Original Article

Influence of permanent magnetic fields on creep and microhardness of iron-containing aluminum alloy

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ABSTRACT

The necessity and urgency of studying plastic strain of metals is determined by both scientific significances of the problem and requirements of practice. So the objective of this work is investigation of aluminum alloy creep under action of static magnetic fields. This subject matter is of practical importance for engineering since the parts of engineering constructions are subject to various loads which may lead to their damage or even creep rupture. Based on the experiments performed by us, it is found that creeping increases under stable magnetic field; the main features appear at the first creep stage. Investigation of these processes will help to predict time dependence of creep strain and its rate as well as durability and plasticity at destruction.

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1. Introduction

It is known that influence of static magnetic field (MF) can change strain characteristics of a number of ionic, ionic-covalent, covalent, molecular and metal solids [1,2]. When discussing such issues, the so-called magnetoplastic effect (MPE) is often mentioned. MPE is a set of phenomena caused by dislocation motion in diamagnetic crystals under the action of external MF with induction of ~1 T and higher in the absence of deforming loads. MPE manifests itself as changes of mechanical characteristics of solids (plasticity, strength, plastic flow, etc.). They may either appear in the presence of MF or be long-term or even irreversible [1,2]. The effect of MF on plasticity of ferromagnetic materials is not considered in the present paper.

An analysis of MPE in diamagnetic crystals makes it possible to classify them in the following way [2]:

1. Plasticity is changed only if the crystals are strained in MF. Presence of MF before or after strain does not change the mechanical properties of crystals [3,4]. As a rule, such materials demonstrate low sensitivity to temperature and high sensitivity to the type of impurity in the crystal.

2. To make magnetic-stimulated effects appear, concurrent action of MF and an external exciting factor (e.g., electric current [5–7], ultrasound [8], etc.) is required.

3. Plasticity of crystals can be changed by MF action before their strain (i.e., the residual changes initiated by MF remain) [9,10].

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The effects related to the residual changes initiated by static MF are of considerable practical interest. At present the effect of preexposure to MF on metal plasticity is known [11]. A change of retardation of dislocations by magnetic-sensitive stoppers as a cause of metal softening after their preexposure to MF was considered in [1,2,9,11]. However, the performed experimental studies did not cover a wide range of the mentioned effects concerning aluminum and its alloys. There are no experimental results on the effect of static MF on creep of aluminum and its alloys Al-Mg-Si.

Therefore, the objective of the present work is experimental investigation of the effect of preexposure to MF of aluminum alloys on the processes of their creep.

2. Materials and methods

For the experiments, we used standard flat aluminum samples with a width of 3.0 mm in working section and a length of 100 mm, which were cut from an aluminum strip 2 mm thick. The material of the tape was an alloy of aluminum with magnesium and silicon Al ≤ 97.9%, Mg ≤ 0.9%, Si ≤ 0.6%, Fe ≤ 0.6%, other (Cu, Ti, Zn) ≤ 0.2%. Other samples were cut from aluminum grade A99 with a content of CaI ≤ 99.99%. Iron in aluminum was in the form of inclusions, the microstructure of the material and the deformation scheme are shown in Fig. 1. The strain of the elemental composition of the inclusion was carried out in the electron microscope column by Energy-dispersive X-ray spectroscopy (EDS).

Samples were made of aluminum sheet by hydroabrasive cutting, which did not allow their strong heating. During the experiments, 45 samples were used, of which 25 were exposed to the field, and 20 – acted as witness specimens.

A magnetic field was created between poles of neodymium magnets. Induction of the magnetic field in the gap B = 0.7 T. When exposed, the lines of induction of the magnetic field were perpendicular to the plane of the sample. The exposure time ranged from 5 min to 120 min. Special studies have shown that the main changes occur during the first 10 min of exposure in the MF. Further, the observed changes are practically independent of the exposure time. That is why in the work the time of the samples’ exposure to a magnetic field was 30 min and always happened at room temperature [12].

Creep analysis was carried out on a test rig with a lever load system under conditions of normalized force during mechanical testing at room temperature. Preliminary measurements made it possible to determine the range of tensile loads (F = 150...190 N) when examining the creep of the samples described above.

3. Results and discussion

It is known [13] that if static stretching force acts on a solid, then its crystal lattice will counteract to the applied force. Macroscopically this will be observed as strain (and subsequently destruction).

Metal creep can be described with a creep curve Δт(ε) (Fig. 1). A strain Δт₂ appears at loading and involves both plastic and elastic components [14]. A curve piece Δт₀...Δт₁ (Fig. 1) at which creep rate is decreasing with time is the first creep stage. At the strain curve piece Δт₁...Δт₂ (Fig. 2) creep rate is insignificantly changed. A practically steady state is observed here. This curve piece is referred to as the second creep stage.

After strain Δт₂, the third creep stage comes. The creep rate is gradually increasing until destruction occurs (at strain Δт₃ and in the corresponding time t₃). Therefore, the creep curves of aluminum alloy were registered only at the first and second creep stages.

Flat samples (length ℓ₀ = 80 mm, width of 3.0 mm) cut from a band (thickness of 2 mm) were used in experiments. The band material was an alloy of aluminum with magnesium and silicon: CAl ≤ 97.9%; CMg ≤ 0.9%; CSI ≤ 0.6%, CFe ≤ 0.4%, other (Cu, Ti, Zn) ≤ 0.2%. MF was between the poles of neodymium magnets. MF induction B in the gap was of 0.7 T. At exposure, the MF induction lines were perpendicular to the sample.
promotes increasing of aluminum alloy strain practically in the whole range of applied stretching loads: immediately after start of loading $\Delta \ell_{\text{B}} = \Delta \ell_{\text{O}} = 40 \mu\text{m}$ at $P = 150$ N and $\Delta \ell_{\text{O}} = 401 \mu\text{m}$ at $P = 180$ N. One should also note an appreciable effect of MF on the constant $\beta$: after "magnetic" exposure it is practically doubled at $P = 180$ N. At the same time, action of MF at the second creep stage practically does not change the creep rate constant $k$. This makes it possible to conclude that the results of samples preexposure to static MF manifest themselves most efficiently at the first creep stage.

The additional experimental arguments for the effect of static MF on the creep processes are presented in Fig. 3. It is not difficult to see that the difference in strains of the check test samples and the samples aged in MF increases with an external load. This is in agreement with the data given in Table 1 as well as those presented by other authors [1,2,15].

When discussing the assumed mechanisms of MF effect on plastic properties of magnesium-containing alloy, it is necessary to take into account one more factor related to presence of iron (up to 0.4%) in the aluminum alloy. Iron interacts with aluminum forming intermetallic phases [16]. Without silicon, the refractive phases $\text{Al}_3\text{Fe}$ and $\text{Al}_5\text{Fe}_2$ are predominant. However, the situation changes if silicon is present: the brittle $\alpha$-phases $\text{Al}_4\text{Fe}_2\text{Si}$ and $\text{Al}_2\text{FeSi}$ become predominant. If (just as in our case) magnesium is present ($C_{\text{Mg}} \sim 0.9\%$), then $\pi$-phases $\text{Al}_5\text{Fe}_2\text{Mg}_3\text{Si}_6$ may appear in the aluminum alloy. The iron-containing intermetallic phases may be formed as plates ($\alpha$-phase) and have ferromagnetic properties.

The purpose of the next part of the work was an experimental study of the effect of preliminary exposure of a constant magnetic field on the microhardness of an aluminum alloy studied earlier.

The microhardness was measured by pressing the Berkovich pyramid, while the load on the pyramid was 1 N. As before, some of the samples were placed in a permanent magnetic field ($B = 0.7$ T, at room temperature) before mechanical tests. The measurement was carried out on 20 samples. The results of the studies showed that when measuring the microhardness on these samples, better reproducibility of the results was achieved at times of exposure to an indentor load of 5 min or more. Therefore, the comparison of the results was carried out in the time range of 6–9 min. The results obtained (Fig. 4) showed a significant difference in the values of the microhardness of samples that had been preliminarily exposed in MF ($HV = 310 \pm 30$ MPa) and the witness specimen ($HV = 420 \pm 30$ MPa).

4. Conclusion

Thus, the study of the influence of permanent magnetic fields on the creep of aluminum alloys was carried out. It was found experimentally that preliminary exposure of samples with a Fe content (~0.4 at. %) in a constant magnetic field (with induction $B = 0.7$ T for 30 min at room temperature) leads to
Table 1 – The constants of aluminum alloy creep ($r^2$ is the pair correlation coefficient).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>150 N</th>
<th>160 N</th>
<th>170 N</th>
<th>180 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$, T</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta\ell_0$, $\mu$m</td>
<td>428</td>
<td>469</td>
<td>490</td>
<td>529</td>
</tr>
<tr>
<td>$\beta$, $10^{-5}$, s$^{-1/3}$</td>
<td>0.59</td>
<td>1.75</td>
<td>1.5</td>
<td>1.8</td>
</tr>
<tr>
<td>$K_0$, $10^{-7}$, 1/s</td>
<td>1.25</td>
<td>1.25</td>
<td>1.38</td>
<td>2.01</td>
</tr>
<tr>
<td>$r^2$</td>
<td>0.975</td>
<td>0.978</td>
<td>0.896</td>
<td>0.897</td>
</tr>
</tbody>
</table>

Fig. 3 – Aluminum alloy creep curves taken at a load $P = 180$ N at room temperature: 1, sample preexposure to static MF $B = 0.7$ T for 30 min; 2, unexposed sample. Inset: a schematic of magnetic-stimulated strain $\Delta\ell_0$ on the applied stretching load $P$.

Fig. 4 – Dependence of the microhardness of HV samples of an aluminum alloy on the time of loading on an indenter ($P = 1$ H) at room temperature: 1, preliminary exposure of samples in a constant magnetic field $B = 0.7$ T for 30 min at room temperature; 2, specimen-witnesses without exposure in MP.

an increase in the absolute strain of the aluminum alloy to 35% and microhardness values. The experimentally weakened aluminum-based alloys after exposure in the MP can serve as an additional method for controlling the structurally sensitive properties of these materials.

Conflicts of interest

The authors declare no conflicts of interest.

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