Shock-wave and spalling phenomena in ultrafine-grained and coarse-grained (α + β) alloy Ti-Al-V treated by a nanosecond relativistic high-current electron beam

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Shock-Wave and Spalling Phenomena in Ultrafine-Grained and Coarse-Grained (α + β) alloy Ti-Al-V Treated by a Nanosecond Relativistic High-Current Electron Beam

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Abstract. The results of experimental and theoretical research of shock-wave and spalling phenomena in ultrafine-grained and coarse-grained (α + β) alloy Ti–6.2% Al–4.0% V (wt %) treated by a nanosecond relativistic high-current electron beam are presented. Data on the dynamics of mass velocity, temperature and shock waves as well as on the interaction of the unloading wave with the rarefaction wave reflected from the back surface have been obtained for an axisymmetric position of the target. It is shown that the strain rate increase from 10^{-3} to 10^{5} s^{-1} in the both grain structures does not change the fracture mechanism and the phase composition in the zone of spalling. The obtained theoretical dependence of the spalling layer thickness to the target thickness corresponds to experimental data.

INTRODUCTION

Multicomponent (α + β)-titanium alloys have wide application in engineering. The problem of increasing their strength under quasi-static loading is solved by the formation of ultrafine-grained structure produced under severe plastic deformation [1, 2]. However, the development of scientific bases and practical ways of increasing the spalling strength in transition from coarse-grained to ultrafine-grained structure under dynamic loading remains an acute problem. According to existing models, the process of spall fracture of metallic materials is considered as the nucleation, growth and merging of micropores and microcracks, which leads to the formation of larger cracks [3–6]. The places of origin of micropores generally correspond to the position of various defects, such as grain boundaries and twins, dislocation clusters, and second phase particles. In this regard, there is a reason to assume that the small grain size and the defect structure of grain boundaries in ultrafine-grained alloys can influence the development of deformation processes and grain-subgrain structural changes before fracture under shock wave loading. A promising tool for the investigation of shock-wave processes and spalling phenomena in the nanosecond range is powerful (10^{10}–10^{11} W/cm^2) nanosecond relativistic high-current electron beams. The penetration depth of relativistic electrons to the metal target is much larger in comparison with laser radiation. It allows one to investigate high-speed deformation and spalling phenomena in massive targets made of different single-phase and heterophase alloys.

This work studies experimentally and theoretically shock-wave and spalling phenomena in ultrafine-grained and coarse-grained (α + β) alloy Ti–6.2% Al–4.0% V (wt %) under the influence of a nanosecond relativistic high-

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current electron beam at an accelerator "SINUS-7" (electron energy 14 MeV, pulse duration 50 ns, power density 2.3×10^{10} W/cm^2).

RESULTS AND DISCUSSION

The targets for irradiation were disks of thickness from 1 to 5 mm with coarse-grained and ultrafine-grained isotropic structures. The coarse-grained structure had an average grain size of about 600 μm and a lamellar shape of α- and β-phase grains. The ultrafine-grained structure had an average size of about 0.7 μm and a globular shape of β-phase grains. In the both structures, the volume fractions of β-phase were identical and equal to 9%. The coarse-grained structure was formed by hot plastic deformation of ingots in the β-phase condition. All grains had two-phase structure and consisted of alternating lamellas of α-phase with a width of 5–10 μm and thin lamellas of β-phase with a width of less than 0.5 μm after cooling.

The ultrafine-grained structure was formed during warm abc-pressing of alloy from the above-mentioned coarse-grained structure. The shape of grains in the both structures was approximately equiaxed, with no crystallographic texture.

As a result of transformation of coarse-grained structure to ultrafine-grained one, the tensile strength to fracture at a speed of 10^{-3} s^{-1} increased from 880 to 1700 MPa, while the relative elongation to failure virtually remained unchanged. However, the fracture mechanism changed from ductile-brittle to ductile with shallow fracture pits.

The irradiation of targets with the both grain structures was performed under the same parameters of the electron beam at an electron accelerator "SINUS-7", which was mentioned in the introduction. The targets for irradiation were shaped as disks of thickness 1, 2, 3, 4 and 5 mm. After one electron beam pulse of duration 50 ns a pit of depth about 0.9 mm formed on the irradiated (front) surface of the target. In the case of the target thickness 2 and 3 mm, spall fracture formed near the rear surface (Fig. 1).

The thickness of the spalling layer in the ultra-fine grained structure increased from 0.25 to 0.42 mm, and the degree of plastic deformation decreased with the target thickness growth from 2 to 3 mm. In the case of 4-mm and 5-mm thick targets, no cracks formed near the rear surface and no spall fracture occurred. The surface of spall cracks had an undulating shape, with alternating ridges and troughs.

The examination of spall fracture surfaces of the targets by optical and scanning electron microscopy revealed that the formation and subsequent fusion of pores in the ultrafine-grained and coarse-grained structures preceded spall fracture. Then, microcracks appeared between the pores and coalesced in a macrocrack. As a result, the surface of spall cracks had an undulating shape with mesoscale fragments of destruction in the form of crests and hollows. In the both grain structures the fracture mechanism at the microscale level did not change with the strain rate growth from 10^{-3} to 10^5 s^{-1} (Fig. 2).

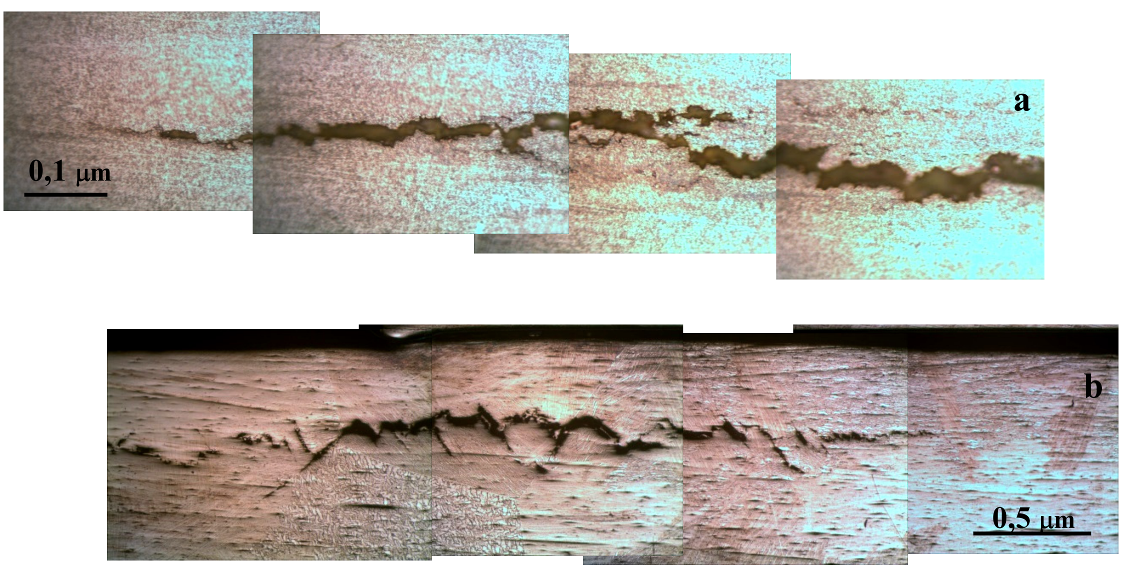
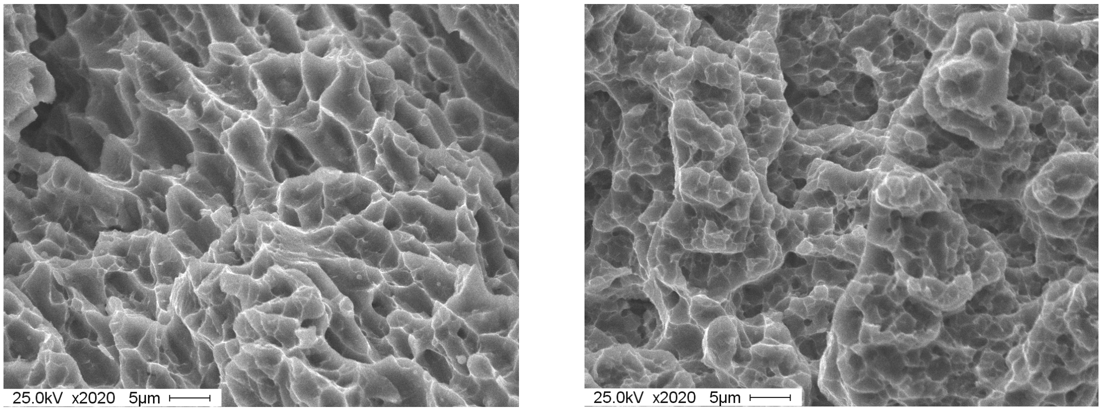


FIGURE 1. Spall cracks in the target of thickness 3 mm in ultrafine-grained (a) and coarse-grained (b) alloy Ti-Al-V



(a) (b)

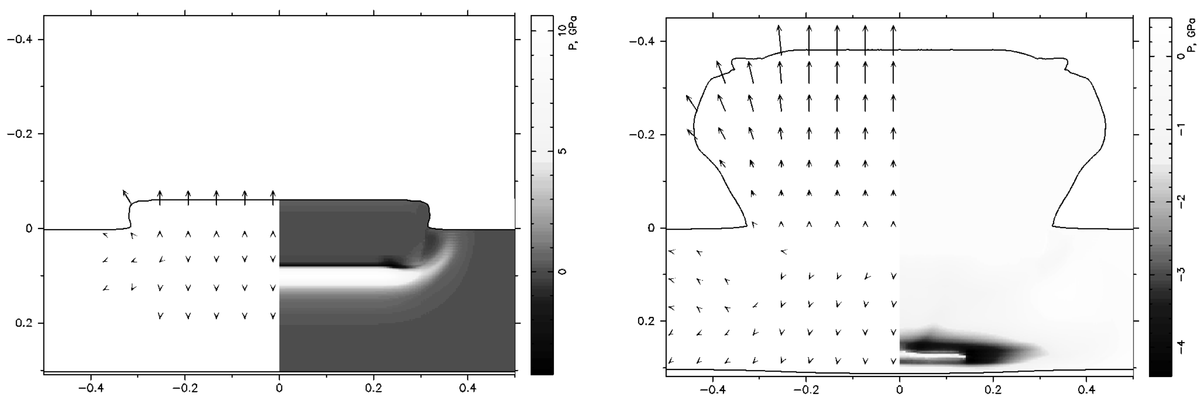
FIGURE 2. Spall fracture surfaces in coarse-grained (a) and ultrafine-grained (b) alloy Ti-Al-V

At the coarse-grained alloy structure the fracture mechanism remained ductile-brittle but the depth of ductile fracture pits increased, which pointed to an increase in the degree of plastic deformation in the zones of ductile fracture. As for the ultrafine-grained structure, the fracture mechanism changed to ductile with a small depth of fracture pits of sizes exceeding the size of grain-subgrain structure elements. These data and the presence of pores before spall cracking allow us to conclude that the formation and coalescence of pores precedes the beginning of microcrack initiation and propagation. The presence of mesoscale crests and troughs on the surface resulted from microcrack nucleation ahead of growing macrocracks.

The impact of a nanosecond relativistic high-current electron beam on the targets of coarse-grained and ultrafine-grained alloy Ti-Al-V was simulated theoretically for an axisymmetric position in the framework of a physical-mathematical model [7]. The dynamics of mass velocity, temperature, pressure and shock waves was calculated using the same parameter values of the electron beam as in the experimental investigation of spall fracture.

As an example, Figure 3 demonstrates (in the plane of symmetry of a cylindrical coordinate system) the calculation results of the field vectors of mass rate U with respect to its value in the center of the radiation spot U_{max} (a) and pressure field (b) at different time points from the beginning of irradiation .

According to the theoretical calculations, the impact of the electron beam results in melting, vaporization and spraying of material on the front surface of the target, as well as in spall fracture near the back surface. The spraying of substance occurs with acceleration. As this takes place, a high-pressure zone with a maximum value of ~23.5 GPa is formed and then a shock wave with an amplitude of ~19 GPa is generated. The shock wave arrival to the rear surface of the target causes an increase in the surface velocity, and the shock wave reflection from the surface leads to the appearance of a rarefaction wave.



(a) (b)

FIGURE 3. Flow field in irradiation of the target with a thickness of 3 mm in ultrafine-grained alloy after 300 ns (a) and 752 ns (b) after the start of irradiation

Subsequent to the shock wave, an incident unloading wave arrives at the surface which causes a decrease in the surface velocity. The destruction of the target near the rear surface is a consequence of interaction of the opposing rarefaction and unloading waves. In this case, the larger is the target thickness, the higher is the mass velocity before fracture. It reaches 5×10^3 and 6×10^3 m/s for targets of thickness 3 and 2 mm, respectively. The value of the spall pulse is 1.8 GPa, and temperature in the spalling zone does not exceed 450 K.

The estimated spalling layer thickness in the ultrafine-grained structure increased from 0.30 to 0.42 mm with the target thickness growth from 2 to 3 mm. This corresponds to experimental data and confirms the accuracy of the spall fracture model under the pulsed action of a nanosecond relativistic high-current electron beam on heterophase ($\alpha + \beta$) titanium alloys with ultrafine-grained structure.

CONCLUSION

The reported results of experimental and theoretical investigations show the same spall fracture patterns for ($\alpha + \beta$) titanium alloy Ti-Al-V with ultrafine-grained and coarse-grained structure under the influence of a nanosecond pulsed electron beam. In the both structures, the strain rate growth from 10^{-3} to 10^5 s^{-1} does not change the fracture mechanism and the phase composition in the fracture zone. The used model of spall fracture of ultrafine-grained ($\alpha + \beta$) alloy Ti-Al-V under the influence of the electron beam corresponds to the experimental data.

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