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# INFLUENCE OF ALTERNATING MAGNETIC FIELD ON STRUCTURAL RELAXATION AND MAGNETIC PROPERTIES OF REACTOR VESSEL STEEL 15Kh2NMFA IN A STRESS-STRAIN STATE

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The paper presents the results of a study of the relationship between relaxation processes of structure formation caused by the effect of an alternating (50 Hz) magnetic field and changes in the magnetic properties of reactor vessel steel 15Kh2NMFA in a stress-strain state. Structural relaxation and changes in the magnetic properties of the steel are due to the activation of microplasticity processes stimulated by an alternating magnetic field in places of structural inhomogeneity with a high level of internal stresses.

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## INTRODUCTION

Under operating conditions, products made from structural materials may be subject to various influences that lead to the degradation of their properties due to changes in the structural state, including the occurrence of high internal stresses. The [1, 2] describes a number of methods and physical mechanisms for influencing various physical fields by activating relaxation processes, including treatment by alternating magnetic fields, for the targeted change of the structural state and physical and mechanical properties of structural materials and the formation of a given set of operational characteristics.

Alloy steels, including reactor vessel steel 15Kh2NMFA, are structural materials for nuclear power engineering. The development of methods for extending the service life of products made of this class steels is an important task in materials science. It is possible to reduce the tendency of a material to deteriorate its operational properties by eliminating the effects caused by structural defects and an increase in the level of residual stresses during operation.

Previously, results were obtained confirming the possibility of leveling the relief and reducing the level of internal stresses, increasing the ductility reserve of reactor vessel steel 15Kh2NMFA in the stress-strain state and its welded joints as a result of magnetic treatment (MT), consisting of the effect of an alternating (50 Hz) magnetic field. It has been established that the amplitude-time mode of MT (H = 40 kA/m at T = 300 K for a time of t = 15 min) provides a significant improvement in the complex of physical and mechanical properties of steel, including an increase in its impact toughness and deformation compliance [3–6]. Note that a decrease in the level of internal stresses in deformed 30CrMnSi steel samples is also achieved under the influence of a pulsed magnetic field [7].

In a structurally inhomogeneous and nonequilibrium ferromagnetic medium, several different mechanisms of structural state and domain structure reorganization can act simultaneously under magnetic action. As a basis for the magnetoplastic effect, the nonequilibrium kinetics of the electron-phonon subsystem of a crystal under the action of an alternating magnetic field was considered in the review [8]. The role of the dislocations dynamic properties in a mechanically unstable state in the development of microplastic processes during MT was determined in the work [9]. The objectives of this work, which is a continuation of previous studies, provide for obtaining new results that contribute to the clarification of the physical nature of time effects associated with the relaxation of the crystal and magnetic sublattices of a ferromagnetic in a stress-strain state under cyclic magnetic action.

## MATERIAL AND RESEARCH METHODS

The chemical composition of the steel is given in Table.

To achieve the hardening effect due to the high concentration of crystal lattice defects and the presence of peak residual stresses, the steel plate was subjected to deformation by rolling under cryogenic conditions ($\varepsilon \sim 57\%$, T = 90 K). The disks cut from the strained plate had a thickness h = 1 mm, diameter d = 10 mm.

Chemical composition of steel 15Kh2NMFA

| Element | C | Si | Mn | S | P | Cr | Cu | Ni | Mo | V |
|---|---|---|---|---|---|---|---|---|---|---|
| Chemical composition, wt.% | 0.13…0.18 | 0.17…0.37 | 0.3…0.6 | 0.012…0.013 | <0.035 | 1.8…2.3 | 0.07 | 1.0…1.5 | 0.5…0.7 | 0.1…0.12 |

MT consisted of keeping the specimen in an alternating magnetic field of strength H=40 kA/m at T=300 K for an increasing exposure time t=5…15 min. The magnetic field was created by an electromagnet with pole pieces made of magnetically structurally homogeneous Armko-Fe. The basis of the installation for removing the field dependences of magnetization M(H) and recording hysteresis loops was a device that, in its structural diagram, represents a permeameter (Fig. 1).

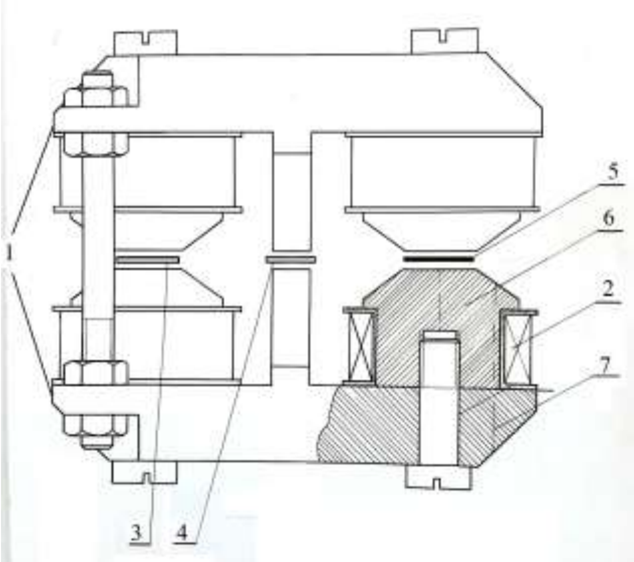


*Fig. 1. Permeameter diagram: 1 – two shaped iron cores; 2 – magnetizing coils; 3, 4 – Hall sensors; 5 – specimen; 6 – pole piece; 7 – permeameter yoke [10]*

As can be seen, this device consists of two shaped iron cores (1), on the poles of which 4 wire magnetizing coils (2) are wound. The coils are connected in such a way as to create a closed magnetic circuit.

In the initial state, the permeameter is balanced so that the central magnetic flux is zero in the absence of a sample. The studied specimen (5) is placed in the measuring gap and, during the process of changing the magnetic field strength, the response signal proportional to the value of the induced magnetic moment of the sample is recorded. The voltage from the Hall sensors (3, 4) was fed to the recorder. The rate of change of the field dH/dt ~ 100…500 (A/m)/s was determined taking into account the quasi-stability of the magnetic state of the sample.

It is important that the MT and measurement of the magnetic properties of the samples were carried out with the magnetic field directed strictly perpendicular to the specimen plane side.

## RESULTS AND DISCUSSION

Steel specimens after severe plastic deformation are characterized by a heterogeneous structure with the presence of a wide range of defects in the crystal structure and elements of structure fragmentation [6]. The total misorientation between different fragments reaches 18º, occasionally separate boundaries of disclination origin with misorientation of 21º are observed. Low-temperature rolling initiates a sharp increase in the value of the coercive force $H_c$ from 910 to 1830 A/m. In ferromagnetic steels subjected to deformation, dislocation tangles are the most effective pinning centers [11]. In our case, due to the high degree of cryogenic deformation, the predominant contribution to $H_c$ should be attributed to the group of high-energy disclination-type defects, which are sources of high level stress fields and lattice rotation [12]. The rotation makes a contribution to the anisotropy energy density [13].

The effect of plastic relaxation as a result of MT is most pronounced in places with higher levels of elastic stresses. The internal stress concentration is reduced due to dislocation multiplication and redistribution, and dispersal of dislocations in the pileups and crumbling of high-angle boundaries [6].

In the phenomenological description of the effect of microplastic relaxation, we use the model of microplasticity of a ferromagnet in a nonequilibrium state, characterized by the presence of dislocations in a mechanically unstable state in fields of high internal stresses [9]. The segment of this dislocation, fixed at the points $x$=0, $x$=l, possessing an isotropic linear stress $\tau$ at the time t=0 has the shape of a parabola caused by the load $b\sigma$ ($b$ is the Burgess vector, $\sigma$ is the value of residual stresses at the location of the segment). The transverse displacement of the segment under the action of the force $b\sigma_M \cos wt$ ($\sigma_M$ is the value of magneto-friction stresses) as a function of $x$ and $t$ satisfies the relation (1):

$$y(x,t) \approx \frac{4bl}{\pi^3 \tau}\left[\sigma_M \cos wt + \sigma e^{-\chi t} \cos w_0 t\right] \sin\frac{\pi x}{l}, \quad (1)$$

where $\chi=B/2M$, $B$ is the damping constant, $w_0=\pi a/l$, $a^2=T/M$. Here $M$ is the mass per unit length of the dislocation.

During one period $2\pi/w_0$ with weak attenuation at the moment when the second term reaches its maximum value, expression (1) increases by the value $\Delta_1 \sim \sigma_M$. Consequently, during the oscillatory motion of the segment, it is possible to reach the critical curvature of the segment line $R \sim l/2$, at which the Frank-Read source begins to operate [14]. In turn, the angle of inclination of the tangents to the Ox axis:

$$\frac{\partial y}{\partial x} = \frac{4bl}{\pi^2}\left[\sigma_M \cos wt + \sigma e^{-\chi t} \cos w_0 t\right], \quad (2)$$

at this moment in time also receives an increment $\Delta_2 \sim \sigma_M$.

As a result, in places where high internal stresses are localized, due to the presence of dislocations in a nonequilibrium state, under magnetic influence, Frank-Read sources are activated. The appearance of dislocations generated by MT leads to the activation of dislocation reactions, the implementation of relaxation processes of structure formation with the corresponding redistribution of internal stresses.

The ongoing reorganization of the dislocation substructure causes significant changes in its magnetic properties. There is a 25% drop in $H_c$ and a 22% increase in saturation magnetization after a total MT time of 15 min. If the magnetization reversal process of a sample that has undergone intense deformation is described by a typical hysteresis curve, then MT leads to a hysteresis loop similar to that of a ferromagnetic under uniaxial loading (Fig. 2). During magnetization reversal, large jumps in magnetization (A, B) with duration of 0.1 s are observed on the ascending and descending branches of the hysteresis loop.

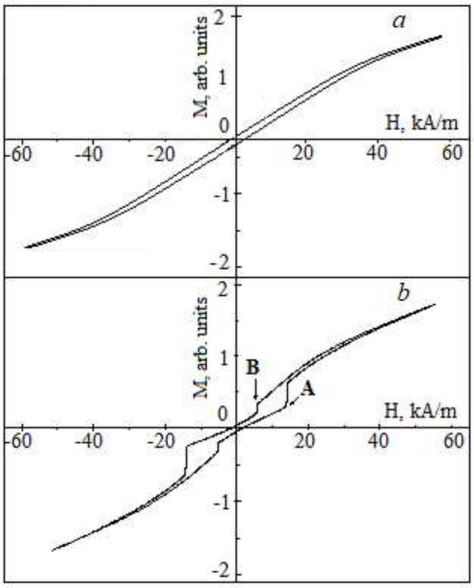

*Fig. 2. Hysteresis loops of a 15Kh2NMFA steel specimen, pre-deformed by rolling by 57% at T=90 K (a) and subjected to MT for 15 min (b)*

It follows from the experimental conditions that the direction orthogonal to the rolling plane, along which the magnetization was oriented during the MT process, becomes the direction of the easiest magnetization in a certain part of the specimen. This direction is distinguished due to the non-uniform distribution of the maximum deflections of dislocation segments in the state of unstable equilibrium caused by deformation by rolling. A further increase in the MT duration does not affect the magnetic properties of the material.

## CONCLUSIONS

In 15Kh2NMFA reactor vessel steel, which is in a non-uniform stress state, the activation of relaxation processes, stimulated by an alternating magnetic field, consisting of the redistribution of dislocations in the pileups and a decrease in the level of internal stresses, leads to a significant change in magnetic properties.

The implementation of the structural approach in methods for eliminating negative effects caused by residual stresses lies in optimizing the relaxation processes of internal stresses and managing the restructuring of dislocation substructure.

The results obtained are of independent interest and help to clarify the applicability of magnetic-structural analysis of ferromagnetic structural materials.

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## ВПЛИВ ЗМІННОГО МАГНІТНОГО ПОЛЯ НА СТРУКТУРНУ РЕЛАКСАЦІЮ ТА МАГНІТНІ ВЛАСТИВОСТІ КОРПУСНОЇ СТАЛІ 15Х2НМФА У НАПРУЖЕНО-ДЕФОРМОВАНОМУ СТАНІ

***В.І. Соколенко, Н.А.Черняк***

Наведено результати дослідження зв'язку між релаксаційними процесами структуроутворення внаслідок дії змінного (50 Гц) магнітного поля та зміною магнітних властивостей корпусної сталі 15Х2НМФА у напружено-деформованому стані. Структурна релаксація та зміна магнітних властивостей сталі зумовлені активацією процесів мікропластичності, стимульованих змінним магнітним полем у місцях структурної неоднорідності з високим рівнем внутрішніх напружень.

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