Journal of Applied Mechanics and Technical Physics, Vol. 37, No. 3, 1996

HIERARCHY OF STRUCTURES FORMED IN DYNAMIC LOADING OF COMPOSITE MATERIAL

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UDC 669.018.75

The behavior of homogeneous materials under high-velocity loading is a complicated process that depends on the properties of the constituents, the inner structure of the material, loading conditions, etc. Kul'kov et al. have studied [1] the shock loading of a composite material of the hard-alloy type in which the matrix could be either in a stable or in a metastable state. In the stable austenite state, the material fails without visible change in the structure of samples. If the matrix is in a metastable state, dynamic action with equal collision velocities does not lead to discontinuity of the material. In this case the material structure shows some peculiarities that are not characteristic of the stable state of the matrix: an increase in dislocation and deformation-twin density is accompanied by a martensite rearrangement of the matrix lattice and by the formation of a particular structure of mesocracks [1], which are arranged in an ordered fashion in the sample's volume.

However, these fragmentary data on structural changes have not given a comprehensive idea of the behavior of materials under high-velocity loading. A more detailed analysis of structure evolution is required at various scale levels. The present work is a continuation of [1, 2] and is aimed at studying the evolution of the structure and phase composition of the material at different scale levels: a) the macrolevel, i.e., the sample as a whole or a part of it (1–10 mm); b) the mesolevel, the level of a grain (1–20 μm); c) the microlevel, a slip band, second-phase particles (10^{-7}–10^{-8} m) (in accordance with the classification of [3]), and their interaction.

A hard alloy of tungsten carbide and high-manganese steel (30% by weight) was studied. The matrix was in the metastable austenite state formed by saltpeter hardening above 1370 K. The average size of the starting tungsten carbide grain, as determined by the secant method [4], was 2.5 μm.

Samples were taken in the form of disks 60 mm in diameter and 4.5 mm in thickness. Shock loading was performed by a cylindrical steel element striking a plate of the studied alloy at a velocity of about 1200 m/sec.

The macro- and microstructures of the loaded samples were studied with a NEOFOT-21 optical microscope. The changes in the phase composition of the material were recorded by the x-ray diffraction method on a DRON-UM1 setup with filtered copper radiation.

The study of the loaded samples showed significant structure changes at the different scale levels. Let us discuss these sequentially.

Macrolevel. The macropicture of fracture demonstrates that the disks are broken into large fragments due to propagation of radial cracks from the striker–target contact and is similar to that of WC–Co alloy fracture observed in [5]. On some of the fragments in the immediate vicinity of the puncture hole, one can see sickle-shaped cracks. On the rear side of the plate, a split with a diameter twice as large as that of the puncture hole is formed. The central part of the striker–target contact consists of small fragments of different shapes.

Macrostructural investigations of the cross-sections of composite samples after shock loading showed that on the rear side of the target there is a characteristic material zone with a size equal to half the sample

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Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 37, No. 3, pp. 109–114, May–June, 1996. Original article submitted March 29, 1995.

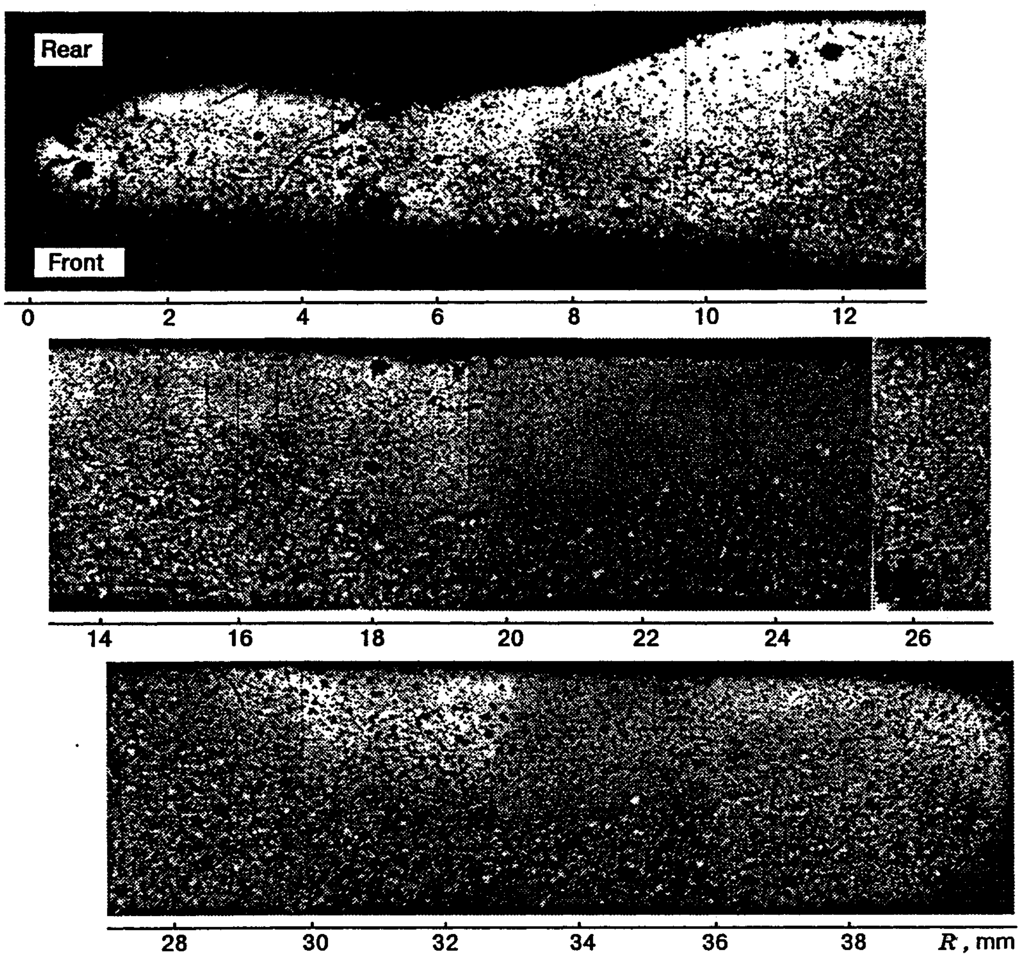

Fig. 1

thickness whose structure differs from the main structure (Fig. 1). This zone can be represented as overlapping cup-shaped regions in which the extent of overlapping decreases with distance from the split cone up to complete separation of the regions. The width of the regions on the rear surface equals the difference between the crater and the puncture hole radii. Inside the cup-shaped zones one can see macrocracks propagating from the rear surface through the entire zone thickness with numerous branchings.

Analysis of the interface between the rear zone and the main material shows that there are a great number of mesocracks, most of which are formed into tracks similar to those of [1]; in a narrow region of the sample the tracks are parallel to one another and perpendicular to the shock-wave propagation direction, and in the material volume that is immediately adjacent to the contact site they are parallel to the crater (Fig. 2). The distances between the cracks in the track obey the rule described in [1].

The microrigidity in this region of the material varies from 7 GPa (which corresponds to the initial state of the sample) to 10 GPa with a typical oscillation period equal to the size of cup-shaped zones. As the distance between these zones and the shock center grows, the absolute value of the oscillations in them decreases with preservation of their period (Fig. 3).

Mesolevel. Microstructural investigations of the interface between the cup-shaped zones and the main material revealed a sudden transition from the composite matrix structure, which consists of separate well-faceted tungsten carbide grains located in the binding phase, to large rounded carbide conglomerates (Figs. 4a and 4b); the binding phase also changes its morphology. Inside these conglomerates, regions of a new white (unpickled) phase exist, which are mostly elongated and lens-shaped. Columnar formations of coalesced

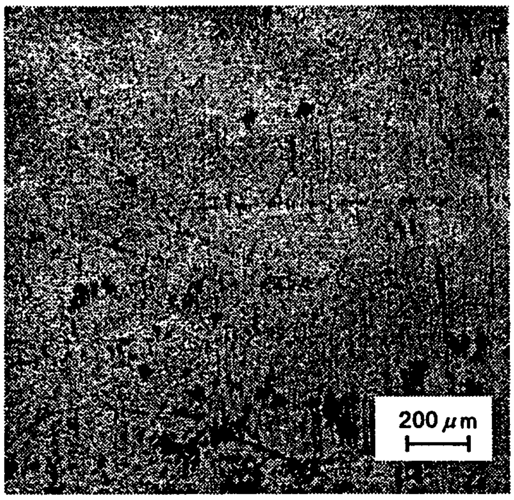

Fig. 2

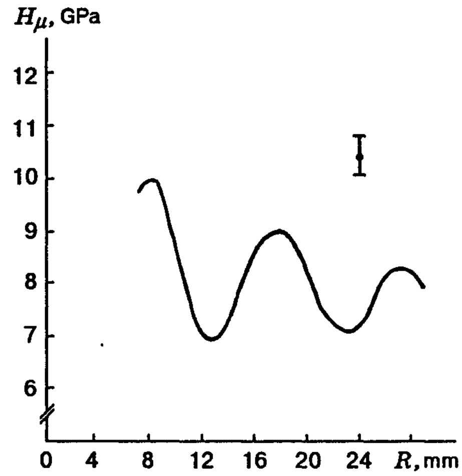

Fig. 3

tungsten carbide grains often occur at the interface between the zone and the main material (Fig. 4c).

In the material volume that is immediately adjacent to the split surface on the sample's rear side (Fig. 4d), one can see columnar carbide formations of various orientations with lengths of 300–400 μm.

Analysis of the carbide grain sizes showed that on the striker–target contact surface the average carbide grain size is different from the initial one and is 2.5 μm. In the cup-shaped zones on the target's rear side, the grain size increased almost twofold and is 4.5 μm.

The radical structure change in the material in the cup-shaped zones at the mesolevel could be due not only to energy localization and to the combined motion velocity of these mesovolumes of the material, but also to a considerable local temperature rise in these regions.

Microlevel. Dynamic loading of the samples causes the FCC → BCC and FCC → HCP transitions in the binding phase. In the material volume that is immediately adjacent to the shock site, 70% of the austenite undergoes transition to martensite. On the rear side of the target only 30% of the γ-phase was subjected to transition. X-ray diffraction analysis from the end section surface adjacent to the crater also shows an HCP lattice of about 10% ε-martensite. The hardening phase in the material volume corresponds to the HCP lattice of tungsten carbide. However, x-ray diffraction analysis of the fracture surface shows a cubic phase which is close in structure to a carbide of the $Me_{12}C$ type and has lattice parameters that are somewhat different from the literature data. This could be due to the nonequilibrium formation of the carbide under conditions of rapid loading with a simultaneous local temperature rise.

Indeed, stepped annealing of the loaded samples reduces the intensity of diffraction maxima assigned to the given cubic phase, and, after annealing for 1 h at a temperature of 720 K, these maxima completely disappear. The intensity of diffraction maxima assigned to the HCP–WC transition increases sharply. The appearance of the nonequilibrium cubic phase of tungsten carbide indicates that upon shock loading of the composite there is a significant local rise in temperature, which reaches 1270 K according to [6].

In shock loading, plastic deformation is known [7] to concentrate in narrow shear zones. In addition to energy localization, theoretical calculations and velocity measurements of the free surface of a steel target in [8, 9] showed that the configuration of the plastic wave front at different scale levels is nonuniform. In a composite material, the nonuniformity of the shock wave front at the meso- and microlevels can be even more significant, since the hardening agent and the matrix differ greatly in their physicotechnical properties; at the macrolevel this characteristic can be more uniform. The joint action of temperature, nonuniform velocity of motion of mesovolumes, and high pressures bring about a drastic structural change in the material at the micro- and mesolevels.

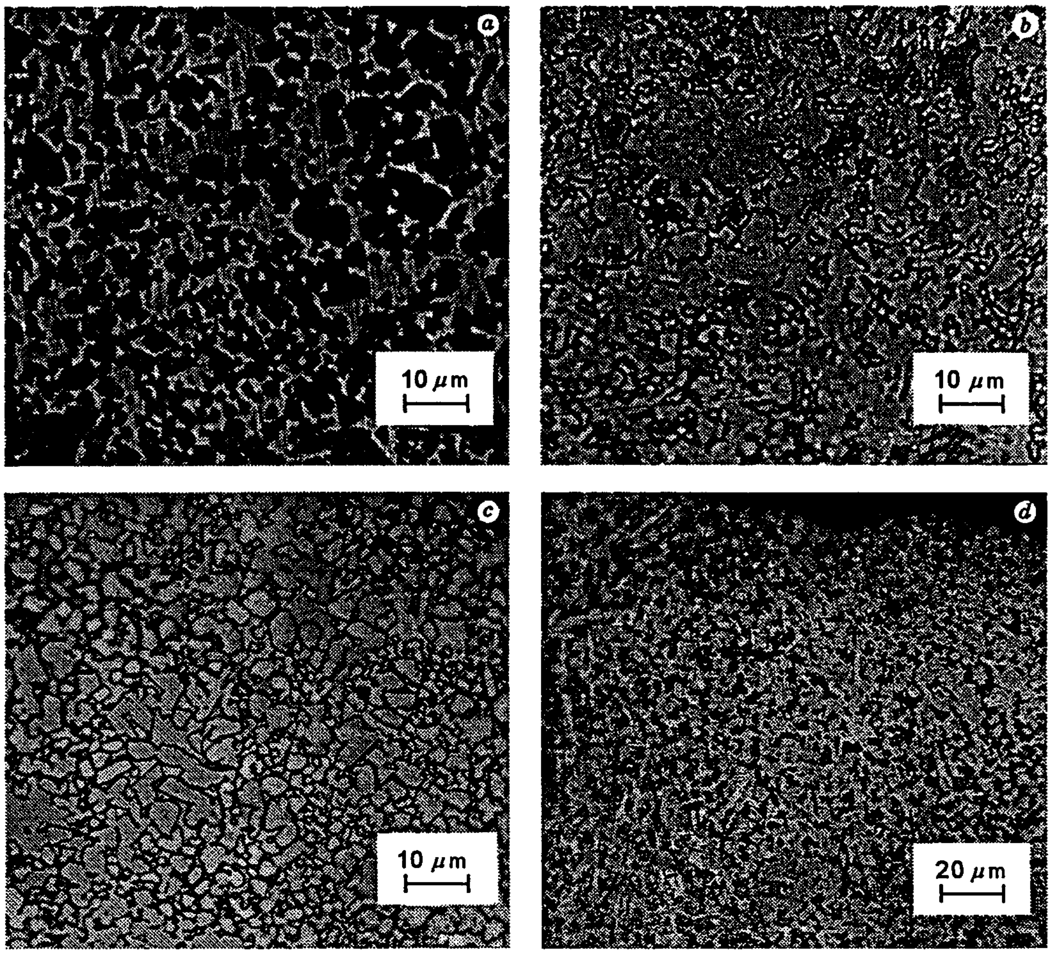

Fig. 4

These circumstances are responsible not only for crater formation, but also for structural changes in the material of the presplit region of the sample. In particular, the cup-shaped zones appear to be the initial stage in crater formation. However, the formation of tracks consisting of mesocracks that are perpendicular to the propagation direction of the split cracks reduces the level of stresses in these regions, contributing thereby to the conservation of material continuity. The same factors appear to be responsible for the formation of adiabatic shear strips [7] located inside the coalescent carbide conglomerates as unpickled white regions. These effects bring about a decrease in the scale of the structural level of fracture from single macrocracks to multiple mesocracks.

Thus, the study has shown that the formation of a nonequilibrium multiphase structure in the matrix and strengthening agent at the macrolevel and the periodic location of zones with different microstructures at the mesolevel are due to the nonuniform pressure distribution, nonuniform plastic deformation, different shear velocities of mesovolumes of the material, and considerable local heating of the material. The above causes, in turn, are dependent on the shock loading parameters (shock wave pressure and amplitude) and on the original structure of the composite (phase composition, austenite stability, carbide grain size, etc.).

In volumes of the material in which the main action is due to energy localization, the binding phase undergoes transformation to reduce the scale of the structural level of plastic deformation, and the mesocracks formed reduce the scale of the structural level of failure. The changes occurring in the micro- and mesostructures suggest multisite crater generation.

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