EFFECT OF ALTERNATING MAGNETIC FIELD ON CREEP OF IRRADIATED VESSEL STEEL 15Kh2NMFA

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The influence of alternating magnetic field on the creep at 600 K of irradiated vessel steel 15Kh2NMFA was studied. Structural investigations of the steel specimens after various actions were carried out. It is shown that the effect of alternating magnetic field on the plastic flow of strengthening by irradiation steel is ambiguous. Depending on the processing mode is observed as the active development recovery processes, and increase the stability of the structure during creep.

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INTRODUCTION

Ferrite-perlite steel 15Kh2NMFA used to manufacture pressure vessel for nuclear reactors VVER-400 and VVER-1000 and is characterized by low induced activity, weak vacancy intumescences, low creep, and high resistance to high-temperature and helium embrittlement [1]. The pressure vessels of VVER-type reactors are operated at temperatures of ~ 600 K and exposed influence by neutron and gamma radiation. Relatively low operating temperature and the effects of the radiations are capable of causing in vessel steel the changes in microstructure leading to radiation-induced degradation of mechanical properties.

In a series of papers [1-3] shown hardening vessel steel in operation: the yield stress is increased, resulting in an increase in temperature ductile-brittle transition.

Among structural-phase changes which effect on the mechanical properties of materials under irradiation can be distinguished the generation nonequilibrium concentration of point defects, the evolution of the dislocation structure, the dynamic recrystallization, the segregation of impurities at the boundaries, the phase transformations, etc. Hardening of irradiated materials can be reduced by annealing. It has been shown in relation to the welds of VVER-1000 [4].

Vessel steel 15Kh2NMFA is ferromagnetic, which determines the influence of the magnetic structure on the defect structure due to the relationship of the magnetic and lattice subsystems. In the study of strained steel 15Kh2NMFA the softening effect was observed as a result of the impact an alternating magnetic field, which depends both on the field amplitude and the duration of exposure [5]. It has also been shown the influence of the alternating magnetic field on the irradiated steel microhardness [6]. The observed effects of softening deformed and irradiated vessel steel can be associated with the occurrence of relaxation processes in the defect structure when exposed to moving domain boundaries and magnetostrictive stress [5, 6]. We can assume that the processes of drift diffusion can not only initiate decrease of internal stresses, but also to stabilize the structural state, as well as improve resistance to external mechanical loads.

In this connection it is interesting to study the influence of different modes of action of the alternating magnetic field on the creep of specimens irradiated steel 15Kh2NMFA at temperatures appropriate operating for the pressure vessel of nuclear reactor.

MATERIAL AND EXPERIMENTAL PROCEDURE

We investigated specimens cut from solid billet after standard factory processing. Tests were carried out at the transition stage creep in the mode of step-loading at a temperature of 600 K. The tension increase at each stage was 4…5 MPa. Accuracy of measurement of elongation was ~ $5 \cdot 10^{-5}$ cm. Activation parameters and the levels of internal stresses were determined using differential techniques described in [7].

Thermostating sample was carried out using the hollow cylindrical resistance furnace. Limitation of heat flow was achieved by using special screens and insulation. Specimen temperature with accuracy of 10^{-2} K was measured by differential chromel-alumel thermocouple using digital voltmeter.

Irradiation of samples was performed on a linear accelerator CAT-1, characterized by the electron energy of E = 12 MeV to E = 6 MeV when the average current from 2.5 to 255 mkA. The current density on the irradiated object was varied in the range of 0.5 to 50 A/cm^2. Electron accelerator equipped with a cooling output devices, which control the temperature of irradiated objects. Operating temperature did not exceed 70 °C.

Magnetic treatment of the samples consisted of exposure to an alternating magnetic field frequency of 50 Hz at a temperature of 300 K. The magnetic field H is created by a solenoid.

Samples of steel in different structural states were investigated:

1) initial state or the state of supply, which corresponds to the standard factory heat treatment (mode 1);

2) electron irradiation with E = 10 MeV and dose $D = 5 \cdot 10^{19}$ cm^{-2} (mode 2);

3) electron irradiation with E = 10 MeV and dose $D = 5 \cdot 10^{19}$ cm^{-2}, and then the processing by alternating magnetic field of H = 700 Oe for 2 hours (mode 3);

4) electron irradiation with E = 10 MeV and dose $D = 5 \cdot 10^{19}$ cm^{-2}, and then the processing by alternating magnetic field of H=700 Oe for 3 hours (mode 4);

5) electron irradiation with E = 10 MeV and dose $D = 5 \cdot 10^{19}$ cm^{-2}, and then the magnetic processing in the pulsed mode: the number of cycles $N = 4 \cdot 10^3$ with the amplitude H = 1,2 Oe for 30 min (mode 5).

RESULTS AND DISCUSSION

A characteristic feature of the observed creep steel 15Kh2NMFA at T = 600 K after all treatments throughout the stress range is the small instantaneous deformation, which is ~ 0.02% at stresses up to the yield strength and ~ 0.05…0.07% at stresses higher yield.

The magnitude of creep rate at stresses below the yield strength is ~ $(0.5…1)\cdot10^{-6}$ s^{-1}; at stresses above the yield strength is ~ $(5…6)\cdot10^{-6}$ s^{-1} (Fig. 1).

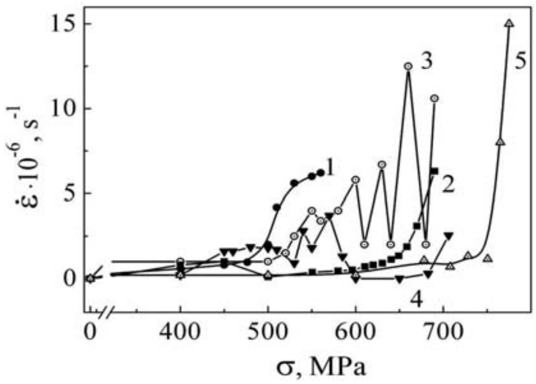

Fig. 1. Dependence of creep rate at T = 600 K on the applied stress for steel 15Kh2NMFA samples: 1 – the initial state; 2 – electrons irradiation E = 10 MeV, D = $5\cdot10^{19}$ cm^{-2}; 3 – the irradiation + exposure alternating magnetic field for 2 hours; 4 – the irradiation + exposure to alternating magnetic field for 3 hours; 5 – the irradiation + treatment in pulsed mode for 30 min

The activation volume, calculated from the experimental data, is ~ $1.2\cdot10^{-21}$ cm^3 throughout the region of the applied stresses, indicating a strong localization of plastic flow. Plastic deformation can be localized at the separation boundaries (grains, phase and boundaries of fragments) and is a result of the dislocations motion in the boundaries areas, as well as processes of displacement and diffusion of point defects.

In the initial state the yield strength of the steel is about ~ 480 MPa, ultimate strength of ~ 570 MPa. Electron irradiation leads to an increase in of yield strength to about 650 MPa, and the ultimate strength to about 700 MPa. Strengthening of the material is due to the appearance of new pinning points for dislocation formed as a result of arise non-equilibrium concentration of radiation point defects and their complexes.

Processing in an alternating magnetic field by the modes 3 and 4 leads to the decrease of internal stresses and, as a consequence, to decrease in the yield stress practically to its original value Whereas the ultimate strength after both treatments remain on the stress level of irradiated material.

Creep of irradiated steel samples processed by alternating magnetic field modes 3 and 4 at stresses higher than yield point becomes unstable. We observed a non-monotonic dependence of the creep rate on the applied stress, and the amplitude of such jumps in the creep rate decreases with increasing time of preliminary magnetic treatment from 2 to 3 hours. This may be the result of inhomogeneous local changes of structure, formed during the irradiation, under the action of a magnetic field, which was the strongest in microvolumes with maximum internal stresses. Due to inhomogeneity of structure, there is a different intensity of plastic flow in the structural deformation elements, i.e. different creep rate with increasing applied stresses.

Creep of samples after treatment in a pulsed mode 5 takes on an entirely different character: we can see increase the yield strength and significant decrease the rate of creep (see Fig. 1, curve 5).

It should be noted that during the creep of specimens in the initial state at stresses slightly above the yield strength observed local area of inhomogeneous plastic flow. It was shown [8] that it is the result of the kinetic instability of the structure due to changes in the conditions of deformation, and its restructuring under the influence of a slowly increasing load in step-loading mode of creep at T = 600 K. In irradiated and treated with an alternating magnetic field samples such restructuring during creep at stresses $\sigma \sim \sigma_{0,2}$ is not observed.

Irradiation by electrons with energy of 10 MeV and dose of $5\cdot10^{19}$ cm^{-2} causes significant distortion of the material [1]. This is the displacement of atoms from their equilibrium positions (static distortion), the formation of point defects and their clusters, creating the areas of elastic deformation. These factors, along with the pinning of dislocations by impurities are the cause of hardening of the material and reduce the creep rate (see Fig. 1, curve 2).

Structural studies have shown that after creep at the time of fracture in the structure of the samples irradiated steel are contains evidence of previous recovery processes, but dominated the areas with a high degree of defectiveness (Fig. 2).

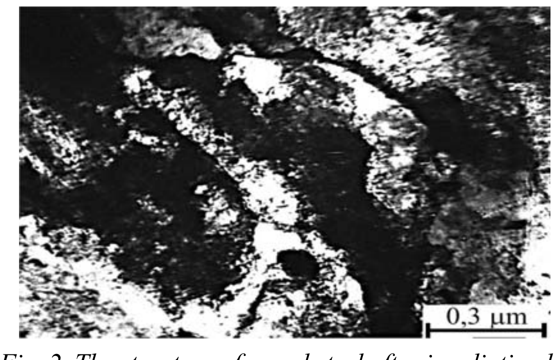

Fig. 2. The structure of vessel steel after irradiation by electrons with an energy of 10 MeV, D = $5\cdot10^{19}$ cm^{-2} and deformation by the stepped creep at T = 600 K and $\sigma \approx \sigma_B$

There is seating microstrain localization effects in the form of dislocation clusters at the boundaries, which are powerful barriers to the movement of dislocations and subsequently places nucleation of microcracks.

Processing of an alternating magnetic field the specimens of irradiated vessel steel decrease the internal stresses due to redistribution of defects. It is leads to a decrease in the yield strength and also initiates a local transformation during creep the structure formed at irradiation, the most visible in the places of the maximum distortion. In particular, in the accommodative zones ordering dislocations is observed.

Change in a defect state is associated with the intensification during magnetic treatment the diffusion streams of point defects and their complexes in the direction of the most powerful sinks: of boundaries and their joints, as well as directly along the boundaries. It can be assumed that the diffusion processes are as lattice character with acceleration dislocation creep and a drift: the domain boundaries sweep point defects and they accumulate near the boundaries.

It is known that under ferromagnetic magnetization the interconnected elastic and magnetic fields of dislocation interact with the domain boundaries, which facilitates the slipping and annihilation of dislocations [9-11].

Furthermore, as a result of magnetostrictive elastic stresses caused at repeated remagnetization in the lattice may arise nonuniform internal stress field. This will raise the probability of occurrence of dynamic recovery. Relaxation mechanisms may be: cross slip dislocations, atoms return to the equilibrium position, increasing the recombination zone of Frenkel pairs. It should be noted the discrete flow of the relaxation processes on the sample volume caused by heterogeneous distribution of defects and internal stresses, and also the degree of defectiveness of the material.

The results of structural investigation of specimens processed by the modes 3 and 4 allow stating the active development of relaxation processes during creep with the restructuring of the initial structure until the fracture and the creation of a new recovery structure with the formation of the polygonal boundaries. Formed polygonal structure has high disorientation angles between subgrains exceeding 10°.

Completeness and heterogeneity of recovery processes under the action of tensile stress and temperature is determined by the degree of pinning of dislocations by point defects and their complexes, as well as by different intensities of plastic flow in the structural elements of deformation (Fig. 3,a,b).

Interaction of domain boundaries with point defects and dislocation during remagnetization leads to a redistribution of dislocations and some ordering of the defect structure. Consequently, the interaction force between dislocations and dislocations with domain boundaries are comparable. As a result, in the magnetic treatment, along with the depletion of moving defects decreased mobility domain boundaries [12]. This means that the efficiency of the magnetic field influence on the structure of the ferromagnetic is reduced and further structural changes are possible when changing the magnetic action, particularly when using the periodic switching on and off magnetic field.

Structure of the samples after treatment in a pulsed mode 5 is not obvious signs of recovery. Are often frozen elements of the initial state (see Fig. 3,c). Increased stability of the structure is likely due to the coarsening of its elements in boundary regions during the previous treatment by mode 5, which hinders the recovery processes and increases the strength properties and creep resistance.

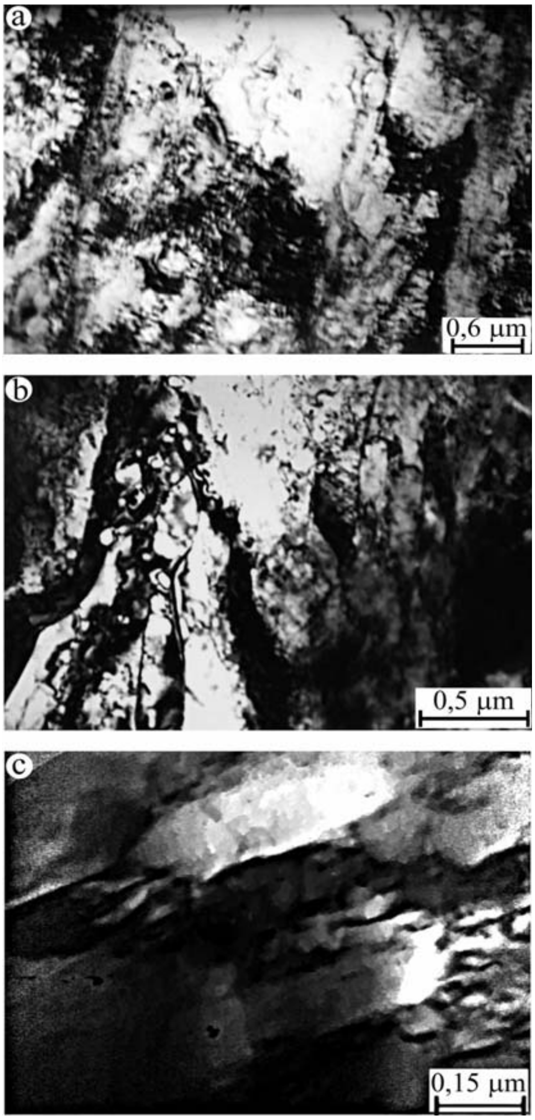

Fig. 3. Structure of the vessel steel processed by modes 3 (a) and 4 (b) and by the mode 5 (c) after creep at $T = 600$ K and $\sigma \approx \sigma_B$.

Thus, we can conclude that treatment in an alternating magnetic field of the strengthened radiation steel by modes 3 and 4 allows to lower the polygonisation temperature during creep, which is usually more than 0.4 T_m and is observed in the steady creep stage; and the recovery processes are slowed down as a result of magnetic treatment in a pulsed mode.

CONCLUSIONS

Effect of alternating magnetic field on the plastic flow of strengthened by radiation the vessel steel 15Kh2NMFA is ambiguous. We can see, depending on the treatment regime, as an active development of recovery processes and increase in of the stability of the structure during creep.

Processed by alternating magnetic field H = 700 Oe for 2…3 hours of the steel reduced the level of internal stress due to redistribution of defects, which leads to a reduction in yield strength of the material. This gives rise to the instability of plastic flow of the steel samples due to inhomogeneous local transformation of structure, formed after irradiation, most notably in the areas of maximum distortions.

Treatment with magnetic field in a pulsed mode increases the stability of the structure during creep due to coarsening of the original structure and inhibition of recovery processes

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ВЛИЯНИЕ ПЕРЕМЕННОГО МАГНИТНОГО ПОЛЯ НА ПОЛЗУЧЕСТЬ ОБЛУЧЕННОЙ КОРПУСНОЙ СТАЛИ 15Х2НМФА

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Изучено влияние переменного магнитного поля на ползучесть при 600 К облученной корпусной стали 15Х2НМФА. Проведены структурные исследования образцов стали после различных обработок. Показано, что влияние переменного магнитного поля на процессы пластического течения упрочненной облучением стали неоднозначно. В зависимости от режима обработки возможно как активное развитие возвратных процессов, так и повышение устойчивости структуры в процессе ползучести.

ВПЛИВ ЗМІННОГО МАГНІТНОГО ПОЛЯ НА ПОВЗУЧІСТЬ ОПРОМІНЕНОЇ КОРПУСНОЇ СТАЛІ 15Х2НМФА

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Вивчено вплив змінного магнітного поля на повзучість зразків опроміненої корпусної сталі 15Х2НМФА при температурі 600 К. Проведено структурні дослідження зразків сталі після різних обробок. Показано, що вплив змінного магнітного поля на процеси пластичної течії зміцненої опроміненням сталі неоднозначно. Залежно від режиму обробки можливо як активний розвиток процесів повернення, так і підвищення стійкості структури в процесі повзучості.