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Effect of neutron irradiation on swelling, elastic modulus and thermal conductivity of V–Ga alloys

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Abstract

Vanadium and vanadium alloys with gallium, chromium and cerium were irradiated at 400°C in the BR-10 reactor. The neutron fluence was $5.15 \cdot 10^{25}$ n/m^2 ($E > 0.1$ MeV). The elastic modules (E and G) and swelling of the alloys were measured after irradiation. It is established that swelling in the alloys is negligible and the elastic properties do not change significantly after irradiation. The experimental results are briefly discussed.

1. Introduction

At present, V–Ti–Cr alloys are considered as a promising low-activation structural materials for fusion reactors [1,2]. However, titanium impairs the activation behaviour by producing long-lived radionuclide ^{39}Ar [3,4].

If was shown previously [5,6] that V–Ga alloys have better radioactivity decay behaviour than V–Ti–Cr alloys. The tensile properties, thermal conductivity, elastic modules and corrosion resistance in lithium of the alloys are comparable to those of V–Ti–Cr alloys [5–7].

Neutron irradiation may lead to changes of thermal conductivity and elastic modulus of materials. These changes will be influenced by temperature and thermal stress levels in the first wall. In this connection, the influence of neutron irradiation on elastic modulus and thermal conductivity for V, V–Ga, V–Ga–Ce and V–Ga–Cr alloys were performed. The swelling behaviour was also studied.

2. Experimental procedure

Vanadium alloys were arc melted from vanadium (with a total content of O, N and C was about 0.051 wt%), electrolytic chromium, high purity gallium and cerium. Six or seven remelts were used to produce uniform distribution of alloying elements. The primary working of each ingot was performed by rolling at 1200°C. Materials were cold rolled after intermediate annealing at 1000°C for 1 h in vacuum to produce sheets 1.5 mm-thick. Specimens with dimensions $1.5 \times 1.5 \times 22$ mm were machined from these materials and annealed at 1000–1100°C for 1 h in a vacuum of $7 \cdot 10^{-5}$ Pa. The results of chemical analysis are given in Table 1.

Specimens of the alloys were irradiated in the BR-10 reactor to a neutron fluence of $5.15 \cdot 10^{25}$ n/m^2 ($E > 0.1$ MeV) at 400°C. They were sealed in (He + Ar)-filled stainless steel capsules and were wraped in Mo-foil to prevent contamination from alloying elements in the steel.

Swelling of the alloys was determined using a hydrostatic weighting method. The thermal conductivity λ was calculated from the Widemann–Franz relation:

$$\lambda = LT/\rho \quad (1)$$

with the experimental values of resistivity measured in the range of temperatures from 20°C to 970°C. In the expression (1) where $L = 2.45 \cdot 10^{-8}$ W Ω/K^2 (Lorentz's

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Table 1
The compositions of the alloys (based on results of chemical analysis)

No	Composition, at.% [a]
1	Vanadium
2	V–1.86 Ga
3	V–6.29 Ga
4	V–2.61 Ga–0.05 Ce
5	V–4.19 Ga–0.05 Ce
6	V–4.51 Ga–5.66 Cr

[a] Concentrations of interstitial impurities (wt%): O – 0.025; N – 0.009; C – 0.021.

constant), T – temperature, K; ρ – resistivity, Ω/m. The elastic modules (E, G) were determined by the method of internal friction. Poisson's ratio μ was calculated based on the expression

$$\mu = (E/2G) - 1, \qquad (2)$$

where E is the Young's modulus, G the shear modulus. Resistivity and elastic modulus were measured in a vacuum of $6 \cdot 10^{-7}$ Pa.

3. Experimental results and discussion

The experimental data show that the alloying of vanadium with gallium decreases the swelling: the swelling of vanadium alloys is <0.2%, while one of pure vanadium is about 1.36% (Table 2). This value is 0.069% for V–1.86 at% Ga and is 0.28% for V–6.29 at.% Ga. It is probably that change of density for V–6.29 at.% Ga caused by radiation – enhanced precipitation of the second phase particles (V_3Ga) (limit of solubility of gallium in vanadium is ~6 at.% at room temperature [5,6]). Additional alloying V–Ga alloys with cerium leads to small decrease in swelling (0.157%). Combined alloying vanadium with gallium and chromium suppresses the swelling of specimens, even there is a little increase of density.

Table 2
The densities of the alloys before and after irradiation and their swelling (irradiation at 400°C in the BR-10 reactor, the neutron fluence is $5.15 \cdot 10^{25}$ n/m^2 (E > 0.1 MeV))

No	Composition, at.%	Density, g/cm^3		$\Delta d/d_0$, % ($\Delta d = d - d_0$)
		Unirradiated, d_0	Irradiated, d	
1	Vanadium	6.124	6.043	−1.36
2	V–1.86 Ga	6.1470	6.14274	−0.069
3	V–6.29 Ga	6.25373	6.23615	−0.28
4	V–2.61 Ga–0.05 Ce	6.12478	–	–
5	V–4.19 Ga–0.05 Ce	6.15784	6.14816	−0.157
6	V–4.51 Ga–5.66 Cr	6.23952	6.25535	+0.25

The experiments have shown that irradiation influence insignificantly on thermal conductivity (Fig. 1). For irradiated V–1.86 Ga alloy for example this value is close to initial one.

Temperature dependences of elastic modulus and Poisson's ratio of pure vanadium and its alloys before and after irradiation given in Figs. 2–4. In contrast to thermal conductivity changes, irradiation of the alloys results in decrease of elastic modules and Poisson's ratio. At the same time the temperature dependence of these alloys like one of unirradiated materials.

During the temperature rise, the Young's (E), shear (G) modulus and Poisson's ratio μ of irradiated specimens decreased are similar to unirradiated alloys. Deviation from the temperature dependence of the elastic modulus (defect of modulus) is inherent in the temperature range of 200–350°C. It is mainly connected with dislocation motion due to the start of interstitial impurity migration [8,9]. It leads to reductions in the elastic stress, the Young's and the shear modulus. The modulus of the irradiated alloys is lower than for the unirradiated alloys. This is probably explained by redistribution of interstitial impurities. Apparently, the decrease in the elastic modulus is caused by segregation of interstitial impurities to sinks and to clusters of radiation defects [10–12].

Different alloying additions change the levels of elastic properties in irradiated materials. For example, Young's and shear modulus for irradiated pure vanadium decrease by 5% and 3%, respectively, and Poisson's ratio decreases by 3–12% in the temperature range 20–400°C. Alloying vanadium with gallium and cerium results in larger decreases in elastic modulus (by 9–10%) and Poisson's ratio (by 2–6%) (Fig. 4). Alloying vanadium with gallium and chromium leads to insignificant change in these properties: Young's modulus decrease by 2%, shear modulus by 0.5% and Poisson's ratio by 5%.

4. Conclusions

1. It is shown that the swelling of V–Ga alloys and V–Ga alloys alloyed additionally with Ce or Cr is negligible after neutron irradiation at 400°C (fluence $5.15 \cdot 10^{25}$ n/m^2).
2. The elastic properties of the alloys do not change significantly after neutron irradiation at 400°C.
3. The results obtained show additionally prospects for studying alloys of V–Ga as promising low-activation structural materials for fusion reactors.

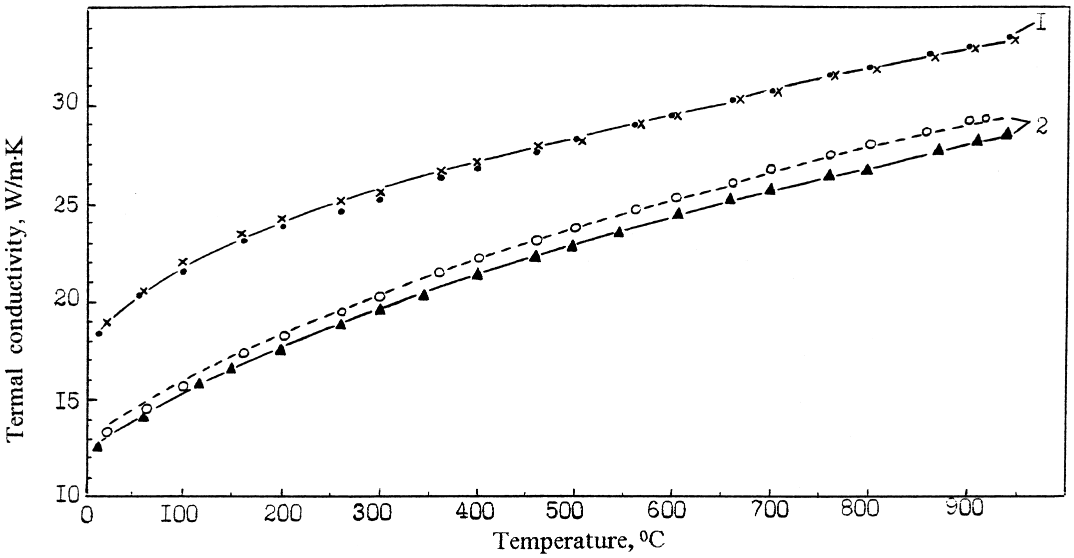

Fig. 1. The temperature dependence of the thermal conductivity of V–1.86 at.% Ga (1) and V–4.19 at.% Ga–0.05 at.% Ce (2) alloys before (1 –x, 2 – o) and after (1 – •, 2 – ▲) irradiation at 400°C in the BR-10 reactor. The neutron fluence is $5.15 \cdot 10^{25}$ n/m^2 ($E > 0.1$ MeV).

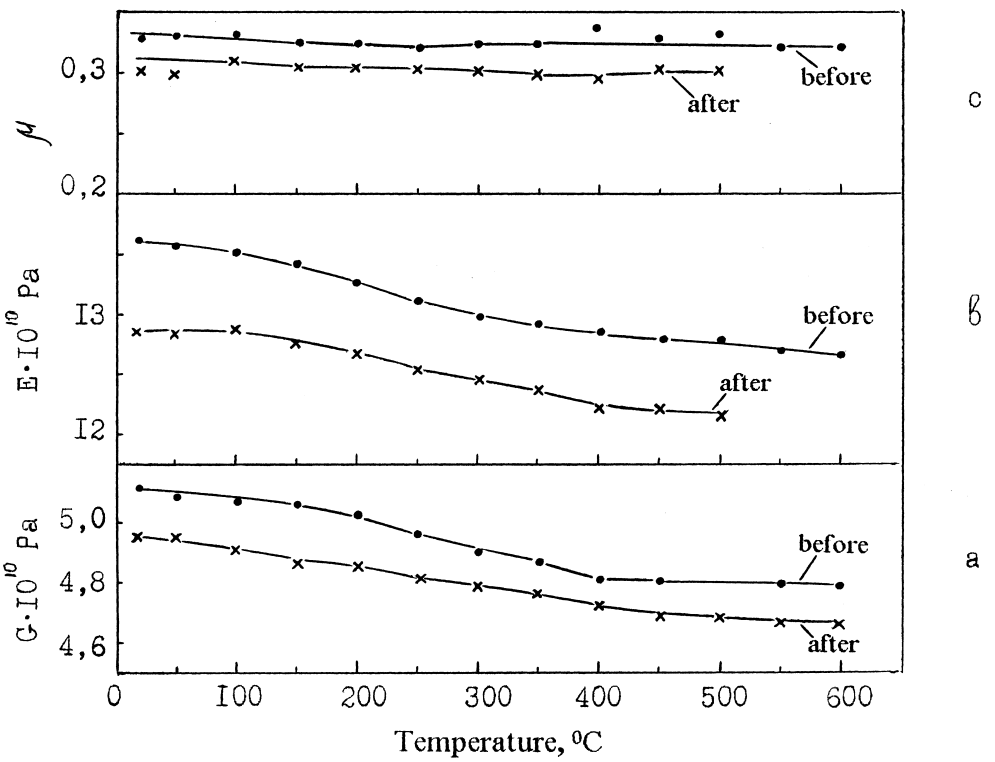

Fig. 2. The temperature dependence of shear modulus G (a), Young's modulus E (b) and Poisson's ratio μ (c) of vanadium before (•) and after (x) irradiation at 400°C in the BR-10 reactor. The neutron fluence is $5.15 \cdot 10^{25}$ n/m^2 ($E > 0.1$ MeV).

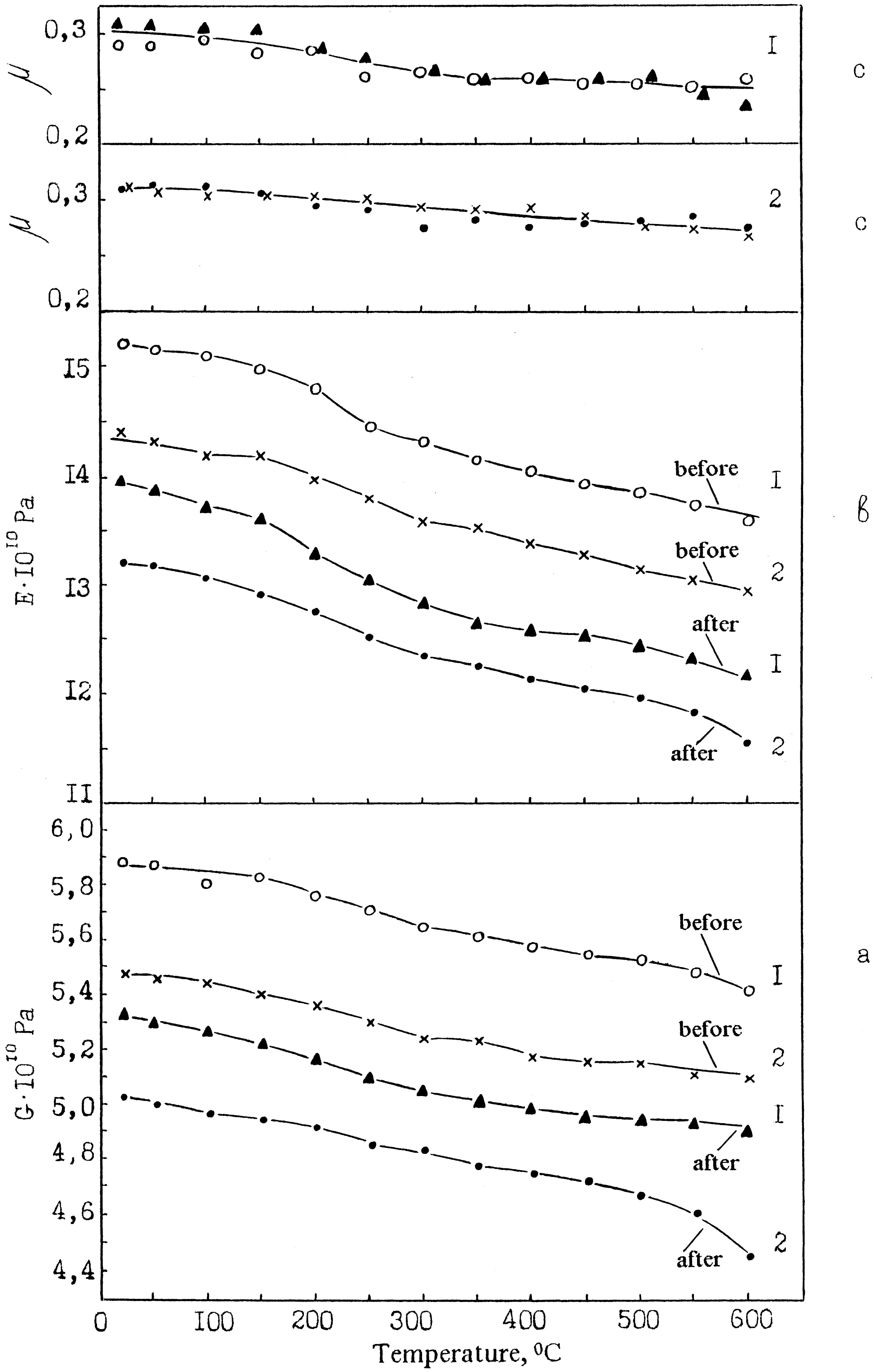

Fig. 3. The temperature dependence of shear modulus G (a), Young's modulus E (b) and Poisson's ratio μ (c) of V–6.29 at.% Ga (1) and V–2.61 at.% Ga–0.05 at.% Ce (2) alloys before (1 – o, 2 – x) and after (1 – ▲, 2 – •) irradiation at 400°C in the BR-10 reactor. The neutron fluence is $5.15 \cdot 10^{25}$ n/m^2 ($E > 0.1$ MeV).

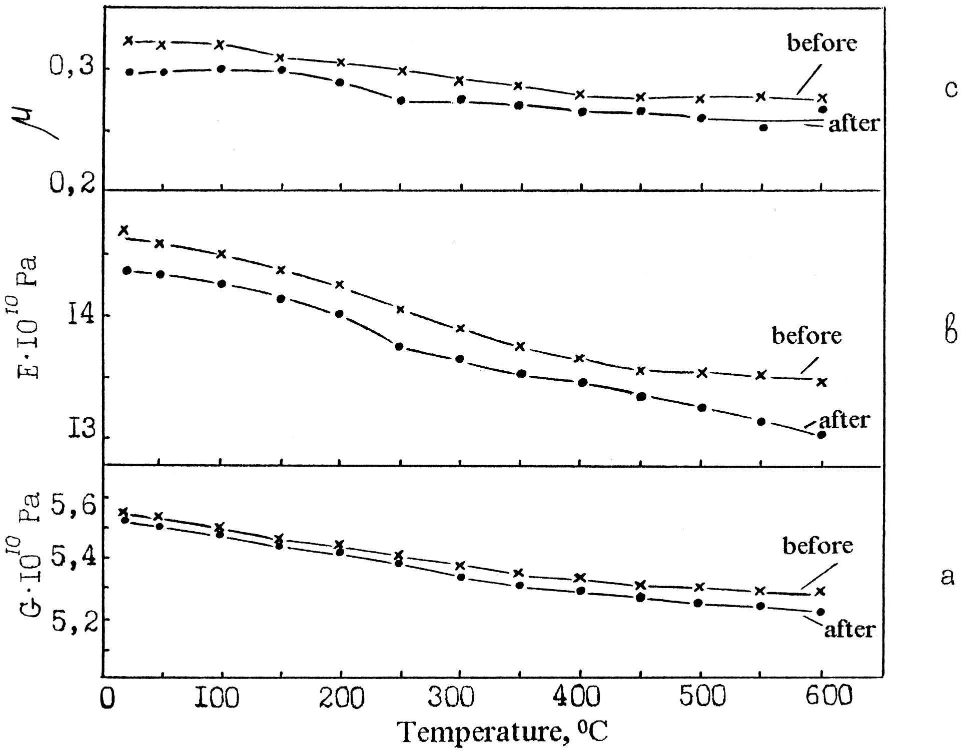

Fig. 4. The temperature dependence of shear modulus G (a), Young's modulus E (b) and Poisson's ratio μ (c) of V–4.51 at.% Ga–5.56 at.% Cr alloy before and after irradiation at 400°C in the BR-10 reactor. The neutron fluence is $5.15 \cdot 10^{25}$ n/m^2 ($E > 0.1$ MeV).

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