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Influence of internal stresses on the intensity of corrosion processes in structural steel

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ABSTRACT

Introduction. The behavior of metal in a corrosive environment can be ambiguous, which is due to the peculiarities of the corrosion process. Both external and internal factors influence the corrosion process. External factors are determined by temperature, humidity, type of corrosive medium, etc., while internal factors depend on the parameters of the system (material): the presence of inclusions, phase composition, structure, and the magnitude of internal residual stresses. Internal factors ambiguously affect the behavior of the material in a certain aggressive medium, which ultimately affects the time of corrosion damage of the material and, as a consequence, the time of operation of objects made of this material. Therefore, differentiation of the influence of various internal factors on the rate of corrosion process in an aggressive environment is a priority area of research. **The purpose** of the present work is to consider the influence of the magnitude of internal residual stresses on the rate of corrosion process in an aggressive medium – 5 % sulfuric acid solution. **The object of research** conducted in the work is sheet rolled steel *St3* as received after different magnitude of plastic deformation, from which the specimens under study were made. **The methods of investigation:** microstructural study of deformed specimens was carried out on optical microscope *Olympus GX53*; software *SIAMS 800* was used to compare the structure of the obtained material with the atlas of microstructures, determine the score of grain structure, determine the anisotropy of the structure after deformation of the material; X-ray diffractometer *DRON-7* was used to register diffraction patterns and determine internal stresses; laboratory scales *SHIMADZU UW620h* was used to measure the mass of the specimens under study; tensile strength of the material's specimens was measured. **Results and Discussion.** The obtained results show that the plastic deformation of the material in the rolling direction has an ambiguous effect on the structure anisotropy. When the degree of plastic deformation increases, there is an ambiguous change in the grain anisotropy value, which is associated with the internal effects of the processes occurring in the material structure during plastic deformation, such as: sliding of the crystal lattice in the {111} <110> directions; the occurrence of reverse residual internal stresses due to the presence of inclusions in the steel structure. However, the degree of plastic deformation correlates quite well with the magnitude of internal residual stresses. The increase in the magnitude of internal residual stresses leads to an increase in the corrosion rate of structural steel *St3* in 5 % hydrochloric acid solution. The obtained dependence is described by a linear equation with a high coefficient of determination, which indicates that there is a strong relationship between the magnitude of internal residual stresses and the rate of corrosion of the material. At the same time, the coefficient of influence of internal stresses on the corrosion rate is equal to 0.72, which additionally proves the existence of interrelation between the considered parameters.

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Introduction

The presence of residual stresses in steel products can lead to warping of the surface, formation of cracks under mechanical stresses, changes in the behavior of structures under different loads and contribute to accelerated corrosion process [1–3]. In view of the fact that at the sites of industrial enterprises in most

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cases the equipment works with aggressive media that accelerate the corrosion process, the presence of internal stresses affecting this process becomes a significant factor. However, it should not be forgotten that various mechanisms [8–11] related to the presence of inclusions, the magnitude of internal stresses, the dispersion of the material, etc. take part in the process of corrosion damage. The influence of these mechanisms on the corrosion process is ambiguous, that is why it is necessary to clearly differentiate the effect of second-order stresses on corrosion processes.

There are thermal methods for treating products to reduce internal stresses such as: annealing, tempering and cold working [7]. The use of thermal methods can reduce the strength of the material or even lead to increased corrosion susceptibility.

Mechanical methods can also be used to reduce internal residual stresses. The most widespread method is based on material stretching at room temperature. The essence of the method is the plastic deformation of the material not exceeding 0.5–2% [4].

It should be clarified that plastic deformation is understood as the change in geometric dimensions remaining after the removal of the load [5]. The decrease in the magnitude of internal stresses during this kind of plastic deformation is associated with a slight distortion of the metal crystal lattice under the action of tangential stresses, resulting in irreversible displacement of atoms. After removal of external tensile stresses, the elastic component of deformation is eliminated [17, 18]. A small part of the strain remains, and the material is almost completely free from residual stresses [6]. Plastic deformation occurs due to slip and twinning processes, resulting in an increase in the number of linear defects in the form of dislocations [3, 7].

The literature review conducted shows that the influence of the residual stress state of the material on the corrosion rate is not fully studied [1–3]. Literature sources mainly consider the process of electrochemical corrosion of metal depending on the magnitude of tensile stress applied to the object [3], but there is no data reflecting the initial state of the material and its influence on the rate of corrosion process.

Based on the above, this paper examines the effect exerted by the plastic deformation of the material on the corrosion rate of low alloy carbon steel *St3*.

Research methodology

The results given in this paper are obtained on specimens made of *St3* steel sheets as received. This steel is widely used to manufacture various steel structures, pipes and equipment.

The specimens 4×70×25 mm in size were cut across the rolling direction.

Determination of internal stresses was carried out on X-ray diffractometer *DRON-7*, according to the method of *S.S. Gorelik* [3]. The method is based on the comparison of data obtained on the specimens under study with the data obtained on the reference specimens, which is an annealed material with the minimum magnitude of internal residual stresses.

Corrosion tests of the specimens were carried out in laboratory conditions for 72 hours at temperature 20 °C. A 5 % hydrochloric acid solution was used as an aggressive medium. The container with the specimens under study and aggressive medium was placed in the thermostat; there was no direct contact between the specimens under study.

The mass of specimens was determined using laboratory scales *SHIMADZU UW620h* as an average value of three measurements. Geometric dimensions of the specimens were determined using a caliper.

Corrosion tests were carried out according to the method [6]. The criterion for assessing the corrosive effect was the corrosion rate, which was calculated using the formula:

$$v = \frac{\Delta m}{St}, \tag{1}$$

where Δm is a relative weight loss (g); S is a surface area of the specimen in contact with an aggressive medium (m^2); T is a time of contact of the specimen with an aggressive medium (days).

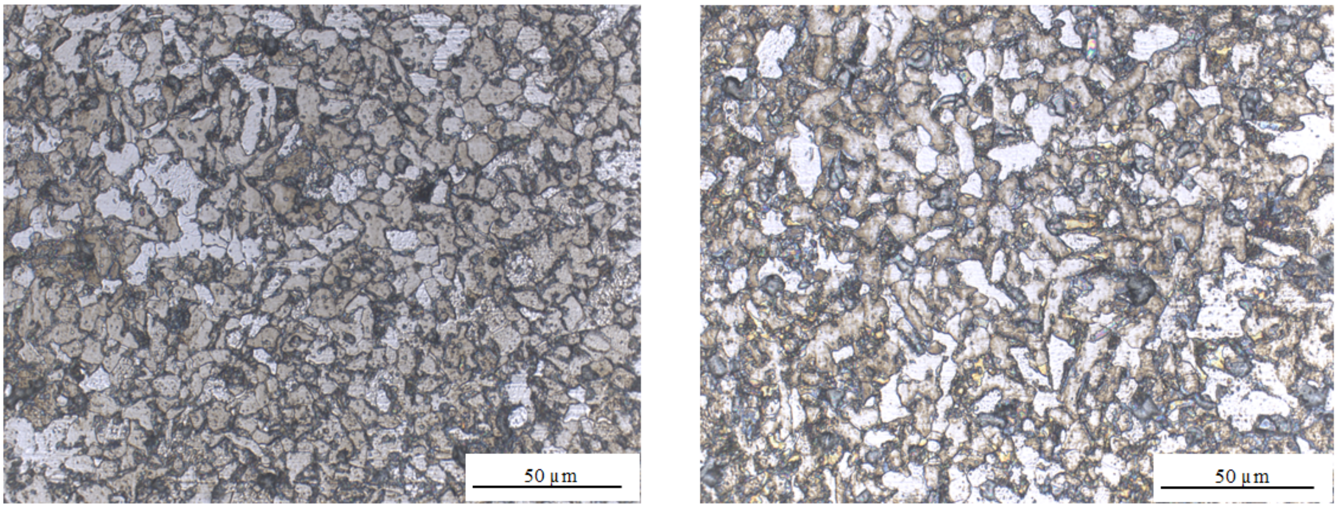
The specimens were stretched using a universal testing machine *I1185M* (100 kN). The measurement accuracy was not more than ±1 %.

The structure of the material was analyzed using the software package "*SIAMS 800*". Some obtained results are reflected in [10, 11, 15, 16].

Results and discussion

Specimens cut across the rolled direction were deformed under slow loading at a rate not exceeding 0.1 mm/s. Specimen No.2 was deformed by 1.5 %, specimen No.3 was deformed by 3.0 %, specimen No.4 was deformed by 4.5 %, specimen No.5 was deformed by 6.6 %. Specimen No.1 was not deformed, so it had the lowest magnitudes of internal stress. This difference from the theory is due to the direction, in which the specimen was cut from a plate of rolled metal. Deformation means the change in the length of the specimen expressed as a percentage of the original size.

The microstructure of the specimen being investigated is shown in fig. 1.



a *b*

Fig. 1. Microstructure of the specimens at magnification of 500X:
a – specimen No. 1; *b* – specimen No. 3

When analyzing the microsections, it was found that the structure is presented by a ferrite-perlite mixture in the ratio of 81.7 % ferrite and 18.3 % perlite. The structure corresponds to score 8 according to *GOST 8233*: the minimum grain score is 8, the maximum grain score is 13; grains occupying the largest area on a microsection correspond to a score of 11.

When rolling the metal, grains are pulled out in the rolling direction and, consequently, internal stresses are redistributed; its maximum magnitude will also be observed in this direction, as evidenced by diffraction patterns (fig. 2).

The specimens were stretched at a rate of 0.1 mm/min. Table 1 shows the results of determining the basic mechanical characteristics for specimen No.5.

Since the specimens were cut across the rolling direction, it is natural to assume that the lowest magnitude of internal stresses will be observed in the initial state in the longitudinal direction relative to the external load. During deformation, redistribution of stresses may occur and its magnitude may increase (fig. 4).

Fig. 4 shows that with increasing plastic strain of the specimens there is an increase in the magnitude of internal residual stresses in the direction of rolling. After deforming the specimens, corrosion tests were carried out, the results of which are shown in fig. 5.

The tests were carried out in a thermostat at a constant temperature. To clarify the data obtained, the experiment was carried out twice. Specimens were preliminary prepared by electrochemical etching.

It can be seen that the corrosion rate increases with increasing material strain, which is also due to the increase in the magnitude of internal stresses (fig. 6).

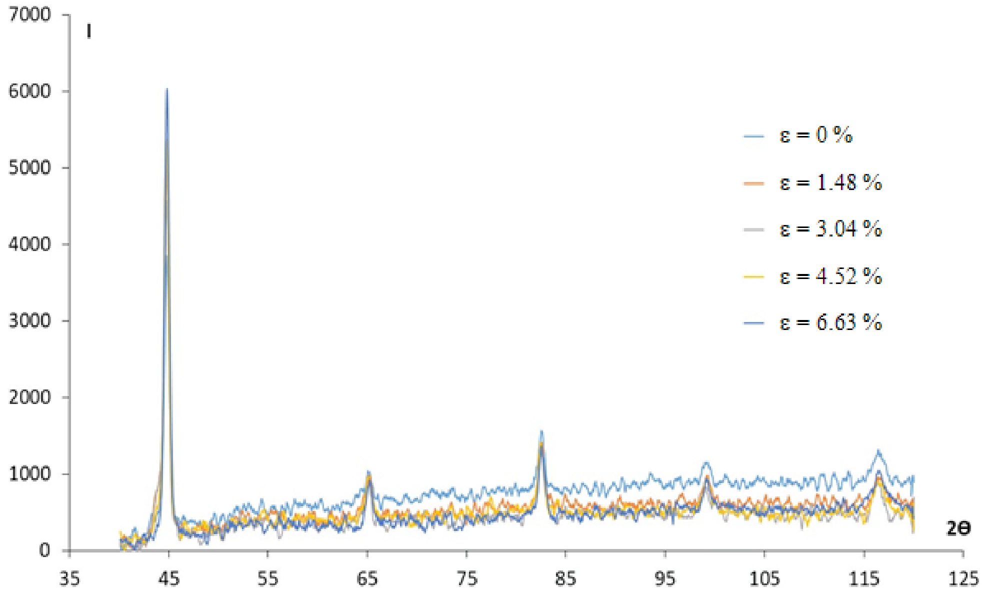


Fig. 2. Diffraction patterns obtained on the specimens being studied

Table 1

Mechanical characteristics of specimen No.5

Upper yield stress (N)	1,220
Lower yield stress (N)	1,21
Offset yield stress (N)	1,130

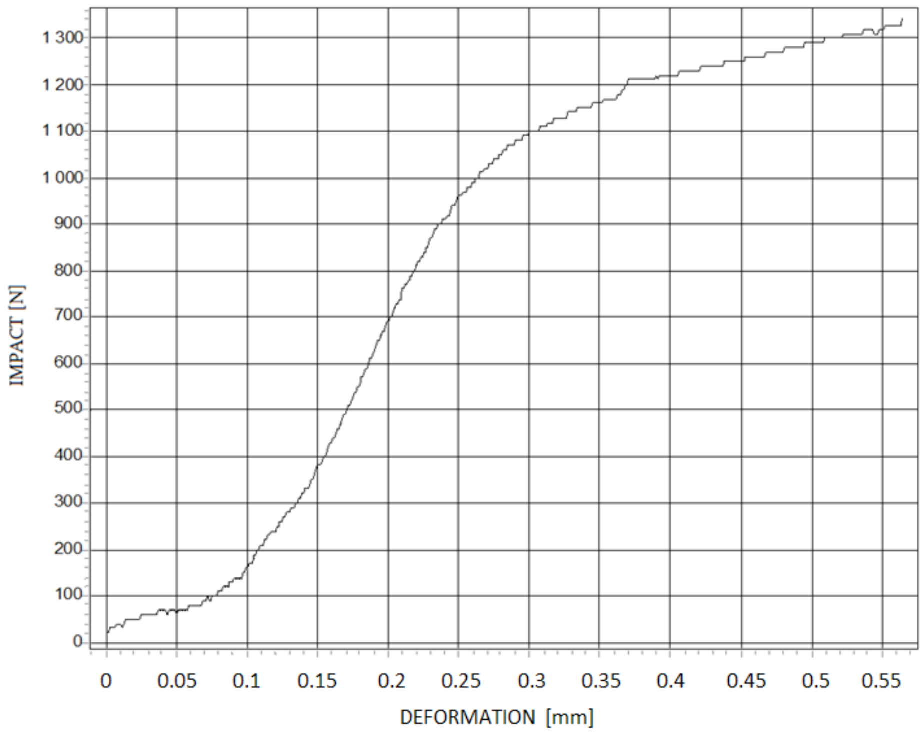


Fig. 3. Tensile diagram for specimen No.5

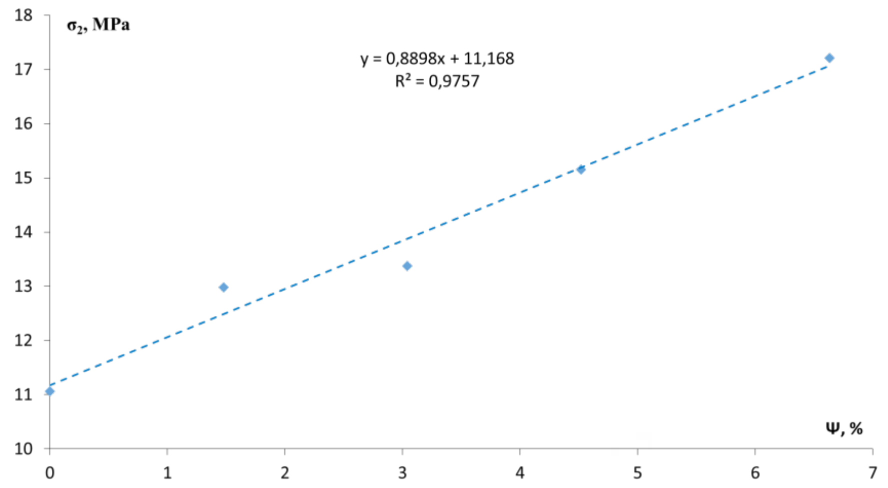


Fig. 4. Change in the values of internal stresses with increasing degree of residual deformation of the material

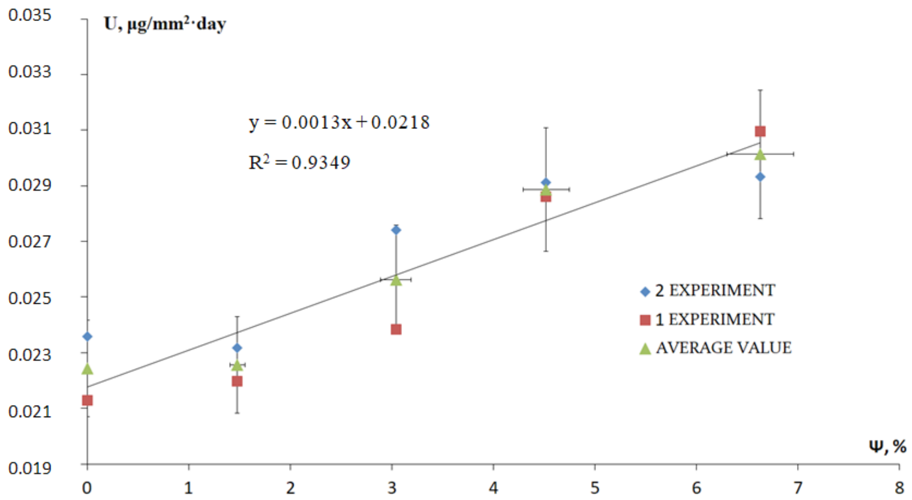


Fig. 5. Dependence of the corrosion rate on the specimen deformation

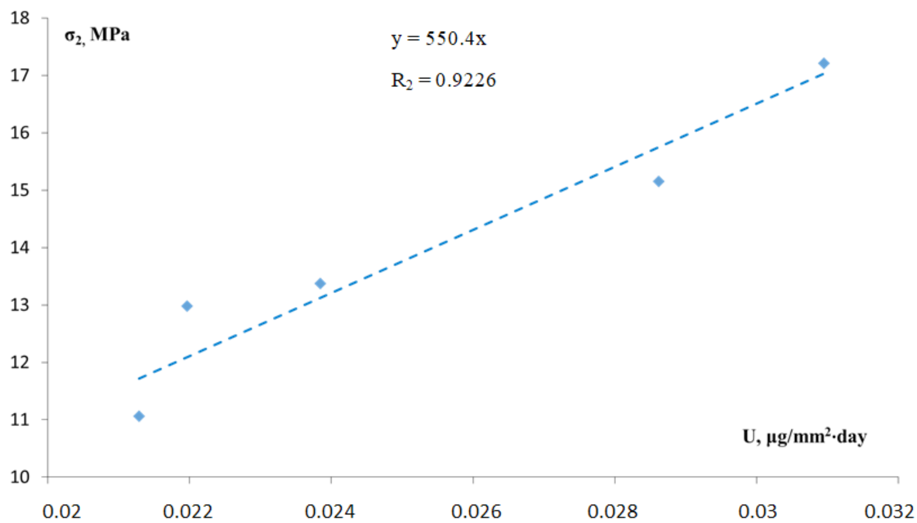


Fig. 6. Dependence of the internal stresses on the average corrosion rate (based on the results of 2 experiments)

As can be seen from fig. 6, the corrosion rate has a linear dependence on the magnitude of internal stresses. It should be noted that the maximum change in grain size in this experiment was 20% of the original (table 2). Fig. 7 shows the image of specimen No.3 structure processed in the *SIAMS 800* software. Grain boundaries are highlighted in red.

Table 2

Some parameters of the specimen being investigated

D_{min} [μm]	2.56	2.82	3.04	2.95	2.87
L, [mm]	0	0.370	0.760	1.130	1.590
Ψ, [%]	0	1.48	3.04	4.52	6.63
Δd, [%]	0	10.07	18.71	15.33	12.09

D_{min} is the minimum grain size; *L* is the specimen elongation;
Ψ is the residual deformation of the specimen;
Δ*d* is the average change of grain size at material deformation.

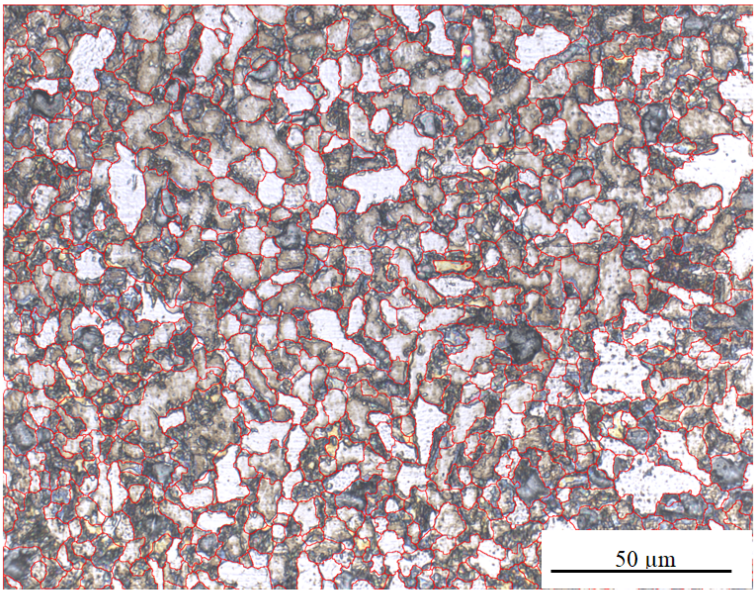


Fig. 7. Microstructure of specimen No.3 at 500X magnification with constructed grain boundaries

The maximum change was observed when the material deformed to 3 %, then relaxation processes occurred in the structure and the grain sizes in two directions became equal, which led to a decrease in the average values. The average values of the maximum grain sizes in the longitudinal and transverse directions relative to the external tensile force are used for comparison (fig. 8).

This process is also evidenced by the change in longitudinal and transverse grain dimensions expressed in the degree of anisotropy (fig. 9). The degree of anisotropy is defined as the ratio of transverse d_2 to the longitudinal d_1 grain size.

It should be noted that as the strain of the material increases, the dislocation density in the material also increases, the stronger the impact on the metal [24, 25].

The deformation at the initial stage is due to the sliding of a small amount of dislocations present in the material. As the degree of material's deformation increases, the number of dislocations moving in the

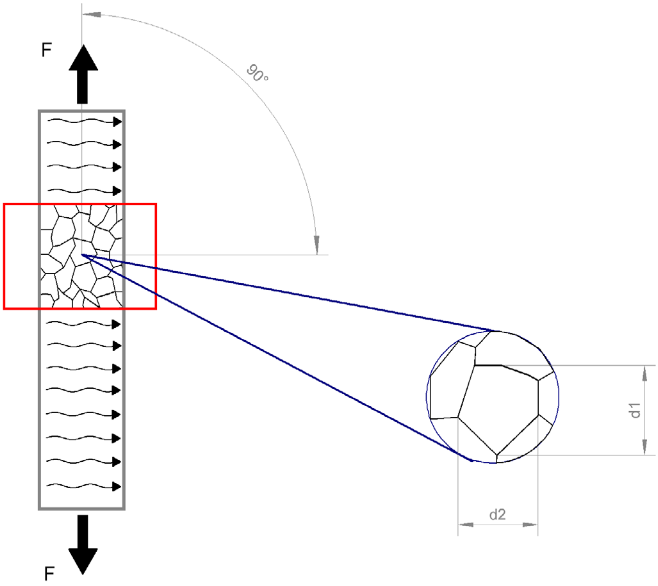


Fig. 8. Schematic representation of the specimen being investigated with texture formed by rolling

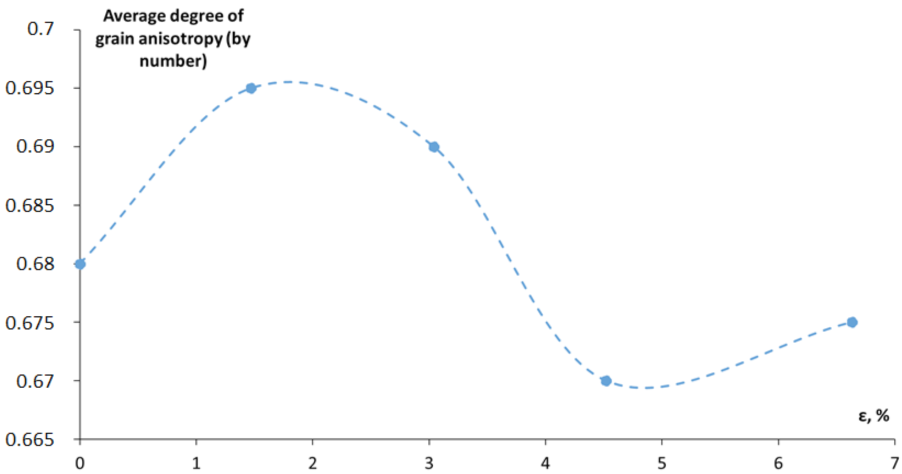


Fig. 9. Dependence of the average degree of grain anisotropy (by number) on the value of residual strain of the specimens being studied

crystal increases. This leads to an increase in collisions between dislocations, which hinder its further sliding, resulting in the formation of clusters unable to move through the crystal. The movement of new dislocations formed during deformation is restricted by the clusters, resulting in hardening of the metal [8]. The presence of this fact can affect the average grain size determined by X-ray diffractometry and lead to an increase in the degree of grain anisotropy.

The relationship between corrosion and internal stresses during plastic deformation is due to changes in the number of structural defects in the crystal. Such changes occur by sliding of dislocations within several sliding systems characteristic of the observed crystal lattice. Sliding occurs along planes and crystallographic directions characterized by dense packing of atoms, and hence the least resistance to shear. Plastic deformation in such a case sets dislocations in motion and increases the probability of its annihilation when it meets a dislocation of a different sign [9, 17, 18].

The literature indicates that plastic deformation of phases with body-centered cubic lattice (*BCC*) is caused by the slip of crystallographic directions {110} <111> [19].

Residual stresses of opposite sign can occur in the material during cold rolling due to inclusions [20]. The reverse stress can increase the anisotropy of the material. We can observe the results of such a process in fig. 6. Sources of anisotropy can be other microstructure features besides texture and grain morphology, such as oriented dislocation structures [21–23].

We use the influence coefficient to determine the influence of internal stresses on the corrosion rate. This coefficient is determined by determining the small deviations observed between the parameters under study.

$$N = \frac{|Y_{\max} - Y_i|}{\Delta X_i} \frac{X_i}{Y_i}, \tag{2}$$

where X_i is the corrosion rate value; Y_i is the magnitude of internal residual stresses; ΔX_i is the incremental value of corrosion rate; Y_i is the maximum internal residual stresses.

The influence coefficient of internal stresses is determined from the central region of the experimental dependence by formula 2.

We find that the coefficient of influence of the magnitude of internal stresses on the corrosion rate is 0.72.

Conclusion

1. It is established that the initial state of the material has a direct effect on the corrosion process in an aggressive medium. This effect is illustrated using the example of deformation of *St3* structural steel and changes in its corrosion rate in a 5 % hydrochloric acid solution.

2. It is found that with increasing the degree of plastic deformation along the rolling direction, the magnitude of internal stresses increases. The magnitude of internal stresses is governed by a linear correlation dependence on the magnitude of residual strain of the material with a coefficient of determination $R^2 \approx 0.98$.

3. When the degree of plastic deformation increases, there is an ambiguous change in the value of grain anisotropy, which is associated with internal effects occurring in the structure of the material processes during plastic deformation, such as: the sliding of the crystal lattice in the directions {110} <111>; the occurrence of inverse residual internal stresses due to the presence of inclusions in the steel structure.

4. The magnitude of internal residual stresses and corrosion rate of the material have a direct linear relationship, which is described by a regression equation of linear type with $R^2 \approx 0.92$. Thus, the coefficient of influence of the magnitude of internal stresses on corrosion rate is equal to 0.72, that proves the presence of interrelation between the parameters under consideration.

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Conflicts of Interest

The authors declare no conflict of interest.