INTERSCALE MOMENTUM EXCHANGE IN DYNAMICALLY DEFORMED HETEROGENEOUS MEDIUM

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Abstract. Two regimes of interaction of shock wave and microstructure in heterogeneous medium are studied: (i) equilibrium reversible interscale momentum exchange, (ii) non-equilibrium irreversible momentum exchange. The first regime corresponds to propagation of shock wave in a medium of pre-existing heterogeneity. During the second regime, a dynamic heterogeneity is dominant. Shock tests of D16 Al alloy within impact velocity range of 85÷450 m/s revealed a dependence of above regimes on the strain rate. Maximum dynamic strength is found to be realized at the impact velocity where macroscopic strain rate equals to the local strain rate corresponding to the mesoscale.

Key words: particle velocity variation, velocity defect, interscale momentum exchange, dynamic recrystallization, spall-strength.
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INTRODUCTION

Response of solid on shock is determined by interaction of shock front and structure of the solid. Physically, the shock front and structure appertain to different scale levels of deformation. The average particle velocity belongs to macroscale, whereas characteristics of the structure – to microscale. So, the problem of interaction of the shock front and structure is the problem of interaction between scales, which is realized through a momentum and energy exchange between scales. Transition from one scale to another supposes a change of regime of the interscale momentum and energy exchange. In turn, the regime of the interscale exchange may be reversible or irreversible depending on the strain rate. The reversible interscale momentum exchange flows in a medium of the initial heterogeneity, whereas the irreversible exchange supposes an avalanche-like increase of the heterogeneity caused by the non-linear properties of dynamically deformed medium.

1. THE INTERSCALE MOMENTUM EXCHANGE

According to Duvall's classification, there are three kinds of shock-wave decay in solids: (i) geometrical decay, (ii) hydrodynamic decay and (iii) "maxwell" decay [1]. Beside the

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enumerated kinds of the shock-wave decay which are also peculiar for the uniform medium, in the heterogeneous medium an additional kind of shock-wave decay takes place - "fluctuative" decay. It characterizes a decrease of the mean particle velocity caused by the particle velocity non-uniformity of dynamic straining. The fluctuative decay changes the mean particle velocity resulting in the velocity defect.

In dynamically deformed heterogeneous medium the mean particle velocity and the particle velocity dispersion, D^2, are not independent. There is a following relationship between particle velocity dispersion, D^2, and defect of mean particle velocity $\Delta u(x,t)$:

$$\Delta u(x,t) = u(x_0,t) - u(x,t) = -\frac{1}{2}\frac{\partial\left(D^2\right)}{\partial u} \quad (1)$$

Here $u\ (x,t)$ is a current value of the particle velocity and $u\ (x_0,t)$ is a referent particle velocity. The interscale momentum exchange law in the form (1) has been found in experiments on shock loading of steel and copper [2] owing to simultaneous registration of the mean particle velocity and the particle velocity dispersion [3].

Eq. (1) can be written in the form

$$\Delta u = D\frac{dD/dt}{du/dt}. \quad (2)$$

When

$$dD/dt = du/dt \quad (3)$$

the velocity defect equals to the particle velocity variation

$$\Delta u = D. \quad (4)$$

In the case of a steady plastic wave, the particle velocity variation reaches maximum value in the middle of plastic front and becomes zero to the top of the front. This means that the velocity pulsations at the mesoscale are reversible. They exist only within the steady plastic front transferring the momentum from mesoscale to macroscale and back. Even so, if the free surface velocity at the plateau of compressive pulse equals to the velocity of impactor ($\Delta U = (U_{уд} - U_{fs}^{\max}) = 0$), the particle velocity pulsations don't take away the momentum and energy. Analogous situation is known to exist in turbulent liquid where the large-scale pulsations don't dissipate energy providing only a momentum transportation.

Eq. (1) reflects a current character of the interscale momentum exchange. However, a swinging of the velocity pulsations requires a time. In this situation, one can introduce an averaging of the interscale momentum exchange process in the form:

$$\int_{t-\tau}^{t}\left(\frac{1}{2}\frac{\partial D^2}{\partial u}\right)ds \le \Delta u\tau, \quad (5)$$

where τ is a time of averaging which can be considered as "incubation time" for the interscale momentum exchange. In the case of equilibrium regime of the interscale momentum exchange, when condition (3) is fulfilled, the criterion (5) is transformed to the form:

$$\int_{t-\tau}^{t} D(s)ds \le \Delta U_{кр}\tau, \quad (6)$$

where ΔU_{cr} is a critical value of velocity defect which corresponds to elementary displacement $\Delta U_{кр}\tau$. The multiplaying of both sides of Eq.(6) by acoustic impedance ρC_l yields:

$$\rho C_0 \int_{t-\tau}^{t} D(s)ds \le \Delta\sigma\tau, \quad (7)$$

where right hand side $\Delta\sigma\tau = \rho C_0 \Delta U\tau$ is the elementary momentum transferred to deformed material for the incubation time.

For the turbulent regime to be initiated, solid must transit into the structure-unstable state. After the point of instability is achieved, the heterogeneous structure is formed. The irreversible energy and momentum loss results from the intensive self-consistent forming of the shear band structure [4].

Transition of solid into the structure-unstable state bears a statistical nature. This is a special kind of the synergetic process which is known as a noise-induced transition [5]. Criterion for the transition of shock-deformed solid into the structure-unstable state takes the form [2]:

$$\left(\frac{D}{u}\frac{\dot{D}}{\dot{u}}\right) \geq 1 \qquad (8)$$

Criterion (8) affirms that the transition into the structure-unstable state happens, when rate of change of the velocity variation becomes higher than the rate of change of the mean particle velocity. This corresponds to the situation when strain rate at the mesoscale higher than that at the macroscale. Specifically, for D-16 Al alloy tested in this work the criterion (8) begins to fulfill just at the impact velocities higher 382 m/s. The transition into the structure-unstable state has also been fixed in the shock-deformed copper [2,6].

2. EXPERIMENTAL RESULTS

Shock loading of D16 Al alloy under uniaxial strain conditions was conducted on 37 mm bore single stage light gas gun. All the specimens were the disks of 52 mm in diameter and 15 mm thick. The free surface velocity and the velocity variation were registered by using two-channel velocity interferometer [3]. The independent measuring of the impact velocity and the free surface velocity allows to register the velocity defect $\Delta U = U_{imp} - U_{fs}^{\max}$ at the plateau of the compressive pulse.

Results of shock tests of D16 aluminum alloy within impact velocity range of 30÷450 m/s are provided in Table 1, where the following designations are used: $U_{fs}^{\max}$ - maximum free surface velocity, ΔU is the velocity defect at the top of compressive pulse, W is the pull-back velocity. In Fig. 1 the dependencies for $W = f(U_{imp})$, $\Delta U = f(U_{imp})$ and $D = f(U_{imp})$ are plotted together. Region of strain rates corresponding to impact velocities of 85÷451 m/s is subdivided by two sub-regions, separated by the impact velocity of 382 m/s. In the first sub-region (85÷382 m/s), the particle velocity variation is determined by the pre-existing non-uniformity, whereas the velocity defect remains constant and equals to 20 m/s. In the second sub-region, the particle velocity non-uniformity is determined by the non-linear behavior of shock-deformed medium. After impact velocity of 382 m/s, the defect grows very fast with the increasing of impact velocity. This region of impact velocities corresponds to the irreversible regime of the interscale momentum exchange. From the point of view of physics of phenomenon, this region corresponds to the intensive shear banding and dynamic recrystallization. The impact velocity of 382 m/s corresponds to resonance regime, when rise-time of shock front coincides with the incubation time of the interscale momentum exchange.

Table 1. Results of shock tests of D16 Al alloy (all the values are in m/s).

U_{imp},	U_{tr}	U_{max}	D_{max}	W	ΔU
30.2	-	19	0	-	11.2
85	75	79.1	10	68.7	5.9
91.5	85	87.7	0	-	3.8
134	72	109.4	0	84.4	26.4
195	136.6	167.4	10	106.4	27.6
195	138.5	173.7	10	112.2	21.3
237	196	203.3	28.7	117.3	33.7
243	215	239.6	14	143.2	3.4
247	200	217.8	0	125	29.2
250	188	225.4	0	123	24.6
315	275	307.8	18.4	133.7	7.9
370	327	334	36.2	120	36
382	340	360	28.3	150.3	20.7
422	326	345	50.4	86.4	79.2
451	288.8	300.4	25.8	116.7	150.6

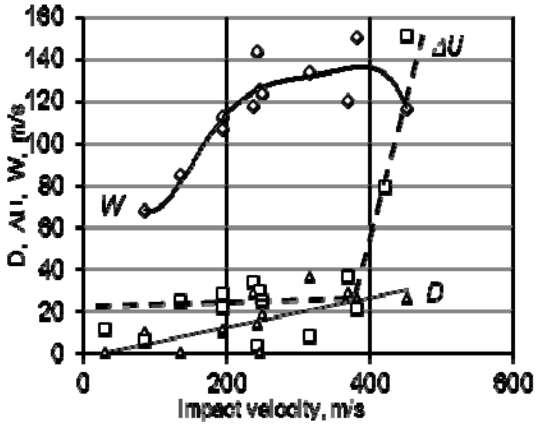

Figure 1. Pull-back velocity, *W*, velocity defect, ΔU, and velocity variation , *D*, versus impact velocity.

3. MMETALLOGRAPHY AND X-RAY INVESTIGATIONS

Initial structure of D16 Al alloy is presented by 15÷35 μm grains filled with the inclusions (up to 20 μm) of Al_2CuMg phase. Up to impact velocity of 382 m/s the state of structure doesn't differ very much of initial state. The structural state of material changes at the impact velocity of 382 m/s. X-ray analysis shows that density of dislocations in (111) and (100) planes monotonously increases with the increase of impact velocity. Analogous trend was found for regions of coherent scattering which dimensions decrease from 650 to 400 A^0. Investigation of structural state of post-shocked targets shows that one of mechanisms which determine the structural change of material is a dynamic recrystallization (DRX). DRX results in nucleation of assembles of small (< 5 μm) equal-axis grains (Fig. 2). Activation of DRX occurs when a high density of dislocations is accumulated in the (111) planes. This process corresponds to the irreversible regime of the interscale exchange, when a very intensive dynamic heterogenization of structure begins.

The specifics of shock-induced DRX-process described in the present paper is a very small duration as compared to loading pulse. In this situation, the well-known mechanisms of DRX cannot be operative. In the case of shock deformation, the mechanism of rearrangements grounded on the concept of collective nanoshears may be suggested [7]. Each nanoshear is localized within 3÷10 atomic distances and provides a discrete disorientation of crystalline lattice in neighbor regions of crystal. The collective nanoshearing flows along all the boundaries of grain structure simultaneously, similar to martencite transition. Analogous nanoshears were found in Ti-Ni alloy [8].

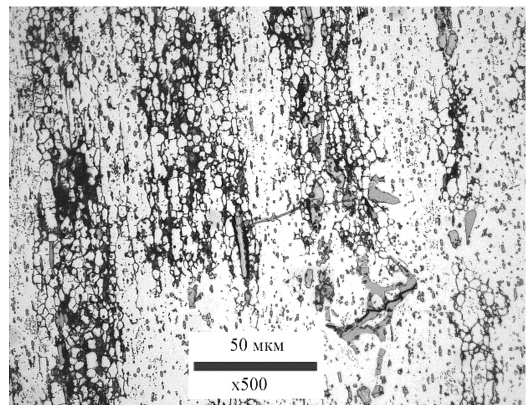

Figure 2. Dynamic recrystallized in shear bands

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