Phase transformations and spall fractures of high-purity cerium under explosive loading [*]

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Introduction. Cerium is an element with a single 4f-electron. Nevertheless, under the action of pressure and temperature, it fairly simulates features in the behavior of an actinide having five 5f-electrons. More than 50 years ago, the process of isostructural (with preservation of the crystal lattice type) γ–α-electronic phase transformation with a high jump (~20%) in the specific volume was experimentally observed in cerium [1,2]. Cerium is only one element of the Mendeleev's Periodic table, which has the critical point in the solid-phase range both in the case of positive (compressive), and negative (tension) stresses. An unusually complex phase diagram for cerium [3] and the location of its critical points in the region of relatively low pressures and temperatures have made cerium the object of numerous experimental researches though mainly static ones. Dynamic experiments, i.e. shock-wave and explosive experiments with samples made of metallic and moreover high-purity (99.99 %) cerium, are few in number [2]. We can mention only the following:

- electrocontact measurements performed at VNIIEF in 1968-69 (Altshuler, Bakanova et.al. [4,5]);
- discrete diagnostics by LANL in 1973 (Gust, Royce [6]);
- analog diagnostics by LLNL in 1975 (Carter et al. [7]);
- high-resistance manganin gauge at VNIIEF in 1999 (M.N. Pavlovsky et.al. [8]);
- PVDF-gauge at VNIIEF in 2005 (Borisenok et.al. [9]);
- optical analyzer technique and the manganine gauge technique to measure sound velocity in cerium being shock-compressed within 30-140 GPa (Zhernokletov, Kovalev et.al. [10]);
- laser VISAR-diagnostics at VNIIEF in 2007 (Pushkov, Ogorodnikov, Erunov [11]);
- laser-interferometric VISAR-diagnostics on high-purity cerium samples (Hixson et al. 2002, Cherne et al. 2005-2007 [12]).

The purpose of this work is to obtain new data on spall strength of high-purity cerium being loaded in the region of γ–α and α–liquid phase transformations.

Material, samples, and conditions of their explosive loading. Wedge samples (30×40×6 mm^3, 12°00′ angle) of cerium having high-purity (99.99 wt %) and the 6.75 g/cm^3 initial density were manufactured in LANL and delivered to RFNC-VNIITF for investigations. These samples were loaded through the 12Kh18N10T steel base-plate with the 5-mm thickness by sliding and normal detonation of an HE layer having different type and thickness. We used the PETN-based plastic explosive with the 0.7-, 1-, and 5-mm thick layers, as well as the HMX-based explosive composition, the layers being 10-, and 20-mm thick.

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Diagnostic technique. The optical-lever method was used for wave processes registration [2]. Typical streak camera records of experiments when cerium samples were loaded by sliding and normal detonation are given in figure 1. The PETN-based plastic explosive with the 1-mm thick layer was used in experiment #620 and the same plastic explosive with the 5-mm thick layer – in experiment #622.

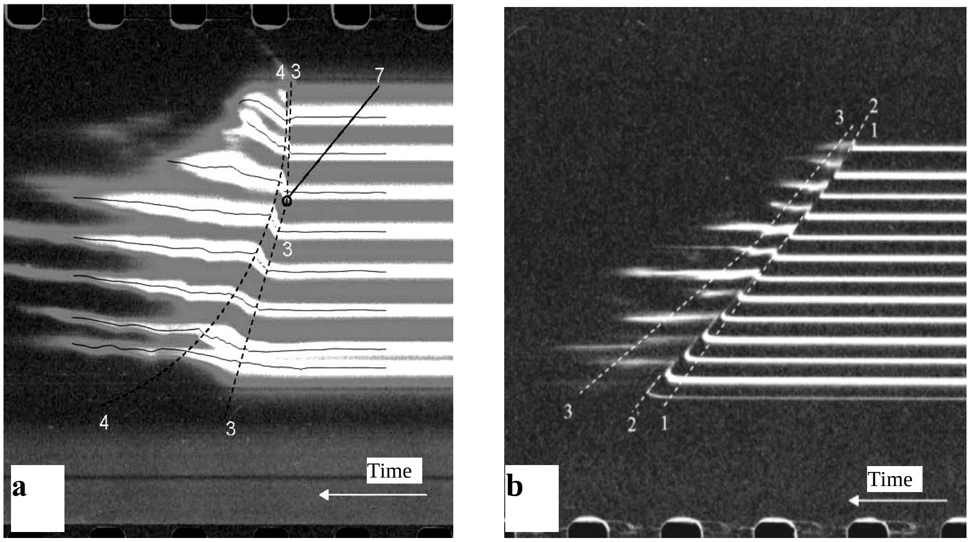

Fig. 1 – Streak camera records of experiments #620 and #622 when cerium samples are loading by sliding (a) and normal (b) detonation.

Results and their discussion. Our new results on isentropic and shock compression of Ce in the region of its γ–α and α–liquid phase transformations in stress waves are given in the (D,u)-, and (σ_{xx},V/V_0)- coordinates in Fig. 2 (a and b).

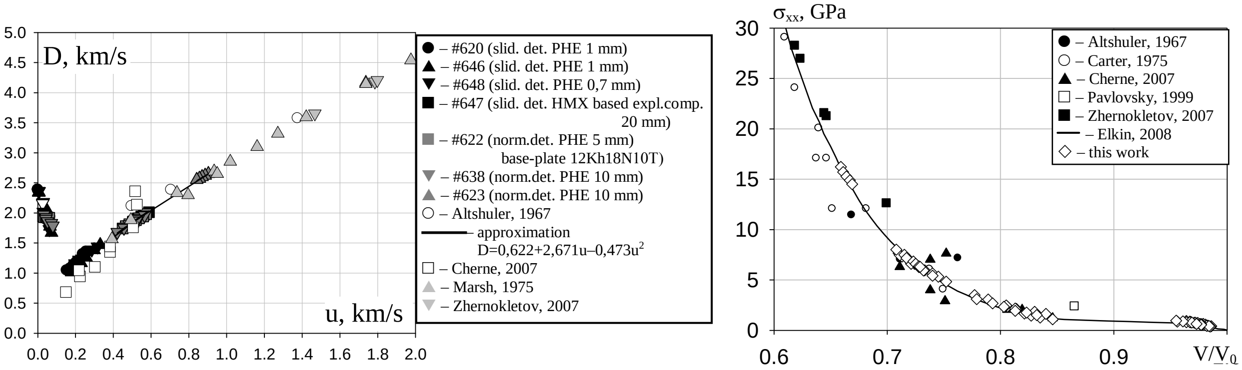

Fig. 2 – Hugoniot data for Ce in the (D/u)-, and (σ_{xx},V/V_0)-coordinates

Figure 2 gives for comparison all experimental data available for Ce and the result of their approximation by a new multiphase equation of state, which was derived by V.M.Elkin et.al. [3] based on the Aptekar-Ponyatkovsky model.

Figure 3 gives the first data on spall strength of the low-melting cerium under its explosive loading through the 12Kh18N10T steel base-plate with the 5-mm thickness by sliding and normal detonation of an HE layer having different type and thickness.

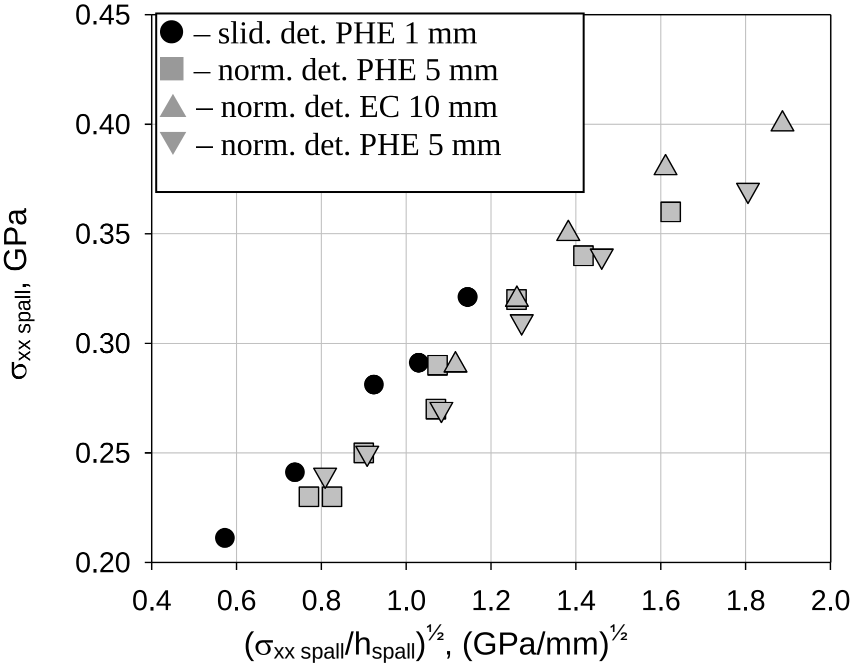

Fig 3 – Spall strength correlation with the tensile stress gradient.

Spall strength of cerium $\sigma_{xx\ spall}$ = 0.2–0.4 GPa is noted to correlate well with the tensile stress gradient in the fracture region.

Summary

1. VNIITF results on compressibility of high-purity unalloyed cerium when it is explosively loaded in the region of its initial γ-phase and in regions of its γ-α and α-liquid phase transformations are presented. All available experimental data were verified and generalized. Boundaries of one-, two-, and three-wave configurations in cerium were determined in the (D,u)-, and (σ_{xx}, V/V_0)-coordinates.
2. New data on the stress-wave structure and parameters and their variation throughout the wedges for four explosive loading conditions realized with different loading-pulse amplitudes and durations were obtained on wedge samples using the photochronographic optical-lever method. Not only the smeared γ-α-phase precursor but also the elastic precursor were reliably recorded in the high-purity unalloyed cerium in the realized modes of its explosive loading.
3. Our experiments confirmed theoretical prediction that the Hugoniot does not cross the α-ε–phase equilibrium boundary. At $\sigma_{xx} \leq 16$ GPa, the optical lever method registered a sudden drop in the intensity of the light reflected from the sample's free surface and this can be explained by the shock-wave melting of cerium.
4. Experimental velocity profiles for the free surface of wedge samples, as well as the calculated longitudinal and bulk sound velocities, i.e. 1.9 km/s and 1.2 km/s, were used to estimate the first spall thickness and cerium spall strength, i.e. 0.2–0.4 GPa, which depend on stress pulse gradient in the tensile region.

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