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Influence of a Magnetic Field with Induction up to 0.5 T on the Dynamics of the Deformation Characteristics of Lead

A. A. Serebryakova[a],* (ORCID: 0000-0003-3979-7777), D. V. Zaguliaev[a], (ORCID: 0000-0002-9859-8949), and V. V. Shlyarov[a],*** (ORCID: 0000-0001-8130-648X)**

[a] Siberian State Industrial University, Novokuznetsk, Russia
**e-mail: aserebrakova87@gmail.com*
***e-mail: zagulyaev_dv@physics.sibsiu.ru*
****e-mail: ShlyarovVitaly@yandex.ru*

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Abstract—The effect of a magnetic field on the deformation characteristics of a diamagnetic material Grade C2 lead (99.98% purity) is studied. Initially, the creep process and the microhardness were studied in the initial state, then such studies were carried out using d.c. magnetic fields with inductions 0.3, 0.4, and 0.5 T in the process of creep of the samples and magnetic processing of the samples to study the dynamics of the microhardness and the plasticity parameter. The results of creep tests indicate the presence of an ambiguous nature of the influence of the magnetic field on the creep rate; a change in the sign of the effect was found with an increase in the value of the magnetic field induction to 0.4 and 0.5 T. Also, the alternating nature of the influence of the magnetic field was also established in the study of the microhardness. In addition, it is found that the use of a magnetic field in the process of sample creep quantitatively influences the percentage of the relative residual elongation of the sample (it decreases as compared to the initial one with an increase in the magnetic field induction) upon destruction and the creep process time (increases compared to the initial one at increase in the magnetic field induction). A rational exposure time in a magnetic field during the microhardness tests was revealed, it was found that the maximum effect of a magnetic field manifests itself at exposures for 1 h, in connection with which two exposure modes in this range (0.25 and 0.5 h) are studied.

Keywords: lead, diamagnet, magnetic field, induction, deformation characteristics, relative residual elongation, creep, microhardness

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INTRODUCTION

In recent years the interest to studying the influence of magnetic fields on alloys and metals is very topical [1, 2]. It is particularly concerned the magnetic treatment area. The magnetic treatment of metals and alloys, by definition, is an action of a d.c., a.c., or pulsed magnetic field on a material or a finished product for controlled change in the structures and properties of a treated object for some time. The results of such actions are dependent on many factors, among which are magnetic properties of a material. As known, metals and alloys are classified in their magnetic properties into several main groups: paramagnets, diamagnets, ferromagnets, and antiferromagnets [3, 4]. The researchers have been studying these materials over entire world. For example, in [5, 6], those authors analyzed the experimental data on the influence of a magnetic field on the microhadness of aluminum, copper, titanium, and magnesium alloys. It is found that the microhardness of the alloys is markedly changes as compared to that of the samples that were not subjected to exposure in a weak magnetic field. A magnetic field is substantiated to influence the type, structure, and properties of dislocation obstacles during plastic deformation. The effect of magnetic field on the dislocation mobility [7] was studied by changes in the magnetic field induction. A decrease in the magnetic field induction is revealed to increase the material plasticity. According to the studies, magnetic field influences the macroplastic properties of a metal. In above reports, the influence of magnetic field on deformation behavior of copper, that is a diamagnet in its magnetic nature, was studied. In this work, we present the results of studies of a diamagnetic material such as Grade C2 lead, which is topical for the continuation of studying deformation behavior of diamagnets in external magnetic field.

EXPERIMENTAL

In this work we studied the creep rate, the percentage of relative residual elongation, the creep process time, and microhardness of lead C2. These characteristics were chosen, since the parts and components of devices manufactured from this material are continuously subjected to mechanical damages during their service.

The creep was studied on samples of Grade C2 lead (wire 2 mm in diameter) with purity of 99.98% and the impurity content no higher than 0.12%. The microhardness tests were carried out on lead C2 samples in the form of a rectangular parallelepiped 12 mm in height, 5 mm in width, and 15 mm in length.

The creep process was studied on a setup with an electromagnet and a motion sensor developed and manufactured at Siberian State Industrial University [8]. The magnetic field induction was controlled by varying electric current in the coils and was: 0.3, 0.4, and 0.5 T.

Before the microindentation procedure, we performed the magnetic field treatment in four modes. Modes 1, 2, 3, and 4 were exposures in magnetic fields with inductions B 0.3, 0.4, 0.5 T for 1, 2 , 3, and 4 h. Then the microindentation by Vickers was carried out on HVS-1000 microharsness tester (Fig. 3): the test load was 10 g, the loading time and the time under load were 10 s, and the unloading time was 5 s. The data array obtained in the experiment was processed in Excel and Origin Pro 8 software.

RESULTS AND DISCUSSION

The mechanical test data (sample elongation ε, mm, and creep process time t, h) were used to construct curves of the creep process of a technically pure lead (Fig. 1).

Figure 1 shows the most characteristic creep curves obtained during the lead fracture in the initial state ε_{init} and during action of magnetic field ε_{mf}, which contain the stages of the logarithmic, steady-state, and accelerated creep. The linear stage is indicated by the solid line. The creep rate is this line slope. In the initial state, the creep rate was 0.902 mm/h (Fig. 1, ε_{init}). As magnetic field is turned on, we can observe the dynamics of the creep rate values in the dependence on the magnetic field induction during entire time of the creep process. At the induction B = 0.3 T, the creep rate increased by 87% up to 1.692 mm/h as compared to the initial value (Fig. 1, $\varepsilon_{mf0.3}$). At B = 0.4 T, the creep rate decreases as compared to the initial value to 0.0919 mm/h (Fig. 1, $\varepsilon_{mf0.4}$). At B = 0.5 T, the creep rate also decreases as compared to the initial value to 0.0662 mm/h (Fig. 1, $\varepsilon_{mf0.5}$). Thus, the use of increased magnetic field inductions during the creep process led to a decrease in the creep rate by 94% and 97%, respectively.

Now we will analyze the changes in the percentage of the relative residual sample elongation δ and the creep process time t_{creep} by the data of Fig. 2.

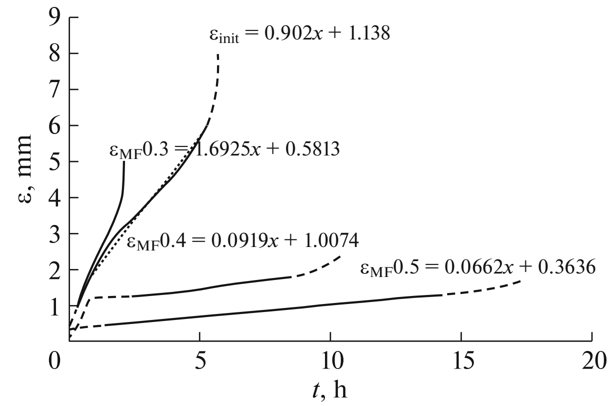

Fig. 1. Creep curves of polycrystalline lead in (ε_{init}) initial state and (ε_{MF}) under action of magnetic field with inductions B = 0.3, 0.4, and 0.5 T.

Figure 2a shows that the percentage of relative residual elongation of the sample in the tests without magnetic field is δ_{init} = 6.18%. According to the histogram (Fig. 2a), the percentage of relative residual elongation of the sample monotonically decreases as magnetic field induction B used during plastic deformation increases. During the deformation and fracture of the samples in magnetic field B = 0.3 T, the percentage of relative residual elongation of the sample decreases to $\delta_{0.3}$ = 4.6% (Fig. 2a). As the magnetic field induction increases to B = 0.4 and 0.5 T, the percentage of relative residual elongation of the sample are $\delta_{0.4}$ = 3.8% (Fig. 2a) and $\delta_{0.5}$ = 3.7% (Fig. 2a), respectively. The maximum decrease in the percentage of relative residual elongation of the sample (by a factor of 1.6 as compared to that in the initial state without magnetic field) is observed during the creep process at induction B = 0.5 T.

Then, we consider the dynamics of the average creep time. The average creep time was calculated by the data obtained for five samples for each of modes. We obtained the following values: t_{creep} = 5.69 h without MF, $t_{creep0.3}$ = 5.47 h at B = 0.3 T, $t_{creep0.4}$ = 11 h at B = 0.4 T, and $t_{creep0.5}$ =18.1 h at B = 0.5 T. According to these data and the histogram in Fig. 2b, magnetic field B = 0.3 T causes insignificant decrease in the creep process time. Then, as the magnetic field induction used in the creep tests increases, the creep time increases. The maximum increase by a factor of 3.1 was found as lead was subjected to action of magnetic field with B = 0.5 T. Note that there is a correlation: as magnetic field increases, the creep process becomes last longer, but the sample becomes to undergo a less deformation (according to the dynamics of the percentage of relative residual elongation of the sample). It can be assumed that the increase in the magnetic field retards the process of dislocation formation in the material, and the fracture occurs much solely.

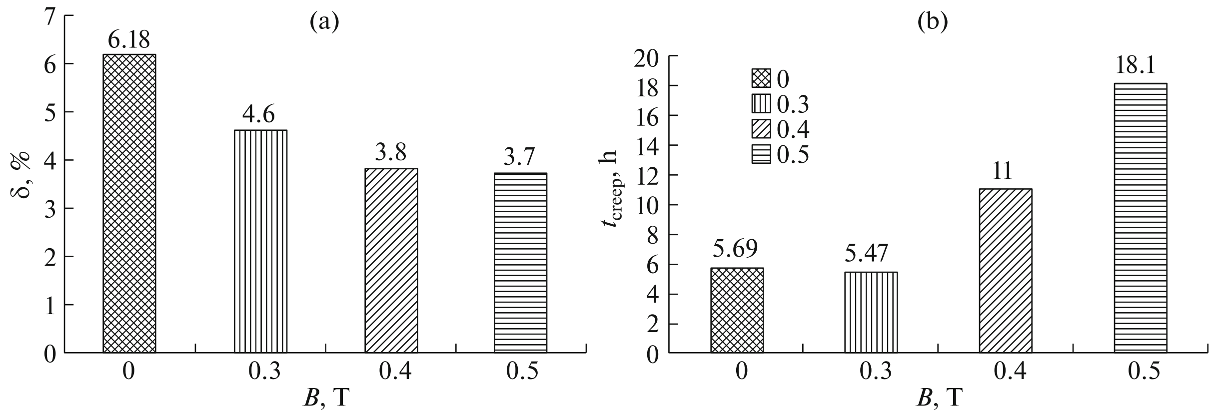

Fig. 2. Dependences of (a) the percentage of the relative residual elongation of the sample at fracture δ and (b) the creep process time t_{creep} on B, T.

Table 1 gives the results of studying the influence of magnetic field on the microhardnes of the lead C2. In each of modes, 20 measurements of the microhardness were carried out, and Table 1 gives the averaged data. The tests were carried for three samples, and each of the samples was studied at one of the above values of the magnetic field induction. The average microhardness of the sample in the absence of magnetic field is 7.51 HV. The microhardness was measured in external magnetic fields (Table 1) at exposure times 1, 2, 3, and 4 h, and in the initial state. The microindentation data show that the maximum effect is detected at the exposure time in magnetic field of 1 h (indicated by the color in Table 1) and is observed immediately after removing the sample from magnetic field (the initial effect). In this connection, the treatment time range was extended, since the problem of behavior the microhardness in the intervals from 0 to 1 h arises. In addition, the changes in the microhardness under action of magnetic field were analyzes at three values of the induction 0.3, 0.4, and 0.5 T and two exposure times in magnetic field 0.25 and 0.5 h immediately after exposure of the samples in magnetic field. The results of the studies of the microhardness were used to construct the dependences of the dynamics of the microhardness on exposure times (0, 0.25, 0.5, and 1 h) and the magnetic field inductions (0.3, 0.4, and 0.5 T) (Fig. 3).

The character of the dynamics of the microhardness (HV) is ambiguous (Fig. 3): the microhardness de-creases at the magnetic field induction 0.3 T and increases at the inductions 0.4 T and 0.5 T. Our studies show that magnetic field with induction 0.3 T leads to the decrease in the microhardness of lead C2 by 7.2% (for 1 h of the treatment, the microhardness decreased from 7.22 HV to 6.735 HV (Fig. 3a)) as compared to the initial value (Table 1). Thus, the decrease in the microhardness at this segment has a monotonic character, and there are no critical changes at exposure times 0.25 and 0.5 h. The decrease in the microhardness can demonstrate an increase in the plasticity under action of magnetic field.

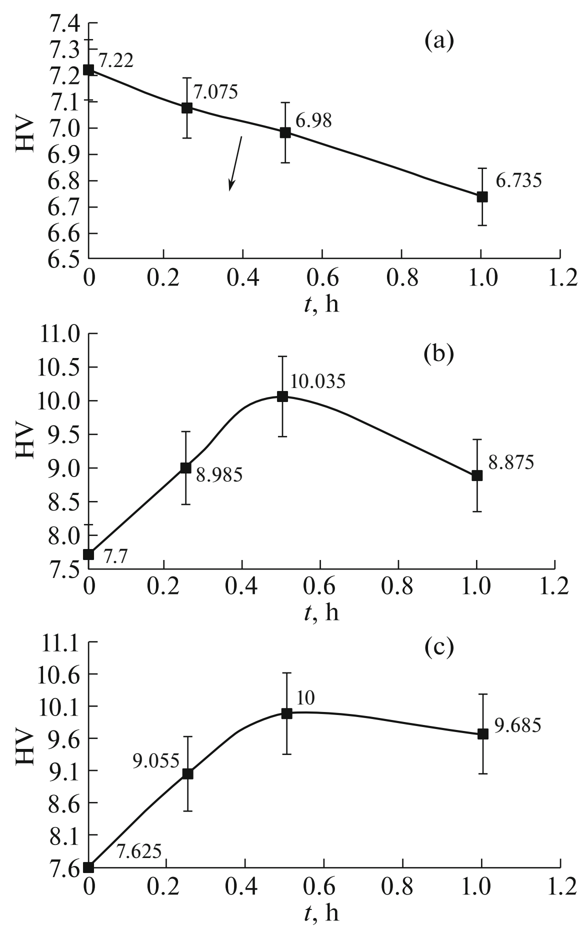

Fig. 3. Microhardness HV vs. The exposure time in the range from 0 to 1 h. B = (a) 0.3, (b) 0.4, and (c) 0.5 T.

Table 1. Results of studies of the microharsness of Grade C2 lead in magnetic field at various inductions

t, h	B, T		
	0.3	0.4	0.5
	HV	HV	HV
0	7.22	7.7	7.62
1	**6.73**	**8.875**	**9.68**
2	6.655	8.87	9.69
3	6.66	8.874	9.7
4	6.66	8.875	9.69

Conversely, the studies of the dynamics of the lead microhardness at the additional exposure times with the magnetic field inductions increased to 0.4 T and 0.5 T show an increase in the material hardness. The lead microhardness increased under action of the magnetic field with induction 0.4 T by 23.75% (the microhardness increased from 7.7 HV to 10.035 HV for 0.5 h of the treatment (Fig. 3b)) as compared to the initial value. The lead microhardmess increased under action of magnetic field with induction 0.5 T by 23.26% (the microhardness increased from 7.6 HV to 10 HV for 0.5 h of the treatment (Fig. 3c)) as compared to the initial value.

CONCLUSIONS

1. The creep and microhardness tests have been carried out for the diamagnetic lead C2 sample; the data in the dynamics of the deformation characteristics have been obtained.

2. The creep rates are analyzed at the linear stage without magnetic field and at magnetic fields with inductions B = 0.3, 0.4, and 0.5 T. The creep rate is found to increase by 87% at B = 0.3 T and to decrease at B = 0.4 and 0.5 T by 94% and 97%, respectively, as compared to the initial values.

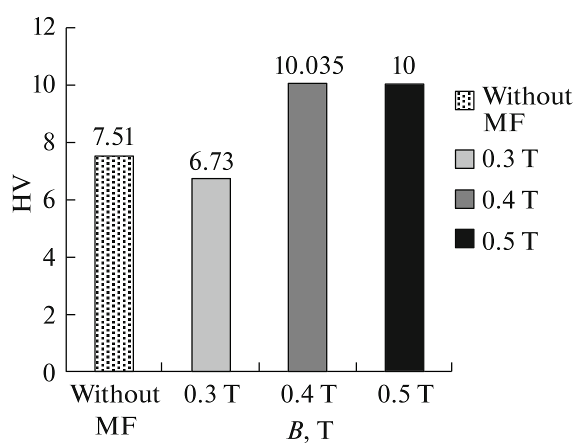

Fig. 4. Dependences of microhardness HV on the use of magneric field and the values of induction B.

3. It is found that the percentage of the relative residual elongation of the samples before fracture δ during the lead creep decreases as the magnetic field induction increases. The maximum decrease in the percentage of the relative residual elongation of the sample is observed as induction B = 0.5 T acts on the sample during the creep process; this decrease is less by a factor of 1.6 than that in the initial state without magnetic field.

4. We revealed the following values of the creep times: t_{creep} = 5.69 h without MF, $t_{\text{creep0.3}}$ = 5.47 h at B = 0.3 T, $t_{\text{creep0.4}}$ = 11 h at B = 0.4 T, and $t_{\text{creep0.5}}$ = 18.1 h at B = 0.5 T. The maximum increase by a factor of 3.1 was found as lead was subjected to action of magnetic field with B = 0.5 T; there is a correlation: as magnetic field increases, the creep process becomes last longer, but the sample becomes to undergo a less deformation (according to the dynamics of the percentage of relative residual elongation of the sample).

5. Our measurements showed that the character of influence of magnetic field on plastic properties of the lead is ambiguous (sign-changing). The difference of the phenomena is observed as the magnetic field induction is changed: during the treatment of the samples, the transition from B = 0.3 T to B = 0.4 and 0.5 T led to increase in their microhardness. Similar situation was observed in the studies of aluminum [8].

6. The increase in the treatment time more than 1 h does not lead t significant changes at all values of the induction. The highest effect is observed in the range of the exposure time in MF from 0.25 h to 1 h: the maximum increases in HV at the exposure 0.5 h with B = 0.4 and 0.5 T are 10.035 and 10 HV, which are higher by 23.75 and 23.26%, respectively, as compared to the initial value. The maximum decrease in the microhardness (to 6.73 HV, which is 7.2% smaller than that in the initial state) is observed at exposure of 1 h with induction B = 0.3 T.

7. Thus, our studies revealed the effect of magnetic field on deformation characteristics of the lead. The effect is supposedly due to action of magnetic field induction on the processes of formation and the motion of dislocation substructure of the material [10]. We plan to confirm these assumptions in further studies using SEM and TEM analyses of the sample fracture portion.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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