plastic extension $R_{p0,2}$ – the stress, under which the relative percentage extension is equal to 0,2%. It is determined for cold drawn steel, which does not have a physical yield limit;
- Modulus of elasticity E – the tangent of the angle between the linear part of the stress-percentage extension curve and the *x*-axis.

In Fig. 4 and Table 2 it can be seen that the two grades of steel have different stress-percentage extension curves. The differences are as follows:

- Lack of yielding in S235JRC;
- Increased by 33% yield strength of S235JRC as compared to S235JR;
- Slightly higher tensile strength (12%) of S235JRC as compared to S235JR;
- Considerably decreased percentage of total extension at fracture (61%) in S235JRC as compared to S235JR.

These differences are foreseeable and can easily be explained with the lack or presence of previous plastic deformation, as well as with the differences in the chemical composition of the tested grades of steel.

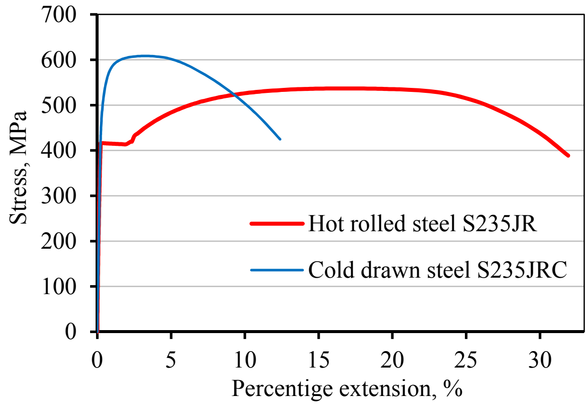


Fig. 4. Stress-percentage extension curve of S235JR and S235JRC steel under tension.

Table 2. Material constants of S235JR and S235JRC steel, determined in Fig. 4.

Value	Yield strength		Tensile strength		Elastic modulus	
Designation, unit	R_{eH}, MPa	$R_{p0,2}$, MPa	R_m, MPa		E, GPa	
Steel S235	JR	JRC	JR	JRC	JR	JRC
Test 1	416	558	537	608	206	208
Test 2	419	564	546	612	204	204
Test 3	421	554	546	606	208	212
Average	**419**	**559**	**543**	**609**	**206**	**208**

5 Corrosion behavior

Corrosion tests are carried out under the standard NACE ASTM TM0169/G31-12a procedure. The shape and size of the test pieces subjected to corrosion testing are shown in Fig.6. Three test pieces have been used for each measurement. A picture of a group of test pieces, cleaned after the experiment, is shown in Fig. 6b.

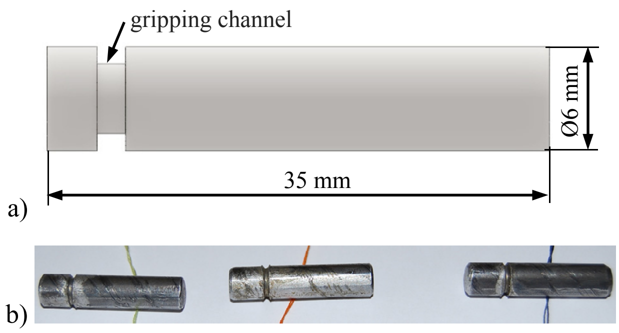


Fig. 6. Test pieces for corrosion testing. a) Overall dimensions; b) General view of the test pieces from S235JR steel, immersed in corrosive solution for 35 days.

Fig. 7 presents four groups of 3 test pieces immersed in corrosive solution. The specific colouring of the solution and the sediment from corrosion products can be seen.

Fig. 7. Test pieces from S235JR steel, immersed in corrosive solution.

Before immersion the test pieces are subjected to the following cleaning procedure: degreasing in alkaline solution (pH 12) at 65ºC for 15 min; cleaning with distilled water; submerging in acid solution (HCl + H_2SO_4); rinsing in distilled water; rinsing with ethanol to remove the residual water. After that the test pieces were weighed with an analytical balance (accuracy of 0,001g) before the immersion tests (weight $w_{b,i}$, i = 1, 2, 3).

The immersion test was performed in order to use the "weight loss method". A 3,5% NaCl (p.a.) water solution was used for this purpose, as it is known [6, 7] that this concentration is more aggressive to iron and carbon steel than natural seawater. All the experiments were performed in open air conditions and at room temperature (22°C).

The test pieces were immersed in the solution from 1 to 5 weeks. The products of corrosion formed on the surface of the test pieces, after the experiments, were removed mechanically with a soft material. This procedure is done very carefully so that only corrosion products are removed. After that they were rinsed in distilled water, dried with ethanol and weighed with the balance (weight $w_{a,i}$).

The percentage weight loss Δw_i between the initial and final states was obtained for each sample and the average value Δw for the three pieces was calculated as follows:

$$\Delta w = \frac{1}{3}\sum_{i=1}^{3}\frac{w_{b,i}-w_{a,i}}{w_{b,i}}100, \%. \qquad (1)$$

The percentage weight loss rate v was calculated as

$$v = \frac{\Delta w}{t}, \frac{\%}{\text{day}}, \qquad (2)$$

where t, in days, is the time of exposure.

The experimentally obtained Δw and v for the two tested grades of steel are presented in Table 3 and Figures 8 and 9.

The data presented here demonstrate that the corrosion behaviour of both grades of steel in the studied interval is similar. The rate of weight loss for both grades of steel is the highest in the first week (higher in steel S235JRC) with following decrease reaching a minimum in the 3rd week, after which there is new increase. The data at the end of the experiment show a trend for a higher rate of weight loss in cold rolled steel, which can be explained with the structural changes in cold drawing and the presence of residual stress from plastic deformation in the surface layer. The trend can be easily visualized as the correlation in Figures 8 and 9 can successfully be approximated by square function. That trend will be tested for an interval of one year in a new study, which has already begun, of both grades of steel.

Table 3. Percentage weight loss Δw and percentage weight loss rate v as a function of exposure time t.

Time t, days	Steel S235JR		Steel S235JRC	
	Δw, %	v, %/day	Δw, %	v, %/day
7	0,11	0,0157	0,17	0,0243
14	0,2	0,0143	0,23	0,0164
20	0,26	0,0130	0,29	0,0145
28	0,4	0,0143	0,43	0,0154
35	0,52	0,0149	0,55	0,0166

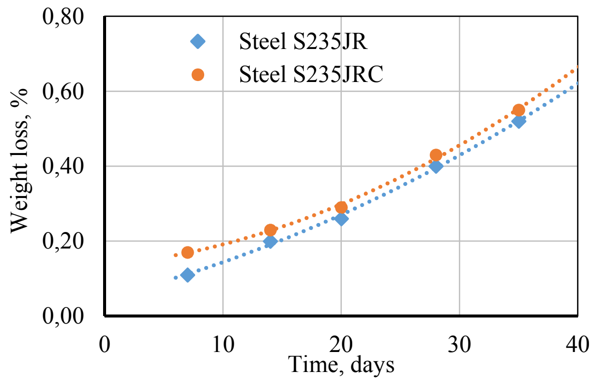


Fig. 8. Percentage weight loss Δw as a function of exposure time.

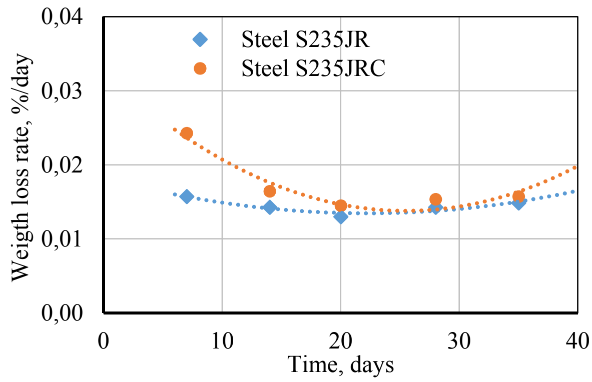


Fig. 9. Percentage weight loss rate v as a function of exposure time.

All test pieces, starting in the first week of the study, were covered with a porous layer of brown corrosion products, which is easy to clean. After it is removed the steel surface remains partially covered with black dense film composed of magnetite, which can be seen in Fig. 6b [6, 8].

The presence of a minimum in the change of the weight loss rate over time (Fig. 9) can be explained in the following way [8]: in neutral water solution and at ambient temperatures, dissolved oxygen is necessary for appreciable corrosion of iron. In air-saturated water, the initial corrosion rate may be high but diminishes over a period of days as the iron oxide film, acting as a barrier to oxygen diffusion, is formed. A study [9] explains that iron

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corrosion is initiated by pits and spreads out in the form of corrosion product layers, one of which is poorly adherent. According to the authors, the role of the occluded pits is negligible as compared with the porous film effect. At the corrosion potential two diffusion processes are detected: the diffusion across the layer and the mass transport in the liquid phase. The degree of coupling between the two processes is dependent on the immersion time. The oxygen transport is produced not only in the liquid phase but also through the porous layer of the corrosion products. Further increase in the weight loss rate can be related to the impact of chloride ions on the dense film formed. According to [10, 11] these ions enter the passive film and destroy the film only when a sufficiently high concentration gradient is created on the surface, which requires some time.

6 Conclusion

The paper presents the results from tension tests of two grades of steel – S235JR and S235JRC, in the shape of rods with a diameter of 6 mm, which are similar in chemical composition and designation, but differ in the way the metal has been worked and in the mechanical properties. We have determined the qualitative and quantitative differences in the stress-strain curves of both materials and have discussed the reasons for having them. Cold drawing has led to an increase in the yield limit by 33%, which allows for just as higher operation loads to be applied to the S235JRC steel rods. The S235JR hot rolled rods have considerably better plastic properties and can bear by 61% greater total deformations at fraction.

In order to determine the corrosion behaviour of the two grades of steel 15 test pieces from each grade were tested. They were immersed in 3,5% water solution of NaCl from one to five weeks. Each test piece was carefully cleaned and weighed before and after immersion in a corrosive medium. The results from the experiment have been presented, analyzed and explained. As expected the two types of material have similar corrosion behaviour but the cold drawn rods corrode faster.

The findings presented here are from the initial stage of an extensive study of the impact of corrosion on the mechanical properties of steel. The results from the tension tests will be used to be compared with the results from the mechanical tests of the test pieces immersed for a longer time in the same solution. The results of the 5-week test of corrosion behaviour indicate that the test pieces need to remain in the solution much longer for corrosion to be of an extent that will significantly affect the stress-strain curves. This led to the preparation and the start of a new experiment, where large groups of test pieces from the two types of material will be immersed in the solution from 2 to 12 months.

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References

1. D. Dwivedi, K. Lepková, T. Becker, Carbon steel corrosion: a review of key surface properties and characterization methods, RSC Advances, **7**(8), 4580-4610 (2017)
2. A. Almusallam, Effect of degree of corrosion on the properties of reinforcing steel rods, Construction and Building Materials, **15**(8), 361-368 (2001)
3. H. Lee, Y. Cho, Evaluation of the mechanical properties of steel reinforcement embedded in concrete specimen as a function of the degree of reinforcement corrosion, International Journal of Fracture, **157**(1-2), 81-88 (2009)
4. A. Shetty, I. Gogoi, Performance enhancement of TMT rebar in accelerated corrosion, Journal of Civil Engineering Research, **2**(1), 14-17 (2012)
5. N. Tonchev, *Material science and materials technology* (in Bulgarian), VTU “T. Kbleshkov”, Sofia (2010)
6. H. Möller, E. Boshoff, H. Froneman, The corrosion behaviour of a low carbon steel in natural and synthetic seawaters, Journal of the Southern African Institute of Mining and Metallurgy, **106**(8), 585-592, (2006)
7. S. Dexter, Corrosion in seawater. In: *S. Cramer, B. Covino (Edts.), ASM Handbook, 13C Corrosion: environments and industries*, ASM International, Ohio, 27-41 (2006)
8. R. Revie, *Corrosion and corrosion control: an introduction to corrosion science and engineering* (John Wiley & Sons, 2008)
9. D. You, N. Pebere, F. Dabosi, An investigation of the corrosion of pure iron by electrochemical techniques and in situ observations, Corrosion science, **34**(1), 5-15, (1993)
10. L. Li, C. Wang, S. Chen, X. Yang, Investigation of oscillatory electro dissolution processes by chloride ion perturbation, Proc. of 16th International Corrosion Congress, Beijing, China (2005)
11. L. Li, J. Luo, B. Lu, S. Chen, Effect of interface chloride ion perturbation on oscillatory electrodissolution. Electrochimica acta, **50**(16-17), 3524-3535 (2005)