On the effect of a weak magnetic field on corrosion wearing of steel plates

S.N. Yakupov\textsuperscript{1}, G.G. Gumarov\textsuperscript{1,2}, N.M. Yakupov\textsuperscript{1}

\textsuperscript{1}Institute of Mechanics and Engineering - Subdivision of the Federal State Budgetary Institution of Science "Kazan Scientific Center of the Russian Academy of Sciences" 2/31, Lobachevsky str., Kazan 420111 Russia

\textsuperscript{2}Kazan E. K. Zavoisky Physical -Technical Institute (KPhTI), Sibirsky tract, 10/7, 420029 Kazan, Russia

gumarov@kfti.knc.ru

Abstract. The previously discovered effect of the corrosive wear increasing of thin-walled St3 steel plates oriented parallel to the magnetic field lines of the Earth's magnetic field was investigated. The remanent magnetization of the samples was measured on a rectangular grid. A relatively large value of the normal components of the residual magnetization was established for parallel orientation of the samples. The slowing down of corrosion is associated with the action of the magnetic field gradient on paramagnetic ions in the electrolyte.

Introduction

Corrosion is a spontaneous destruction of metallic materials due to chemical or electrochemical interaction with the environment [1]. At the same time, electrochemical corrosion differs in that the ionization of metal atoms and the reduction of the oxidizing component of the corrosive medium do not occur in one act and their rates depend on the electrode potential of the metal. This type of corrosion is most common and occurs when metals interact with liquid electrolytes. Thus, corrosion is directly related to the motion of charged particles, which causes its dependence on magnetic fields of different nature. The source of magnetic fields can be external magnetic fields, residual magnetization of steel structures, external currents, terrestrial magnetic field, etc. Magnetic fields can affect the stability (integrity) of the passivating layer, which, as is known [2, 3], is formed on the metal surface, which is in an aggressive environment.

The magnetic field can influence on metal corrosion by acting on the ionic electrode kinetics [4], on mass transfer [5], on the formation of an oxide / hydroxide layer [6] on the interface, or on the potential difference at the metal-solution interface [7]. To describe the effect of the magnetic field on the transport of ions, a magnetohydrodynamic theory is used, to which, in particular, reviews [8-10] are devoted.

Mechanisms of the effect of magnetic fields on corrosion are not completely established. Often the results of researches are contradictory [11]. It is reported that the magnetic field reduces the susceptibility to corrosion of stainless steel [12]. On the other hand, a magnetic field applied perpendicularly to the surface of stainless steel reduces the repassivation potential [13]. Under the action of a constant magnetic field, the corrosion-fatigue life of 17G1C steel increases by 1.37 times in air and by 1.2 when exposed to a corrosive medium (3% NaCl) [14]. In a NaCl solution, the magnetic
field increases the corrosion resistance of nickel-zinc alloys with a low nickel content [15]. A magnetic field applied to iron samples in a solution of sulfuric acid makes it possible to reduce the corrosion of an iron sample by 80% [16]. The effect of benzene compounds on the corrosion of steel under the action of a magnetic field is considered in article [17].

The negative effect of the influence of the residual magnetic field on the process of corrosion wear was obtained by the author of [18]. It is noted that the enhancement of corrosion contributes to five factors (complex), among which residual magnetization.

A number of studies have shown the effect of reducing the corrosive wear of steel samples in an aggressive liquid in the presence of a magnetic field [19-201], a method and a device [21], developed on the basis of this effect, are proposed. The effect of the orientation of steel samples on the direction of the Earth's magnetic field lines on corrosion wear was observed [22]. It has been established that samples with surfaces that are parallel to the lines of force of the Earth's magnetic field are subject to greater corrosion wear. It was suggested that the magnetic field appearing on the surface of the sample creates an additional force of attraction of the passivating layer to the base of the sample.

The proposed work investigates the mechanism of the influence of a weak magnetic field on the corrosion of steel samples. For this purpose, the remanent magnetization along the surface of both the original samples and those that have passed the corrosion test cycle was measured. Also forces that can be responsible for the effect of increasing the corrosion of thin-walled steel plates oriented parallel to the earth's magnetic field lines were analyzed.

**Materials and Methods**

To study the corrosion wear of the samples [20], circular plates of St3 with a diameter of 10 cm and a thickness of 0.6 mm were used. Two groups of samples (ten in each) were placed in one container with 16% sodium hypochlorite solution in water. The mutual orientation of the Earth's magnetic field and samples of the first group (W-E) is shown in Fig. 1. The lines of force of the magnetic field lie in the plane of the plate. Components of the magnetic field [23]: horizontal \( H_{\text{HOR}} = 0.16 \) G, vertical \( H_{\text{VERT}} = 0.51 \) G, the resulting field \( H_{E} = 0.53 \) G. In this case, the lines of force of the Earth's magnetic field penetrated the second group (N-S) of samples at an angle of 73° to the normal to the surface of the plates. Samples were being held in the medium under study for 30 days.

**Results**

To evaluate the degree of corrosion of the samples, an experimental-theoretical method was used, which is a combination of experimental study of samples and theoretical processing of experimental data using the ratio of the nonlinear theory of shells [24]. According to [24], the samples are fixed along the contour in a special installation and are loaded with a uniform pressure \( p \). Knowing the deflection of the sample \( H \) at a given pressure \( p \), proceeding from the relations of the nonlinear theory of shells, one can determine their reduced (integral) modulus of elasticity.

The dependences of the mean deflection on pressure for two groups of samples are shown in Fig. 2. Curves are the result of averaging over 10 measurements. The measurement error was about 5% (shown in the figure). As can be seen from Fig. 2, the deflection of samples from the group (N-S) is less than for samples from the group (W-E). Those samples from group (N-S) undergo less corrosive wear than samples from group (W-E).

Normal components of the residual magnetization \( M_{\text{RN}} \) of the samples were measured using a GM2 magnetometer from AlphaLab Inc (accuracy of \( \pm 0.01 \) G). The measurements were carried out on a rectangular grid with a step of 1 cm. The distribution of the remanent magnetization of the initial samples and after holding for 7 days in different plate orientations relative to the earth's magnetic field are shown in Figures 3 and 4, respectively.

The central (working) part of the sample with a diameter of 8 cm is included in the stage of determination of the stiffness of the samples under study [23]. Measurements of the normal component of the remanent magnetization in the central part of the plates with averaging over all measured points have shown that for the initial plates the average value of \( M_{\text{RN}} \) is of the order of 0.71 Gauss, and for...
samples in the WE orientation 0.2 G, in the NS orientation 0.25 G.

**Fig. 1.** Mutual orientation of the Earth's magnetic field and group samples (W-E). All the components of the field lie in the plane of the plate.

**Fig. 2.** Dependence of the average deflection $H$ on the pressure $p$ for two groups of samples.

**Fig. 3.** Characteristic distribution of the normal component of the residual magnetization $M_{RN}$ of the original plates.

**Fig. 4.** Typical distribution of the normal component of the residual magnetization of MRN plates with different orientations.

The change in the magnetization of steel parts and structures with long exposure in weak magnetic fields can be related to the effects of vibrations and alternating loads, which are always present in one form or another. In vibrations, the frictional forces between domains are relaxed and their orientation is facilitated in the direction of the external field, i.e. magnetization is facilitated [25]. Variable mechanical stresses lead to an increase in the magnetoelastic energy [26], which in turn causes a change in the magnetization. The increase in the magnetization intensity of a sample in a magnetic field also occurs under the action of ultrasound [27]. Ultrasound causes in the sample variable mechanical stresses, which as a result leads to an increase in the magnetization. The residual magnetization of the sample with the field switched on is reduced by ultrasound.

It should be noted that the topography of the residual magnetization distribution of the initial plates of St3 is largely determined by their prehistory - the methods of rolling, cutting, deformation, storage, etc. The relatively large integrated $M_{RN}$ is associated with the storage conditions in the form of a vertical stack. This changes the demagnetizing factor, which causes the growth of the normal components of the $M_{RN}$.

In the theoretical description of the change in the magnetization of a ferromagnet under mechanical loading, it is necessary to take into account factors such as the level of internal stresses and internal
scattering fields that determine the magnitude of the potential barriers of 90 and 180-degree domain walls, texture, grain anisotropy, the pressure mechanism on domain walls, structure, etc. [28]. To describe the magnetoelectric changes in the magnetization of ferromagnets under the tensor nature of loading in weak magnetic fields, a phenomenological model has been proposed. For the relatively simple case of an elastically bent long tube, it is shown that the magnetization distribution will, albeit with a nonlinear coefficient, repeat the flexural stress distribution [29].

It has been experimentally established [30] that the normal component of the magnetic field of the scattering of a channel from Cm3 depends practically linearly on the distance measured from the middle of the part. The tangential component of the scattering field is maximal at the center of the channel and is noticeably smaller than the normal one. In the case of a thin plate and small magnetization fields, as well as small stresses, the residual magnetization distribution is complicated and unpredictable, which necessitates experimental measurements of its distribution over the surface. The magnetization of the surface of the ferromagnetic component leads to a strongly inhomogeneous scattering field above its surface. Different forces of magnetic origin, which can affect the electrochemical processes, which is the process of corrosion, are considered. This is the force of the paramagnetic gradient, caused by the cation concentration gradient; the force associated with the gradient of the magnetic field; The Lorentz force and the electrokinetic force [31]. The force of the paramagnetic gradient acts in the direction of the concentration gradient, i.e. in the direction of ordinary diffusion, and its influence can usually be neglected. The influence of the latter two forces is determined by the tangential component of the magnetic field [31], which is relatively small in the case of scattering fields associated with remanent magnetization.

The effect of residual magnetization on the pitting corrosion of low-carbon steel is attributed to the effect of the magnetic-field gradient force [32]:

$$F_B = \frac{\chi_m c \nabla B}{\mu_0},$$

Here $B$ is the induction of the magnetic field, $c$ is the concentration of the electrolyte, and $\chi_m$ is the molar susceptibility of the electrolyte. On the basis of studies using optical and scanning electron microscopy, it was shown that the maximum depth of the corrosion pits, as well as their average depth, is much smaller in magnetized samples. Finite element calculations using the FEMM program confirm the model proposed by the authors for the effect of the magnetic field on corrosion, indicating the maximum gradient of the magnetic field at the edge of the wells [32].

The gradient of the magnetic field can lead to the outflow of metal chlorides that prevent the formation of the passivating layer from the bottom of the pit towards the edges. As a result, the growth of the pits slows down, and the average mass loss due to corrosion in the unmagnetized sample is several times greater [32]. The maximum values of the residual magnetic induction, according to our measurements for the samples of plates from St3, amounted to about 1-2 Gauss, i.e. close to the values used in [32]. As a result, taking the value of the magnetic field gradient of 150 T/m [31], $c=10^3$ mol/m$^3$, $\chi_m = 10^{-5}$ m$^3$/mol according to [31], we obtain the value $F_B=0.5$ N/m$^3$ for the force. Such a force, acting at the beginning of the process of formation of a corrosive pit, can have many large values in the process of its growth.

The strength of the magnetic field gradient is also explained by the weakening of corrosion on high-purity iron samples (99.9%) and single-crystal iron in a strong external magnetic field (7.5 kOe) [33]. The effect is explained by the attraction of iron ions to regions with a high flux density of the magnetic field, that is, to the edge regions. Hydrogen ions are displaced from these regions in connection with the law of electroneutrality. As a result, the dissolution rate of iron in the presence of a magnetic field is reduced by approximately 80%.

**Conclusion**

In weak magnetic fields, including in the Earth's magnetic field, due to the presence of background
mechanical influences and vibrations, the magnetization of the ferromagnetic elements of the structures changes. To study the effect of magnetic fields on corrosion processes, information on the topography of the remanent magnetization, on the regions of the maximum gradients of the magnetic field, is of particular importance. The gradient of the magnetic field, which is formed, including in the areas of corrosive depressions, can to some extent influence the corrosion process. In particular, this may be due to the outflow of metal chlorides that prevent the formation of a passivation layer from the bottom of the pit towards its edges [32]. An additional force of attraction of the passivating layer to the base of the sample also contributes to this role [22] due to the gradient of the magnetic field.

The nature and location of regions with the maximum gradient of the magnetic field depends not only on the presence of various inhomogeneities in the structure of the material and the concentration of mechanical stresses, but also on the orientation of the samples in a magnetic field. The performed measurements of the normal components of the residual magnetization of the circular plates of St3 showed its relatively large values for the N-S orientation of the samples. Correlation of the magnetic field gradient with its component normal to the surface indicates the influence of the corresponding force on the corrosion process.

It is necessary to further investigate the relationship between weak magnetic fields, residual magnetization, mechanical stresses and corrosion processes.

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