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SELF-HEALING EFFECT OF STRAIN LOCALIZATION BANDS IN CONDITION OF DYNAMICAL LOADING

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In 1944, Zener C. and Holomon J.H. explained the cause of the adiabatic shear bands appearance by the loss of plastic deformation stability of under high-speed loading, which results from the transition of the work of deformation into heat, which leads to thermal softening, the formation of narrow strain localization bands. Despite numerous studies, the thermomechanical model could not offer any physical ideas about the origin and development of the localization process, is incapable of predicting where the deformation bands originate, does not answer the question of why localization occurs in a narrow band when the neighboring material remains undeformed. This situation is explained by the fact that structural studies are conducted on saved samples and describe the changes that have occurred with the material as a result of explosive loading, but the reason for the change can not be established fundamentally, including the presence of high temperature in the strain localization bands. To do this, one must know the features of the deformation process, which form a microstructure in the localization bands. A huge number of publications, where the localized deformation bands are explained by the presence of high temperature, are not proof of the thermomechanical model of strain localization. explained the cause of the adiabatic shear bands appearance by the loss of plastic deformation stability of under high-speed loading, which results from the transition of the work of deformation into heat. This leads to thermal softening, the formation of narrow strain localization bands. Despite numerous studies, the thermomechanical model could not offer any physical ideas about the origin and development of the localization process, is incapable of predicting where the deformation bands originate, does not answer the question of why localization occurs in a narrow band when the neighboring material remains undeformed. This situation is explained by the fact that structural studies are conducted on saved samples and describe the changes that have occurred with the material as a result of explosive loading, but the reason for the change can not be established fundamentally, including the presence of high temperature in the strain localization bands. To do this, one must know the features of the deformation process, which form a microstructure in the localization bands. A huge number of publications, where the localized deformation bands are explained by the presence of high temperature, are not proof of the thermomechanical model of strain localization.
Numerous experiments [1-3] show that under pulsed loading, strain localization bands occur in the zones of unloading waves interference, where the stress does not exceed the dynamic strength of the material,

and the material continuity is preserved. The cause of localization of plastic deformation is high-speed stretching, and not thermal softening. The strain localization bands are essentially incomplete spall cracks.

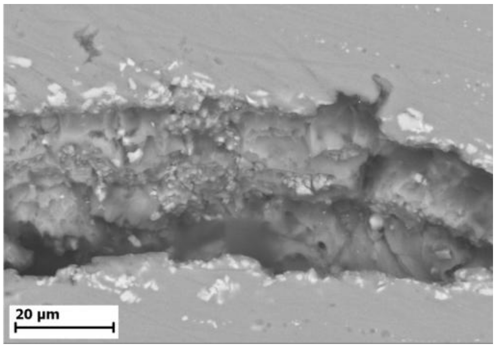

Figure 1. The localized deformation band in an aluminum alloy

The intermetallic (Fig. 1) in the alloy had a size of 1 - 2.5 μm and were located in the sample by colonies, the distance between which varied from 15 to 40 μm. The segregation of the hardening phase particles at spall damage (cracks and strain localization bands) indicates the mass transfer of particles from the adjacent layer of matrix material to the places of developing fracture. The thickness of the layer from which the intermetallics migrate is 10 - 20 μm. Inside the localization band, the particles undergo fragmentation, especially for insoluble intermetallics based on impurity elements of iron and silicon ($Al_{12}Mn_2Cu$), (Al-Fe-Si) and (Al-Fe-Si-Mn), their size (~ 3.5 μm) Is reduced 4 - 8 times. The phase composition of the hardening particles changes. Before deformation, the core of coarse particles contained insoluble intermetallics around which a bright rim enriched with copper formed. After deformation, the contour of the rim of particles fragments was preserved, but its color approached the color of the base alloy, which indicates a loss of copper.

The fine intermetallics, with a size of 1 - 2 µm, with two θ (Al_2Cu) and three-component composition S (Al_2CuMg) in the initial alloy, had the form of irregular polygons. After deformation (Fig. 2), they acquired rounded outlines, and their size did not exceed 0.5 µm. Intermetallics in the localized deformation bands undergo dissolution.

Figure 2. Microstructure of the strain localization band in an aluminum alloy

In steels with perlitoferritnoy structure similar processes occur. Pearlite colonies decrease or completely disappear when localized deformation bands pass through them. To the spall damage zone, carbon, which appears as a result of the cementite decomposition, migrates. At present, the dislocation nature of the cementite decomposition is sufficiently substantiated [4]. It is believed that the removal of carbon atoms from cementite occurs when particles are cut by dislocations, and the migration (drift) of the atoms goes to the stress field of dislocations. Using the energy-dispersion analysis method, carbon-depleted regions adjacent to the localization band, 20 - 40 μm in thickness, and carbon-enriched bands of localized deformation were observed. The decrease in microhardness [5] in a layer 50 μm thick on both sides of the band confirms the carbon migration to spall damage sites. In the localized deformation bands, the cementite plates are crushed, the particle size becomes less than the critical 0.25 μm, which occurs in steels just before destruction.

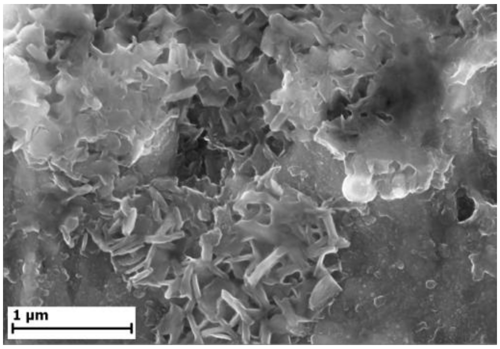

Figure 3. Crushing of cementite plates in the localized deformation zone of a steel sample

The gray areas in Figure 3 are the areas of cementite in perlite dissolution. Enrichment of the material with carbon inside the band, due to the additional supply of carbon from the matrix, leads to the fact that metastable carbide χFe_3C_2 is detected in the adiabatic shift bands (a synonym for the localized deformation bands) [5]. At the boundary of such a region, spheroidal cementite originates. With an increase in the impulse amplitude load above 13 GPa, a large amount of spheroidal cementite is formed in the bands, apparently due to the carbidization of ferrite (Fig. 4).

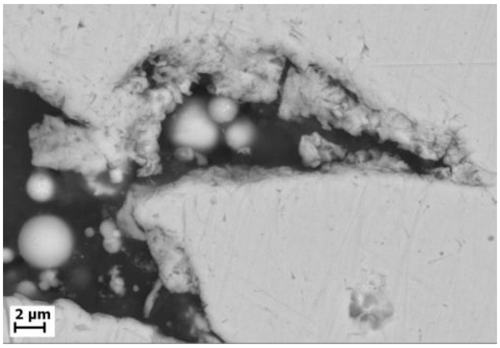

Figure 4. Spheroidization of cementite in the localization band

Migration of intermetallic compounds, carbon from matrix material to the damage zone, internal structure rearrangement, fragmentation, dissolution of intermetallics are processes that promote self-healing of growing destruction, and which are aimed at compensating for the occurring changes in the process of high-speed deformation. In fact, the process of self-healing is a mechanism of structural relaxation, accompanying the spall damage formation. It is important to note that all these processes (masstransfer, dissolution) are well known for quasistatic deformation [6]. However, their nature is very different. The distance to which the hardening particles drift is 2 - 10 nm, while in impulse processes, the thickness of the layer is tens of microns. Spheroidization requires long-term high-temperature annealing. The question arises - why the impulse nature of the load is accompanied by an acceleration of the processes. The answer gives an examination of the x-t diagram of the spall fracture formation (Fig. 5).

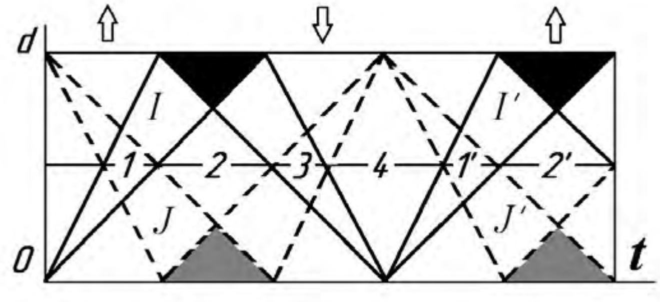

Figure 5. *x-t* diagrams of the spall damage formation

At the time of the shock wave passage (end loading of a flat specimen), unloading waves appear on the lateral faces, which, after passing to the opposite face, return to their original position. And this process is repeated many times. It can be seen that the wave processes of the unloading waves interaction between themselves and with the sample faces are accompanied by a stress oscillation. A standing wave appears in the sample. Because of symmetry, the transverse component of the mass velocity on the symmetry axis is equal to zero - it is a node of a standing wave, and the free surface is an antinode, where the stress is always early zero. A characteristic feature of standing waves is the closed regions formation, a length of 1/4 wavelength (between the antinode and the node of the wave), where the amount of energy is conserved, and does not exchange with neighbor regions. The oscillation continues without the external forces action after the shock wave attenuation. Standing waves are not substantially waves because they do not move, and perform oscillating motion of the medium. It is important to note that the formation of spall damage is accompanied always by reverberation of waves in the ultrasonic frequency range. Traditional spall fracture models do not take into account waves reverberation.

It is interesting to estimate the decay time of a standing wave. Calculation of the attenuation coefficient is based on the geometric interpretation of conservation laws. The part of the internal energy transferring into heat is equal to the area on the *P-V* diagram between the Michelson line and the unloading isentropic. For an ideal elastic-plastic medium (hardening modulus $M = 0$), the specific energy loss *e*, depends on the dynamic yield stress σ_T [7], and is equal $e = 2\sigma_T(\varepsilon - \varepsilon_g)/3\rho_0$, ε is the deformation degree, and ε_g is the deformation in the elastic precursor. The attenuation coefficient α is equal to the ratio of the energy *e* to the internal energy of the shock-compressed material. For example, in a spall steel plate, the frequency of stress oscillations is $\nu \approx 1.6$ MHz, the period of the standing wave is $T = 0.63$ μs, the ultrasonic vibrations go to the region of elastic deformation with an attenuation coefficient $\alpha \approx 0.04$ μs^{-1}, for 40 μs, having made 62 oscillations. The change in the coefficient α as it decays in the region of elastic deformation is difficult to estimate, since Data for the amplitudes of ultrasonic oscillations of the order of 1 - 2 GPa are absent. Dynamic deformation of the sample continues for a long time after the shock wave has time to die out and the deformation time exceeds by several orders of magnitude the duration of the initial compression pulse.

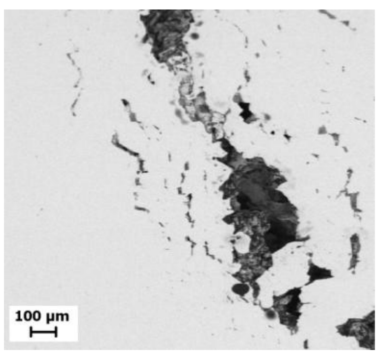

Figure 6. Spall damage at end loading of a flat elongated specimen

In conditions of reverberation of waves, in addition to the fundamental wave $\lambda_0/4 = d/2$, additional standing waves with lengths arise $\lambda_n/4 = d/2n$, where n is an odd number. Each strip of localized deformation in Figure 6 is a node of standing waves different from the fundamental tone of natural oscillations.

It should be noted that in spite of the property of standing waves to conserve energy and not to exchange with neighbors, migration of hardening particles is observed in the experiment. This is possible only if the bands of spall damage themselves exhibit the property of attracting. The cause of attraction is associated with dislocations. In the process of high-speed stretching, dislocations acquire an electric charge. The potential difference arises between the regions inside the band, where there is an intensive multiplication of dislocations in the deformation process, and an area outside the band, in which there are no fresh dislocations. The experimentally observed electromagnetic emission signal, which is generated during the development of the deformation band in the Al-Mg alloy, is equal to EME ~ 100 μV. [8]. The oscillation range of 103-106 Hz reflects structural relaxation.

Under dynamic loads, the relaxation mechanism, as the response of a material to an external action, manifests itself in the form of a self-healing process, which aims to compensate for the changes that occur when the material is stretched at high speed. The formation of spall damage is always accompanied by a transverse stress oscillation in the ultrasonic frequency range, which substantially increases the duration of the impulse deformation of the material after the shock wave is damped. Particularly it is necessary to emphasize the property of the localized deformation bands to attract "building material" to the points of spall damage. Without the property to attract the hardened particles and atoms of carbon could not leave the closed area in the standing wave.

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