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The effect of a constant magnetic field on the creep of an aluminum alloy with iron-containing inclusions during stretching

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The influence of a constant magnetic field on the creep processes of an inhomogeneous aluminum alloy with ferromagnetic inclusions has been studied. It was experimentally found that preliminary exposure of samples in a constant magnetic field with induction $B = 0.3-0.7\,\mathrm{T}$ leads to a decrease ($\sim 30\%$) in the value of the modulus of elasticity characterizing the ratio of mechanical stress to relative deformation of the material after prolonged application of a constant load. The description of the observed changes was carried out within the framework of the Kelvin viscoelastic body model. Changes in the viscosity element in the model are determined by the magnetically stimulated changes occurring at the interphase boundaries (inclusion-matrix).

Keywords: creep, aluminum alloy, ferromagnetic inclusions, magnetic field.

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The phenomenon of creep is known to occur when a solid body is constantly exposed to an external force (stress), resulting a time-dependent change of deformation [1]. The resulting deformations are irreversible, even if the stress in the sample is below the yield strength. Creep issues are extremely relevant for the designing of materials and devices operating under high mechanical loads: components of aircraft engines (turbine blades and discs, combustion chambers, etc.), chemical reactors, building structures, etc. [1,2]. In addition to external mechanical forces, materials and devices are often exposed to other external impacts (electric, magnetic fields, etc.), which can significantly affect the dynamics of the considered processes. It should also be emphasized that today metal matrix composites with various inclusions are very actively used in technological practice [2]. Creep processes in such heterogeneous systems also require detailed studies and appear to be extremely relevant.

The study of metals and alloys is of interest both from the point of view of practical application in metalworking, and from the point of view of identification of the mechanisms of dynamics of the defective structure of the material, resulting in its destruction. The creep models that exist today cover not only single crystals but also polycrystals [1,2].

In most cases, the change of creep of metals and alloys is associated with the dynamics of linear defects in case of a prolonged plastic deformation of samples [3]. As for the characteristic development times of creep processes, they can vary from fractions of seconds [4–6] to tens of hours depending on the material, applied mechanical stresses and temperature [7–9]. For example, when studying the dynamics of the formation of deformation bands during creep in Al$-$Mg alloy, it was found that the start of the deformation stage on the creep curve begins with the nucleation and rapid expansion of the primary deformation band, generating an acoustic emission signal during 1 ms [5,6]. On the other hand, the creep processes were recorded for about 6 h for testing uniaxial tension and aging of Al$-$Li alloy samples cut at different angles γ to the direction of rolling of the material [7].

The characteristic creep times of the material varied from 1 to 16,h during the study of the impact of electric pulse treatment on the creep of aluminum alloys [8]. The creep times were ~ 18 h the effect of temperature on the creep deformation of an Al alloy was studied [9]. Similar papers consider the „classical“ creep of materials as an aftereffect occurring during the deformation of samples under the impact of constant mechanical stress.

The presence of precipitates and inclusions in crystals significantly affects mechanical properties (including creep processes) as noted in jcite9, since they are additional stress concentrators and centers of localization of structural defects [10,11]. Aluminum alloys with iron-containing inclusions are examples of structurally heterogeneous materials. External impacts (permanent magnetic field, electric current, annealing) can significantly affect the mechanical properties of such materials. Earlier, we discovered the impact of a constant magnetic field on the processes of plastic deformation of aluminum alloys with ferromagnetic inclusions [12]. However, transient processes during loading and unloading of the sample and the effect of pre-magnetic exposure on them were not considered. Therefore, the purpose of this paper is to consider magnetically stimulated transient processes in the creep conditions of an aluminum alloy with iron-containing inclusions.

As before, the object of the study was flat aluminum samples consisting of heads designed to fix the sample in grips and a working part with a constant cross section $S_0 = h_0 b_0$ ($h_0 = 3\,\text{mm}, b_0 = 5\,\text{mm}$) and a length of $l_0 = 30\,\text{mm}$ [12,13].

The structure and chemical composition of the matrix and inclusions were analyzed using optical (Metam-P1, Russia) and scanning (Jeol JSM-7610F Plus, Japan) electron microscopy, as well as X-ray diffraction analysis (Brucker D8 Discover, Germany). The results of studies allowed determining the chemical composition of the matrix ($C_{\text{Al}} \leqslant 95.8$ at.%, $C_{\text{Fe}} \leqslant 0.6$ at.%, $C_{\text{Mn}} \leqslant 0.4$ at.%, $C_{\text{Si}} \leqslant 2.3$ at.%, the rest — other impurities, including O, B) and inclusions ($C_{\text{Al}} \leqslant 52.6$ at.%, $C_{\text{Fe}} \leqslant 46.2$ at.%, $C_{\text{Si}} \leqslant 0.6$ at.%, the rest — other impurities, including O, Mg, B). The Al and Fe_4Al_{13} ($FeAl_3$) phases were found using the data of X-ray diffraction studies of the matrix and inclusions, which is consistent with the results obtained earlier [13].

The creep of the material under uniaxial loading of the samples was studied using a lever-type unit (with a force ratio of 1:10). It ensured the constancy of the load during the measurement process, as well as the possibility of stepwise application and removal of the load on the samples. The measurement processes were carried out at room temperature. The elongation during the tensile testing of the sample was recorded using a pointer micrometer ($\pm 10\,\mu$m), whose readings during creep were recorded using a digital camera (recording speed 30 frames per second). The source of the permanent magnetic field (MF) was neodymium magnets with MF maximum induction value of $B = 0.7$ T. The time of exposure in the constant MF was 30 min at room temperature.

Let's consider the viscoelastic Kelvin body for analyzing transient processes when samples are loaded under the creep conditions [14]:

$$\sigma + n\frac{d\sigma}{dt} = H\varepsilon + nE\frac{d\varepsilon}{dt}. \tag{1}$$

Here and further σ, ε — the effective mechanical stress and relative deformation of the sample, respectively, n — the relaxation time. The first terms in the right and left parts of the expression (1) can be neglected in the case of a stepwise load application, when $n\frac{d\sigma}{dt} \gg \sigma$ and $nE\frac{d\varepsilon}{dt} \gg H\varepsilon$. Then the expression takes the form

$$\frac{d\sigma}{dt} = E\frac{d\varepsilon}{dt}, \tag{2}$$

and, therefore, $\sigma = E\varepsilon$.

Therefore, the value E is the instantaneous modulus of elasticity (the ratio of stress to relative deformation under stepwise load application). In the case of a very slow load application, when the derivatives in (1) are small and can be neglected, it follows from (1) that

$$\sigma = H\varepsilon. \tag{3}$$

Here, the value H has a sense of the modulus of elasticity (the ratio of stress to relative deformation of the material after prolonged application of constant load).

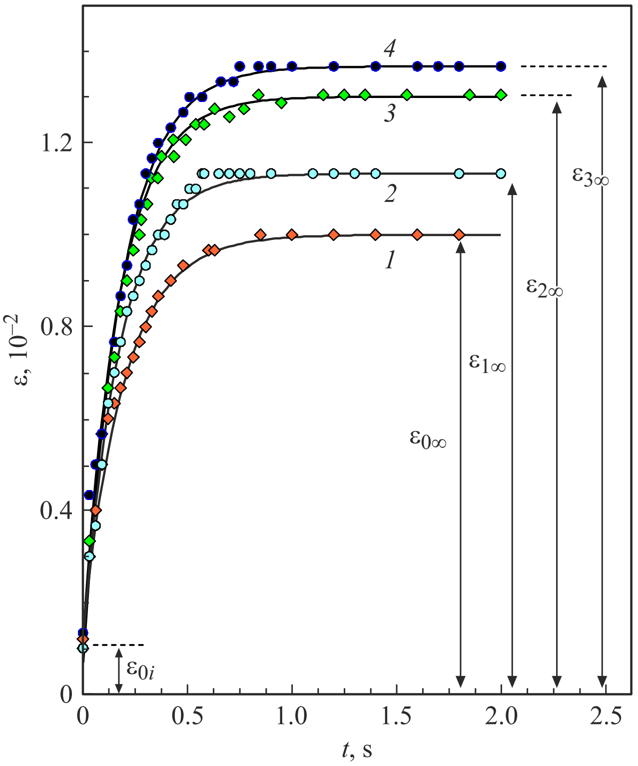

Figure 1. Field dependence of creep curves $\varepsilon(t)$ of samples after „instantaneous“ application of load $\sigma_0 = 66.7$ MPa. The samples were exposed immediately before the creep tests for 30 min at room temperature under the induction of a uniform magnetic field $B = 0$ (*1*), 0.3 (it 2), 0.5 (it 3) and 0.7 T (*4*).

A three-link Kelvin model was used for an aluminum alloy reinforced with microscopic iron-containing inclusions. The model takes into account the elastic modulus of the matrix E_1 and inclusions E_2. If the stress σ_0 is set as a step („instantaneous“ loading), then the deformation $\varepsilon(t)$ will tend to a constant value $\varepsilon(t) = \sigma_0/H$, where the value H in our model will be defined as

$$H = \left(\frac{1}{E_1} + \frac{1}{E_2} + \dots + \frac{1}{E_k}\right)^{-1}.$$

Since the number of elastic elements in the model under consideration is $k = 2$, we have the following

$$H = \frac{E_1 E_2}{E_1 + E_2}.$$

Therefore, a plastic deformation occurs in the boundary regions around the inclusions because of the preliminary exposure of samples in a magnetic field and subsequent magnetostriction of inclusions, as a result of which the elastic modulus E_1 and H change.

In relation to the experimental sample (rectilinear rod), on which the mechanical stress $\sigma = \sigma_0 = \text{const}$ begins to act at the moment $t = t_1 = 0$, the deformation dynamics in

Field dependence of mechanical characteristics of samples under instantaneous loading

№	Parameter	MF induction value B, T			
		0	0.3	0.5	0.7
1	Relative deformation ε_{i0}, 10^{-2}	0.10	0.12	0.10	0.10
2	Relative deformation $\varepsilon_{i\infty}$, 10^{-2}	9.7	11.2	13.0	13.8
3	Module E, GPa	70	60	70	70
4	Module H, GPa	6.7	5.9	5.1	4.9

this case will take the following form [14]:

$$\varepsilon(t)=\frac{\sigma_0}{H}\left(1-\left(1-\left(\frac{H}{E}\right)e^{-\frac{H}{nE}t}\right)\right). \qquad (4)$$

At the same time, the initial deformation of the rod $\varepsilon(0)=\varepsilon_0=\sigma_0/E_0$ at time $t_1=0$, and the relative elongation of the rod $\varepsilon(t)=\varepsilon_\infty=\sigma_0/H$ at $t\to\infty$.

Let us now consider the dynamics of the creep of our sample under tension ($\sigma_0=\text{const}$) after exposure to a constant magnetic field. The study results are shown in Fig. 1. The obtained dependence describes the process of creep of the material under constant stress. It is not difficult to see (the curve *1* in Fig. 1) that the instantaneous deformation increases over time and asymptotically approaches the value of σ_0/H under the action of σ_0.

The changes of the dynamics of deformation are observed in addition to the increase of plastic deformation of the material after preliminary magnetic exposure (curves *2–4* in Fig. 1): the value of ε_∞ increases with an increase of the magnetic induction B. The results of processing of the experimental data are summarized in a table. As a result of numerous experiments, a decrease of the value of the elastic modulus H was recorded after preliminary magnetic exposure of the samples. The dependence of the modulus H of the samples on the induction of the magnetic field is shown in Fig. 2. As we found out earlier [13], the MF influences the defective structure due to the magnetostriction of iron-containing inclusions in the alloy matrix (insert in Fig. 2). The resulting local mechanical stresses result in an increase of the concentration of freshly introduced dislocations in the boundary areas of the phase separation, which further participate in the process of plastic the flow of the material. An increase of B results in an increase of the local stresses at the interfacial boundaries, where the dislocation density increases. Such changes of the defective structure affect the entire deformation process, including transient processes during loading and stress relaxation during unloading. The modulus H is a structurally sensitive parameter reflecting the effect of premagnetic exposure on the mechanical properties of the studied aluminum alloys (creep).

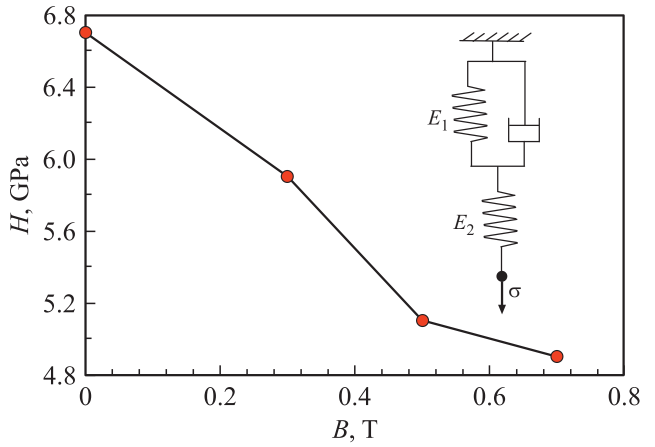

Figure 2. Field dependence of the elastic modulus H of the material after application of a constant load σ_0. The viscoelastic Kelvin model is shown in the insert.

Thus, magnetically stimulated changes of the creep of aluminum alloy samples with iron-containing inclusions are considered in the paper. A change of the relative deformation and modulus of elasticity of the samples H was experimentally found after their preliminary exposure to a constant magnetic field. A decrease of H by $\sim 30\%$ is associated by the authors with the processes of plastic deformation at the matrix–inclusion interfacial boundaries as a result of magnetostrictive deformation of inclusions during exposure of the material in the constant MF. The observed changes were described within the framework of the model of the Kelvin viscoelastic body. It should be emphasized that the change of structure in case of preconditioning in a magnetic field and subsequent deformation are different processes. The resulting magnetically stimulated deformation changes at the interfacial boundaries (inclusion–matrix) determine the corresponding changes of the viscosity element in the considered model of the viscoelastic body.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] T.N. Tak, A. Prakash, S.M. Keralavarma, I. Samajdar, P.J. Guruprasad, J. Mech. Phys. Solids, **179**, 105385 (2023). DOI: 10.1016/j.jmps.2023.105385

[2] W. Abd-Elaziem, J. Liu, N. Ghoniem, X. Li, J. Mater. Res. Technol., **26**, 3025 (2023). DOI: 10.1016/j.jmrt.2023.08.068

[3] X. Xiao, S. Li, L. Yu, Int. J. Plast., **157**, 103394 (2022). DOI: 10.1016/j.ijplas.2022.103394

[4] S. Verheyden, L. Deillon, A. Mortensen, Acta Mater., **234**, 118037 (2011). DOI: 10.1016/j.actamat.2022.118037

[5] A.A. Shibkov, M.A. Zheltov, M.F. Gasanov, A.E. Zolotov, A.A. Denisov, M.A. Lebyodkin, Mater. Sci. Eng. A, **772**, 138777 (2020). DOI: 10.1016/j.msea.2019.138777

[6] A.A. Shibkov, A.E. Zolotov, A.A. Denisov, M.F. Gasanov, Tech. Phys. Lett., **48** (7), 66 (2022). DOI: 10.21883/TPL.2022.07.54043.19228.

[7] X. Wang, Z. Shi, J. Lin, Int. J. Mech. Sci., **260**, 108659 (2023). DOI: 10.1016/j.ijmecsci.2023.108659

[8] K. Chen, L. Zhan, Y. Xu, Y. Liu, J. Mater. Res. Technol., **9** (6), 15433 (2020). DOI: 10.1016/j.jmrt.2020.10.100

[9] L. Zhang, H. Li, T. Bian, C. Wu, Y. Gao, C. Lei, Chin. J. Aeronaut., **35** (10), 8 (2022). DOI: 10.1016/j.cja.2021.10.019

[10] Y. Wang, S. Lin, Z. Dong, J.H. Park, Q. Wang, H. Ni, W. Mu, Mater. Charact., **205**, 113299 (2023). DOI: 10.1016/j.matchar.2023.113299

[11] I. Todaro, R. Squatrito, S. Essel, H. Zeidler, Mater. Today Proc., **10** (2), 277 (2019). DOI: 10.1016/j.matpr.2018.10.407

[12] A.A. Skvortsov, D.E. Pshonkin, V.K. Nikolaev, P.A. Kulakov, Mech. Res. Commun., **129**, 104071 (2023). DOI: 10.1016/j.mechrescom.2023.104071

[13] M. Friha, V. Nikolaev, A. Skvortsov, D. Pshonkin, S.-E. Friha, P. Kusnetsova, J. Magn. Magn. Mater., **589** (1), 171532 (2024). DOI: 10.1016/j.jmmm.2023.171532

[14] Y. Zhao, H.C. Liu, G.E. Morales-Espejel, C.H. Venner, Tribol. Int., **171**, 107562 (2022). DOI: 10.1016/j.triboint.2022.107562

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