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Influence of high magnetic fields on the cyclic crack resistance of design elements of the fusion reactor

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The purpose of the present article was analysis of influence of the strong magnetic fields, including a pulsed magnetic field, on the mechanical properties of magnetic materials. Owing to creation of super-conducting magnetic systems, it was possible to use strong magnetic fields in such perspective field as thermonuclear or fusion power. Therefore problems of electromagnetic elasticity become essential from the point of view of engineering methods of designing such responsible designs and calculating of their durability. Because the fusion power in the power system of the 21st century gets concrete outlines, in the present work the problem of the influence of strong magnetic fields on durability of materials will be considered with reference to operation reliability of the ITER (International Thermonuclear Experimental Reactor).

Key words: fusion power, International Thermonuclear Experimental Reactor, cyclic crack resistance

1. INTRODUCTION

The urgency of creation in the nearest decades of generating capacities on the basis of thermonuclear synthesis has been proven by forecasts and calculations [1]. It is supposed that because of the growth of population and a more uniform consumption of energy in the regions, energy production will increase by 2050 approximately three times in comparison with the present level and will reach 10^{21} J per year [2]. There are doubts that in the foreseeable future the former energy source, organic fuel, will be replaced with other kinds of fuel. It will occur due to exhaustion of natural resources and contamination of the environment, which by estimations of experts should come much earlier, than cheap natural resources will be consumed (to the atmosphere 17 million tons of dioxide and other gases due to burning of fuel are daily exhausted).*

In the present industrial society, more than half of energy is used in a mode of constant consumption not dependent on the time of the day and season. But on this constant base capacity daily and seasonal fluctuations are imposed. Therefore the power system should consist of the base power, which supplies society with energy on continuous or quasi-continuous level, and power resources, which are used as required. It is expected that renewed energy sources such as solar energy, burning of biomass, etc., will be used basically for a variable component of energy consumption, and as the base power the nuclear energy generating capacities will be used. At present, in energetics only nuclear fission reactions have been mastered. Controlled thermonuclear fusion is a perspective direction for base power energetics. In comparison with nuclear fission reactions, thermonuclear fusion has a set of indisputable ecological and technological advantages. First of all this is absence of the long-living radioactive elements, which are inherent for nuclear fission reactions. In spite of the fact that neutrons activate the first wall of the thermonuclear reactor, the modern condition of material science allows to produce constructional materials in which the induced activity of the first wall decreases to a safe level during 20–40 years after a stopping of the reactor. It means that after the specified period materials of the fusion reactor can be utilized.

Differently from this situation, in fission reactors the radioactive waste which requires their remaking and storage during tens of thousand years is produced. Except the incomparably higher radiation safety, the thermonuclear power energetics possesses practically inexhaustible resources of fuel, enough for manufacturing energy during hundreds of years.

The prospect of development of base power energetics of the 21st century on the basis of thermonuclear fusion puts a set of new scientific-technical problems, particularly in the field of material science. Their solution is not required in the case of designing and operating nuclear fission reactors.

In the thermonuclear reactor, alongside with such well studied factors of influence on physicomechanical

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properties of constructional materials as neutron radiation and hydrogen [3], it is also necessary to consider the presence of strong magnetic fields which influence the mechanical properties of materials [4, 5].

2. SYSTEM FOR MAGNETIC CONFINEMENT OF PLASMA IN ITER

The principle of magnetic confinement consists in the use of a high magnetic field for isolation of hot plasma from the first wall of the reactor. The principle of a magnetic catcher was invented by A. D. Sakharov in 1950 and was named Ņokamak – an abbreviation for the torus chamber and magnetic coils. A scheme of Tokamak is shown in Fig. 1 [2].

Toroidal magnetic coils create the basic magnetic field in the torus chamber, which contains hot plasma. Essential for the stability of plasma is the plasma current which flows along the toroidal plasma ring and generates a poloidal magnetic field directed along the small circle of the torus.

The summarized magnetic field has force lines in the form of the infinite spirals covering the central line of toroidal plasma – a magnetic axis. Therefore, force lines of the magnetic field form in Tokamak toroidal magnetic surfaces closed and enclosed into each other. The plasma current is supported by the vorticity electric field created by the primary winding of the inductor. Thus, the plasma circle plays a role of a secondary winding.

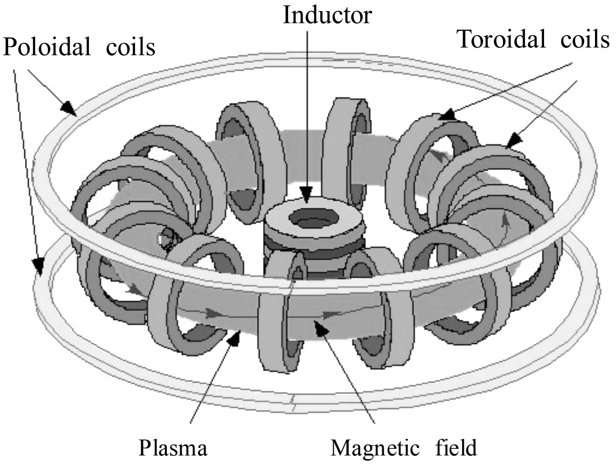

Fig. 1. Principal scheme of Tokamak [1]

It is obvious that the inductive maintenance of the current in Ņokamak is limited by the reserve of magnetic field flow in the primary winding and is possible only during a finite time. The time limit of the restriction of hot plasma by magnetic field exactly defines the cyclicity of the Tokamak operation.

Except for toroidal coils and the primary winding of the inductor, in the TOKOMAK also poloidal windings are necessary for maintenance of plasma stability and the control of its position in the chamber.

The currents flowing in poloidal coils create electromagnetic forces acting on the plasma current and therefore able of changing its position in the chamber and the form of cross-section of the plasma ring. With the help of the currents in the system of poloidal coils, force lines of the magnetic field are diverted in the divertor, a special part of the chamber. The diverted configuration of plasma is shown in Fig. 2 [6]. The divertor allows to supervise better the energy flux from plasma and to reduce impurities in plasma.

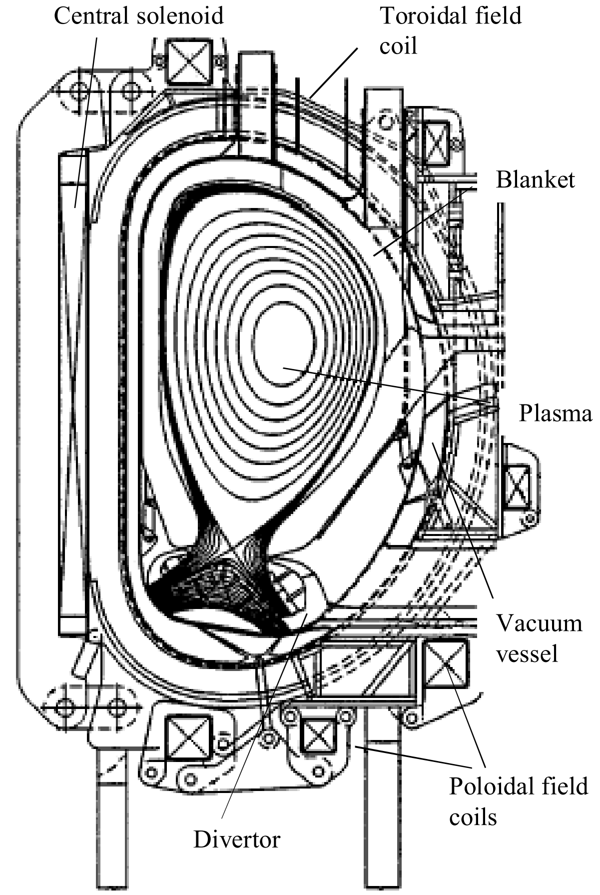

Fig. 2. Cross-section of Tokamak with the plasma vertically extended and diverted magnetic configuration [6]

The engineering design of the modern Tokamak – the ITER reactor – has been finished in 1998 [7]. The basic physical and technical parameters of the unit are shown in Table and its general view is presented in Fig. 3 [7].

When designing the ITER device and calculating the durability of materials it is necessary to consider two forms of electromagnetic-elastic interaction caused by an 21 MA electric current of plasma and the magnetization of materials by toroidal and poloidal magnetic fields.

In the first case, the electric current interacts with a magnetic field influencing the constructional material, and there are Lorentz's electromagnetic forces in materials. In constructional materials of the Tokamak, mainly eddy currents proceed and flow.

Table. **The nominal parameters of ITER**

Parameter	Value
Aspect ratio, A/a (major/minor radius)	6.2 m / 2.0 m
Plasma volume	840 m^3
Surface	678 m^2
Cross-sectional area	21.9 m^2
Plasma current	15 MA
Toroidal field on axis	5.3 T (for radius 6.2 m)
Fusion power	500 MW
Burn flat top	> 400 s
External heating power	40 MW
Radiated power	48 MW
Energy multiplication	10

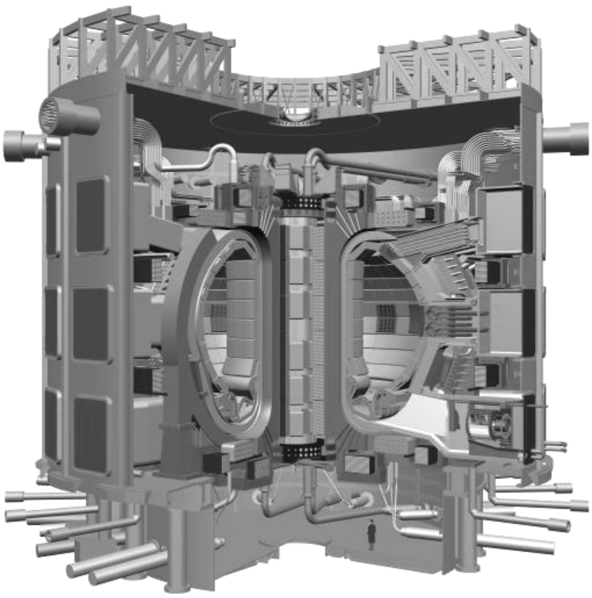

Fig. 3. General view of ITER device based on Tokamak concept [7]

These eddy currents are the induced currents arising due to change of the magnetic field of plasma. On the other hand, electromagnetic-elastic interaction in magnetic materials is caused by induced magnetization.

3. A REVIEW OF THE THEORY OF ELECTROMAGNETIC ELASTIC FORCES

To prevent the instability and destruction of the constructional materials applied in conditions of the influence of strong electromagnetic fields and for good safety, studies of electromagnetic breaking forces based on the theory of electromagnetic elastic forces are required.

Theoretical research of electromagnetic breaking forces is based on equations of the general theory of electromagnetic elastic forces [8–15]. However, the general basic equations of the known theory are extremely complex and unacceptable for practical application in the field of electromagnetic breaking forces.

Therefore in works [16–20] attempt to deduce a maximally simplified approximate analytical expressions for different forms of the electromagnetic-elastic interaction has been made. Below, as an example of such expressions, analysis of the dynamics of a ferromagnetic containing a crack body located in a magnetic field, considering the influence of induced magnetization is presented.

Using the given analysis, expression for stress intensity factor whose maximal value increased by 45, 209% [16, 17] has been deduced. The problem of the shock response of the ferromagnetic body containing crack 2a in the extent along the X axis was considered, at present the system of coordinates 0 – X, Z was used.

Considering the condition of a jump of the magnetic field, for the homogeneous magnetic flux density vector B_o, the magnetic field intensity vector H_o, the magnetization vector in a rigid condition following parities took place:

$$B_{oz}^{e} = B_{o}, H_{oz}^{e} = {}^{B_o}\!\big/_{\mu_\rho}, M_{oz}^{e} = 0,$$

$$B_{oz} = B_o,\ H_{oz} = B_o/\mu_\rho,\ M_{oz} = B_o/\mu_o\mu_\rho, \tag{1}$$

there B_o is a constant; $\mu_\rho = 1 - \chi$ is the relative magnetic permeability.

The top index *e* corresponds to a field in free space outside of a ferromagnetic body; the bottom index *z* means a component along Z axis (the index *x* – a component along the X axis). The other components of magnetic quantities are equal to zero.

The disturbances field caused by the micro-shift *u* was considered; in view of it, the magnetic quantities were expressed as follows:

$$B = B_o + b,\ H = H_o + h,\ M = M_o + m, \tag{2}$$

there *b, m, h are* magnetic quantities of the disturbance field which are assumed homogeneous with *u*.

The basic equations of electromagnetic elasticity [17] in the assumption of the quasi-static model for electromagnetic-elastic interaction in view of equations (2) were represented in the following way:

$$h_{zx} - h_{xz} = 0,\ h_{zx} + h_{xz} = 0, \tag{3}$$

$$\nabla_1^2 u_x + \frac{1}{1-2v}(u_{xx} + u_{zz})_x + 2(\chi B_o/G\mu_\rho)h_{xz} = \frac{1}{c_2^2}u_{zz},$$

$$\nabla_1^2 u_z + \frac{1}{1-2v}(u_{xx} + u_{zz})_z + 2(\chi B_o/G\mu_\rho)h_{zz} = \frac{1}{c_2^2}u_{zt}, \tag{4}$$

there v is Poisson's ratio, and ∇_1^2 is the two-dimensional Laplacian operator for variables *x, z*.

Parities for the components of electromagnetic elasticity, which were considered as a conclusion of equations (3), (4), were represented as follows:

$$b_x = \mu_o\mu_r h_x,\ b_z = \mu_o\mu_r b_z$$

$$m_x = \chi h_x,\ m_z = \chi h_z \tag{5}$$

$$\sigma_{zz}^{D} = \{(1+2\chi)B_{o} / \mu_{\gamma}\}h_{z}$$

$$t_{xx}^{D} = \sigma_{xx}, t_{xz}^{D} = t_{zx}^{D} = \sigma_{xz} + (\chi B_{o} / \mu_{\rho'})h_{x}$$

$$t_{zz}^{D} = \sigma_{zz} + 2(\chi B_{o} / \mu_{\gamma})h_{z} \tag{6}$$

$$\sigma_{xx}^{D} = -(B_{o} / \mu_{\rho'})h_{z}, \sigma_{xz}^{D} = \sigma_{zx}^{D} = B_{o}h_{z}$$

$$\sigma_{zz}^{D} = ((1+2\chi)\, B_{o} / \mu_{\rho})h_{z}, \tag{7}$$

there $t_{xx}^{D}, t_{xz}^{D}, t_{zz}^{D}$ are components of mechanical stresses of electromagnetic elasticity, and $\sigma_{xx}^{D}, \sigma_{xz}^{D}, \sigma_{zz}^{D}$ are components of electromagnetic mechanical Maxwell stresses.

Thus, the top index D reflects the form of record of the dipole model. The magnetic potential φ_{m} was entered and the potentials of wavy movement φ_{h}, ψ_{h} were presented in the following form:

$$h_{x} = \varphi_{mx},\ h_{z} = \varphi_{mzx} \tag{8}$$

$$u_{x} = \varphi_{hx} + \psi_{hz},\ u_{z} = \varphi_{hz} - \psi_{hz}. \tag{9}$$

Equations (4) for the field were represented in the following form:

$$\nabla_{1}^{2}\varphi_{m} = 0, \tag{10}$$

$$\nabla_{1}^{2}\psi_{h} = \frac{1}{c_{2}^{2}}\psi_{ht}, \tag{11}$$

there c_{1}, c_{2} are the velocities of expansion wave and shear wave distribution which obey the following parities:

$$c_{1} = \left(\frac{2-2\nu}{1-2\nu}\right)^{1/2} c_{2}, \quad c_{2} = (G/p)^{1/2}. \tag{12}$$

Further the case of shock wave incidence perpendicularly to the plane of the crack was considered; the incident wave was expressed as follows:

$$u_{z}^{t} = ((c_{2}/c_{1})^{2}/G)\, p_{o}(z - c_{1}t)H(t - z/c_{1})$$

$$u_{x}^{t} = 0, \quad h_{x}^{t} = h_{z}^{t} = 0, \tag{13}$$

there p_{o} is a constant which has the dimension of mechanical stresses; *H*( ) is the Heavysaide step function.

Thus, the top index *i* designates an incident wave. In the case when the shock wave according to the parity (13) dissipates by crack, the condition of jump has the following form:

$$h_{x}^{es}(x,0) - h_{x}^{s}(x,0) = -(\chi B_{o} / \mu_{o}\mu_{\rho})u_{zx}^{(s)}(x,0)$$

$$(|x|<a),\ \ \varphi^{(s)}(x,0) = 0(|x| \le a) \tag{14}$$

$$\mu_{0}h_{z}^{es}(x,0) - \mu_{o}\mu_{\rho'}h_{z}^{s}(x,0) = 0(|x| \le a)$$

$$\varphi_{m}^{es}(x,0) = 0(|x| < a) \tag{15}$$

$$t_{xx}^{Ds}(x,0) = 0(|x| < \infty)$$

$$t_{zz}^{Ds}(x,0) = (\chi^{s} B_{o} / \mu_{\rho'})h_{z}^{s}(x,0) - p_{o}H(t) \tag{16}$$

$$(|x|) \le a)$$

$$u_{x}^{s}(x,0) = 0(a < |x|). \tag{17}$$

Here the top indexes *s, es* designate the dissipated components of electromagnetic elasticity parameters inside and outside of a ferromagnetic body.

The solution was found by means of reduction to the integral equation of the first kind of the system of the double integral equations received with the use of double integral Laplace–Fourier transformation. For the leading edge of a crack *x* = *a*, the dynamic stress intensity coefficient was represented in the following form:

$$K_{h1} = \lim_{x \to a^{+}} (2(x-a))^{1/2}\ t_{xx}^{Ds}(x,0,T) + \sigma_{xx}^{Ds}(x,0T)), \tag{18}$$

there $T = c_{2}t/a$ is the dimensionless time.

In [19], results of the numerical solution for definition of the influence of the magnetic field $b_{c} = (B_{o}/\mu_{o}G)^{1/2}$ on the character of dynamic stress intensity coefficient behavior in time are presented. The calculation was made for the value of a normalized magnetic induction $b_{c} = 0.005$, which corresponds to the value of a magnetic induction 1.8 T, and $\nu = 0.3$, $\chi = 10000$, $\mu = 10^{11}$ Pa.

Calculation has shown that the maximal value $K_{hl}/p_{o}a^{1/2}$ increases approximately 200% in comparison with the static solution $K_{hl} = p_{o}\, a^{1/2}$ in absence of a magnetic field $b_{c} = 0$.

In [21], the solution of the problem of calculation of stress distribution in an infinitely long narrow strip containing Griffit's crack has been explained.

The problem was considered with reference to a soft ferromagnetic strip in a homogeneous magnetostatic field perpendicular to the plane of the crack. The basic equations and Fourier transformations of solutions of field equations are presented, the boundary conditions are formulated and the system of two dual integral equations is deduced. The system of two dual integral equations further was reduced to one integral Fredholm equation of the second kind, from which the auxiliary function was defined. Expression for the stress intensity coefficient (the parameter which describes the intense-deformed condition in the top of a crack) was received in the closed form through an auxiliary function.

The percentage of increase in the stress intensity coefficient, caused by presence of the normalized magnetic induction b_{c}, was calculated as follows:

$$n_{1} = \frac{K_{h1} - K_{h1}\big|_{b_{c}=0}}{K_{h1}\big|_{b_{c}=0}} \times 100. \tag{19}$$

The numerical solution showed a 20% increase of the stress intensity coefficient under the effect of a static magnetic field and preservation of a flat deformation state.

4. EXPERIMENTAL DATA ON THE INFLUENCE OF ELECTROMAGNETIC BREAKING FORCES

In [5, 22], experimental data on the influence electromagnetic-elastic interactions on the strength of materials are presented. In [5], the first form of interaction – in the presence of electromagnetic Lorentz forces in material – was investigated. In [22], the influence of induced magnetization on fatigue failure of magnetic materials is explained.

As a material for research of the first form of interaction a tensile, non-magnetic material – stainless steel 304 [5] – has been chosen. Analysis of the tensile material destruction arising under the action of electromagnetic force was made using nonlinear fracture mechanics.

In experiment, a beam with a side-on crack through which the unsteady electric current *I* flowed and which was in a homogeneous magnetic field *B* was used. Two types of loads were considered: one was electromagnetic force set by a vector received from the electric current and a magnetic field density vectors, and the other was the impulse thermal load caused by Joulean heat. Owing to presence of an electric current density feature at the top of the crack, the thermal load also concentrated near the top of the crack.

The dynamic electromagnetic force deformed the beam in such a manner that the disclosing of the crack took place. During the experiment, the initial and processing time, crack size, crack growth and crack propagation rate were measured. The homogeneous static magnetic field was equal to 0.85 T and was generated by an electromagnet; the capacity, inductance and resistance in the circuit generating the current were equal to 22 mF, 11 μH, 45 mΩ, respectively. It has experimentally been shown that at the maximal value of the current exceeding 12 kA, the crack growth rate could reach 2 m/s.

In [22, 23], as a material for research, magnetic low-alloyed steel 12ГН2МФАЮ was chosen. The experiment was made on low-alloyed steel welded seams, because the zone of a seam is a place of occurrence of fatigue cracks. Fatigue tests at harmonic loading were made with a frequency of 10 Hz and the specified deformation of the sample, with measurement of the forces that arose from the maximal bend of the sample. Prismatic samples (thickness 24 mm and width 40 mm) were tested on a three-point bend mechanical test system. Distribution of a crack on the surface of the sample was observed visually for control of its length *2C* changes using an optical microscope.

For measurement of crack depth *a* and definition of its form (*a*/*c*), the method of drawing of “control labels” during cycles at the lowered loading was used. As a result of the measurements received by using the “control labels”, the dependence $a = f(c)$ according to tests of a series of samples was under construction. Presence of dependence $a = f(c)$ allowed to construct not only the kinetic diagram of growth of the face crack $c = f(N)$, where N is the number of cycles, but also the kinetic diagram of growth of a crack inside the sample $a = f(N)$.

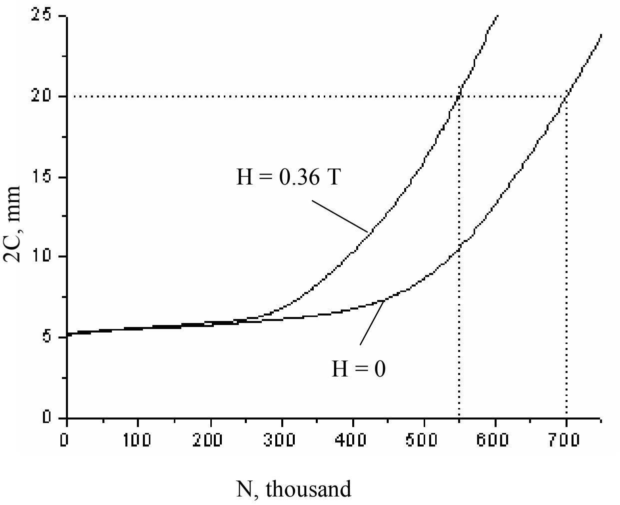

Fig. 4. Kinetic diagram of growth of face half-elliptic cracks during 700 thousand cycles

The exact knowledge of face half-elliptic cracks form, in the presence and absence of a magnetic field, allowed to establish the dependence of the influence of a magnetic field on the growth of a face crack on the size of the plasticity zone, which is different for half-elliptic cracks on the surface and inside the sample.

No changes of the form of the crack were found, allowing an assumption of the absence of relation between the size of the plasticity zone and magnetic field influence on the growth of a fatigue crack.

Fatigue tests in presence of a magnetic field were carried out by magnetization of a part of a sample containing a welded seam with a crack. The magnetic field was created by a solenoid cooled with water, the induction vector being directed perpendicularly to the surface of the crack. The magnetic field intensity was calculated according to the geometry of the solenoid and direct current. Samples were tested at a magnetic field intensity of 0.36 T.

The influence of the magnetic field on cyclic crack resistance of welded connections was estimated by comparing the kinetic diagrams of growth of face cracks in the absence and presence of a magnetic field. Compared were dependence $c = f(N)$ and $a = f(N)$. Cyclic loading was performed on the basis of 400 to 750 thousand cycles, depending on the bending load. In Fig. 4, kinetic diagrams of crack growth are shown in the presence and absence of a magnetic field during 700 thousand cycles. Under reduction of loading cycles, the influence of a magnetic field crack resistance decreased.

5. CONCLUSIONS

In this work, the results of experimental and theoretical researches in the field of electromagnetic fracture mechanics, which makes a basis for the calculation of strength and estimation of reliability of constructional materials and mechanisms working in conditions of strong magnetic fields are presented. For mechanisms and designs of thermonuclear reactors (ITER), because of the influence of intensive electromagnetic fields a high reliability is required. Thus, the rational designing and maintenance service of the mentioned designs and mechanisms is impossible without application of electromagnetic fracture mechanics.

Furthermore, it is desirable to investigate in more detail both the theoretical and experimental aspects of electromagnetic fracture mechanics, however, now the experimental research of fracture in strong magnetic fields is formidable; hence, it is necessary to develop reliable theoretical methods of estimation and explanation of the electromagnetic fracture phenomena.

Additionally, constructional materials of ITER are exposed to shock electromagnetic forces caused by plasma instability; therefore, also research of electromagnetic fracture dynamics is necessary. As the designs of ITER represent welded joints, special attention should be given to the problem of fatigue crack resistance of welded seams, primarily to experimental researches.

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STIPRIŲJŲ MAGNETINIŲ LAUKŲ ĮTAKA TERMOBRANDUOLINIŲ REAKTORIŲ KONSTRUKCINIŲ ELEMENTŲ CIKLINIAM ATSPARUMUI ĮTRŪKIAMS

Santrauka

Šio darbo tikslas – atlikti stiprių magnetinių laukų (ir impulsinių magnetinių laukų) įtakos stipruminėms magnetinių medžiagų savybėms analizę ir šios problemos vertinimą. Sukūrus superlaidžias magnetines sistemas tapo įmanomas technologinis stiprių magnetinių laukų taikymas tokioje perspektyvioje srityje, kaip termobranduolinė energija. Todėl elektromagnetinio tamprumo, ciklinio pleišėjimo atsparumo klausimai tampa ypač svarbūs konstrukcijų projektavimo ir stipruminių skaičiavimų požiūriu. Kadangi termobranduolinė energetika XXI a. energetikos sistemoje tampa labai perspektyvi ir jau įgauna realųjį pavidalą, šiame darbe stiprių magnetinių laukų įtakos stipruminėms medžiagų savybėms problema nagrinėjama reaktoriaus ITER (Tarptautinio termobranduolinio eksperimentinio reaktoriaus) eksploatavimo patikimumo atžvilgiu.

Raktažodžiai: termobranduolinė energija, tarptautinis termobranduolinis eksperimentinis reaktorius (ITER), ciklinis atsparumas įtrūkiams

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ВЛИЯНИЕ СИЛЬНЫХ МАГНИТНЫХ ПОЛЕЙ НА ЦИКЛИЧЕСКУЮ ТРЕЩИНОСТОЙКОСТЬ КОНСТРУКЦИОННЫХ ЭЛЕМЕНТОВ ТЕРМОЯДЕРНЫХ РЕАКТОРОВ

Резюме

Целью настоящей работы является проведение анализа состояния проблемы влияния сильных магнитных полей на прочностные свойства магнитных материалов, включая воздействие импульсного магнитного поля. Благодаря созданию сверхпроводящих магнитных систем стало возможным технологическое использование сильных магнитных полей в такой перспективной области, как термоядерная энергия. Поэтому вопросы электромагнитной упругости приобретают чрезвычайно важное значение с точки зрения инженерных методов проектирования конструкций и расчета прочности. Поскольку перспективы термоядерной энергетики в энергетической системе XXI в. приобретают конкретные очертания, в настоящей работе проблема влияния сильных магнитных полей на прочность материалов рассматривается применительно к надежности эксплуатации термоядерного ITER (Международного термоядерного экспериментального реактора).

Ключевые слова: термоядерная энергия, Международный термоядерный экспериментальный реактор (ITER), циклическая тре-щиностойкость