DEFORMAÇÃO DE LIGAS DE ALUMÍNIO SOB INFLUÊNCIA DA CARGA ADICIONAL

DEFORMATIONS OF ALUMINUM ALLOYS UNDER THE INFLUENCE OF AN ADDITIONAL LOAD

ДЕФОРМАЦИИ АЛЮМИНИЕВЫХ СПЛАВОВ ПОД ВЛИЯНИЕМ ДОПОЛНИТЕЛЬНОЙ НАГРУЗКИ

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RESUMO

Sob a influência de um campo magnético constante, há uma deformação das partículas sólidas. Esses processos no futuro levam à destruição. Portanto, os autores investigaram esses processos em mais detalhes. Ao estudar a fluência das amostras, foi utilizada uma máquina do tipo alavanca. Durante as medições (em temperatura ambiente) simultaneamente com a aplicação da carga (realizada por etapas), um alongamento da amostra foi registrado com um micrômetro (escala de 10 μm), em cada estágio de carregamento. O equipamento de teste forneceu uma carga constante durante a medição, bem como carga e descarga suaves. Com base nos experimentos realizados, verifica-se que o rastejamento aumenta sob o campo magnético estável; os principais recursos aparecem no primeiro estágio de fluência. Assim, a exposição preliminar de amostras em um campo magnético constante (com indução $B = 0,7 \text{ T}$ por 30 minutos à temperatura ambiente) leva a um aumento na deformação absoluta da liga de alumínio para 35%. As constantes de deformação do material são também determinadas sob condições de "fluxo- β ". Um aumento na constante de deformação do material no primeiro estágio de fluência foi determinado 6 vezes maior. A investigação desses processos ajudará a prever a dependência do tempo da deformação por fluência e sua taxa, bem como a durabilidade e a plasticidade na destruição.

Palavras-chave: Ligas de alumínio, ensaios mecânicos, ímãs de neodímio, força estatística, rede cristalina.

ABSTRACT

Under the influence of a constant magnetic field, there is a deformation of solid particles. These processes in the future lead to destruction. Therefore, the authors investigated these processes in more detail. When studying the creep of the samples, a lever-type machine was used. During the measurements (at room temperature) simultaneously with the application of the load (carried out by steps), an elongation of the sample was recorded with a micrometer (division price 10 μm), at each loading stage. The test rig provided a constant load during the measurement, as well as smooth loading and unloading. Based on the performed experiments, it is found that creeping increases under stable magnetic field; the main features appear at the first creep stage. Thus, preliminary exposure of samples in a constant magnetic field (with induction $B = 0.7 \text{ T}$ for 30 minutes at room temperature) leads to an increase in the absolute deformation of the aluminum alloy to 35%. The material deformation constants are also determined under " β -flow" conditions. An increase in the material deformation constant at the first stage of creep was found to be more than 6 times. Investigation of these processes will help to predict time dependence of creep strain and its rate as well as durability and plasticity at destruction.

Keywords: Aluminum alloys, mechanical tests, neodymium magnets, statistical force, crystal lattice.

АННОТАЦИЯ

Под действием постоянного магнитного поля происходит деформация твердых частиц. Эти процессы в будущем приводят к разрушению. Поэтому авторами и были исследованы эти процессы. При изучении ползучести образцов использовалась рычажная машина. Во время измерений (при комнатной температуре) одновременно с применением нагрузки (выполняемой ступенями) удлинение образца регистрировалось микрометром (цена деления 10 мкм) на каждой стадии загрузки. Испытательная установка обеспечивала постоянную нагрузку во время измерения, а также плавную загрузку и разгрузку. На основании проведенных экспериментов установлено, что при стабильном магнитном поле увеличивается ползучесть; основные функции появляются на первой стадии ползучести. Таким образом, предварительная экспозиция образцов в постоянном магнитном поле (с индукцией $B = 0,7$ Т в течение 30 минут при комнатной температуре) приводит к увеличению абсолютной деформации алюминиевого сплава до 35%. Константы деформации материала также определяются в условиях « β -потока». Увеличение константы деформации материала на первой стадии ползучести было более чем в 6 раз. Исследование этих процессов поможет предсказать временную зависимость деформации ползучести и ее скорости, а также долговечность и пластичность при разрушении.

Ключевые слова: *алюминиевые сплавы, механические испытания, неодимовые магниты, статистическая сила, кристаллическая решетка.*

INTRODUCTION

Recently, active studies of the behavior of a solid in a magnetic field have been carried out. The paper describes the effect of magnetic fields on a solid body, which leads to its deformations (Smirnov *et al.*, 2001; Velikhanov, 2014). Magnetoplastic effects (MBE) are dynamic effects, and the magnetic field affects the motion of dislocations. In many cases, parts and components of machines and structures of modern power plants, electromagnetic devices, vehicles, recording and reproduction devices, measuring and scientific instruments, etc. work under the conditions of imposing permanent or alternating magnetic fields (MP) of varying intensity. In connection with this knowledge of the behavior of the mechanical characteristics of magnetic and non-magnetic materials in the presence of such fields is of great practical importance (Tyapunina *et al.*, 2003). Knowledge of the physical regularities of the manifestation of MPE allows to create also new technological methods for controlling the mechanical characteristics of solid materials (Makara *et al.*, 2001).

The effects related to the residual changes initiated by static MF are of considerable practical interest. At present the effect of pre-exposure to MF on metal plasticity is known (Li *et al.*, 2014). A change of retardation of dislocations by magnetic-sensitive stoppers as a cause of metal softening after their pre-exposure to MF

was considered in (Alshits *et al.*, 2003; Morgunov, 2004; Skvortsov *et al.*, 2015; Li *et al.*, 2014). There are also a lot of works connected with magnetically stimulated processes in the crystallization of aluminum alloys (Ran *et al.*, 2005; Kang *et al.*, 2017), as well as the influence of permanent magnetic fields on the mechanical properties of other metals (Morgunov, 2004; Alshits *et al.*, 1994; Kang *et al.*, 2017).

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 influence of pre-exposure to MF of aluminum alloys on the processes of their creep.

MATERIALS AND METHODS

The experiments were carried out using various loads on aluminum alloys under the influence of constant magnetic fields. At the same time, the authors justified the absolute deformation.

A magnetic field was created between poles of neodymium magnets. The exposure time ranged from 5 min to 120 min. 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.

For the experiments, we used standard flat aluminum samples with a width of 3.0 mm in working section and a length of $l_0 = 80$ mm, which were cut from an aluminum strip 2 mm thick.

When studying the creep of the samples, a lever-type machine was used. During the measurements (at room temperature) simultaneously with the application of the load (carried out by steps), an extension of the sample was recorded with a micrometer (division price 10 μm), at each loading stage. The test rig provided a constant load during the measurement, as well as smooth loading and unloading.

Special studies have shown that the main changes occur during the first 10 minutes 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 minutes and always happened at room temperature (Zhan *et al.*, 2016).

RESULTS AND DISCUSSION:

When a statistical force acts on a solid body, it soon leads to its destruction (Batalha *et al.*, 2014). It is known (Batalha *et al.*, 2014) 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 deformation (and subsequently destruction) (Skvortsov *et al.*, 2001).

Metal creep can be described with a creep curve $\Delta l(t)$ (Figure 1, inset). A deformation Δl_0 appears at loading and involves both plastic and elastic components (Garofalo, 1968). At the deformation curve piece $\Delta l_1 \dots \Delta l_2$ (Figure 1, inset) creep rate is insignificantly changed. A practically steady state is observed here. This curve piece is referred to as the second creep stage.

After deformation Δl_2 , the third creep stage comes. The creep rate is gradually increasing until destruction occurs (at deformation Δl_3 and in the corresponding time t_3). Therefore the creep curves of aluminum alloy were registered only at the first and second creep stages.

Flat samples (length $l_0 = 80$ 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: $C_{\text{Al}} \leq 97.9\%$; $C_{\text{Mg}} \leq 0.9\%$; $C_{\text{Si}} \leq 0.6\%$, $C_{\text{Fe}} \leq 0.4\%$, other (Cu, Ti, Zn) $\leq 0.2\%$. 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 plane. The exposure time was varied from 5 min to 120 min. Special studies showed that the main changes occurred in the first 10 min of exposure. Further observed changes practically did not depend on the exposure time. That is why the time of sample exposure to MF at room temperature always was 30 min.

Here ϵ_0 is relative deformation immediately after start of loading; the constants β and $m = 1/3$ are independent of loading time (Garofalo, 1968); k is creep rate at the second creep stage; Δl , Δl_0 and l_0 are absolute deformation, that immediately after start of loading and deformation for relative deformation ϵ , respectively.

It is more conveniently to deal with absolute deformation since just it is registered experimentally:

Then we determine the constants in Eq. (1) (both before action of static MF and after it) using the experimental results on samples creep at different stretching loads ($P = 150$ N...190 N).

The typical experimental results obtained at stretching loads of 170 N and 180 N are presented in Figure 1 and Figure 2 (those obtained at the rest of loads do not differ principally from the above ones.) The results of creep curves approximation according to Eq. 2 are given in Table 1.

One can see that sample pre-exposure to static MF (induction $B = 0.7$ T) for 30 min at room temperature promotes increasing of aluminum alloy deformation practically in the whole range of applied stretching loads: immediately after start of loading $\Delta l_{0B} - \Delta l_0 = 40$ μm at $P = 150$ N and $\Delta l_{0B} - \Delta l_0 = 401$ μm at $P = 180$ N. One should also note an appreciable effect of MF on the constant β : after "magnetic" exposure it is practically doubled 6 times 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 pre-exposure 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 Figure 2, inset. It is not difficult to see that the difference in deformations 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 (Alshits *et al.*, 2003; Morgunov, 2004; Soika *et al.*, 2015).

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 (Gottstein, 2004). Without silicon, the refractive phases Al_3Fe and Al_5Fe_2 are predominant (Li *et al.*, 2016). However, the situation changes if silicon is present: the brittle α -phases Al_8Fe_2Si and Al_5FeSi become predominant. If (just as in our case) magnesium is present ($C_{Mg} \sim 0.9\%$), then π -phases $Al_8Fe_3Mg_3Si_6$ may appear in the aluminum alloy. The iron-containing intermetallic phases may be formed as plates (α -phase) and have ferromagnetic properties.

The intermetallic particles of that form per se adversely affect the mechanical properties of aluminum alloys by reducing their plasticity and increasing their porosity. Therefore the aim of the further part of our work was experimental investigation of the effect of static MF on mechanical properties of aluminum alloy with C_{Al} no less than 99.9%. In such crystals, iron concentration does not exceed 0.001%. This is over two orders of magnitude less than was in the previous experiments.

The mechanical tests were performed using a tensile-testing machine (20 kN). Specific elongation, true rupture strength, ultimate stress and proportionality limit were registered. The yield strength was examined because of absence of yield plateau (Figure 3). One can see from the obtained stress-strain diagrams (Figure 3) that their behavior is the same until the stretching corresponding to the ultimate stress. However, the curves begin considerably diverge as the neck appears. As a result, we obtained that after exposure to MF (2, Figure 3) the samples are more plastic as compared to the check-test ones (1, Figure 3). This result also is in a qualitative agreement with the data given in (Alshits *et al.*, 2003; Morgunov, 2004; Soika *et al.*, 2015) where softening of Al single crystals subject to action of static MF was discovered. Thus, despite the

absence of iron atoms in the alloy, the effect of magnetic pre-exposure still is observed. This means that one should consider not only the magnetic-plastic effect (Molotskii and Fleurov, 2000) but the influence of iron-containing intermetallic phases as well when analyzing magnetic-stimulated changes in aluminum alloys.

CONCLUSION

In the work, experiments were used that made it possible to determine the degree of deformation of aluminum alloys under the influence of constant magnetic fields. After the second deformation, a third stage of creep begins, at which the creep rate gradually increases until destruction occurs. Therefore, the creep processes in this paper were considered exclusively in the first and second stages. The authors established that the preliminary exposure of samples in a constant magnetic field (with induction $B = 0.7$ Tl for 30 minutes at room temperature) contributes to an increase in the deformation of the aluminum alloy. The observed softening of the aluminum alloy after exposure to MF can serve as an additional method to regulate the structurally sensitive properties of such materials.

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Figure 1. Aluminum alloy creep curves taken at a load $P = 170$ N at room temperature: 1 — sample pre-exposure to static MF $B = 0.7$ T for 30 min; 2 — unexposed sample. Inset: a schematic of deformation time dependence (creep curve) conventionally divided into three creep stages

Figure 2. Aluminum alloy creep curves taken at a load $P = 180$ N at room temperature: 1 — sample pre-exposure to static MF $B = 0.7$ T for 30 min; 2 — unexposed sample. Inset: a schematic of magnetic-stimulated deformation $\Delta\ell_B$ on the applied stretching load P

Figure 3. Diagram of aluminum alloy stretching ($C_{Al} > 99.9\%$): 1 — a check-test sample; 2 — sample after 0.5-hour exposure to static MF (induction of 0.7 T) at room temperature.

$$\Delta \ell(t) = \Delta \ell_0 + \beta \cdot \ell_0 \cdot t^m + k \cdot \ell_0 \cdot t. \quad (1)$$

Table 1. The constants of aluminum alloy creep (r^2 is the pair correlation coefficient)

Parameter	Stretching load							
	150 N		160 N		170 N		180 N	
B, T	0	0.7	0	0.7	0	0.7	0	0.7
$\Delta \ell_0, \mu m$	428	469	490	529	554	748	818	1205
$\beta, 10^{-5}, s^{-\frac{1}{3}}$	0.59	1.75	1.5	1.8	2.28	5.1	2.13	12.1
$K, 10^{-7}, s^{-1}$	1.25	1.25	1.38	2.01	0.25	2.30	0.60	1.00
r^2	0.975	0.978	0.896	0.897	0.956	0.986	0.987	0.999