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STRUCTURE AND PROPERTIES OF THE DEFORMED STATE

Deformation of Commercial-Purity Titanium in a DC Magnetic Field

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Abstract—The deformation behavior and structure of commercial-purity titanium is studied under creep in a dc magnetic field. The action of a magnetic field is found to increase the strain rate at the steady-state creep stage. Failure occurs via a ductile dimple mechanism. The dimple size depends on the deformation conditions, namely, in a dc magnetic field or without the field.

Keywords: commercial-purity titanium, creep, fracture, fracture dimples, induction, dc magnetic field

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INTRODUCTION

The effect of a magnetic field on the properties and structural and phase states of materials has been studied for several decades. As early as 1929, Gerbert [1] showed that repeated changing the magnetic polarity of a metal ensures an increase in its hardness to the same extent as low-temperature annealing. To date, it was found that a high magnetic field (with an induction to 45 T) decelerates the recovery process in cold-rolled ferromagnetic alloys and facilitates preferential formation of certain textural components. A change in the phase equilibrium temperature, which reaches several tens of degrees, was noted [2]. The effect of a high magnetic field on the γ–α transformation in ferromagnetic materials was found in [3]. In [4], the possibility of decreasing the corrosion rate of an Al–3.0 Mg alloy in a magnetic field was demonstrated was demonstrated.

The application of a Ti–6Al–4V coating by laser facing in a low magnetic field allowed one to increase the wear and crack resistance of the prepared composite [5]. Treatment in a magnetic field B = 2–10 T at 400°C for 30 min allowed the authors to optimize the microstructure and to improve the mechanical properties of the Ti–6Al–4V alloy prepared by selective laser melting; in particular, the grain refining effect was increased, whereas the yield strength and plasticity of the specimen annealed in a magnetic field of 8 T were 1092.1 MPa and 15.1%, respectively [6].

The problem of magnetoplasticity is being comprehensively studied in order to purposefully control the plasticity of materials [7–9]. The effects related to residual changes caused by static magnetic field are of substantial interest for practice. In [8], an increase in the creep rate by 25% was found after exposure of an aluminum alloy specimen in the magnetic field $B \approx$ 1 T. This is explained by magnetostriction expansion of ferromagnetic FeAl inclusions present in the aluminum matrix, which initiates the generation of new dislocations. The decrease in the strain resistance to 25% upon tension and compression in a dc magnetic field of ~1 T was observed in studying ferromagnetic (steel), paramagnetic (aluminum), and diamagnetic (copper) metallic materials [10].

As was shown in [11], preliminary application of a magnetic field B = 0.7 T for 30 min at room temperature increased the strain of an aluminum alloy (Fe ≈ 0.4 wt %) almost at all creep stages. In [12], the effect of magnetic field on the structure, dislocation density, grain size, elongation, and microhardness of titanium alloy TS4 was studied. These results showed that the application of 2-T magnetic field allows one to increase the dislocation density by 1.6 times. It was found also that, after treatment with a high dc magnetic field, the average relative elongation of alloy TS4 increases by ≈30% as compared to that of untreated specimens and is 12–13%, and the microhardness increases by ≈8%. The authors relate the changes with changing the dislocation density [12, 13]. As was found in [14, 15], the application of permanent magnets and pulsed magnetic fields of different strength led to an increase in the plasticity of a VT3-1 alloy. The application of a dc magnetic field was shown to be equivalent to a decrease in the deforming force by 10%. The found experimental regularities were explained by the fact that the magnetic field weakens the bonds of dislocations with local stoppers that retard the dislocation motion.

In the present study, the effect of a dc magnetic field on the deformation behavior, structure, and peculiarities of failure of commercial-purity titanium under creep is investigated. As was found earlier [16],

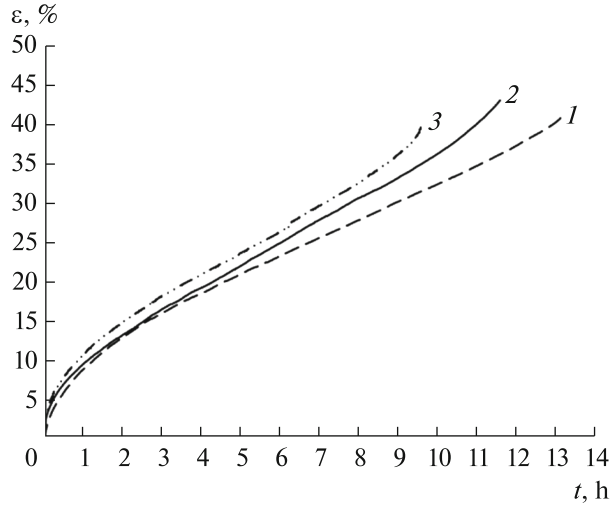

Fig. 1. Creep curves of commercial-purity titanium measured (*1*) without magnetic field and in magnetic field (*2*) $B = 0.4$ T and (*3*) $B = 0.5$ T.

the action of a magnetic field on commercial-purity titanium is accompanied by a decrease in the microhardness by 3–8% in accordance with the induction. A dc magnetic field is assumed to affect creep as well.

EXPERIMENTAL

The effect of a dc magnetic field on commercial-purity titanium, the chemical composition of which comprises 97.17 wt % Ti, 0.33 wt % V, 0.25 wt % W, and 0.24 wt % Al (analysis was carried out on a TESCAN VEGA SB microscope), was studied. Cylindrical specimens 5 mm in diameter and 250 mm in length were subjected to tension at a constant stress of 212 MPa at a temperature of 20°C in dc magnetic fields of 0.4 and 0.5 T. Preliminarily, the specimens were annealed at 800 K for 2 h and subsequently subjected to furnace cooling. For experiments, a specially constructed installation was used [17, 18]. The displacement was recorded with an optical-mechanical sensor to an accuracy of 50 μm; the data obtained were processes using the Origin Pro 8.5 and Microsoft Excel software. The approximation of curves and determination of the portion of steady-state creep stage were performed using an Aproximator software that was specially developed.

The microstructure was analyzed using an Olympus LEXT OLS4100 laser scanning microscope. To form optical contrast, specimens were etched in an aqueous solution of fluoric and nitric acids ($HF : HNO_3 : H_2O = 1 : 1 : 6$). The morphology of the fracture of specimens was analyzed using a TESCAN Vega SB scanning electron microscope.

RESULTS AND DISCUSSION

Figure 1 shows the creep curves of commercial-purity titanium. Note that a magnetic field does not affect the critical strain upon creep resulting to failure; on average, $\varepsilon_{cr} = 41.7\%$. In this case, under creep conditions in zero magnetic field, the time before failure is 13.1 h; in applying a magnetic field of 0.4 T, it decreases to 11.8 h or by 10.4%; in the case of applying the 0.5-T magnetic field, the time is 9.6 h or its decreases by 27.3%. The faster failure indicates the disordering of material in the magnetic field. The average creep rate of titanium at the steady-state stage (it was determined as the tangent to the creep curve) without magnetic field is 2.4 ± 0.4%/h. In a 0.4- or 0.5-T magnetic field, it increases by ≈45%, namely, to 3.5 ± 0.69 and 3.6 ± 0.44%/h, respectively.

Figure 2 shows the typical grain structure of titanium. It mainly consists of isotropic recrystallized grains; their minimum size is 5.3 μm; the maximum and minimum sizes are 259.7 and 68 μm, respectively. The grain size distribution corresponds to lognormal

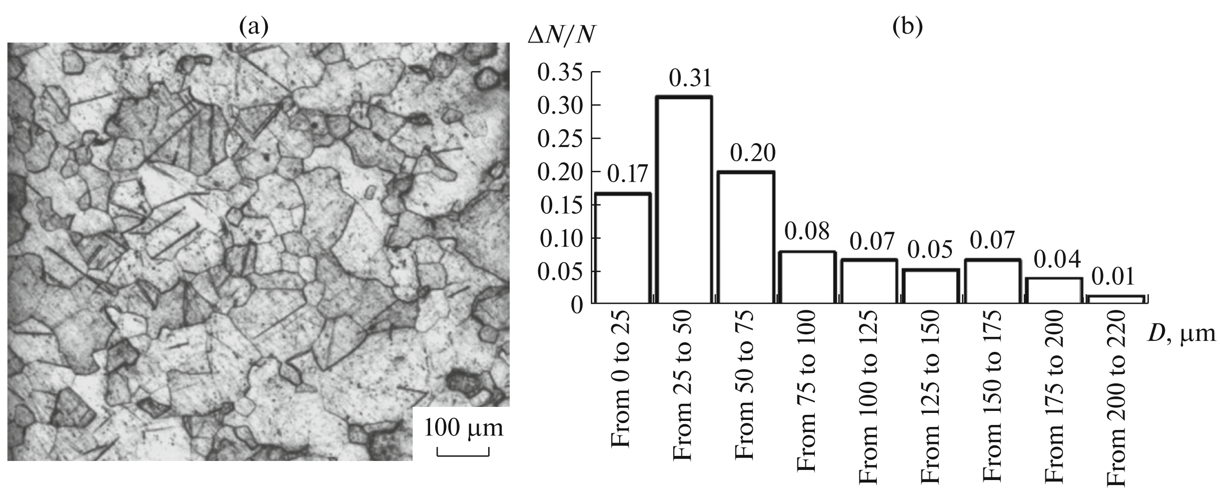

Fig. 2. (a) Structure and (b) grain size distribution of commercial-purity titanium in the initial state.

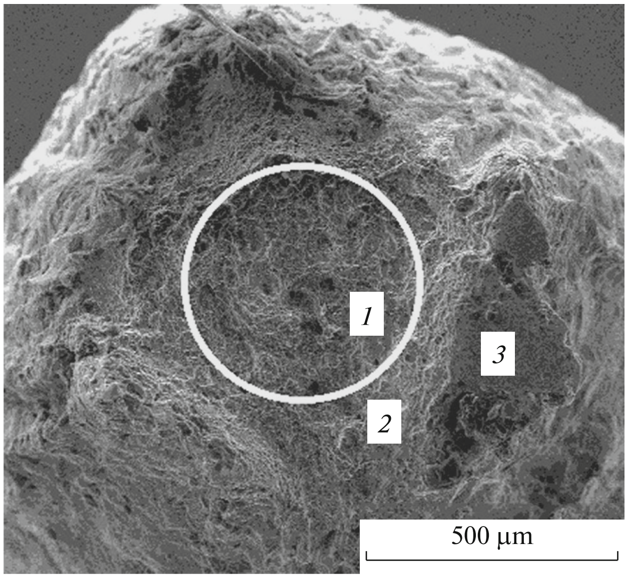

Fig. 3. Fracture of titanium during creep in a magnetic field B = 0.4 T: (*1*) fiber zone, (*2*) radial zone, and (*3*) shear zone.

single-mode one (see Fig. 2b). The average grain size differs from the most probable grain size; this fact indicates the incompleteness of the collective recrystallization process.

The plain cylindrical specimens subjected to tensile tests are characterized by the following fracture zones: fiber, radial, and shear zones [19]. Figure 3 shows the appearance of fracture of titanium specimen failed under creep conditions in the magnetic field. The fracture is ash grey in color and has a highly rough tarnish surface. Whatever the creep conditions (in the magnetic field or without it) the failure mechanism of the materials is ductile transcrystalline (Fig. 4). Near dimples and within dimples, shear bands disordered relative to each other are observed (are shown by arrows). Figure 5 shows the microstructure on a slightly bigger scale, which is characterized by shear bands.

An analysis of the fracture dimple size within the fiber zone indicates the complex character of the effect of dc magnetic field on the behavior of commercial-purity titanium upon creeping. In particular, without magnetic field, the average dimple size is 7.2 ± 0.57 μm; the size decreases to 5.5 ± 0.44 μm in the case of failure upon creeping in the magnetic field B = 0.5 T. The application of a magnetic field of 0.4 T during plastic deformation leads to the increase in the average dimple size to 8.6 ± 0.68 μm. It should be noted that, whatever the creep conditions (in applying magnetic field or without it), the dimple size in the shear zone is substantially lower than that in the fiber zone.

The dimple size is assumed to depend on the relative plasticity of matrix and number of micropore nucleation sites [20]; i.e., the higher the number of micropore nucleation sites, the smaller the fracture dimples. A dc magnetic field applied during plastic deformation of commercial-purity titanium is thought to affect the behavior of point stacking faults and to increase the number of dimple nucleation sites. Grain boundaries, dislocations, and subgrain boundaries can be nucleation sites. To confirm this fact, the relation between the strength and dislocation mobility should be noted. In particular, it was found in [21, 22] that, as the dislocation mobility increases, the microhardness of crystals decreases.

The plastic deformation process is accompanied by continuous interaction of dislocations with each other and point defects. At different times, mechanisms were developed for the spin-dependent phenomena that occur during chemical reactions, and three possible spin conversion mechanisms (Δg, ΔJ, HFI) and their possible combinations were determined [23, 24]. In the case of Δg mechanism, the spin state changes because of differences in the g factors of interacting radicals. In the HFI mechanism, a hyperfine interaction is taken into account; it consists in the interaction

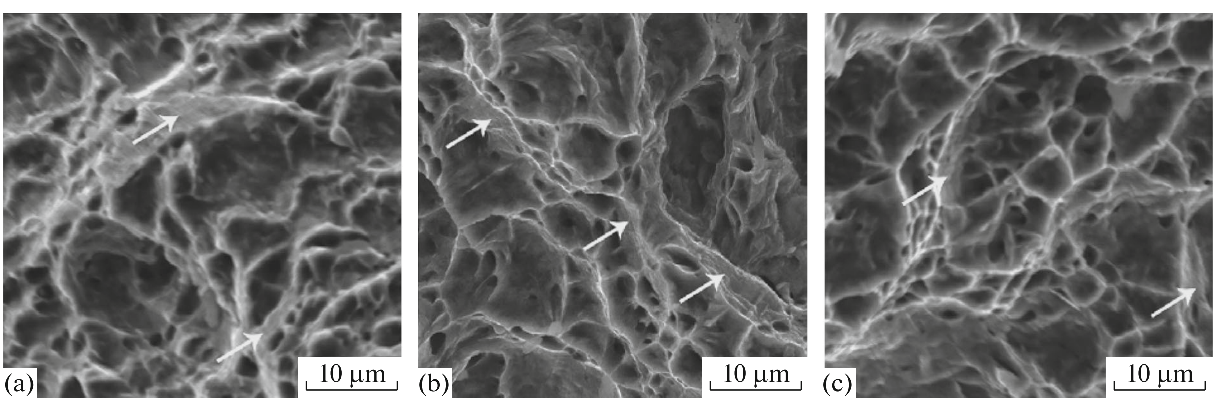

Fig. 4. Structure of the fiber zone of titanium fracture formed upon creep (a) without magnetic field and in a magnetic field of (b) 0.4 and (c) 0.5 T.

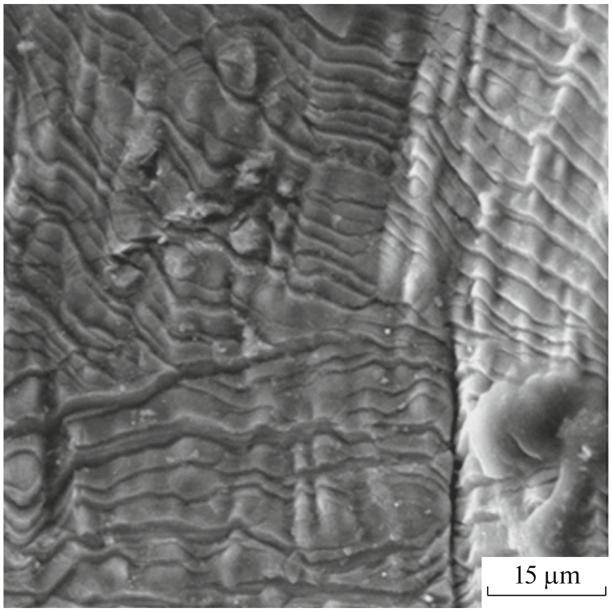

Fig. 5. Microstructure of titanium with shear bands (B = 0.4 T).

between the magnetic moments of defect electrons and the magnetic moments of nuclei. The interaction can correspond to the interaction with the central nucleus (nuclei) of a defect (hyperfine interaction, HFI) or the interaction with the nuclei surrounding a paramagnetic defect (superhyperfine interaction, SHFI). Finally, the ΔJ mechanism considers the spin catalyst of transformations in pair with the third spin carrier [25].

The effect of a dc magnetic field on the plastic deformation processes in metallic paramagnetic materials is most likely to be due to the Δg mechanism. The interaction of dislocation with paramagnetic impurities is thought to be accompanied by the formation and break of covalent bond between them; this is an additional factor for the retardation of dislocations, since an additional energy is necessary for breaking a covalent bond. Near a dislocation core, where the electron shells of atoms are highly distorted, there are electrons with unpaired spins, which are localized at bends and steps, and a paramagnetic impurity atom has an electron with unpaired spin; this is accompanied by the formation of a covalent bond between an atom belonging to a dislocation and a paramagnetic impurity defect [26, 27].

Based on the aforesaid, the plastic deformation without a magnetic field can be represented as follows: a titanium atom belonging to a dislocation approaches a point defect (that can be para- or ferromagnetic interstitial and substitutional atoms). After that, along with an elastic interaction, the formation of a covalent bond in the S state (total spin of the system consisting of two particles is zero) between an atom belonging to a dislocation and a point defect takes place. Further, the motion of the atom belonging to a dislocation is related to elastic overcoming an obstacle and breaking the covalent bond from the S state. In this case, the total energy necessary for overcoming an obstacle consists of the energy for overcoming the elastic interaction and the energy for breaking the covalent bond. After the interaction has passed, the dislocation continues to move to the next obstacle.

Under the action of a dc magnetic field after the formation of a covalent bond, the radial pair transfers from the S state to an electron-excited T state. This statement agrees with the data in [28], according to which such a transition was noted when a magnetic field was turned on. In this case, the higher the magnetic field strength, the higher the frequency of such transitions.

Thus, a magnetic field affects the covalent bond and transforms the radial pair from state S to T, which facilitates bond breaking since the energy required for breaking the radical pair being in the S state is higher than that for the pair being in the T state. This leads to an increase in the dislocation mobility and, therefore, the creep rate.

CONCLUSIONS

(1) Tension of commercial-purity titanium at room temperature in the presence of a dc 0.4- or 0.5-T magnetic field leads to an increase in the creep rate at the steady-state stage by ≈45 or 50%, respectively.

(2) The fracture mechanism of commercial-purity titanium is ductile and mainly transcrystalline; the fracture surface contains a great number of dimples, the size of which depends on the magnetic field.

(3) Deformation in the presence of a dc magnetic field can change the macromechanical characteristics of commercial-purity titanium; in this case, the effect of a field on its structure is insignificant. This finding can be of interest as preliminary treatment during metal forming.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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