ISSN 1027-4510, Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques, 2017, Vol. 11, No. 6, pp. 1338–1341. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © D.V. Zagulyaev, K.A. Osintsev, S.V. Konovalov, V.E. Gromov, A.P. Semin, 2017, published in Poverkhnost', 2017, No. 00000, pp. 00000–00000.

Variation of Strength Characteristics of Titanium Surface Layers Under Magnetic Field Effect[1]

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Received March 3, 2017

Abstract—In work using micromechanical test method it is determined that the magnetic field (0.6 T) reduces the mechanical properties of commercially pure titanium and their subsequent stabilization. The dependence of the microhardness on the time of the magnetic field treatment is established. We define a linear dependence of the microhardness on the processing time for the value of the induction of the magnetic field of 0.3 Tesla. Magnetic influence with the induction of 0.4 T is characterized by the exponential dependence of the microhardness on the processing time. Established threshold value holding time of 0.5 hour, below which the effect is observed irrespective of the influence of the magnetic field of the magnetic induction. The hypothesis of a magnetic field on the mechanical properties of the surface layers of commercially pure titanium, which qualitatively explains the observed dependence.

Keywords: microhardness, magnetic field, relaxation, induction, the titanium surface layer
DOI: 10.1134/S1027451017060234

INTRODUCTION

The magnetic field effect on the physical and mechanical properties of nonmagnetic metallic materials was studied in a large number of papers [1–8]. The emphasis is on the issue of weak magnetic fields effect on the real structure and plasticity of nonmagnetic' materials including the metallic (Al, Cu, Zn etc) ones. A number of theories of magnetic field effect on metallic paramagnetic metals based on the change in defect mobility on placing the metals in magnetic field were proposed. However, the defect mobility depends on temperature of melting and it is necessary to compare the experimental data obtained in the same conditions for two paramagnetic metals with different melting temperature for one-to-one verification of the described theories. Nowadays the magnetic field effect on polycrystalline aluminum is known to the scientific world and is well understood. But there is no experimental data on magnetic field effect concerning any other paramagnetic metal. In this context it is necessary to conduct investigations on magnetic field effect on deformation characteristics of paramagnetic metal with higher melting temperature than aluminum. In this paper the commercially pure titanium was used as the test material.

In this connection our paper a continuation of studies of weak magnetic field effect on the deformation characteristics of polycrystalline, paramagnetic metallic materials whose general purpose is to determine the physical mechanisms responsible for the change in mechanical properties.

The purpose of the research is experimental study of magnetic field effect with induction up to 0.6T on microhardness of commercially pure titanium VT-1-0. The chemical composition is shown in Table 1.

The test specimens had the shape of rectangular parallelepiped 0.4 × 1 × 1. The sample preparation consisted in the annealing at temperature 800 K during 2 hours followed by the cooling in the furnace necessary for obtaining the material structure of homogeneous state. Then, the mechanical polishing and chemical etching necessary for the exhibition of the material structure were done. The time of etching was chosen experimentally. The average grain size in the initial state amounted to 79.1 μm.

The magnetic field was created by electromagnet. The induction regulation was done by changing the current strength flowing in coils. The measurements of magnetic field induction value were done with milliteslameter TPU accurate to 0.01 mT. The specimens were located perpendicular to induction lines in the magnetic field. The geometry of magnetic field was unchanged in all tests.

Measurements of microhardness were done with microhardness meter HVS-1000 according to micro Vickers method for three variants: without magnetic

[1] The article is published in the original.

Table 1. Chemical composition of titanium VT-1-0

Fe	C	Si	N	Ti	O	H	Impurities
Up to 0.25	up to 0.07	up to 0.1	up to 0.04	99.24–99.7	up to 0.2	up to 0.01	other 0.3

field effect, immediately after holding in magnetic field and after definite time intervals. In this case, the value of magnetic field induction and holding time in it were changed. The measurements of microhardness were done by grain body excluding the falling of the indenter to the boundary. The standard methods of mathematical statistics were used for data processing [16]. The microhardness value was averaged not less than by 30 measurements. Quantitatively, the magnetic field effect was characterized by a relative change in microhardness:

$$Q = \left[\frac{HV - HV_0}{HV_0}\right] \times 100\%,$$

where HV – value of specimen's microhardness held in magnetic field, HV_0 – initial value of microhardness.

INFLUENCE OF MAGNETIC EFFECT TIME ON TITANIUM MICROHARDNESS

The experimental studies of time effect of magnetic processing on VT-1-0 titanium showed that the decrease in microhardness value with its subsequent stabilization to the initial value by the exponential law took place. The analysis of the initial effect (being observed immediately after the action) of magnetic field on titanium microhardness shows that the increase in holding time in magnetic field results in the decrease in microhardness depending on the parameters of processing (Fig. 1).

The analysis of dependences shows that for different values of magnetic field induction the stable decrease in microhardness value with increase in the holding time in the field is observed, in addition, the initial effect action increases with the increase in the value of magnetic field induction. It should be noted that the threshold time of processing after which the magnetic field effect is not observable, for the values of magnetic field induction up to 0.5 T is time equaling to 0.5 of hour. However, for processing regime 0.6 T and holding during 0.5 hour the microhardness decrease reaches the value 6.5%.

As the initial magnetic field effect on microhardness is different for different holding time it becomes interesting to analyze the dependence of time necessary for stabilization of microhardness on time of action (Fig. 2). It is seen that for the magnetic field induction equaling to 0.3 T it has the linear character (Fig. 2a). For the values of magnetic field induction being 0.4T it has the exponential character (Fig. 3b) and for induction 0.5 T the time necessary for reaching the initial value depends on holding time in the magnetic field (Fig. 2c). It is seen that when time of effect being 0.75 hour the effect of action relaxes during one hour, and further increase in holding results in the increase in relaxation time to 24 hours.

On the basis of the experimental data obtained as a result of the research let us try to explain qualitatively the possible physical mechanism of magnetic field

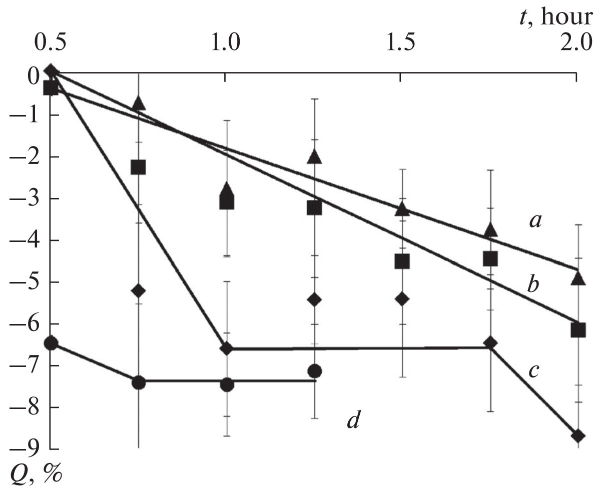

Fig. 1. Dependence of relative microhardness change (Q) on the time effect of magnetic field for different values of magnetic field induction: a – 0.3T, b – 0.4T, c – 0.5T, d – 0.6T.

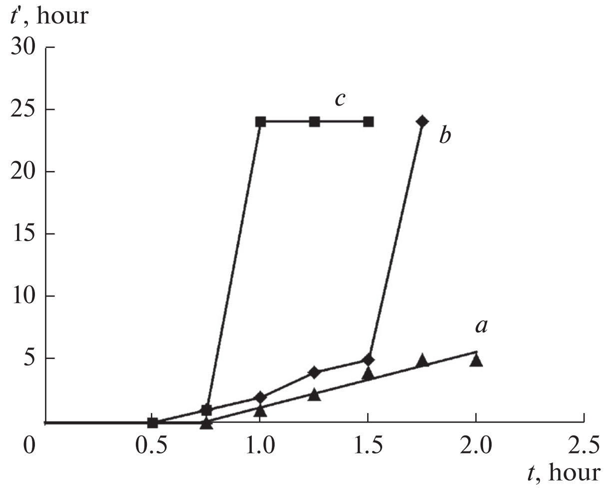

Fig. 2. Time dependence of microhardness value stabilization (t') on the time of magnetic field effect (t): 0.3 T (a), 0.4T (b), 0.5T (c).

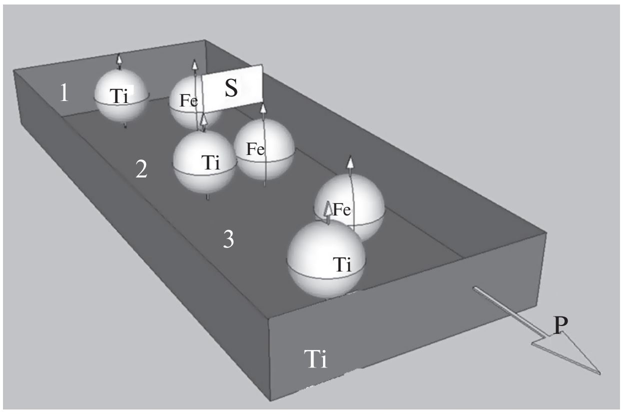

Fig. 3. Interaction of titanium atoms with iron atoms in the process of plastic deformation without magnetic field.

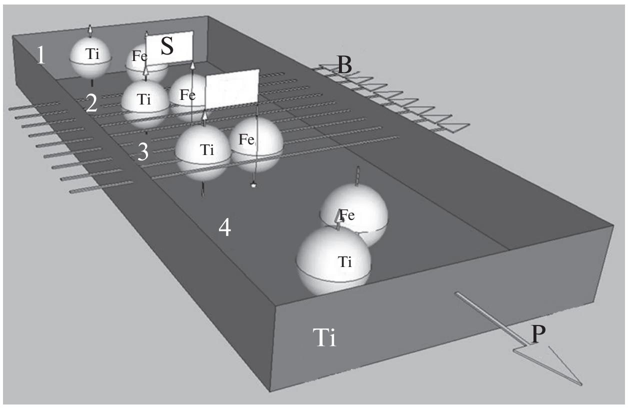

Fig. 4. The interaction of atoms of titanium to atoms of iron in the process of plastic deformation when exposed to a magnetic field.

effect on deformation characteristics of titanium connected, in our opinion, with the change in defect substructure state.

In considering the possible mechanism of magnetic field effect on deformation behavior of metallic materials take into account the connection between the strength and mobility of dislocations. As 10^6–10^{10} dislocations in 1 cm^3 are usually present in a crystal, their displacement results in the microscopic deformations. When changing the mobility of these defects, the plastic deformation of crystals can be controlled and it is confirmed by the results of the research [5] where it is established that when the mobility of dislocations increases the microhardness of bismuth decreases.

The process of plastic deformation is accompanied by the continuous interaction of dislocations to one another and point defects where para-and ferromagnetic interstitial and substitutional atoms manifest themselves as such. In our case it is iron because in VT-1-0 titanium its content amounts to 0.25% of mass fraction. If it is supposed that the interaction of dislocation with paramagnetic impurities has not only elastic character then it can be stated that it is the additional factor of the dislocation retardation because the additional energy is necessary for breaking the covalent bond (Fig. 3).

The formation of covalent bond between one atom belonging to dislocation and ferromagnetic impurity defect is possible because both titanium and iron have electrons with unpaired spin [6]. Hence, the process of plastic deformation is accompanied with many times repeated chemical reactions.

Consider the process of plastic deformation proceeding in time in the absence of magnetic field (Fig. 3) shows the different time stages of the process, *1* – titanium atom belonging to the dislocation approaches the point defect where para- or ferromagnetic interstitial and substitutional atoms (iron atom is shown in the figure as the example) manifest themselves as such. Further, in addition to the elastic interaction the formation of covalent bond takes place in *S* state between one atom belonging to the dislocation and point defect – 2. Further, the movement of the atom belonging to the dislocation is connected with elastic overcoming the obstacle and breakage the covalent bond from *S* state. In this case the total energy necessary for overcoming the obstacle is combined from the energy necessary for overcoming the elastic interaction and the energy necessary for breaking the covalent bond. After the interaction had proceeded the dislocation continues its further motion to the next obstacle.

Figure 4 shows one act of plastic deformation in the presence of magnetic field and time moments 1 and 4 demonstrate the approaching and removing the dislocation from the point defect. However, after the formation of covalent bond 2 the transition of radical pair from S to T state and its further breaking takes place under the magnetic field effect. In this case the energy necessary for breaking the covalent bond from T state is less than from S one.

It can be concluded from the above that the magnetic field affects indirectly the process of plastic deformation. It can be supposed that the magnetic field when affecting the covalent bond converts the radical pair from the singlet to triplet state. It makes its breaking easier because the energy necessary for breaking the radical pair being in the singlet state is larger than in the triplet one [7]. It results in the increase in dislocation mobility and as a consequence to the decrease of microhardness. The supposition evidenced indirectly can be supported by the fact that under the similar parameters of processing the magnetic field effect on titanium is less expressed than on aluminum. Firstly, it can be connected with the mobility of defects at the same temperature of tests.

As the mobility of defects in aluminum at room temperature is somewhat larger than in titanium consequently, the magnetic effect should be manifested

Table 2. Comparison table of magnetic field effect 0.3T on microhardness of aluminum A85 and titanium VT-1-0 under different time of processing

Holding time, hour	Aluminium – A 85		Titanium – VT-1-0	
	relative change of microhardness, %	measurement error, %	relative change of microhardness, %	measurement error, %
1	–8.7	1.2	–2.8	1.6
1.5	–10.3	0.8	–3.3	0.9
2	–12.5	0.8	–4.9	1.3

stronger in aluminum, which is observed in comparing the experimental data obtained in aluminum [4] and titanium (Table 2).

The analysis of the table shows that at the same parameters of processing the magnetic field effect on aluminum is almost 3 times stronger than on the commercially pure titanium.

CONCLUSION

It was established in the course of the research that magnetic field effect on commercially pure titanium VT-1-0 leads to the decrease in the value of microhardness followed by its relaxation during the time depending on the parameters of processing. The confidence of the obtained data is confirmed by the correlation of the obtained data with the papers of other authors. In particular, the relaxation character of magnetic field effect on microhardness of nonmetallic materials was established by Golovin Yu. I. in polymers [1], C60 crystals [2] and NaCl crystals [3]. It is established in our research that the increase in magnetic effect time leads to the intensification of the microhardness reduction process. It is determined that the time of microhardness stabilization depends linearly on the time of processing for the value of magnetic field induction 0.3 T, has exponential character for induction 0.4 T and has a complicated form for 0.5 T. The threshold of holding time is determined equaling to 0.5 hour and during less time the magnetic field effect is not observable independent of magnetic field induction. It was attempted to explain qualitatively the obtained effects on the process of plastic deformation with simultaneous effect by magnetic field from the point of view of magnetic fields.

ACKNOWLEDGMENT

The research was financially supported by the state assignment, the application number 3.1283.2107/PCh

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