Magnetic memory. Mechanical tests and proposed mechanisms

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Abstract. The article considers the issue of an attempt to experimentally study the effect of constant magnetic fields on the processes of plastic deformation of aluminum alloys. An analysis of the influence of a magnetic field on the creep of an Al alloy with iron inclusions is presented. Estimates of the supposed mechanisms of the influence of the magnetic field on the creep processes are given.

1. Introduction
The effect of magnetic fields on the physical and mechanical properties of nonmagnetic materials has been studied as a phenomenon for several decades [1]. Investigators mark the effect of magnetic memory as the most interesting and relevant of its kind. Magnetic memory is a change in the physical and mechanical properties of a crystal after exposure to a magnetic field due to magnetic action on sensitive centers in the crystal structure of the material. Such changes in mechanical properties can persist for a certain time.

At the atomic level, there is no definitive understanding of the principle of operation of the magnetic memory effect, so the theoretical question remains open. An external magnetic field affects the processes of spin-dependent reactions in the dislocation-stopper complex. However, there is a whole chain of physical processes that is reliably recorded at the macroscopic level, such as: magnetically stimulated dynamics of dislocations and its effect on plastic deformation of the material. Various additives, such as ferromagnetic inclusions, can significantly affect the picture of plastic deformation of samples after exposure to a magnetic field. These data make it possible to recreate a qualitative picture of the effect of magnetic stimulation on the processes of plastic deformation of some non-magnetic alloys.

The main task of this study is to attempt to experimentally study the effect of magnetic memory of some aluminum alloys containing Fe-inclusions, as well as the processes of stimulating plastic deformation of aluminum alloys using an external magnetic field.

2. Materials and equipment
Creep tests were carried out on a German WP-600 Creep Testing Machine. Figure 1 shows the installation and a dial gauge that records the absolute elongation.
Figure 1. Lever Type WP-600 Creep Testing Machine.

The test piece was placed in special clamps, then the load was set. In the course of measurements, simultaneously with the application of the load, the elongation of the sample was recorded using a micrometer at each stage of loading. The test setup provided a constant load in the measurement process, as well as smooth loading and unloading.

The experiments were performed using aluminum-magnesium alloy 6063 with microscopic iron inclusions with a volume concentration of ~ 2.5 %. Previously, some of the samples were exposed in the field of a permanent magnet with an induction $B \leq 1$ T for 30 min. After that, the samples that have already been processed and the witness samples were tested for creep under uniaxial loading (figure 2).

Figure 2. Samples before and after the creep test.

Test data for determining the magnetostriction of ferromagnetic inclusions, which provides local mechanical stresses and the generation of fresh dislocations in the vicinity of the inclusions, are the main reason for magnetoplasticity [2].

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3. Results and discussion
The test results showed an increase in plastic deformation of the exposed samples by 25% compared to the reference samples.

A preliminary analysis of the chemical composition of the samples showed the presence of iron in the paramagnetic matrix of aluminum, the subsequent analysis of scanning electron and transmission microscopy confirmed the presence of solid-state precipitates of the second phase in the alloy (figure 3).

![Figure 3. Fe-containing inclusion in the aluminum matrix of the sample.](image)

The results of experiments for tensile loads in the range of 150 ... 180 N are shown in figure 4.

![Figure 4. Creep curves for Al, which were recorded at step voltage in the range (150 ... 180 N) at room temperature. 1 - witness sample; 2 - exposure of the sample in a magnetic field.](image)
Evaluation of the obtained experimental deformation curves made it possible to determine the assumed mechanisms of creep. The calculated values of the activation energy allow us to assume that the unsteady stage of creep is controlled by the processes of crossing or cutting of dislocations in orthogonal slip planes. From this assumption it follows that the process of intersection of dislocations is a thermally activated process with an activation energy at zero stress $\Delta E_i$.

The activation energy is calculated by the formula:

$$\Delta E_n = \Delta E_i - \gamma (\sigma - \sigma_{VN}),$$

where $\gamma$ is the activation volume; $\sigma_{VN}$ – average local internal stress caused by other dislocations in parallel slip planes.

The creep rate is determined as follows:

$$\dot{\varepsilon} = N \cdot A \cdot b \cdot \nu \cdot \exp \left\{ \frac{-\Delta E_i + \gamma (\sigma - \sigma_{VN})}{RT} \right\}$$

where $N$ is the total number of dislocation sources; $A$ is the average area covered by the expanding loop; $b$ is the Burgers vector; $\nu$ is the natural frequency of vibrations of a single dislocation loop.

In the course of the experiments, the values of the activation energy of the creep process of the samples were obtained before and after exposure to a constant magnetic field (table 1).

| $P$, N | 150 | 160 | 170 | 180 |
|-------|-----|-----|-----|-----|
| $E_n$, eV, $B = 0$ | 0.124 | 0.124 | 0.124 | 0.124 |
| $E_n$, eV, $B \neq 0$ | 0.125 | 0.125 | 0.125 | 0.125 |

From the data obtained, it can be concluded that the magnetic field has an insignificant effect on the activation energy of the creep process [3]. The magnetic field noticeably affects the dynamics of the activation volume of the $\gamma$ process, which is associated with the density of dislocations in the material matrix near $Fe$-containing inclusions.

The magnetoplastic effect is the localization of mechanical stresses in the vicinity of inclusions in a magnetic field, which is sufficient to generate fresh dislocations and soften the material. The experimentally observed magnetoplastic effect can be explained by the fact that this alloy $Fe_x Al_{1-x}$ has high magnetostriction constants at $x = 86-87\%$.

The formula (3) calculates mechanical stresses in a magnetic field.

$$\sigma_m = \lambda_m \cdot B,$$

where $\lambda_m = 8 \cdot 10^8 N \cdot (T \cdot m^2)^{-1}$ is the magnetostriction coefficient of the alloy $Fe_x Al_{1-x}$.

Normal stress $\sigma_m = 560$ MPa in a magnetic field $B = 0.7$ T. The results obtained exceed the yield point stress of $\sigma_y = 120$ MPa, on this basis, an increase in creep can be observed. If $r_0$ is the radius of inversely proportional dependence $\sigma_m$ on the distance to the center of the inclusion, then the radius of plastic deformation of the zone has the form $r = r_0 \cdot \frac{\sigma_m}{\sigma_y} = 6$ $\mu m$. This is comparable to an average inter-inclusion spacing of 12 $\mu m$. 


Based on the above, it can be concluded that MF can lead to magnetization of Fe-magnetic inclusions. Each particle forms local $\sigma_m$ ones using the magnetostriction effect and increases the plastically deformed zone around the inclusion. These changes are saved even after the MP is turned off. These estimates are the most probable, but they do not exactly prove that the magnetostrictive mechanism is the main one.

4. Material destruction work
In the first approximation, the process of plastic deformation of a material can be considered from the point of view of the law of conservation of energy. If we neglect the heat losses due to the friction of the crystal lattice [4], then all the deformation energy expended will be spent on the work of destruction.

$$ A_p = \int_0^{\varepsilon_{cr}} \sigma(\varepsilon) \cdot d\varepsilon, $$

where $\sigma(\varepsilon)$ is the acting stress under uniaxial tension, $\varepsilon_{cr}$ is the maximum deformation of the material.

Since the acting stress depends on the plastic deformation, we assume that

$$ \sigma(\varepsilon) = \sigma_p \cdot (1 + \varepsilon), $$

where $\sigma_p$ is the ultimate tensile stress. Then (4) after transformations will look as follows

$$ A_p = \frac{\varepsilon_{cr}^2}{2} + \sigma_p \cdot \varepsilon_{cr} \cdot \sigma_p \cdot \varepsilon_{cr} $$

On the other hand, this same fracture work can be shown graphically in a tensile diagram, in which the total work performed will correspond to the area under the deformation curve (figure 5).

**Figure 5.** Diagram of stretching of samples before and after exposure to a magnetic field. 1 - witness sample; 2- sample after exposure to a constant magnetic field with an induction of 0.7 T. Zone 1 is the beginning of macroplastic deformation. Zone 2 - the beginning of the dynamic return stage.
As can be seen from the graph, changes in the nature of deformation are observed from the beginning of the stage of strain hardening. Estimating $A_p$ according to equation (6), based on the experimental tensile curves, we obtain an increase in the work of plastic deformation of the material by 20% compared to the witness sample.

Such changes are provoked by the magnetostrictive effects of inclusions in the material matrix, which significantly affect the dislocation dynamics and, as a result, plastic deformation in general.

5. Conclusions

1. The analysis of the influence of MF on the creep of an Al alloy with iron inclusions has been carried out.
2. It was revealed that the preliminary exposure to the MF ($B \leq 0.7$ T) promotes an increase in the deformation of the alloy (up to 30%), the value of the activation volume of the alloy $\gamma$. The changes caused by the MF are confirmed by the dynamics of the initial creep rates at the unsteady stage of creep.
3. Estimates are given of the supposed mechanisms of the influence of the magnetic field on the creep processes, which are associated with the dynamics of dislocations and the magnetostriction of Fe-inclusions.
4. Numerical calculations of $\sigma_m = 560$ MPa are obtained, which contribute to an increase in the plastically deformed zone around the inclusion.

References

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