PHASE TRANSITIONS AND SPALL FRACTURES OF ZIRCONIUM UNDER EXPLOSIVE LOADING

E. Kozlov

► To cite this version:

E. Kozlov. PHASE TRANSITIONS AND SPALL FRACTURES OF ZIRCONIUM UNDER EXPLOSIVE LOADING. Journal de Physique IV Proceedings, 1991, 01 (C3), pp.C3-675-C3-679. 10.1051/jp4:1991394 . jpa-00250540

HAL Id: jpa-00250540

<https://hal.science/jpa-00250540>

Submitted on 1 Jan 1991

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

PHASE TRANSITIONS AND SPALL FRACTURES OF ZIRCONIUM UNDER EXPLOSIVE LOADING

E.A. KOZLOV

All-Union Research Institute of Technical Physics, P.O. Box 245, 454070, Chelyabinsk-70, USSR

Résumé : Les résultats de recherche sur l'évolution adiabatique du choc et la structure de l'onde de choc dans le zirconium sont présentés dans un domaine où les transitions polymorphiques primitives et secondaires existent. Les caractéristiques sur l'adiabate du choc à $\sigma_x = 9,2$ GPa, $V/V_0 = 0,9184$ découverts par les analyses métallographiques et radiographie X sur les échantillons sont liées à la transition de phase irréversible $\alpha \rightarrow \omega$ dans le zirconium. Les paramètres de relaxation rapide du précurseur élastique dans la phase α sont estimés ainsi que ceux des conditions d'écaillage. On note des microfissures à caractère visqueux dans la phase α et d'autres à caractère fragile dans la phase ω .

Abstract - Results of investigating the shock adiabat and the shock wave structure in zirconium, in the region of the first and the second polymorphic transitions, are presented. The discovered feature on the shock adiabat at $\sigma_x = 9.2$ GPa, $V/V_0 = 0.9184$, as the results of metallographic and roentgenostructural investigations of conserved samples showed, was connected with proceeding the irreversible $\alpha \rightarrow \omega$ phase transition in zirconium. Parameters of quickly relaxing elastic precursor in the initial α -phase were estimated. Conditions of spall fracture arising were determined. It was noted a viscous character of spall microfractures in α -phase and a brittle one in ω -phase.

1.- Introduction.

Zirconium is one of a few elements, for which it was succeeded to conserve the high pressure phase in the metastable state after static /1/ and shock-wave pressure /2/ effects and the subsequent unloading. If under the static loading it was investigated the zirconium phase diagram in every detail (figure 1) in the range of up to 10 GPa (in the range of $\alpha \rightarrow \omega$ transition), the data of zirconium behavior under the explosive loading /2-4/ were restricted. In /3,4/, while using the discrete method of the wave process registration, it was obtained 25 points of shock adiabat of zirconium in pressure range of 15-150 GPa.

The aims of this work were:

- obtaining data of shock compression and shock-wave structure in the region of the discovered /3/ phase transition, as well as in the range below 15 GPa, that was not earlier investigated experimentally;

Fig.1.- Phase diagram of unalloyed zirconium. 1 - boundary of equilibrium $\alpha \rightarrow \omega$ phase transition /17/; 2 - boundary of $\alpha \rightarrow \omega$ transition according to /14/; 3 - boundary of $\omega \rightarrow \alpha$ transition according to /15/; 4 - shock adiabat. Experimental points: 5 - /11/, 6 - /12/, 7 - /14/, 8 - /13/, 9 - /14/, 10 - /2/, 11 - /15/, 12 - /17/, 13 - /18/.

- investigating the spall fracture of unalloyed zirconium in α - and ω -phases;
- studying structure changes and the phase composition of samples, subjected to the explosive loading and conserved after tests;
- analysis of changing mechanical characteristics (microhardness) of material, underwent the elasto-plastic deformation in the region of initial α - phase and subjected to irreversible $\alpha \rightarrow \omega$ phase transition.

2.- Material, samples and explosive loading conditions.

Investigations were conducted on unalloyed zirconium, produced by vacuum remelting of iodide zirconium bars. Zirconium content was 99.8 mass %. The main impurities were nickel ($6.6 \cdot 10^{-2}$ mass %) and silicon ($4 \cdot 10^{-3}$ mass %). Roentgenostructural phase and metallographic analyses show the availability of only α -phase of zirconium in the initial state. The initial density and microhardness are equal to be 6.50 g/cm^3 and 125 kg/mm^2 , respectively.

Samples of two types were used (figure 2):

- wedges, which were cut from the parallelepiped, having sizes $30 \times 90 \times 135 \text{ mm}$ with $20^\circ 00'$ and $25^\circ 00' \pm 5'$ angles;
- hooves, milling from disks, having sizes $\varnothing 120 \times 30 \text{ mm}$ with $9^\circ 00' \pm 5'$ angle.

The explosive loading of the first type samples was realized by sliding detonation and the second type samples - by normal detonation of explosives, having different powers and thicknesses, as shown in figure 2.

Loading conditions were selected so, that:

- to realize states in the region of the first and the second phase transitions while using zirconium samples;
- to conserve samples, which underwent explosive loading in the region of the first $\alpha \rightarrow \omega$ transition for the following studying them by metallographic and roentgenostructural analysis methods and by measuring microhardness;
- to realize on the conserved samples spall fractures of different extent in the range of α - and ω -phase of zirconium for the later comparing the character of spall micro- and macrofractures with the registered parameters of loading pulse.

3.- Experimental method.

For the wave process recording immediately under explosive loading it was used the known /5-8/ method of the optical lever, which allows:

- to perform registrating not one, but two shock compression parameters simultaneously: the wave velocity and the free surface velocities of samples;
- to realize continuous registrating the free-surface velocity during the sequential output of compression and rarefaction waves upon it;
- to obtain information in one experiment at once for several free surface points, removed from loading surfaces in different distances.

Some typical photo-chronograms are shown in figure 2.

Fig. 2.- Experimental conducting schemes (a,b) and typical photo-chronograms (c,d). c - plastic explosive with 1 mm thickness; d - TNT-RDX 3/7 with 40 mm thickness; 1 - studied sample; 2 - polished free surface of sample; 3 - slit diaphragm system; 4 - plate explosive with thickness of 0.35-20 mm; 5 - explosive charge $\varnothing 120 \times 20-120 \text{ mm}$; 6 - explosive lens; 7 - detonator.

Fig. 3.- Shock adiabat of unalloyed zirconium. a) - ($\sigma_x, V/V_0$) is in the region up to 28 GPa; b) - ($\sigma_x, V/V_0$) is in the region up to 150 GPa; c) - (D, u)-relationship. It's seen the parameters of elastic precursor in initial α -phase, the feature, corresponding to the $\alpha \rightarrow \omega$ phase transition at $\sigma_x = 9.2$ GPa, and plateau, corresponding to the $\omega \rightarrow \chi$ phase transition at $\sigma_x = 26-36.5$ GPa.

4.- Results.

By using the optical lever method there were obtained 65 points on the shock adiabat of unalloyed zirconium in the range of 0.1-50.0 GPa (figure 3).

There were verified the results [3,4] of zirconium shock compression, including results, obtained in the phase transition region under the stress of 26.0-36.5 GPa. It was found that one-wave configuration was spreading along zirconium in the mentioned stress range (figure 2 d).

Data of shock compression and of shock-wave structure, in uninvestigated earlier stress range up to 15 GPa (figure 3a), were obtained. It was discovered a slight bend in the zirconium shock adiabat at $\sigma_x = 9.2$ GPa, $V/V_0 = 0.9184$, $D = 4.135$, $u = 0.340$

km/s, which was, probably, connected with proceeding $\alpha \rightarrow \omega$ transition in zirconium under the explosive loading. The fact of proceeding the irreversible $\alpha \rightarrow \omega$ transition was confirmed by metallographic and roentgenostructural investigation results of the same samples (figure 4 a, b).

Fig. 4.- Microstructures of the initial α -phase of zirconium (a - $\times 200$) and ω -phase of zirconium (b - $\times 1000$), that conserved after explosive loading in metastable state. Incipient spall fracture in α -phase (c - $\times 200$) and brittle microcracks in ω -phase (d - $\times 200$).

In zirconium it was observed arising two-wave configurations (figure 2 c), connected with elasto-plastic deformation of zirconium in the region of the initial α -phase. Parameters of the quickly relaxing elastic precursor were estimated to be equal to: $\sigma_x^{\text{HEL}} = 0.66$ -0.12 GPa, $u = 0.022$ -0.004 km/s.

There were received spall fracture data of unalloyed zirconium in α -phase in case of loading it by sliding detonation of the plate of plastic explosive (figures 4 c, d and figure 5).

As at [6], the spall macrofracture, arising in zirconium, was observed while outcoming on to the sample free surface, the plastic wave, the amplitude of which is equal to 3.0 - 4.0 GPa, under the conditions of pressure drop in the wave front:

$\frac{d\sigma_x}{dr} = 0.13$ -0.32 GPa/mm, where $r = x/\cos\theta$ is the distance, moved by the shock-wave front, x is variable thickness of the wedge sample and θ is the angle, formed by the shock-wave front and initial position of the loading surface.

By the metallographic analyses there was obtained information of zirconium spall microfracture character in α - and ω -phase at the level of separate material grains (figure 4 c, d).

By roentgenographic methods there were determined parameters of a grid of ω -phase, remained in the metastable state after unloading: $a = 5.035$ Å and $c = 3.110$ Å. These values are in agreement with data [2], however, appearing the ω -phase in conserved samples was observed in our experiments at higher pressures.

It was found the essential (by a factor of two) microhardness increase of the material, subjected to explosive loading. This increasing was connected mainly with proceeding the irreversible $\alpha \rightarrow \omega$ transition in zirconium. Only insignificant changing the microhardness of zirconium, subjected to elasto-plastic deformation in the region of the initial α -phase, was observed.

Fig. 5.- Change of stresses along the thickness of wedge samples while their loading by sliding detonation of plate charge explosives, having different powers and thicknesses. Numbers near the curves correspond to the thicknesses of used plastic explosive layer.

5.- Conclusion.

Results of investigating the shock adiabat and the shock wave structure in zirconium, in the region of the first and the second polymorphic transitions, are presented. The discovered feature on the shock adiabat at $\sigma_x = 9.2$ GPa, $V/V_0 = 0.9184$, as

the results of metallographic and roentgenostructural investigations of conserved samples showed, was connected with proceeding the irreversible $\alpha \rightarrow \omega$ phase transition in zirconium. Parameters of quickly relaxing elastic precursor in the initial α -phase were estimated. Conditions of spall fracture arising were determined. It was noted a viscous character of spall microfractures in α -phase and a brittle one in ω -phase.

REFERENCES

1. Tonkov E.Y., Phase Diagrams of Elements under High Pressures (Nauka Moscow 1979)
2. Kutsar A.R., German V.N., Nosova G.J., Rep. Acad. Sci. USSR 213 (1973) 81
3. M. van Thiel, Kusubov A.S., Mitchell A.C., Compendium of Shock Wave Data, LLNL, UCRL 50108, 1967.
4. Marsh S.P., Los-Alamos Shock Hugoniot Data, University of California Press, Berkely, Los Angeles, London, 1980.
5. Fowles G.R., J. Appl. Phys. 38 (1961) 1475
6. Kozlov E.A., Muzirya A.K., Chinkova R.H., et al., Phys. of Comb. & Expl. 4 (1984) 123
7. Kozlov E.A., Rep. Theses of the First All-Union Symposium on Macroscopic Kinetics and Chemical Gas Dynamics, 1984, v. 2, part 2, 52-53.
8. Gornovoy A.A., Kozlov E.A., Shorochov E.V. et al., Phys. of Comb. & Expl. 1 (1989) 142
9. Marsh J.M., Rice M.H., McQueen G. et al., Phys. Rev. 108 (1957) 196
10. Jamieson J.C., Science 140 (1963) 72
11. Bridgman P.W., Proc. Amer. Acad. Arts. Sci. 81 (1952) 165
12. Vereschagin L.F., Semerchan A.A., Kusun N.I. et al., Rep. Acad. Sci. USSR 138 (1961) 84
13. Jayaramen A., Klement W., Kennedy G.C., Phys. Rev. 13 (1963) 644
14. Itinosae, Proc. of the Second Symposium on High Pressures, 24-26 Dec. 1969, Sendai, Japan.
15. Silbershtain V.A., Nosova G.I., Estrin E.I., Phys. of Met. & Met. Sci. 35 (1973) 584
16. Bychkov Y.F., Lihanin Y.N., Maltsev V.A., Phys. of Met. & Met. Sci. 36 (1973) 413
17. Silbershtain V.A., Chistotina N.P., Zharov A.A., et al., Phys. of Met. & Met. Sci. 39 (1975) 445
18. Yohra Y.K., J. Nucl. Mat. 75 (1978) 288