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STRAIN CORRELATION AT DIFFERENT STRUCTURAL LEVELS FOR DYNAMICALLY LOADED HOLLOW COPPER CYLINDERS

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Abstract - A quantitative correlation between continual values of strains and microstrains have been determined. The plastic flow instability in copper developed into the system of cracks, has been revealed. At high rate strain a succession of engagement of structural strain levels has been shown to be dependent on the size of grain in an initial structure and to be determined by the relation between the values of mean strain rate at a continual level and the rate of internal stress accommodation due to rotational modes.

Structure-strained states of metals under explosive loading are of great interest in the study of bond formation at explosive welding and compacting. In [1] it is demonstrated that to obtain high-strength bonding by the above methods, plastic deformation should be localized in a certain region on contact surfaces. However, the strain correlation at different structural levels at dynamic loading and shear localization conditions at a macrolevel are difficult to be determined experimentally. The approaches to the hierarchy of structural strain levels and succession of their engagement in the materials subject to loading are described in [2,3]. The results of microscopic strain measurements of specimens subjected to plane-wave shock loading are presented in [4].

The aim of this paper is to determine both (i) quantitative correlation between continual values of strain and its values at a microscopic level and (ii) the change of these relations dependent

on initial structure of the shock-loaded specimens. The attempt was made to analyze the high-rate plastic deformation mechanism in terms of the hierarchy of its structural levels established for a quasistatic strain. The experiments on explosive strain were performed with hollow thick-walled cylinders as proposed in [5]. The experimental arrangement is illustrated in Fig. 1. The authors selected this scheme for the following reasons:

Fig.1.

1. A cylindrical geometry allows calculation of material strain at a continual level on the basis of initial and final radii [6] provided a medium is incompressible, and determination of strain velocity field by means of the measurement of the internal surface velocity.

2. A thick-walled cylinder conserves, due to its inertia, a symmetry of a specimen as a whole. Significant distortions may be avoided due to an invariable asymmetry of the detonation process. Due to high thickness of walls, the axial detonation velocity considerably exceeds the value of particle velocity; thus, a motion directed to a centre may be considered as a dominating one.

3. Copper was chosen as a typical representative of materials demonstrating a "hydrodynamical" behaviour under explosive loading. It was also used as a model material to study the processes responsible for the bond formation under explosive welding [5] and compaction of powders [8]. Besides, the unexpected effect of shear strain localization was observed in copper upon collapsing of a cylinder, as a result of which a system of helical cracks was formed [5]. And, after all, this choice is due to the presence of annealing twins in copper which allow quantitative measurements of residual microstrains.

The microstrains ε_r , ε_φ of the material may be calculated from an initial position (r) of some its element and a final one, ρ [6]:

$$\varepsilon_\varphi = \frac{\rho}{r} - 1 = \frac{\rho}{(b_0^2 - b_1^2 + \rho^2)^{1/2}} - 1,$$

$$\varepsilon_r = \frac{r}{\rho} - 1 = \frac{(b_0^2 - b_1^2 + \rho^2)^{1/2}}{\rho} - 1.$$

Here b_0 , b_1 are the initial and final external radii of a cylinder. Just b_0 and b_1 were used in the calculations, because b_1 may be measured with a higher accuracy than an final radius a_1 . The estimated initial microstrain rate ε_r ($r = a_0$) is $2 \cdot 10^5 \text{ s}^{-1}$.

The cylinders with three types of initial structures were used in the studies: fine-grained ($d \approx 0.50 \text{ mcm}$), row-grained ($d \approx n \text{ mm}$) and row-grained layered structures. In the latter case, both the internal and external layers were dispersion-strengthened alloys, Cu - 1 vol. % Al_2O_3 , their initial thicknesses being $\approx 0.75 \text{ mm}$.

Its pronounced circular boundaries were revealed by etching. The present geometry made it possible to control a cylindrical symmetry of the process in the regions adjacent to the internal surface, where $\varepsilon_r \approx n \cdot 100 \%$ (Fig. 2).

Fig. 2, $\times 6$

Fig. 3.

After loading the cylinders under the same conditions, the strains ε_r and ε_ϕ were determined. The $\varepsilon_r(r)$ dependence is presented in Fig. 3. It should be noted that ε_r variations observed near the internal surface of the cylinder are qualitatively analogous to shear strain ε_c near the weld [7]. The microhardness H_V ($P = 50 \text{ g}$) was measured, and the structure was analyzed both just after the explosion and recrystallization annealing at optimal temperatures [1].

Mutual for all the specimens is the presence of developed localized plastic deformation bands (LPDB) similar to the zones of intense plastic flow on contacts under explosive welding and compacting. The strain in the localized flow zones was measured via twins a part of which occurred to be in the region of localized plastic strain. The value of ε_r was measured using the expression

$$\varepsilon_r = \frac{l - l_0}{l_0},$$

where l is the length of the section (e.g., twin width) in the zone of localized plastic shear band, and l_0 is the initial value. To estimate ε_r , the twin initially normal to the radius was chosen (Fig. 4).

Radius ρ corresponding to the middle of the twin (region A) was equal to 1.46 mm, $2b_1 = 25.5$ mm, $2b_0 = 27.5$ mm. The measured value of $\varepsilon_{r,\text{micro}} = 3.64$, and $\varepsilon_{r,\text{macro}} = 2.66$. It should be noted that the region B adjacent to A did not undergo radial strain. Thus, it may be concluded that there are available the adjacent regions whose microstrains differ by several times, and macrostrains corresponding to the same radius essentially differ from microstrains.

The localized flow zone in fine-grained cylinders is bounded by the radius $\rho \approx 3$ mm ($r \approx 5.5$ mm), the continuum value being $\varepsilon_r \sim 100$ %. At a distance of $\rho \sim 1$ mm ($\varepsilon_r \sim 500$ %, cracking is developed along the bands of localized plastic shear (Fig. 5).

In row-grained cylinders, the first bands of localized shears are at a distance $\rho \sim 6.8$ mm ($r \sim 8.5$ mm), the continuum value of ε_r being 26.5 %. As approaching to the centre, the number of localized shears increases and the concentration gradient reaches the maximum at $\rho \sim 3$ mm. This effect manifests itself most pronouncely in the breaking of the interface between the inner-oxidization layer and the surrounding material and in the appearance of structural formations in this layer if the boundary is at a distance of 3 mm from the centre (Fig. 6).

Fig. 4, $\times 200$

Fig. 5, $\times 20$.

Fig. 6, $\times 14$.

The effect of the strengthening phase, in which the size of particles varies over the range 200 to 350 Å and the distance between them is 800 to 1500 Å, on final strain structures of row-grained particles, has not been revealed. The radius $\rho \sim 3$ mm is characterized by an abrupt increase in the continuum strain ϵ_r (Fig. 3) and the development of localized plastic bands in fine-grained copper.

The variations in microhardness over the cross-sectional area of the deformed cylinder coincide with the flow structure (Fig. 7). In the centre of the cylinder, where $\epsilon_r \approx n \cdot 1000\%$, a strip-cast structure is observed, $H_v = 60-70$ units. At a certain distance from the centre, one may distinguish three regions. Region I extending to the distance $\rho \approx 2$ mm is characterized by a high frequency of local high values of microstructure. For Region II the mean values of H_v are lower, the frequency of maximum H_v is less and the distance from the outer boundary to the centre is, approximately, 6 mm. The strengthening degree of periphery Region III is the lowest one.

It has been found that the initial grain size in cylinders affects not only the development of localized bands of plastic flow but also their structure. In the cylinders with the 50 mcm grain size, the direction of these bands coincides with that of maximum shear stresses (Fig. 5). This demonstrates that (i) there is no relation between them and the system of crystallographic slipping and (ii) that plastic stability has been lost that corresponds to the transition of plastic flow to a macrolevel in the adopted hierarchy of structural strain levels. The direction of the localized bands immediately after the explosion in cylinders with row grains is difficult to be determined due to considerable distortion in initial structures. Besides, each band may be interpreted to be the so-called rotational plate with respect to a

grain. This is seen from the variations in slipping line directions in parts of the twin through which the localized plastic zone passes (Fig. 4). Besides, this is in agreement with the fact that shear strain accommodation in the band is due to rotational modes of strains in the grain volume surrounding it. Thus each of LPDB represents a structure fragment increasing the number of boundaries per unit square which mask the direction of localized plastic strains. Their geometry is evident in the structure obtained by recrystallization annealing at homologous temperature $T = 0.4$ (Fig. 8). As is seen from Fig. 8, in row-grained cylinders, like in fine-grained ones, the presence of the bands is not associated with crystallographic structure. Their direction coincides with that of maximum shear stress.

By the adopted classification of structural levels of strain, the continual value $\varepsilon_r = 30\%$ corresponding to the development of the LPDB in row-grained structure, represents the boundary between the plastic strain realized via the motion of individual dislocations and the next level associated with the motion of their assemblies resulting in fragmentation of grain internal structure [3].

Accommodation of structural nonconformities at the translation shears is realized via rotational modes leading to the re-orientation of fragmented structure. Under high-rate strain ($\dot{\varepsilon} \geq 10^5 \text{ s}^{-1}$) the loss of plastic stability and transition to the highest structural strain level, macrolevel at $\varepsilon_r = 30\%$, are indicative of the fact that the localization effect is amplified by the absence of uniform structural elements accommodating the translational shear due to the rotational modes. In fine-grained initial structure, propagation of the LPDB is observed in the region of high continual values of ε_r . In this case the elements accommodating the structural nonconformities due to translational shear are likely to be associated with small sizes of grains. The mechanism of accommodation processes in fine-grained specimens is responsible for the peculiarities of the structure of the plume-like strips (Fig.5) which are etching-resistant. They are similar to "white bands" which may appear in steel and other alloys under intensive plastic strain including explosive welding and strengthening.

It should be noted that there is the difference between the patterns of cracking of the specimens having different grain size. For fine-grained structure, the cracking is directly associated with the LPDB; in row-grained copper, the main cracks are connected with LPDB propagating to the region of low values of ε_r . Branchings of the main cracks pass along the grain boundaries or the LPDB corresponding to higher ε_r .

Fig. 7.

For row-grained materials, the development of localized strains at higher structural level at lower values of ε_r demonstrates that the material "refuses" to store the energy of plastic strain at lower structural levels under the given conditions of high-rate loading. This results in the decrease in specific heat release on contacting surfaces under explosive welding and compaction hampers the formation of the near-contact necessary-size region of intense plastic deformation. This may badly influence the conditions of bonding formation [1].

Fig. 8, $\times 11$.

Conclusions.

1. The method of studying the developed high-rate plastic strain

based on explosive compression of thick-walled hollow cylinders has been proposed. It allows the zones with a controlled value of average strain (ε_r , ε_p) to be obtained and thus the hierarchy of its structural levels and their dependence on an initial state of material to be studied. The instability of plastic flow in Cu developing into the system of cracks upon the cavity collapse has been first discovered.

2. The succession of engaging the hierarchy of structural strain levels is defined by the relation between the value of average strain rate at a continual level and the accommodation rate of internal stresses by rotational modes.

3. In fine-grained materials, the macrocrack formation follows the pattern of maximum shear stresses which are not associated with a crystalline structure. In row-grained copper, it has been established by the method of successive recrystallization that the patterns of maximum shear stresses coincide only for the bands of localized plastic strain, and there is a qualitative disagreement between the crack geometries in fine-grained structures.

4. A qualitative determination of the difference between the given continuum value of strain ε_r and its value at a microlevel gives the value $\sim n \cdot 100\%$.

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