

# Structure and properties of a Cu-37 wt.%Zn alloy subjected to quasi-spherical explosive loading

I. V. Khomskaya<sup>1,2,†</sup>, V. I. Zel'dovich<sup>1</sup>, A. E. Kheifets<sup>1</sup>, N. P. Purygin<sup>3</sup>

<sup>†</sup>khomskaya@imp.uran.ru

<sup>1</sup>Mikheev Institute of Metal Physics, Ural Branch RAS, 18 S. Kovalevskaya St., 620990, Ekaterinburg, Russia

<sup>2</sup>Ural Federal University, 19 Mira St., 620002, Ekaterinburg, Russia

<sup>3</sup>Russian Federal Nuclear Center — Zababakhin All-Russia Research Institute of Technical Physics, 13 Vasilyev St., P. O. Box 245, 456770, Snezhinsk, Russia

The relations between the parameters of loading by powerful convergent shock waves (such as high pressure — 40 – 300 GPa, high-speed deformation —  $10^6$  –  $10^7$  s<sup>-1</sup>, tensile stresses — 0.25 – 1.75 GPa at unloading and temperatures 100 – 2500°C) and structural changes (the main of which are effects of localized deformation, the beta-alpha-beta transformations, melting and crystallization) in alloy Cu-37 wt.%Zn (brass) have been studied. The study was performed using the ball samples having a diameter of 60 and 40 mm. The balls were subjected to the explosion of a spherical explosive charge with thickness of 10 и 20 mm. The explosion was initiated from twelve points uniformly distributed over the charge's surface. The calculated pressure was 40 и 70 GPa on the ball's surface and 180 и 300 GPa in the ball's centers. To protect the samples against destruction by tensile stresses arising during their unloading, the samples and the charges were placed into a massive metal can. The correlation between macro- and microstructural changes and the geometrical conditions of shock-wave loading has been found. Effects of the interaction of converging shock waves at loading and the related phenomena of the plastic deformation localization and the fracture were studied. The radial cracks in the spherical samples were formed at a certain distance from the focusing center where the tensile stresses at unloading exceeded the dynamic ultimate strength of the material. It was determined that in the spherical sample made of brass this distance was equal to a half of the sample radius, and the value of the tensile stress is approximately 1.3 GPa, that is close to the spall dynamic strength of brass — 1.75 GPa and exceeds the ultimate static strength of brass in 5 times.

**Keywords:** shock waves, volumetric tensile deformation, high pressure, phase transformations.

## 1. Introduction

Due to the effect of energy cumulation, high pressure is created in the ball samples at the loading by shock waves [1]. According to E. I. Zababakhin, the cumulation takes place if energy density in a loaded material increases in automodel way with shock waves approaching to the focus center, i.e. at cumulation the pressure is changed according to the law  $P \sim 1/R$ , where  $R$  is the distance from the focusing center [1]. Near the center the pressure tends to infinity, which is followed by specific radial changes of microstructure and appearance of cavity in the center of the ball sample [2 – 6]. Therefore the observation of the radial microstructure changes and central cavity in the ball samples subjected to explosive loading is a qualitative criterion of cumulation process behavior. As the main part of energy of the shock wave is concentrated in the sample center, the unloading is accompanied by volumetric tension of the material — the process runs as if an explosion occurred in the sample center at the moment of focusing. At high densities of imparted energy the unloading is artificially slowed down using a massive metal can to save the sample. This results in a significant and volumetric tension strain of samples which is difficult to obtain experimentally via other methods [7].

Thus the loading of the ball samples by powerful converging shock waves is a tool for experimental study of the properties of metals and alloys at volumetric tension.

The experiments with the ball samples loading by powerful converging shock waves are unique to a certain extent as they allow obtaining a set of material sections subjected to dynamic pressure of different amplitude ranged from 40 to 300 GPa in the same sample [1 – 7]. The structural changes resulted from the explosive loading give an opportunity to evaluate the range of pressures, strains and temperatures operating during the sample loading. The deformation impact of shock waves causes different defects of crystal structure: vacancies, interstitial atoms, dislocations, stacking faults, twins that leads to considerable strengthening of the loaded material [8]. High pressure caused by the shock wave promotes phase transformations accompanied by a specific volume decrease. At the same time, the tensile stresses in the waves of unloading can cause the forming of phases with a specific volume exceeding the initial one [8]. The phase transformations in the shock waves occur in a big number of centers within microsecond intervals of time creating conditions for formation of highly dispersed structures [8,9]. Note that the loading by powerful shock waves with a pressure 100 GPa and higher leads to an increase of the temperature,

which has a strong effect on the structure formation. The temperatures after unloading can reach hundreds and even thousands degrees Centigrade. Cooling after unloading results in the same phase and structural transformations as in the course of commonly used heat treatment, the only difference is that the temperature duration is small while the cooling speed is extremely high.

The work was aimed to study the relations between pressure and temperature at loading by quasi-spherical shock waves and microstructural changes in the brass balls caused by deformations and phase transformations as well as to evaluate the brass strength in the conditions of volumetric tension.

## 2. Material and experimental techniques

The Cu-37 wt.% Zn alloy was taken as a starting material. The alloy consists of  $\alpha+\beta$  phases that is convenient for studying the deformation and temperature effects caused by the shock waves impact. The chemical composition of the brass under study is close to the phase boundary between  $\alpha$  and  $\alpha+\beta$  regions, i.e. the  $\alpha\rightarrow\beta$  transformation can take place in the alloy if the temperature changes. The ball samples with a diameter of  $d=40$  and  $60$  mm, hereafter designated as d40 and d60, correspondingly were subjected to quasi-spherical loading. The shock waves were created by the explosion of spherical charge of an explosive substance with thickness of 20 and 10 mm, correspondingly. The explosion was initiated from the surface at twelve points distributed on the sphere uniformly with nonsynchronism not exceeding  $\sim 10^{-7}$  s [2]. Unloading was carried out isoentropically in the expansion wave spreading from the sample surface. To prevent the samples fracture caused by tensile stresses arising during unloading process, the sample and the charge were placed into a massive metal can [2].

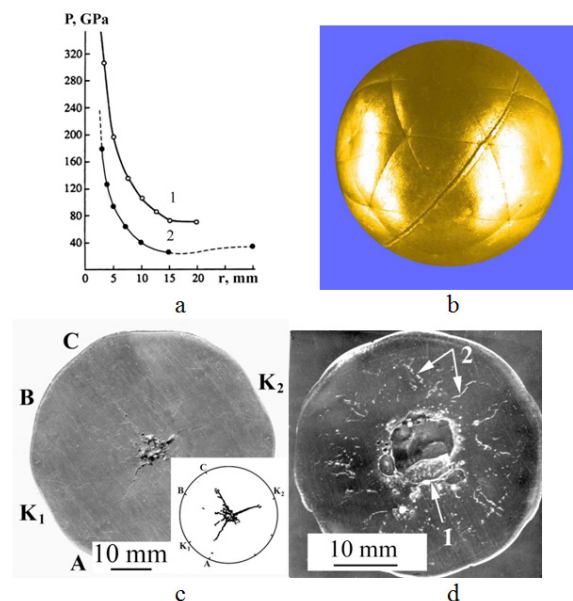
To study the structural changes at explosive loading the balls were cut in half. Microstructure examinations were carried out on the microscopes EPITIP-2 and JEM-200CX, metallographic samples and foils for transmission electron microscopy were prepared using standard methods. Microhardness was measured on PMT-3 at the loading 0.49 N. It is a difficult task to calculate the pressure distribution in the samples taking into account asynchronicity of detonation waves on the surface and interaction of shock waves in the ball volume. Therefore, the evaluation of pressure in the balls was performed in approximation of spherical symmetry (one-dimensional motion). The results of pressure evaluation are presented in fig.1a. It should be mentioned that the pressure increase in the ball d60 (curve 2, fig. 1) starts not on the surface but at some depth inside the ball (according to evaluation  $r=15$  mm or 0,5 of the ball's radius) taking into account wave processes connected with a small number (comparing with a spherical loading) of initiation points (twelve). Then the pressure in the balls d60 and d40 increased according to the law  $1/r^n$ , where  $r$  is a distance from the ball center and  $n$  is assumed to be equal to 0,9 [1]. One can see (fig. 1) that the pressure in the ball d40 (curve 1) is considerably higher than that in the ball d60 (curve 2); this is due to the application of a spherical charge of explosive substance of higher thickness

in the ball of a smaller diameter. The pressure in the ball d40 comes up to 300 GPa at the distance 4 mm from the center, while it doesn't exceed 180 GPa in the ball d60. These values are reached in about  $10^{-5}$  s from the explosion initiation. The temperature increased together with the increase of pressure in the balls.

## 3. Results and discussion

After loading the form of the balls was slightly changed and became like dodecahedrons. Fig. 1b shows the view of the sample surface with smooth peaks and convex faces. The face centers of quasi-dodecahedron were coincided with projections of the explosion initiation points ( $K_1, K_2$ , fig. 1c). The lines corresponding to impingement of detonation waves and creating regular pentagons are clearly distinguished (fig.1b). The lines of the first order are the ribs of quasi-dodecahedrons, the lines of the second order connect the face centers with the peaks of quasi-dodecahedrons. Fig. 1 shows the view and scheme of diametrical plane of the ball d60 section. In the center there is a cavity of irregular form of 5–7 mm with irregular ragged edges created by integration of some small cavities with "bridges" 0,5–1,5 mm thick and stretched radial cracks.

The cavity was formed by uniform tensile stresses in the ball center. Extensive cracking propagated in radial directions connecting the ball center with projections of explosion initiation points ( $K_1, K_2$ , fig. 1c) or in direction towards the intersection points of diametrical plane of section with the lines of interaction of detonation waves on the ball surface (A, B, C, fig.1c). The cracks appeared during unloading from external surface. It is seen that the majority of stretched cracks were originated in a spherical layer located 15 mm from the ball center. The crack location (fig.1) is associated with localization of deformation in the sample, i.e. specified



**Fig. 1.** The pressure change along the radius of the brass balls (a): curve 1 -  $d = 40$  mm, curve 2 -  $d = 60$  mm and the views of the surface (b) and the planes of diametrical section of the balls d60 (c) and d40 (d) after loading by means of 12 points (quasi-dodecahedrons).

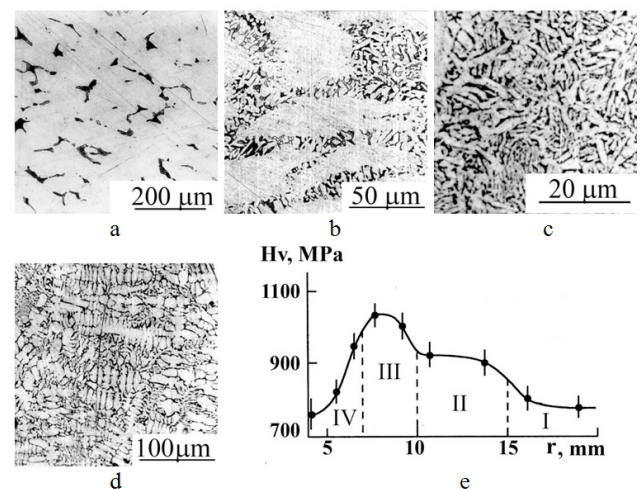
by the geometry of the experiment. Spreading towards the ball's center the cracks are connected with the internal cavity. The cracks appeared at the places where the value of uniform tensile stresses began to exceed the dynamic break point of the material. For brass it occurs at the distance approximately equal to half radius of the ball. Appearance of the cracks at this distance from the center means that high-speed deformation (with specific time of the order  $10^{-5}$ – $10^{-6}$  s) of volumetric tension is sufficient to destroy the brass sample. According to the extrapolation of the curve of copper cold compression [10] into the region of negative pressures, the approximate value of developed tensile stresses is equal to 1,3 GPa, i.e. close to dynamic spall strength of brass (1,75 GPa) measured at the strain rate of  $5 \cdot 10^5 \text{ s}^{-1}$  [11] and in five times exceeds static ultimate strength of brass at uniaxial tension (which is equal to 0,25 GPa). Thus, the strength of brass in the conditions of volumetric tension is considerably higher than that at other types of deformation.

A cavity of 8–12 mm with a smooth edges (fig. 1d) was formed in the central part of the ball d40. A long part with round edges (see arrow 1, fig. 1d) takes about one third of this cavity. As it is shown below, this part has a dendritic structure, i.e. it is a region of a “flown down hot melt”, the location of which allows us to judge about the ball's position during the loading. Around the central cavity in a spherical layer 5–10 mm from the center one can see the pores, in the next layer 10–15 mm from the center there are hair cracks mainly of the radial direction oriented to the peaks and centers of the faces of quasi-dodecahedrons (see arrows 2, fig. 1d). The crack position suggests that their appearance is associated with the effects of interaction of convergent shock waves as in the ball d60 (fig. 1c). Note that in the ball d40 the cracks were not connected with the internal cavity as it took place in the ball d60. Analyzing the structural changes described below, one can conclude that such reducing of cracking can be explained by a higher temperature in the ball of a smaller diameter.

Microstructure analysis of the ball d40 revealed four “ring zones” (or spherical layers) with different structures (fig. 2a-d). The initial structure of the brass sample was retained unchangeable in zone I (external zone) of the sample having a width about 5 mm. The microstructure consisted of the  $\alpha$ -phase with some  $\beta$ -phase regions with a length of 20–40  $\mu\text{m}$  and a thickness of 20  $\mu\text{m}$  (fig. 2a). In the initial structure, the volume fraction of the  $\beta$ -phase was 10–15%. The calculated pressure in zone 1 is 70–75 GPa (curve 1, fig. 1). Figure 2e shows the results of measurements of microhardness along the sample radius. One can see that the microhardness near the ball's surface does not differ from the initial one (750 MPa) but at the distance of 3–4 mm from the surface increases up to 800 MPa. In zone II with a width of 5 mm the areas of strongly localized deformation are seen. The strain value in this zone evaluated according to the elongation of structural constituents towards the strain flow amounted to 60–80%. The hair cracks appeared in this zone as well (fig. 1d, arrows 2). Microhardness in zone II grew from 800 to 920 MPa (fig. 2e). The calculated pressure in zone 2 is 85–110 GPa (curve 1, fig. 1). Figure 2b shows the microstructure of zone III, which had a width about 3 mm. In this spherical layer there are some areas of strongly localized deformation as in the previous zone. Within the elongated

areas of the  $\beta$ -phase a dispersed ( $\alpha+\beta$ ) structure is formed (fig. 2b). The calculated pressure in zone III is 130 GPa (curve 1, fig. 1). Thus, the impulse pressure of 150 GPa and generated temperature (as is shown below) are sufficient to initiate the  $\beta \rightarrow \alpha$  phase transformation. This transformation starts from a big number of centers. As a result, a dispersed structure is formed. Microhardness in zone III grew up to ~1040 MPa (fig. 2e). Zone IV or the “ring” zone (a spherical layer) has a width of 2–3 mm and is located around the central cavity. The structures corresponding to this zone are represented in fig. 2c,d. Spherical layer IV mainly consisted of dispersed two-phase ( $\alpha+\beta$ ) structure, which appeared as a result of the cyclic  $\alpha \rightarrow \beta \rightarrow \alpha$  transformations. The thickness of the bright areas of the  $\alpha$ -phase is 1–4  $\mu\text{m}$ , the thickness of the dark areas corresponding to the  $\beta$ -phase does not exceed 1  $\mu\text{m}$  (fig. 2c). The temperature increase in zone IV is caused by high pressure values (170–250 MPa) in the shock wave (curve 1, fig. 1). The further  $\beta \rightarrow \alpha$  transformation takes place in the course of cooling. There were the areas with dendritic structure (fig. 2d) in the thin layer (with a thickness of about 0,5 mm) around the central cavity. The area of “flown down hot melt” (see 1, fig. 1d) also has the dendritic structure. Analysis of dendrites unambiguously shows that the melting processes followed by solidification took place in the brass at the loading with  $P = 180 \text{ GPa}$ . It means that the central cavity appeared in the ball when the material was in a liquid state. Microhardness within zone IV reduced from 1000 to 750 MPa near the center of the sample (fig. 2e), it corresponded to the structural changes in this zone (fig. 2c,d). Thus, the formation of the melting area followed by solidification around the central cavity and the distinct “ring” zones with different structures take place in the ball d40. Such microstructural changes prove the radial increase of the pressure and a considerable temperature increase and, therefore, energy accumulation [2–6].

In the ball d60 microstructural changes associated with a local increase of pressure, temperature and localization of deformation were mainly found in the central area and in



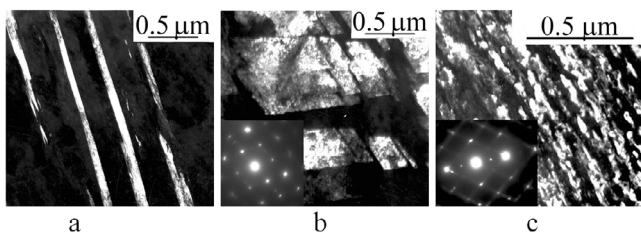
**Fig. 2.** Changes of microstructure (a-d) and microhardness (e) along the radius of the Cu-37% Zn ball with  $d=40 \text{ mm}$  caused by increasing of  $P$  and  $T$ : (a) – the structure near the surface of the sample (zone I); (b) – the  $\beta \rightarrow \alpha$  transformation in areas of the localized flow (zone III); (c) – dispersed ( $\beta+\alpha$ )-structure (zone IV); (d) – dendritic structure around the central cavity (zone IV).



the layers adjacent to the cracks (fig. 1c). In a narrow area around the cavity (0,5–1 mm) and in the areas of “bridges” the recrystallized grains of the  $\alpha$ -phase and dispersed ( $\alpha+\beta$ ) structure similar to that shown in fig. 2c were found. The estimated values of temperature and pressure in these areas compared with the traces of the  $\beta\rightarrow\alpha$  and  $\alpha\rightarrow\beta$  transformations do not exceed  $T=800^\circ\text{C}$  and  $P=130$  GPa. The traces of melting and crystallization in the layers adjacent to the cavity are absent. Thus, in the ball d60 in contrast to the ball d40 pressure and temperature do not considerably increase near the focusing center of the shock waves, but the intensity of tensile stresses was sufficient to form a cavity in the solid-phase state. During the electron microscopic study the deformation twins with the thickness of 0,1–0,5  $\mu\text{m}$  operating in one or two systems (fig. 3a,b) were found throughout the whole volume of the brass ball d60, i.e. the structural changes associated with high-speed deformation, which can be conventionally considered to be uniform, were observed. In some areas of the spherical layer located at the distance of 7–10 mm from the ball center an unusual structure, a mixture of nanoscale crystals of the  $\beta$ - and  $\alpha$ -phases, was detected (fig. 3c). It means that the  $\alpha\rightarrow\beta$  and  $\beta\rightarrow\alpha$  transformations took place in these areas of the sample due to deformation localization, which led to a local increase of temperature at explosive loading. The thickness of the forming crystals was 0,05–0,1  $\mu\text{m}$ . The structure with a similar morphology but composed of the crystals of the  $\gamma$ - and  $\alpha$ -phases was observed earlier in the Fe-28,1%Ni alloy loaded by the planar shock waves with the pressure of 39 GPa [9]; it was shown that extremely dispersed structure was resulted from two factors: compressive impulse with a high pressure and work hardening caused by high-speed deformation. Thus, at the shock wave loading the new phase crystals were formed immediately from a big number of centers but short-time loading process ( $5\cdot 10^{-6}$  s) did not allow crystals to grow bigger.

To discuss the structural changes observed in the ball samples it is necessary to evaluate temperature generated at the shock wave loading of brass (Cu-37%Zn). Let's use the results of the temperature calculations for brass at loading by planar shock waves described in [12] and shown in fig. 4.

Curve 1 shows the increase of the temperature of copper at the shock wave front depending on the pressure value [12]. Curves 2 describing isentropic process of unloading in copper are based on the calculations of temperatures at the shock wave front and in the completely unloaded state [12]. Line 3 illustrates the melting temperature of copper depending on the pressure up to 30 GPa; this dependence

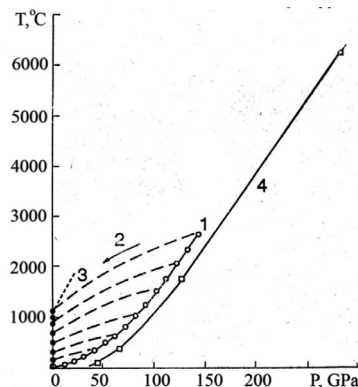


**Fig. 3.** Twins of one (a) and two (b) systems and the nanocrystals of the  $\beta$ -phase (c) in the ball d=60 mm after shock wave loading. Dark-field images in the: (a) — reflection  $220_\alpha$ , zone axis  $[110]_{\text{fcc}}$ ; (b) —  $111_\alpha$ , zone axis  $[110]_{\text{fcc}}$ ; (c) —  $112_\beta$ , zone axis  $[110]_{\text{bcc}}$ .

was obtained by extrapolation of the dependence given in [13]. One can see that the beginning of the melting process for copper can be expected after complete unloading from the pressure 140–150 GPa. Using these results for the studied brass, which has the melting temperature  $170^\circ\text{C}$  lower than the copper's one, the beginning of melting process in the brass sample might be expected after unloading from the pressure 130–140 GPa. In case of a lower pressure the residual temperature is not high enough for melting but can cause the  $\alpha\rightarrow\beta$  phase transformations (figs. 2c, 3c). The results of calculations of temperature at the shock wave front depending on the pressure in the studied brass are presented by curve 4. One can see that curves 1 and 4 are similar but the temperature in brass is lower than in copper at the same pressure. The results of structural study together with evaluation of the pressure distribution at quasi-spherical impulse loading of the ball samples of brass show that melting starts at the pressure  $P\geq 180$  GPa, which is 40–50 GPa higher than the calculated values. The phase  $\alpha\rightarrow\beta$  transformation occurs at the pressure  $P\geq 150$  GPa, which is also higher than 130 GPa. Quantitative discrepancy can be caused by two factors. Firstly, taking into account very short-time impact of the pressure and temperature ( $5\cdot 10^{-6}$  s) the overheating and therefore a higher pressure is required to cause melting and the  $\alpha\rightarrow\beta$  phase transformation. Secondly, to obtain the same temperatures the pressure in brass should be higher than in copper (curves 4 and 1, fig. 4).

#### 4. Conclusions

The relation between the parameters of quasi-spherical shock waves loading (pressure 40–300 GPa, high-speed deformation —  $10^6$ – $10^7$  s $^{-1}$ , tensile stresses at unloading 0.25–1.75 GPa and temperature 100–2500 $^\circ\text{C}$ ) and microstructural changes in the brass ball samples has been established. It was shown that the structure changed due to deformation localization, polymorphous  $\beta\rightarrow\alpha\rightarrow\beta$  transformations, melting and crystallization. The effects of shock waves interaction and their influence on deformation and destruction localization have been studied. It was shown



**Fig. 4.** The results of calculation of temperatures ( $T$ ) that are achieved at shock wave loading of copper and brass: 1 — temperature at the shock front, 2 — schematic representation of unloading process in copper [12]; 3 — dependence of the melting point of copper on  $P$  [13]; 4 —  $T$  at the shock wave front in the brass L63 (our data).

that the radial cracks in the balls were initiated at the distance equal to half radius, i.e. when the value of tensile stresses at unloading began to exceed dynamic ultimate strength of the material. The strength of brass in the conditions of volumetric tension was evaluated. It was shown that the value of tensile stresses is equal to 1.3 GPa, i.e. close to dynamic spall strength of brass and in 5 times higher than its static ultimate strength.

*Acknowledgements. The work has been carried out within the framework of the state assignment on the subject "Structure" (No 01201463331).*

## References

1. E.I. Zababakhin, I.E. Zababakhin. Phenomena of unlimited cumulation. Moscow, Science. (1988) 172 p. (in Russian) [Е.И., Забабахин, И.Е. Забабахин. Явления неограниченной кумуляции. М. Наука. 1988. 172 с.]
2. V.I. Buzanov, N.P. Purygin. Proceeding of X Conf. on Combustion and Explosion. Chernogolovka, (1992). 131-132 p. (in Russian) [В.И. Бузанов, Н.П. Пурыгин. Труды X конф. по горению и взрыву. Черноголовка, (1992). 131-132 с.]
3. B.V. Litvinov, V.I. Zel'dovich, O.S. Rinkevich, N.P. Purygin, V.I. Buzanov. J. de Physique IV. **4** (C 8), 399-402 (1994).
4. A.E. Kheifets, V.I. Zel'dovich, B.V. Litvinov, N.P. Purygin, N.Yu. Frolova, I.V. Khomsakaya, O.S. Rinkevich. Physics of Metals and Metallography. **90**, (Supp 1), 108-132 (2000).
5. V.I. Zel'dovich, I.V. Khomsakaya, N.Yu. Frolova, A.E. Kheifets, B.V. Litvinov, N.P. Purygin. AIP Conference Proceedings. New York: Melville. **849**, 62-67 (2006).
6. I.V. Khomsakaya, A.E. Kheifets, V.I. Zel'dovich, B.V. Litvinov, N.P. Purygin. Physics of Metals and Metallography. **106**, 302-310 (2008)
7. G.I. Kanel', V.E. Fortov, S.V. Razorenov. Physics-Uspekhi. **177**, 809-830 (2007).
8. Shock waves and high-strain-rate phenomena in metals. Ed. by M.A. Meyers, L.E. Murr. NY-L. Plenum press (1981) 512 p.
9. V.I. Zel'dovich, I.V. Khomsakaya, A.A. Deribas, A.N. Kiselev Physics of Metals and Metallography. **60**, 101-108 (1985).
10. R.F. Trunin, L.F. Gudarenko, M.V., Zhernokletov, G.V. Si-makov. Proceeding of VI International Conf. "VI Khariton's Topical Scientific Readings". Sarov. (2001) P. 81-85.
11. G.I. Kanel', S.V. Razorenov, A.V. Utkin, V.E. Fortov. Shock wave effects in condensed media. Moscow. Yanus-K, (1996) 408 p (in Russian) [Г.И. Каннель, С.В. Разоренов, А.В. Уткин, В.Е. Фортов. Ударно-волновые явления в конденсированных средах. М. Янус-К. 1996. 408 с]
12. R.G. McQueen, S.P. Marsh. Appl. Phys. **36**, 1253-1269 (1965).
13. E.Yu. Tonkov. Phase transformations in compounds under high pressure, Moscow. Metallurgy. (1988), **1**, 464 p (in Russian) [Е.Ю. Тонков. Фазовые превращения соединений при высоком давлении. М.: Металлургия. 1988. Т.1. 464 с.]