Spall destruction of coarse-grained and ultrafine-grained titanium on exposure to nanosecond heavy-current electron beam

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Abstract. This paper presents results of experimental and theoretical research of spall destruction of volume coarse-grained and ultrafine-grained titanium when using it as a generator of shock wave of nanosecond relativistic heavy-current electron beam. Computer modeling of effect of an intensive electron beam on the condensed target has been carried out taking into account destruction, phase transitions, dependence of strength characteristics of materials on internal energy. This is considered within elastic, ideally plastic Prandtl-Reiss model. The results of calculations are compared with experimental data.

1. Introduction

Nonconventional sources of thermo-mechanical impact on solid bodies: electron and ionic beams, lasers, x-ray radiations are promising in high pressure physics for research of deformation behavior of materials and constructions at intensive pulse loads [1] and to investigate the spall fracture of metallic materials along with high-speed collision of plates using shock waves generated by the impact of high-current ion and electron beams [2,3]. Experimental and theoretical research of deformation behavior and destruction at shock-wave loading of only small amount of ultrafine-grained metals and alloys have been so far conducted. It turned out that when ultrafine-grained structure is formed, spall strength of some metals and alloys increases, and that of others, on the contrary, decreases. However, the mechanisms of plastic deformation responsible for such different change of spall strength under transition from coarse-grained to ultrafine-grained structure have not been explored yet. This requires additional studies on shock-wave dynamics, deformation behavior, evolution of dislocation substructure and the mechanism of spall fracture of both grain structures.

In the present work, a similar research has been done for ultrafine-grained and coarse-grained VT1-0 titanium. As a generator of shock wave, the SINUS - 7 accelerator was used radiating a nanosecond relativistic heavy-current electron beam: electron energy 1.35 MeV, pulse duration 45 ns, power density $3.4 \times 10^{10}$ W/cm$^2$ [4]. The feature of this beam is volume nature of energy release that makes it possible to study spall fracture of massive targets. Targets were ultrafine-grained (the average grain size $d < 1 \mu$m) and coarse-grained ($d > 10 \mu$m) disks of diameter ~ 20 mm and thickness from 1.67 to 4.05 mm.

Calculations have been carried out within the mathematical model of continuum mechanics [5].
2. Experimental data
Fast heating of the target has volume character and leads to formation of high pressure zone, and the compression wave starts propagating deep into targets. It gradually fades because of interaction with unloading waves from free front surface of the target. After shock wave comes to free back surface of a solid, there is a reflected centered depression wave. At the same time the back surface gets speed. Spall fracture is a consequence of interaction of counter unloading waves (if the tension stress amplitude exceeds dynamic strength). Material destruction causes tension stress value to drop to zero, there arises compression wave (spalling pulse), propagating on the stretched substance from destruction plane to free back surface of solid. By the time the spalling pulse came to surface, the falling depression wave had reduced its speed. Surface speed increases again in the front of the spalling pulse, and in the course of subsequent repeated reflections it undergoes damped oscillations.

It was experimentally established that at the specified parameters of electron beam, when irradiating ultrafine-grained and coarse-grained titanium targets of thickness ranged from 1 to 6 mm, the crater was formed on the face of targets which was the consequence of material ablation. Table 1 gives dependence of thickness of the spalled layer on thickness of the irradiated sample of the ultrafine-grained and coarse-grained VT1-0 titanium. At the same thickness of a sample, the thickness of the spalled layer is approximately identical to coarse-grained and ultrafine-grained structures.

| Sample thickness (mm) | Experimental spall thickness (mm) | Calculated spall thickness (mm) |
|-----------------------|-----------------------------------|-------------------------------|
| Coarse-grained state  | 2.08                              | 0.24                          |
|                       | 3.04                              | 0.32                          |
|                       | 4.05                              | 0.37                          |
|                       | 2.62                              | 0.26                          |
|                       | 3.28                              | 0.32                          |
|                       | 3.89                              | 0.38                          |
| Ultrafine-grained state | 1.67                              | 0.23                          |
|                       | 2.30                              | 0.31                          |
|                       | 3.40                              | 0.35                          |
|                       | 1.99                              | 0.25                          |
|                       | 2.91                              | 0.29                          |
|                       | 3.33                              | 0.33                          |

Researches of fracture surfaces of coarse-grained and ultrafine-grained titanium plates using the scanning electronic microscope are shown in Figures 1 and 2.

On the surface of spallation fracture of coarse-grained 2.08 mm thick titanium plate (Figure 1 a) there are practically no cracks normal to fracture surface.

A great number of material chipping areas are observed as result of crack extension at small angles to fracture surface. The basic elements of the relief are dimples of ductile cleavage whose average size (~ 8 µm) is approximately three times more than the size of the same cleavage dimples in ultrafine-grained titanium plate of the same thickness. On cleavage crests in many fracture fragments (the average size ~ 13 µm) there are cleavage steps that indicates the presence of a brittle component in the overall picture of spallation fracture.

On the surface of spallation fracture of ultrafine-grained 1.67 mm thick titanium plate (Figure 2 a) the general relief of fracture surface is rather uniform, with large-scale fracture fragments from 25 to 100 µm in size. The fragments are located on different levels relative to surface and formed at origin, concentric growth and coalescence of cracks. There is a number of short cracks, which are almost normal to fracture surface, and material exfoliation. The surface of large-scale fragments consists of cleavage dimples of various depth, with average size of dimples ~ 2.5 µm. A part of them is almost flat that prove a small plastic cleavage deformation in the area. Along with cleavage dimples there are larger fragments with cleavage steps on the surface. It indicates the presence of a brittle component when forming such fraction fragments. On the surface of some flat cleavage dimples there are very small (up to 0.5 µm and less) deep dimples or pores.
Figure 1. The surface of spallation fracture of coarse-grained VT1-0 titanium formed on exposure to nanosecond relativistic heavy-current electron beam on the plate of thickness: $a - 2.08$ mm; $b - 3.04$ mm.

Figure 2. The surface of spallation fracture of ultrafine-grained VT1-0 titanium formed on exposure to nanosecond relativistic heavy-current electron beam on the plate of thickness: $a - 1.67$ mm; $b - 2.3$ mm; $c - 3.4$ mm.

A characteristic difference in spallation fracture of the coarse-grained and ultrafine-grained titanium is different size of cleavage cells. Dimple diameter of ultrafine-grained titanium is less than that of the coarse-grained one but their quantity is more.

3. Mathematical modeling

The results of mathematical modeling of irradiation of VT1-0 titanium samples at electron energy $1.35$ MeV, pulse duration $45$ ns, and power density $3.4 \cdot 10^{10}$ W/cm$^2$ are given in Figures 3 - 5. Parameters of the mathematical model [1] titanium VT1-0 are given in Table 2, where $\mu_m$ - the shear modulus; $\sigma_{ym}$ - yield strength; $\rho_0$ - initial density; $c_0$ - the speed of sound; $\gamma_0$ - thermodynamic Gruneisen coefficient; $R_u$ - the universal gas constant, $A$ - atomic weight; $T_{m0}$ - the melting point of the initial isochor; $T_0 = 293$ °K; $\alpha_0$ - initial porosity; $\alpha_{00}$ - residual porosity; $\alpha_s$ - critical porosity; $\psi_1 \psi_1 \psi_3 \psi_4 a_i$ - constants of the material.
Table 2. Constants titanium VT1-0, included in the mathematical model.

| $\mu_m$, GPa | $\sigma_{sm}$, GPa | $\rho_0$, g/sm$^3$ | $c_0$, m/s | $\psi_1$ | $\psi_2$ | $\psi_3$ | $\psi_4$ | $\gamma_0$ |
|--------------|-----------------|-----------------|----------|--------|--------|--------|--------|--------|
| 48,0         | 0,6             | 4,51            | 5110     | 3,465  | 1,44   | 0,479  | 3,52   | 1,33   |

$3R_\mu T_0/A$, KJ/kg $T_{m0}$, °K $\alpha_0$ $\alpha_{00}$ $\alpha_*$ $a_s$, GPa

| 153,0        | 2651            | 1,0001          | 1,0001   | 1,43   | 0,42   |

$\mathbf{t = 0,12 \, \mu s, U_{max} = 4730 \, m/s}$

$\mathbf{t = 0,42 \, \mu s, U_{max} = 7179 \, m/s}$

**Figure 3.** Flow field on irradiation of ultrafine-grained 1,67 mm thick titanium.

The presented calculations involve the following: energy-absorbing zone radius – 3 mm, linear coefficient of absorption - 46 cm$^{-1}$, $U_{max}$ – modulus of the longest vector. In the right half-plane of figures the pressure field (GPa) is shown. A zone of projecting particles of the melted and evaporated material is formed near the high bound of the target. At the projection of substance the recoil momentum propagates in the solid part of the material. Its interaction with the free back bound of the sample leads to formation of a zone of spall back fractures.
The stress profile $\sigma_{11}$ from time $t$ is given for the sample section which is originally remote from the front surface at the distance of 0.0125 cm. In this section the maximum stress ($\sigma_{11} \approx 35$ GPa) is realized. The stress distributions $\sigma_{11}$ (GPa) and relative void volume $\xi$ (%) along the sample axis characterize the occurrence of spall fracture. Tension stresses emerge in the spall zone. The porosity grows at the front surface of the target in the projection zone of liquid particles and in place of spall formation.

**Figure 4.** Dependence of stress $-\sigma_{11}$ on time, stress distribution $-\sigma_{11}$ and relative void volume $\xi$ along the sample axis of ultrafine-grained VT1-0 titanium at 0.42 $\mu$s.
Figure 5. Dependence of stress $-\sigma_{11}$ on time, stress distribution $-\sigma_{11}$ and relative void volume $\xi$ along the sample axis of coarse-grained 3.04 mm thick titanium at 0.7 $\mu$s.

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