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ADIABATIC SHEAR BAND VELOCITIES

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Résumé - On décrit une nouvelle méthode d'étude de la vitesse de propagation des bandes de cisaillement adiabatique sous pression hydrodynamique. L'interprétation des vitesses de propagation dépend de l'évaluation des champs de contrainte et de déformation de la zone dans laquelle se produit cette propagation. On a utilisé le code C-HEMP pour obtenir l'histoire des chargements et on a comparé les résultats avec les observations de bandes de cisaillement adiabatique. On propose une relation quantitative entre la vitesse de la bande de cisaillement adiabatique et la pression. Il semble que la pression a une influence marquée sur le comportement d'une bande de cisaillement adiabatique.

Abstract - A new method of investigating adiabatic shear band velocities under hydrodynamic pressure is described. Interpretation of propagation rates depends on an appreciation of the stress and strain fields into which propagation occurs. The C-HEMP computer code has been used to characterize load histories, and results are described for comparison with the adiabatic shear bands observed. A quantitative dependence of adiabatic shear band velocity on pressure is suggested, and the indication is that pressure alone can be a significant influence on adiabatic shear band behavior.

I - INTRODUCTION

While adiabatic plastic shear cannot occur during low-rate deformations, it has been known for some time that it is an important plastic phenomenon encountered in high-rate machining, upset forging, explosively bursting shells, and rod-plate impacts. Furthermore, it has become apparent that, if the conditions are right, there is little restriction, if any, on which type of materials will undergo adiabatic plastic shear. At least, it is known to have occurred in face-centered-cubic, body-centered-cubic, and hexagonal-close-packed metals; plastics; and ceramics. At this time, interest centers on modeling the process and characterizing materials in such a way that predictions of deformation are possible when adiabatic shear is involved.

Modeling of the adiabatic shear process can be categorized as progressing along two distinctly different, although supplementary, lines. In one approach, the consideration is of a single band. The emphasis is on the appropriate constitutive relations and the relative rates of plastic work and heat conduction. Details modeled, or predicted, are the initiation conditions, temperatures attained, and strain distributions. The shear band is usually implied to extend completely across the deforming material.

In contrast, the model due to Curran et al. deals with a shear band array that is superimposed on the plastic field when the critical condition for adiabatic shearing is attained [1]. With continued loading, adiabatic shear bands continue to nucleate, and those that already exist grow. A special feature of the analysis is that material damage from the shear band array is predicted. The growth referred to here is

the extension of the region of adiabatic shear in the shearing plane, as opposed to changes in the width of an adiabatic shear band (ASB). To avoid confusion with changes in the band width, the rate of extension in the plane of shear will be referred to as the ASB velocity, V_{SB} .

In many practical situations in which adiabatic shear is encountered, the plastic flow occurs while there is extreme pressure in addition to the stresses responsible for the shear. It is the purpose here to describe an investigation of V_{SB} and the way it depends on pressure.

Using rod-plate impact tests, Wingrove and Rogers clearly showed how the length of adiabatic shear bands increase as a function of the extent of punching and, thereby, revealed that the bands do grow with time /2,3/. Later, indirect measurements of V_{SB} were reported by Curran et al. who developed a novel trial-and-error method of determining this velocity from information gleaned from expanding cylinder tests /1/. The bands they observed in 4340 steel (RC Hardness 40) were circular, and the velocity depended on the band radius, R , and the effective plastic strain rate, $\dot{\epsilon}^P$, according to the relation

$$V_{SB} = \dot{R} = CR \dot{\epsilon}^P, \quad (1)$$

with an upper limit given by the sound speed and the imposed plastic strain which must be equal to or greater than the strain from adiabatic shearing. In the cylinder test, the material is precompressed with an explosive load, but the pressure changes drastically with time with the result that no specific pressure can be associated with the velocities determined.

There are apparently torsion-tube tests under development that will allow a normal stress to be applied along the tube axis as the tube is twisted to cause adiabatic shearing. This is an especially attractive test configuration because the loading can be moderately well characterized. However, the normal stress may be limited to the flow stress of the sample.

In the following, a new technique is described for the determination of adiabatic shear band velocities at extremely high pressures.

II - APPROACH

The approach is based on rod and plate impacts with a special configuration that allows a shear band to propagate into precompressed material. For reference, V_{SB} , was determined with no intentional pressure superimposed on the shear. This was

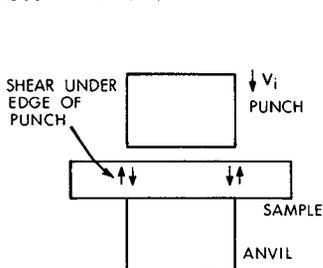


Fig. 1 - Configuration used to determine reference adiabatic shear band velocities.

accomplished with simple rod impacts as shown in Fig. 1. The load duration was controlled with the length of the rod, and a symmetrically placed anvil located behind the sample insured there was no reloading of the shear band. Clearly the material under the punch is compressed on impact, but the region of shearing is at the edge of the punch, and it is not pressurized except as the pressure field under the punch spreads out laterally. Part of the study is to determine the pressure history in the shearing region since this is a general feature of rod-plate impacts. In any event, the pressure tests involve uniform pressurizations in addition to any edge effects from punching.

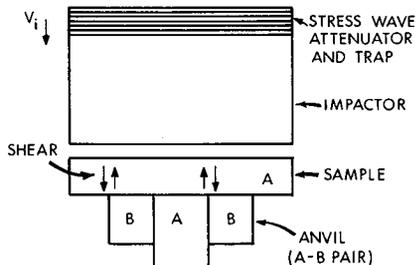


Fig. 2 - Impact geometry used to create adiabatic shear bands under pressure.

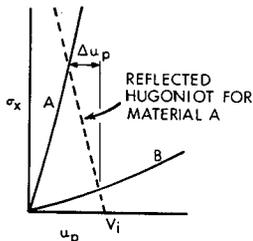


Fig. 3 - Graphical indication of the particle velocity difference created in a material A shock compressed to σ_x when it is backed with an anvil of dissimilar materials A and B.

where σ_y is the yield stress /4/. After the stress wave in the sample reaches the sample-anvil A-B interface, σ_x and u_p can be determined graphically as shown in Fig. 3 for the reflected wave according to the reflection conditions

$$\sigma_x^A = \sigma_x^B ; u_p^A = u_p^B . \tag{4}$$

There is no reflection from the sample-anvil A-A interface which is why the particle-velocity discontinuity, Δu_p , occurs.

Impact velocities and anvil materials were selected to allow meaningful comparisons of the extent of shearing from test to test. For the purpose of these comparisons, Δu_p was held constant in a series of tests including impacts with zero preimposed pressure. Suitable conditions for a particle-velocity discontinuity of 0.11 mm/ μ s in steel samples are listed in Table I.

The configuration used to create adiabatic shear under pressure is shown in Fig. 2. The impactor created a stress wave in the sample and leaves it compressed behind the wave front. The length of the impactor is chosen to insure the pressure is maintained during shearing except as altered by the loading that causes the shear. The shearing action is caused by the A-B material pair of the anvil. When the stress wave in the sample reaches the interface between the sample and material B of the anvil. The result is a particle-velocity discontinuity, Δu_p , above the A-B interface of the

anvil. This discontinuity in particle velocity propagates vertically into the sample as shown in Fig. 2. Whether or not adiabatic shear occurs depends on the magnitude of Δu_p and the load duration. The stresses in the sample and Δu_p depend on the materials and the impact velocity, V_i , as shown in Fig. 3 /4/.

The impact stress normal to the impact interface is given by the impulse momentum relation

$$\sigma_x = \rho_0 u_s u_p \tag{2}$$

where u_s is the shock wave velocity, and the particle velocity, u_p , is half the impact velocity, V_i . The hydrodynamic pressure, p , attained is

$$P = \sigma_x - (2/3)\sigma_y, \tag{3}$$

TABLE I
SHEAR TEST VARIABLES
(Steel Sample, $\Delta u_p = 0.11$ mm/ μ s)

IMPACT VELOCITY mm/ μ s	IMPACT STRESS, σ_x GPa	ANVIL MATERIALS
0.22	0.00	Not Applicable
0.27	5.28	Steel-PMMA
0.34	6.80	Steel-Mg
0.52	10.80	Steel-2024 Al
0.67	14.20	2024 Al-Teflon

The load duration was controlled with the unloading from the free surfaces of the anvil materials. The lengths of these pieces were selected to insure the shear-load duration was the same as in the comparable rod-impact "zero-pressure" test. This allows all results to be compared directly as the effects of pressure are investigated. The length of the steel anvil was 2.54 cm in every test, while the length of the other anvil material was selected according to the relation

$$l^B = \frac{1}{2} \left\{ u_s^B t_{l_0} - u_s^B \frac{l_{so}}{u_s(\sigma_{x1})^{\text{steel}}} + u_s(\sigma_{x2})^{\text{steel}} \frac{l_{so}}{u_s(\sigma_{x1})^{\text{steel}}} \right\}, \quad (5)$$

where the superscripts identify materials, t_{l_0} and l_{so} are the load duration and adiabatic shear band length, respectively, for the "zero-pressure" test, σ_{x1} is the impact stress, and σ_{x2} is the stress in the sample above the anvil material B after the initial shock wave is reflected from the sample-anvil (A-B) interface.

"Zero-pressure" tests have been conducted with three steels. One was a low-alloy Ni-Cr-Mo steel with a hardness of RC 49 (C 0.30, Mn 0.9, P 0.009, S 0.013, Si 0.34, Cu 0.03, Ni 0.97, Cr 0.58, Mo 0.50, Al 0.025 wt. %). The other steels were low-alloy Ni-Cr steels, one with a hardness of RC 34.2 (C 0.22, Mn 0.26, P 0.001, S 0.015, Si 0.19, Ni 3.2, Cr 1.1, Mo 0.2 wt. %) and the other with a hardness of RC 23.5 (C 0.27, Mn 0.27, P 0.001, S 0.008, Si 0.15, Ni 3.47, Cu 0.05, Cr 1.37, Mo 0.17 wt. %). The initial pressure-shear tests have been conducted on the RC 23.5 Ni-Cr alloy.

III - RESULTS

The degree of punching was strongly dependent on the sample hardness, and in some cases, the deformation was insufficient to create adiabatic shearing. In every test, an impression was left in the sample surface with a measurable step, d , at the location of the particle-velocity discontinuity.

Illustrations of the adiabatic shear bands formed in the "zero-pressure" and the pressure-shear tests are shown in Fig. 4. In Table II, a list is given of the impact conditions, the depth of the surface impressions, and the resultant lengths of the adiabatic shear bands formed. In the "zero-pressure" test, the impactor-air pair plays the same role in creating Δu_p as the anvil pair in the pressure-shear test. This is why steel-air is described as the anvil pair for the "zero-pressure" tests listed in Table II.

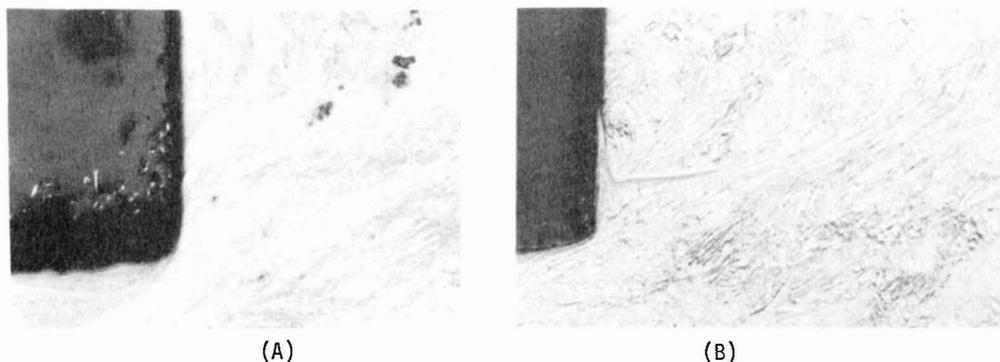


Fig. 4 - Adiabatic shear bands formed (A) in a "zero-pressure" test and (B) at a hydrostatic pressure of 5.28 GPa, X107.

TABLE II
TEST CONDITIONS AND RESULTS

SAMPLE (Steel) HARDNESS RC	ANVIL	IMPACT VELOCITY mm/ μ s	APPROXIMATE PRESTRESS σ_x , GPa	IMPRESSION DEPTH, d mm	LENGTH ADIABATIC SHEAR BAND mm	ADIABATIC SHEAR BAND VELOCITY mm/ μ s
49	steel-air	0.120	0.00	0.069	0.0	
49	"	0.229	0.00	0.345	0.0	
49	"	0.234	0.00	0.47	1.50	0.69
34.2	"	0.233	0.00	1.04	1.72 Total	0.26
34.2	"	0.109	0.00	0.165	0.0	
23.5	"	0.217	0.00	1.42	1.33	0.23
23.5	"	0.100	0.00	0.25	0.0	
26.5	steel-PMMA	0.252	5.28	0.558	0.20	0.29

Load durations were determined by accounting for the critical strain to start adiabatic shear as well as the specific detail that ended it. Adiabatic shear band velocities were determined with these time increments and the adiabatic shear band lengths observed on sample cross sections. These are listed in Table II.

IV - INTERPRETATION OF RESULTS

Steels with different hardnesses were initially tested to establish what impact velocities would be necessary in pressure-shear tests. Results of these tests indicate that V_{SB} increases with hardness. This trend is presumably because flow stress and, therefore, dislocation velocity increases with hardness. The presumption is that V_{SB} depends on dislocation velocity.

The main point of importance is that V_{SB} appears to have been greater for the pressurized steel than for the "zero-pressure" test. This result should be accepted with some caution because the length of the ASB observed in the pressure-shear test was short, and V_{SB} depended on a small time increment. Nevertheless, it is an interesting result when it is considered how pressure might influence V_{SB} .

It is generally acknowledged that adiabatic shear is simply localized plastic flow with plastic heating faster than conductive cooling. Complex materials may undergo concomitant phase changes, but this is not a necessary condition /5,6/. Perhaps an appreciation of V_{SB} is to be gained by relating it to the dislocation motion underlying the plastic flow. At low stress levels dislocation motion is intermittent, but at the critical condition for adiabatic shear, the flow stress is approximately a maximum. Furthermore, adiabatic shear band widths are enormous compared with the distance between dislocations in highly deformed material. It is proposed, therefore, that at the leading edge of an adiabatic shear band, there are always mobile dislocations even though many may be pinned and immobile. Also, for some materials the strain at which adiabatic shear begins is high, and substantial lattice rotation must occur before adiabatic shear begins. In this event, there are always slip planes approximately aligned with the adiabatic shear band and with the slip direction in the direction of maximum shear. For these conditions V_{SB} approximately equals the dislocation velocity. A proportionality constant, C_0 , would account for whatever crystallographic misalignments still exist when adiabatic shearing begins. If the dislocation velocity is given by the Johnson-Gilman equation, then

$$V_{SB} = C_0 V_{\infty} \exp(-\tau_*/\tau), \quad (6)$$

where V_{∞} is the maximum dislocation velocity, and τ_* is a parameter /7/. Recently, Jung proposed that the flow stress for dislocation motion is pressure dependent and given by

$$\tau = \tau_0 (1 - \gamma_0 P) \left[1 + 2P/G_0 (dG/dP) \right], \quad (7)$$

where G is the shear modulus, γ_0 is the compressibility, and the subscript "o" refers to 1 atm /8/. Spitzig and Richmond noted that for steels this is equivalent to the general experimental result that

$$\tau = \tau_0 (1 + 3 \alpha P), \quad (8)$$

where α is a pressure coefficient that is constant and equal to 19.2 TPa^{-1} for all ferrous materials /9/. The pressure dependence of the adiabatic shear band velocity follows as

$$V_{SB} = C_0 V_{\infty} \exp \left[-\tau_*/\tau_0 (1 + 3 \alpha P) \right]. \quad (9)$$

According to Eq. 9, V_{SB} should increase with pressure and be appreciably influenced by high pressure.

The impact configuration introduced here as a means of investigating the pressure dependence of adiabatic shear was intended to be simple to facilitate interpretation. Nevertheless, there are complexities that must be addressed. For example, the lateral spreading of the pressure field under the edge of the punch deserves consideration. This effect has been investigated by simulating actual conditions with computations of the stress histories with the C-HEMP computer code. An illustration of the results is presented in Fig. 5. The spreading of the pressure field under the edge of the punch is evident from the isobars shown, but it is also clear that the tests were essentially as intended with minor adjustments required to account for the actual pressure fields into which the adiabatic shear bands propagated.

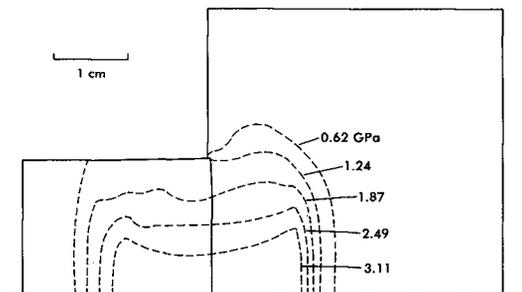


Fig. 5 - Pressure contours 3.01 μ s after an impact at 0.20 km/s.

V - CONCLUSIONS

A. The plate-impact split-anvil technique described for the creation of adiabatic shear in compressed material can be effectively used to determine adiabatic shear band velocities as a function of pressure.

B. Adiabatic shear band velocity increases with sample hardness for the class of steels investigated.

C. Adiabatic shear band velocity, V_{SB} , increased significantly with pressure. It is suggested that V_{SB} is proportional to dislocation velocity and, therefore, depends exponentially on $(1 + 3 \alpha P)^{-1}$.

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