AIP Conference Proceedings

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Citation: AIP Conference Proceedings **1783**, 020211 (2016); doi: 10.1063/1.4966505

View online: http://dx.doi.org/10.1063/1.4966505

View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1783?ver=pdfcov

Published by the AIP Publishing

Evolution of Microstructure and Microhardness of Dispersion-Hardened V–Cr–Zr–W Alloy during Deformation by Torsion under Pressure

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Abstract. Results of the study of the microstructural evolution and microhardness changes of dispersion-hardened V–Cr–Zr–W alloy under severe deformation during torsion on Bridgman anvils are presented. Typical structural states and mechanisms of their formation are revealed for basic evolution stages as well as appropriate microhardness values are determined. It was shown that at true logarithmic strain values (e) in the range $0.7 \le e < 2.7$ the microstructure of the alloy under investigation is characterized by strong heterogeneity. After $e > 2$, the anisotropic submicrocrystalline structure is observed and the formation of two-level nanostructural states was found within grains. In the strain range (e) from 3 to 6.6, submicrocrystal sizes hardly change, but changes of two-level nanostructural state parameters are observed: the nanofragment size decreases and values of elastic curvature of the crystal lattice increases.

INTRODUCTION

The study of the microstructural evolution of metals and alloys of different classes in conditions of severe deformation is one of the important directions of modern materials science. For the development of adequate ideas, it is important not only to identify the main stages of evolution depending on the material class but also to reveal the most important factors that determine the implementation of structural transformation mechanisms and change in the complex of physical and mechanical properties. Currently, researches are conducted mainly in pure FCC metals while the study of these questions about BCC metals and alloys are devoted only sporadic works. Meanwhile the latter were traditionally the base of many construction materials for the application in extreme conditions. As is known, a characteristic feature of these materials is a high reactivity to the introduction of impurities, which can contribute to their transformation into the category of heterophase materials, with the possibility of the individual and cooperative implementation of such strengthening mechanisms as substructure, solid solution, and disperse one.

In this paper, we study features of the microstructural evolution and microhardness during torsion under pressure of dispersion-hardened V–Cr–Zr–W alloy with a high volume fraction of nanosized second-phase particles.

EXPERIMENTAL MATERIALS AND PROCEDURES

The study was conducted with the use of V–8.75Cr–1.17Zr–0.14W–0.01C–0.02O–0.01N (wt %) alloy after complex processing comprising thermomechanical treatment (TMT) stages for dispersing the initial coarse phase [1] and oxygen doping in the chemical heat treatment (CHT) process [2].

Advanced Materials with Hierarchical Structure for New Technologies and Reliable Structures 2016
AIP Conf. Proc. 1783, 020211-1–020211-4; doi: 10.1063/1.4966505
Published by AIP Publishing. 978-0-7354-1445-7/$30.00

TABLE 1. Estimates of shear γ and true logarithmic strain *e* and microhardness values H_μ at a distance from the center of the disk *R* and the number of revolutions *N*

***R*, mm**	***N* = 0.1**			***N* = 1**			***N* = 3**			***N* = 5**		
	γ	*e*	H_μ, GPa	γ	*e*	H_μ, GPa	γ	*e*	H_μ, GPa	γ	*e*	H_μ, GPa
0.5	2.09	0.7	2.39	21	3.0	3.17	63	4.1	3.40	105	4.7	3.89
3.5	14.66	2.7	3.08	146	5.0	4.01	440	6.1	4.15	733	6.6	4.85

The oxygen concentration after low-temperature diffusion doping reached 1.34 (at %).

Specimens of the investigated alloy in the form of disks with the thickness $h \approx 0.2$ mm and diameter 8 mm were deformed by torsion under pressure ~7 GPa at room temperature and the number of anvil revolutions *N* = 0.1, 1, 3, and 5. The specimen thickness after deformation was 0.15 mm. Estimates of shear ($\gamma = 2\pi NR/h$) and true logarithmic ($e = \ln\gamma$) strain are presented in Table 1.

Microstructure after various deformation stages was investigated on a Philips CM-30 TWIN transmission electron microscope (300 kV). Methods of preparation of thin foils for the microstructure research in the section perpendicular to the anvil plane and the method of dark-field analysis of discrete and continuous misorientations are described in detail elsewhere [3].

Microhardness H_μ was determined by the Vickers method in the cross section perpendicular to the anvil plane with the use of the Neophot 21 at the load 0.5 N and 15 s exposure. The microhardness measurement results ata distance from the disc center and the number of revolutions are shown in Table 1.

RESULTS AND DISCUSSION

Figure 1 shows bright field electron microscopy images of the V–Cr–Zr–W alloy microstructure taken from the central (a, b) and peripheral (c) regions of the disk specimen after torsion at *N* = 0.1. The structure in the central region (*R* = 0.5 mm, *e* = 0.7) is characterized by a strong heterogeneity. This is manifested in the presence of areas with the cellular dislocation structure (Fig. 1a), which are combined with extended (up to several microns) grains parallel to the anvil plane (AP) with the width (in the direction of the torsion axis (TA)) not more than 0.2 µm (Fig. 1b). In the peripheral region (*R* = 3.5 mm, *e* = 2.7), the entire volume of the material is presented by the anisotropic submicrocrystalline state (Fig. 1c). Typical grain sizes in the direction parallel to the anvil plane range from one to several microns whereas in the direction parallel to the torsion axis their sizes are in the range from 50 to 150 nm.

As the deformation degree increases, the anisotropic submicrocrystalline state gradually fills the entire volume of the material. At the same time, within grains processes of the formation of nanostructural states of the two-level type are activated (Fig. 2): submicro- and nanograin sizes containing nanofragments (5–30 nm) with the dipole and multipole character of misorientation (Fig. 2b) and elastic curvature of the crystal lattice of hundreds of degrees per micron [4]. The formation of two-level substructures in the material is accompanied by an increase of microhardness values (Table 1, Fig. 3).

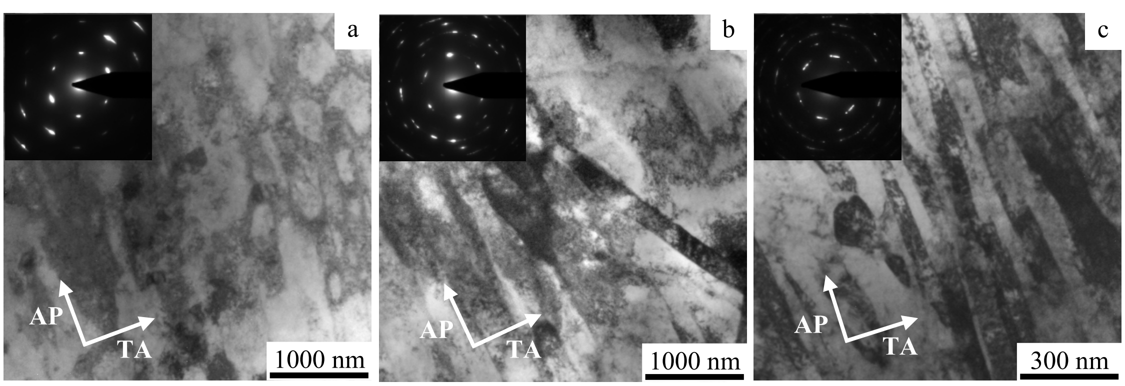

FIGURE 1. Microstructure of V–Cr–Zr–W alloy in the cross section perpendicular to the AP after deformation at *N* = 0.1 in the central (a, b) and peripheral (c) regions of the disk specimen

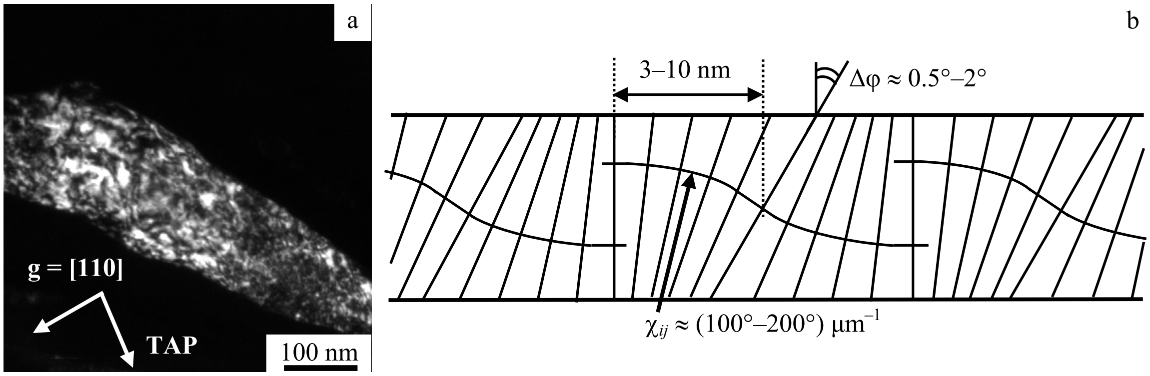

FIGURE 2. Two-level structural state in V–Cr–Zr–W alloy: a dark-field electron microscopic image, $N = 0.1$, $e = 2.7$ (a) and the model of the defect substructure with the dipole character of misorientations (b) [4]

After $e \approx 3$, two-level type substructures become a typical condition of the material and are observed in almost all grains. It was established that in the strain range (e) from 3 to 6.6 grains with high-angle boundaries are hardly changed; the transformation of the microstructure is associated with a reduction in the nanofragment size and increase in the crystal lattice curvature.

It was preciously shown [4–8] that evolution features of the metallic material microstructure under severe deformation by torsion on Bridgman anvils depend on the type of the crystal lattice and its phase stability, initial and acquired strength, homologous deformation temperature, and relaxation ability. These factors largely determine specific stages in the evolution of microstructure and of the complex of physical and mechanical properties as well as basic mechanisms of structural transformation.

It is found that in the investigated V–Cr–W–Zr alloy the stages of microstructural evolution and microhardness are identical to those occurring in V–Ti–Cr vanadium alloy [4] which is characterized by a significantly lower volume fraction of nonmetallic phase particles. High density of ZrO_2-based nanoparticles promotes a more intensive development of evolutionary processes and accelerated flow of the respective stages (submicrocrystalline structure formation, development of two-level substructures) of the material nanostructuring. These features of microstructural evolution also provide a more intense, as compared to the V–Ti–Cr-system, microhardness increase.

SUMMARY

Transmission electron microscopy is employed to study features of evolution of nonequilibrium nanostructural states during torsion under pressure of high-strength vanadium V–Cr–W–Zr alloy with a high volume fraction of nonmetallic phase nanoparticles.

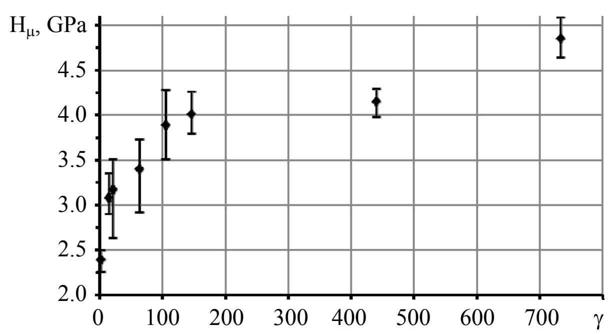

FIGURE 3. Microhardness H_μ of the investigated alloy versus shear strain γ

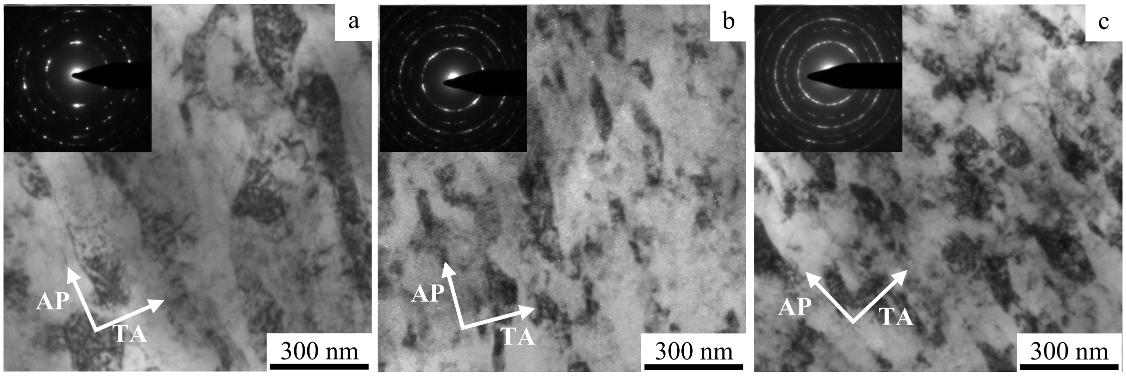

FIGURE 4. Microstructure of V–Cr–Zr–W alloy after $N = 1$, $e = 3.0$ (a), $N = 3$, $e = 6.1$ (b), and $N = 5$, $e = 6.6$ (c)

The following stages of this evolution are detected:

(i) the formation (at true logarithmic strain $e \leq 1$) of the cellular dislocation structure and localized deformation bands parallel to the AP with the crystal lattice reorientation with the width not exceeding 0.2 μm.

(ii) the formation (at $1 \leq e \leq 3$) of the two-level submicrocrystalline (SMC) structure with a high anisotropy degree and submicrocrystals sizes ranging from 50 to 150 nm.

(iii) an increase (in the range $3 \leq e \leq 6$) in defective degrees of the material (increase in the crystal lattice curvature and the nanofragment size reduction) with the formation of the two-level nanostructural state with the crystallite size of several nanometers and the elastic curvature of the crystal lattice of hundreds of degrees per micron.

It is shown that a high density of nanosized particles in V–Cr–W–Zr alloy provides a more intensive, as compared to V–Ti–Cr vanadium alloy, evolutionary process and accelerates the flow of the respective stages (formation of the SMC structure, development of the two-level substructures) of the material nanostructuring.

ACKNOWLEDGMENTS

The work was conducted within the framework of the Program for the Fundamental Scientific Research of the Russian Academies of Sciences for 2013–2020 at a partial financial support of the Tomsk State University Competitiveness Improvement Program. The investigation was carried out using the equipment of the Tomsk State University.

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