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Physical mechanisms of helium release during deformation of vanadium alloys doped with helium atoms

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Abstract

Helium embrittlement of vanadium alloys which are labored for future fusion reactors may be closely related to the transport of helium to critical failure sites within the material (grain boundaries, precipitates, etc.). Recently during high-temperature mechanical tests of helium-doped vanadium alloys by the tritium trick technique, the abnormal helium release peaks have been observed. In this case, a good correlation has been found between the helium release during the deformation and embrittlement processes. Such results have fundamental meaning for understanding the helium behavior during deformation of fusion structural materials. In the present paper, the physical mechanisms of abnormal helium release from deforming vanadium alloys are suggested. The theory of helium release is based on the dynamic-diffusion models of dislocation motion with helium atoms and helium bubbles, where helium atoms and helium bubbles are swept by moving dislocations. In the suggested model, the effect of the strain rate of plastic deformation and pipe diffusion of helium atoms along dislocations on this phenomenon is considered. The theoretical models are compared with experimental results for helium release during deformation of vanadium alloys after helium doping by the tritium trick technique. The temperature dependence of this phenomenon and the effect of strain rate on growth kinetics of helium bubbles are analyzed. The present results allow us to understand the effect of various helium doping techniques (helium trick, cyclotron preimplantation and boron-10 technique) on helium release from deformed vanadium alloys. © 1999 Elsevier Science B.V. All rights reserved.

1. Statement of the problem

Vanadium-based alloys are considered as perspective low-activated structural materials for the first wall of future fusion reactors [1,2]. Many factors determine the radiation resistance of these alloys. The most important among them is the effect of helium on the mechanical properties and especially on radiation embrittlement. Helium embrittlement of vanadium-based alloys has been studied in recent years using several techniques for helium doping, i.e. the tritium trick techniques [3,4], cyclotron implantation [5,6] and boron-10 technique [6]. The role of helium in degradation of mechanical properties of vanadium alloys is not yet clear.

Helium atoms, interacting with a great variety of structure defects, affect the macroscopic behavior of materials [2,3]: radiation embrittlement and hardening, and to a lesser degree, radiation swelling and creep.

The physical mechanisms of helium transportation to grain boundaries (GB) which can accelerate the nucleation and growth of helium bubbles and cracks at GB in stressed materials should be investigated in detail.

Recently, during high-temperature helium embrittlement (HTHE) investigations of vanadium alloys, a new phenomenon related to helium behavior in vanadium alloys has been found [7]. In this study the investigation of mechanical properties of vanadium alloys doped with helium atoms was done using two methods of helium saturation, i.e. cyclotron implantation and the tritium trick technique. The samples were loaded dynamically. It was found, that in the case after helium doping by the tritium trick, during plastic deformation the unusual

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helium release peaks had arisen. In the other case (cyclotron implantation) those peaks have been absent.

These experimental results [7] are quite interesting and important for both physical and technical considerations. So due to this phenomenon there is an additional channel for helium transportation towards GB during plastic deformation. Arising peaks of helium release depend on temperature and are an order of magnitude more than background helium release. Experimental results [7] show that this physical phenomenon arises only at definite conditions and it has the following main peculiarities:

1. Abnormal helium release peaks arise only during plastic deformation of the sample.
2. Strong temperature dependence has been observed. Small and rare peaks have been found at room temperatures. At high temperatures the height of peaks is an order of magnitude more than for peaks at room temperatures. Resultant amount of desorbed helium also increases.
3. Total amount of desorbed helium strongly depends on the alloy composition.

The present study deals with analysis of different physical mechanisms of abnormal helium release peak formation.

Here helium-saturated material with uniform helium distribution in the matrix is considered. The sample elongates with constant strain rate $\dot{\varepsilon}_0$. The experimental results show that plastic deformation leads to abnormal gas (helium) release. Moreover, the peaks' presence and their height depend on a number of factors (temperature, impurities in matrix deformation rate, etc.). We will consider here two methods of saturation of samples: tritium trick technique, and cyclotron preimplantation with high step and small strain rates of deformation during mechanical tests.

2. Dislocation-dynamic mechanism of helium release

2.1. *'Fast' helium atoms*

In this case the material saturation via the trick technique is considered, where the time τ_{He} ($\tau_{\mathrm{He}} \sim R_{\mathrm{d}}/D$, where D is the helium diffusion coefficient) for the diffusion motion of helium atoms from the cell boundary ($l = R_{\mathrm{d}}$, $R_{\mathrm{d}} = (\pi\rho_{\mathrm{d}})^{-1/2}$) to the dislocation is less than the time τ_{d} ($\tau_{\mathrm{d}} \simeq (b/\sqrt{\pi\rho_{\mathrm{d}}}) \cdot (1/\dot{\varepsilon})$, where ρ_{d} is the dislocation density, $\dot{\varepsilon}$ is the strain rate) needed for the dislocation to cover the same distance due to the plastic deformation ($\tau_{\mathrm{He}} \ll \tau_{\mathrm{d}}$).

For the explanation of this phenomenon the model of dislocation-dynamic diffusion is suggested. The process of dislocation motion with helium atoms can be imagined as a two-step process. In the first step diffusion flow of helium atoms to the dislocation line takes place. In the last step dislocation motion occurs.

Solving of diffusion equation related to those processes which allow us to calculate helium distribution and helium amount carried to the surface. Solving the diffusion equations by taking into account elastic interaction of helium atoms with dislocations, we can receive the total amount of helium atoms that come out to the surface

$$N_{\mathrm{tot}} \approx \frac{\pi C_0 S_0 R_{\mathrm{d}}}{2\,\ln(R_0/2R_{\mathrm{d}})}, \tag{1}$$

where C_0 is the initial concentration of helium atoms in material and S_0 is the sample surface.

2.2. *'Slow' helium atoms*

This case coincides with the situation where vanadium samples are saturated by means of cyclotron implantation. In this case $\tau_{\mathrm{He}} \gg \tau_{\mathrm{d}}$, moreover, all of the helium atoms are situated on substitutional sites because they are trapped by free radiation- induced vacancies. Solving some kinetic equations for moving dislocations, we get the total helium current to the surface until rupture of the sample occurs

$$N_{\mathrm{tot}} \approx 2 S_0 \varepsilon_{\mathrm{p}} C_0 L \left\{ \pi \frac{D\rho_{\mathrm{d}}}{\dot{\varepsilon}_0} \frac{r_0}{b} \right\}^{1/2}, \tag{2}$$

where ε_{p} is the elongation at which rupture occurs and r_0 is the core radius of dislocation.

3. Helium release related to helium bubble transport by moving dislocations

Another possible mechanism of abnormal helium release peak formation during plastic deformation is based on transport of helium bubbles to the surface by moving dislocations. It can be divided into three stages. In the first step, helium atoms are absorbed to dislocation and form stable helium clusters. In the second step, bubble growth is released due to helium diffusivity from the bulk and to dislocation and follows along the dislocation line. In the final step the helium bubbles are transported and follow along the dislocation line. In the final step helium bubble transportation towards surface by moving dislocation occurs.

It is supposed that the time of bubble formation on dislocation lines is less than the time of dislocation motion to the surface. According to experimental results (especially for the tritium trick technique), when the helium atoms are located in interstitial positions this approach makes considerable contribution.

Let us designate as λ_p the depth from which the dislocations can come out to the surface.

$$\lambda_p = \int_0^{t_p} V_b(t)\mathrm{d}t, \tag{3}$$

where $V_b(t)$ is the velocity of complex dislocation-helium bubble.

It has been shown that diffusion flow of helium atoms to the dislocation is faster than the dislocation motion. Thus, the dislocation gathers all helium atoms in its own cell. So, all the helium atoms from the near-surface region with size come out to the surface during the rupture time t_p.

So, the total helium amount until rupture is equal to $N = C_0 \lambda_p S_0$, where C_0 is the bulk concentration of helium atoms and S_0 is the surface of the sample.

After the calculations, the number of helium atoms per unit of sample surface in this case is equal to

$$N_s = \frac{l}{32\pi kT} \frac{\sigma b^5 l_b}{C_0} \frac{D_s}{D_a^2} \frac{t_{gr}^2 + t_p t_n}{t_{gr}^2 t_n}, \tag{4}$$

where σ is the applied stress, t_{gr} is the time of bubble growth, t_n is the time of helium bubble formation D_a, D_s are the self-diffusion coefficients for helium atoms and atoms material.

4. Helium release related to sweep out of helium bubbles by moving dislocations

Another mechanism is possible when at the beginning of the process, helium bubbles are formed and grow in the bulk of the material. During plastic deformation, moving dislocations can collect these bubbles and transport them to the surface. This mechanism can be divided into two steps. In the first step, nucleation and growth of helium bubbles take place. In the second step, the transportation of helium bubbles by moving dislocations occurs.

In this case, the total helium amount per unit of surface is given by

$$N_{tot} = \frac{D_s}{32\pi kT} \left[\frac{b}{R}\right]^4 \frac{\sigma b C_0}{R_d^2 C_b^v} t_p, \tag{5}$$

where C_b^v is the helium bubble concentration, R is the average bubble radius.

5. Results obtained

1. Physical mechanisms of helium release from materials doped with helium under dynamic loading were discussed. The principal processes which led to abnormal helium release peak formation during plastic deformation of materials saturated by the tritium trick technique and cyclotron implantation were analyzed.
2. The contribution of dislocation-dynamic model of helium atom diffusion in the formation of helium release peaks was determined in both limiting cases: slow and fast strain rates. The quantitative estimate shows, for the case 'fast' helium atoms (low deformation velocities, slow dislocations and saturation via the tritium trick (helium atoms occupy interstitial sites)) at $C_0 = 300$ appm, $T = 800$ K and sample surface $S_0 = 0.15$ cm^2, the helium amount carried by dislocation is $N_{tot} = 2 \times 10^{15}$. According to the experimental results, it is theoretically enough to form helium release peaks. In another limiting case ('slow' helium atoms) the quantitative estimations show, that at $C_0 = 300$ appm, $\varepsilon = 10\%, L = 10$ µm, $S_0 = 0.15$ cm^2 the total amount of helium release is $N \sim 7 \cdot 10^{13}$. It is enough for the explantation of the experimental data.
3. The mechanism related to the sweep out of helium bubbles by moving dislocation is suggested. Numerical estimations have shown that this mechanism can contribute considerably to peak formation.
4. Temperature dependencies of total helium release for all the discussed mechanisms were analyzed. It was shown that in the model of dislocation-dynamic diffusion, the total helium amount that comes out to the surface has weak dependence on temperature $N_{tot} \sim (\ln A/T)^{-1}$. The other discussed mechanisms have the following temperature dependence:

$$N_{tot} \sim \frac{\exp(-E/kT)}{T},$$

where E is the effective energy migration for helium atoms, which is determined (see part 3) by $E_1 = E_{fv} - 2E_{mHe,}^{v}$ (where E_{mv} is the energy of vacancy migration in the bulk of the material, E_{mHe}^{v} is the energy of helium atom migration in the bulk of the material, E_{fv} is the energy of vacancy formation) and in the case of sweeping of helium bubbles by moving dislocations (see part 4) $E_2 = E_{mv} + E_{fv}$. The obtained theoretical results have good agreement with experimental data [7].

References

[1] H. Matsui, K. Kuji, M. Hasegava, A. Kimura, J. Nucl. Mater. 212–215 (1994) 784.

[2] H. Matsui, Proceedings of Symposium on Materials for Advanced Energy Systems and Fusion Engineering, Tokyo, Japan, p. 271, 994.

[3] D.N. Braski, D.W. Ramey, in: F.A. Garner, J.S. Perrin (Eds.), ASTM STP870, ASTM Philadelphia, 1985, pp. 1211–1224.

[4] D.N. Braski, D.W. Ramey, in: R.L. Klneh et al. (Eds.), ASTM STR1047, ASTM Philadelphia, 1990, pp. 161–178.

[5] M.P. Tanaka, E.E. Bloom, J.A. Horak, J. Nucl. Mater. 103&104 (1981) 895.

[6] W. Van Witzenburg, in: R.E. Stolier, A.S. Kumar, D.S. Gelles (Eds.), ASTM STP1125, ASTM Philadelphia, 1992, pp. 915–927.

[7] H. Matsui, M. Tanaka, M. Yamamoto, M. Tada, J. Nucl. Mater. 191–194 (1992) 919.