

AD A108542

LEVEL II

(12)

NSWC TR 80-499

**DESCRIPTION OF "HOT SPOTS" ASSOCIATED WITH
LOCALIZED SHEAR ZONES IN IMPACT TESTS**

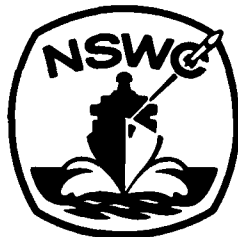
BY C. STEPHEN COFFEY RONALD W. ARMSTRONG

RESEARCH AND TECHNOLOGY DEPARTMENT

21 OCTOBER 1981

DTIC
ELECTE
DEC 15 1981
S D E

Approved for public release, distribution unlimited.



NAVAL SURFACE WEAPONS CENTER

Dahlgren, Virginia 22448 • Silver Spring, Maryland 20910

DTIC FILE COPY

81 12 14 048

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NSWC TR 80-499	2. GOVT ACCESSION NO. AD-A138542	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Description of "Hot Spots" Associated with Localized Shear Zones in Impact Tests		5. TYPE OF REPORT & PERIOD COVERED Report of Research October 1979-September 1980
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) C. Stephen Coffey and Ronald W. Armstrong		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Surface Weapons Center (Code R13) White Oak, Silver Spring, Maryland 20910		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS C6115; ZR00001; ZR02402; R01AA561
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE 21 October 1981
		13. NUMBER OF PAGES 23
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release, distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Hot Spots Dislocations Heat Sensitive Film Impact Shear Zones		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A heat sensitive film technique has been employed to give spatial resolution to the observation of "hot spots" in the impact deformation of soft ionic or molecular crystals and in crystal-filled polymer composites. The temperature of these "hot spots" is estimated to exceed 250°C for even modest impact loads. The heating is interpreted to depend on local shear deformation. The rise in temperature associated with the movement of a number of		

DD FORM 1473
1 JAN 73EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. (Cont.)

equally-spaced dislocations is reexamined. An additional multiplicative effect for the temperature rise due to the dislocation number is obtained if the dislocations are released as a pile-up avalanche from an internal obstacle. This rise in temperature carries over to the association of localized heating of "hot spots" with cracking within polymers because of the equivalence in the continuum approximation of a dislocation pile-up and a physical crack. Two reasons for the heating effect being especially important at cracking sites are that they are typified by the largest internal concentrations of stress which the material can bear before local fracture occurs, and, in so doing, the new crack surfaces supply a ready "sink" for the dissipation of the internal energies at the tips of shear zones.

Some consideration is given to the fundamental process by which dislocation movement can lead to molecular excitations within a crystal, in particular, by the spread of phonons generated at the moving dislocation front.

A

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

NSWC TR 80-499

NTIS GRA&I		☒
DTIC TAB		
Unannounced		☐
Justification		
By _____		
Distribution/ _____		
Availability Codes		
Dist	Avail and/or	
	Special	
A		

FOREWORD

Hot spots have long been acknowledged to have a decisive role in producing ignition in explosives and propellant materials when they are subjected to low level stimulations. The hot spot concept arose because of an abundance of experimental evidence which has shown that ignition can occur in an explosive/propellant under conditions in which the energy supplied to the sample was insufficient to raise its bulk temperature to the levels required to cause ignition. To account for ignition under these conditions it is necessary to postulate that some mechanism(s) are operating which act to concentrate the energy of a low level stimulation into limited regions or hot spots where the local temperatures and energy densities are sufficient to ignite the explosive/propellant sample. To date these mechanisms have never been clearly elucidated nor have the hot spots themselves been adequately described. In this report we present some recent efforts to address these latter two issues and obtain a true physical understanding of hot spots and their origins.

Here we use a heat sensitive film technique to give spatial resolution to the observation of "hot spots" in the impact deformation of soft ionic or molecular crystals and in crystal-filled polymer composites. The temperature of these "hot spots" is estimated to exceed 250°C for even modest impact loads. The heating is interpreted to depend on local shear deformation.

The mechanisms responsible for localizing the deformational energy is examined in terms of the movement of dislocations which are known to localize the deformation in crystalline solids. In particular, two complimentary approaches are used to predict the temperature rise due to moving dislocations. Both give similar results and show that, for the condition that the material undergoes sudden failure, substantial heating will occur in the local region of the crystal slip planes.

This work was carried out in part with Naval Surface Weapons Center Independent Research funds.


J. F. PROCTOR
By direction

CONTENTS

	<u>Page</u>
INTRODUCTION	5
EXPERIMENTAL EVIDENCE FOR HOT SPOTS.	6
MODEL CONSIDERATIONS	8
MICROSCOPIC LEVEL APPROACH	9
SUBMICROSCOPIC ANALYSIS.	11

ILLUSTRATION

<u>Figure</u>		<u>Page</u>
1	Heat Sensitive Film Records of Impacts on NaCl Crystals	16

INTRODUCTION

The internal heating that often occurs in materials undergoing high strain rate deformation has been attributed to the plastic deformation processes taking place within the materials.¹ Frequently, these processes have been associated with the following characteristics: extremely localized plastic deformation zones; significant changes in the overall stress-strain behavior; and premature failure.² Detailed consideration of the microscopic mechanisms by which internal heating occurs has been devoted mainly to describing crystal deformation processes within metallic materials.^{3a,b}

Recently, concern has been shown for the problem of localized plastic flow and internal heating that occurs in non-metallic materials undergoing high rate deformation. For example, dynamic fracturing experiments with pre-cracked polymethylmethacrylate and polystyrene materials⁴ as well as with quartz and glass materials⁵ have shown temperature increases of the order of 10^2 to 10^3 °C which were localized at the intense deformation region centered about the tip of the propagating crack. In the area of solid explosives initiated by low strength compressive waves (<4 GPa), it has long been recognized, based on energy density arguments, that localized hot spots were

¹Zener, C. and Hollomon, J. H., J. Appl. Phys., 15, 22, 1944;
Zener, C., "Fracturing of Metals," p. 3, ASM, Cleveland, 1948.

²Lindholm, U. S., "Mechanical Properties at High Rates of Strain," p. 3, Inst. of Physics, London, 1974.

³a. Eshelby, J. D. and Pratt, P. L., Acta Met. 4, 560, 1956;
b. Nicholas, J. F., Acta Met. 7, 544, 1959.

⁴a. Fuller, K. N. G., Fox, P. G. and Field, J. E., Proc. Roy. Soc. Londa A., 341, 537, 1875.
b. Doll, W., Eng. Fract. Mech., 5, 259, 1973.

⁵Weicher, R. and Schonert, K., J. Mech. Phys. Solids, 26, 151, 1978.

necessary to initiate the explosive reaction.⁶ Early Russian work showed that under impact loading conditions, at least, explosive initiation could be suppressed by preventing deformation from occurring.⁷

The work presented here reflects, in part, our interest in deformation-induced heating in relatively soft, inorganic and organic, crystalline and polymeric materials. Some experimental results will be presented showing evidence of localized heating produced by impact deformation of NaCl crystals.⁸ It is most likely that with appropriate modification the same fundamental processes responsible for localized adiabatic heating in metals are also responsible for the more pronounced localized heating effect that occurs in these certain softer crystals and polymer materials as they undergo rapid deformation.

Based on a previous description of the heating effect due to the motion of a group of evenly spaced dislocations,^{3a} we propose that more significant localized heating can occur when a dislocation avalanche is released from a blocked slip band pile-up configuration.^{9,10} This model permits the achievement of much greater temperature changes in the vicinity of such internal concentrations of stress. In addition, we have attempted to describe the heat generation process on the basis of a quantum mechanical analysis of the phonon field generated by a moving edge dislocation so as to consider the anisotropic nature of the phonon field. It will be shown that this field contains a beam of phonons propagating in the direction of the dislocation motion, but localized to the regions on either side of the slip plane.

EXPERIMENTAL EVIDENCE FOR HOT SPOTS

In experiments at the NSWC, a heat sensitive film has been employed to obtain information on hot spot generation in solids subjected to either impact or to low level shock loading.⁸ In these

⁶Bowden, F. P. and Yoffe, A. D., "Fast Reactions in Solids," Academic Press, London, 1958.

⁷Afanas'ev, G. T. and Bobolev, V. K., "Initiation of Solid Explosives by Impact," Academy of Sciences of the USSR, Institute of Chemical Physics, Israel Program for Scientific Translations, Jerusalem, 1971.

⁸Coffey, C. S., Elban, W. L., and Jacobs, S. J., Proc. 16th JANNAF Combustion Mtg., C.P.I.A., Johns Hopkins Univ., Baltimore, 1979.

⁹Head, A. K., Phil. Mag., 27, 531, 1973.

¹⁰Armstrong, R. W., Coffey, C. S., and Elban, W. L., submitted and accepted for publication in Acta. Met., 1981.

experiments the film is in direct contact with the sample and so is able to detect localized heating. The film has the advantage that it provides good spatial resolution to hot spot detection, but has the disadvantage that it provides only an integrated time history. Time records have been obtained in other ways such as with strain gages. Presently, the film of choice is the 3M Company's Infrared Transparency Film Type 577. This film, normally used to make visual aid transparencies, is easy to handle and rugged enough to yield usable information when subjected to shocks to 2.5 GPa. The temperature sensitivity of the film can be roughly calibrated on the basis of the coloration which occurs when the film is exposed to a transitory heat pulse. Under almost static conditions the film's response threshold is approximately 100°C in which case blackening of the film occurs in a time of 3 to 5 seconds. For heat pulses of a few tens of microseconds duration, the film changes first to a yellow brown and then to a progressively darker brown color depending on the temperature. The threshold temperature is approximately 230°C for 240 μ s heat pulse. No darkening occurs due to pressure alone. The film is useful for monitoring local temperatures in excess of 500°C.

The impact machine employed in these experiments consisted of a hardened steel anvil and striker system mounted on an assembly with vertical guide rails. The material to be impacted was first placed on top of a piece of heat sensitive film, and both of these items were then positioned between the anvil and striker. A 2.5 kg drop weight was used to impact the striker, which transmitted the force of the impact to the sample material and anvil. Strain gages were attached to the anvil. The duration of the impulse was about 220 μ s, and typical strain rates were of the order of 10^4 s⁻¹.

Figure 1 shows the heat sensitive film records obtained for impacts on a few crystal grains of NaCl materials struck from drop heights of 2 and 70 cm. It can be seen that even for a 2 cm drop height, temperatures greater than 100°C and probably of the order of 250°C were generated in localized regions around the recognizable former perimeters of the unstrained salt crystals.

The localization of energy aside, it is unlikely that these temperatures could be achieved through an average or homogeneous operation of the thermal processes that are available to convert the energy of the drop weight into heat in the solid. The coefficient of restitution of the impact machine was greater than .8. The amount of NaCl present in the experiments was from 3 to 5 mg. If all of the energy lost in the impact was expended in heating the bulk of the solid, the temperature rise would be only of the order of 50°C. This temperature rise is insufficient to exceed the film's static threshold limit.

The origin of the localized high temperature regions that surround the impacted salt crystals in Figure 1 can be better understood in terms of the adiabatic heating which occurs on a local

scale along the slip planes of the NaCl crystals during the total crystal failure process. For NaCl these (110) slip planes are oriented at an angle of 45° to the exposed (001) cube faces. Under impact, the NaCl crystals slip along these planes intersecting the circumferential free surfaces; and in the ensuing shear-induced failure process the inclined crystal failure surfaces, particularly the crystal edges, are locally heated to exceptional temperatures, say >> 100°C. The hot crystal edges strike the supporting heat sensitive film around the perimeters of the initial crystal positions causing the film to darken in these particular regions. The bottom surface of the original crystal experiences very little deformation due to the relatively larger surface constraint at the contact area, and consequently no deformation induced heating occurs to darken the film in this region. Impacts on other materials show alternative patterns of heating presumably due to their different slip system geometries or other microstructural characteristics. Sugar, for instance, shows darkening directly under the original crystal site but little darkening around the crystal perimeter. Impacts on crystals of the explosive HMX show heating occurring under the original crystal site long before explosive ignition occurs. When ignition does occur, say, in a composite specimen, it appears to take place in regions where a large amount of local deformation and consequent heating of the material are reasoned to occur.

MODEL CONSIDERATIONS

THE MACROSCOPIC LEVEL. The influence of internal heating on promoting premature failure of high strength ferritic steel in torsion has been examined at different strain rates.² At a torsional shear strain rate of 98 s⁻¹, failure due to plastic instability occurred at a strain value of .20, while at a slower rate of 10 s⁻¹, the strain to failure was .63. At a still slower strain rate, failure occurred at a strain of .73. In these experiments the bulk yield stress remained nearly constant at a value of 1 GPa thus indicating that the amount of plastic work required to fail the steel material decreased with increased strain rate. This effect was attributed to increasingly localized adiabatic heating within the sample which led more rapidly to localized softening and eventual plastic instability of the metal as the deformation rate was increased. Indeed, at the highest strain rate, adiabatic shear bands were observed at the failure site.

On the assumption that all of the plastic work is converted to heat and that the deformation is adiabatic, the maximum change in bulk temperature, ΔT , due to the torsional deformation is expressed as

$$\Delta T = (1/C^*) \int_0^{\gamma_{\max}} \tau d\gamma \quad (1)$$

where τ is the torsional shear stress, C^* is the specific heat per unit volume ($3.5 \text{ MJ/m}^3 \text{ } ^\circ\text{K}$ for steel and γ_{max} is the shear strain at failure.² Evaluating Equation (1) for the experiment which has been described gives calculated increases in temperature values in the range

$$57 \text{ } ^\circ\text{K} \leq \Delta T \leq 205 \text{ } ^\circ\text{K}.$$

One difficulty in reconciling the trend of the experimental results with the evaluation of Equation (1) is that the predicted temperature rise is greater when the plastic strain is larger and yet this occurs at the smaller applied torsional strain rate. This is opposite to the observed condition that the same temperature rise must be reached sooner in the experiments at the higher strain rates. The problem can be overcome to some extent by noting that the plastic deformation behavior became increasingly localized as the strain rate increased and this aspect of the deformation behavior can be accounted for by modifying Equation (1) to give

$$\Delta T = (V_0/V_p) (1/C^*) \int_0^{\gamma_{\text{max}}} \tau d\gamma \quad (2)$$

where V_0 is the volume of the specimen and V_p is the volume of the plastic zone.

THE MICROSCOPIC LEVEL. The above calculations describe bulk phenomena, and while these are informative, they do not indicate the more fundamental microscopic processes that are responsible for deformation localization and heating. An understanding of these processes is required if the problem of localized deformation and heating is to be effectively dealt with.

On a microscopic basis, deformation in a crystalline solid involves the generation and movement of dislocations. Early in the development of this theory, the problem of heat being generated by moving dislocations was considered.³ The temperature rise due to n moving dislocations evenly spaced over a distance λ within a slip band was computed as Equation (3a)

$$\Delta T = n \left[\begin{array}{l} \ln \frac{2K}{C^*v \lambda/n} \quad ; \quad \frac{2K}{C^*v} \\ \left(\frac{\pi K}{C^*v \lambda} \right)^{1/2} \quad ; \quad \frac{2K}{C^*v} \end{array} \right] \gg \lambda \quad (3a)$$

$$\Delta T = n \left[\begin{array}{l} \ln \frac{2K}{C^*v \lambda/n} \quad ; \quad \frac{2K}{C^*v} \\ \left(\frac{\pi K}{C^*v \lambda} \right)^{1/2} \quad ; \quad \frac{2K}{C^*v} \end{array} \right] \ll \lambda \quad (3b)$$

where b is the dislocation Burgers vector, τ is the shear stress, v is the dislocation velocity and K is the thermal conductivity; C^* has been defined for Equation (1). The quantity contained within

the brackets is the temperature increase associated with the movement of a single dislocation, ΔT_{11} , provided that (λ/n) in Equation (3a) is replaced by the distance from the dislocation, $r_0 \geq b$, and in Equation (3b) λ is replaced by r_0 .

Equations (3a and 3b) are immediately useful for showing the trend of the effect of the strain rate, mainly, on increasing the dislocation velocity and, hence, giving a greater increase in temperature for an increasing strain rate. However, for several aluminum materials ΔT in Equation (3b) was estimated to be less than a few degrees.^{3a}

Even though Equations (3a and 3b) give a multiplying effect for the number of moving dislocations, no account is taken of their mutual interactions, particularly, with regard to the natural consequence of the dislocations being arranged in a pile-up configuration.¹⁰ Very large local stresses are known to exist for pile-ups at grain boundaries in polycrystals or at subgrain boundaries in single crystals. The sudden release of such a pile-up would modify, say, Equation (3a) in two ways: τ should be replaced by $(n+1)\tau/2$ as the effective stress on the dislocations within the pile-up, and (λ/n) should be replaced by $\Delta x > b$, the distance separating dislocations at the tip of the pile-up. Thus Equation (3a) becomes

$$\Delta T = n \left[\frac{b(n+1)\tau v}{4\pi} \ln \frac{2K}{C^*v\Delta x} \right] \quad (4)$$

or

$$\Delta T = \frac{n(n+1)}{2} (\Delta T_{11}). \quad (5)$$

There is experimental evidence to indicate that dislocation pile-ups are important as potential sources of heat. In impact experiments involving a wide range of materials, stress build-ups were observed until, in many cases, an abrupt ($< 1 \mu s$) failure occurred.¹¹ In the case of explosive materials, ignition was observed to occur during or shortly after (0-5 μs) failure which indicates that during failure significant localized heating had taken place.

¹¹Heavens, S. N. and Field, J. E., Proc. Roy. Soc. London A, 338, 77, 1974.

The effect of a dislocation pile-up in producing sudden catastrophic yielding and fracture of steel or ionic materials is well known.^{12,13,14}

It is instructive to compare Equations (4) and (5) with the torsional results described earlier for internal heating within a high strength steel material.² For this case we let $\tau < G/20 = 3.9$ GPa, where G is the shear modulus for steel.¹⁵ With $\tau = 1$ GPa, $n \sim 4$. Also, for steel, $k = 60 \text{ J/ms } ^\circ\text{K}$, so $2K/C^* = 3.4 = 10^{-5} \text{ m}^2/\text{s}$, and with a limiting value of $v = 3.2 \times 10^3 \text{ m/s}$ which is the shear wave velocity and $b = 2.5 \times 10^{-10} \text{ m}$, then $(2K/C^*vb) \gg 1.0$. Thus, the condition for Equation (3a) applies in which case the maximum possible temperature increase for a single dislocation is calculated to be $\Delta T_{11} \leq 8^\circ\text{K}$. For the condition of sudden failure of an internal obstacle within the material for which Equation (5) then applies, a maximum temperature rise $\Delta T \leq 10 \times 8^\circ\text{K} = 80^\circ\text{K}$ is obtained. This near instantaneous temperature increase for an individual slip band is within the range of the temperature increases calculated with Equation (1) for the unrealistic bulk heating associated with the plastic work expended during the entire duration of the torsional test. For the present case, the localized temperature increase at the slip band site should promote the activation of additional slip bands in close proximity and the continued development and collapse of pile-ups. These, in turn, ought to produce sufficient local temperature increases to accomplish phase changes even of the type observed for steel.^{1,2}

SUBMICROSCOPIC ANALYSIS. In foregoing analysis, the moving dislocations are treated as isotropic line sources of heat. Clearly this may only be an approximation because the dislocation has a sufficiently complicated structure to suggest that thermal energy may be emitted efficiently only in preferred directions. This suggests the possibility of a more efficient focusing of energy and consequently even higher temperature hot spots. To deal with this possibility a quantum mechanical analysis has been developed of the first order phonon field generated by a moving edge dislocation^{16,17} and will be presented here in outline form.

¹²Cottrell, A. H., Trans TMS-AIME, 212, 192, 1958.

¹³Petch, N. J., Phil. Mag., 3, 1089, 1958.

¹⁴Stokes, R. J. and Li, C. H., "Fracture of Solids," p. 289, Interscience Publ., N.Y., 1963.

¹⁵Armstrong, R. W., Chou, Y. T., Fisher, R. M., and Louat, N., Phil. Mag., 14, 943, 1966.

¹⁶Weiner, J. H., "Fundamental Aspects of Dislocation Theory," Nat. Bur. Stand. (U.S.), Spec. Publ. 317, p. 403, 1970.

¹⁷Coffey, C. S., Accepted for publication in the Physical Review, 15 Dec 1981.

On a microscopic basis the presence of a moving dislocation constitutes a significant local perturbation of the lattice structure of a crystal. From a fundamental view point, it is this interaction between the dislocation and the crystalline lattice structure that is responsible for the heating effects produced by the moving dislocation.

It will be assumed that the dislocation is moving at a low enough velocity so that "relativistic effects" are not important. The expressions for the stress fields due to an edge dislocation are well known.¹⁸ If in a time Δt the dislocation moves a distance Δx then the stress fields at an arbitrary location change by an amount

$$\begin{aligned}\sigma &= \sigma_0 + \sigma' \\ &= \frac{Gb}{2(1-\nu)} \left\{ \begin{array}{c} \sin\theta \\ \cos\theta \end{array} \right\} \frac{1}{r} \left[\frac{1}{1-\Delta x/r} + 0(\Delta\theta) \right],\end{aligned}\quad (6)$$

where the $\sin\theta$ term in curly brackets refers to $\sigma_{rr} = \sigma_{\theta\theta}$ and the $\cos\theta$ term refers to $\sigma_{r\theta} = \sigma_{\theta r}$. The local microscopic strain similarly experiences an incremental change

$$\begin{aligned}\epsilon &= \epsilon_0 + \epsilon' \\ &= \epsilon_0 + \frac{\bar{x} - \bar{x}_0}{d},\end{aligned}\quad (7)$$

where $\bar{x} - \bar{x}_0$ is the incremental change in molecular separation and d is the normal unstrained intermolecular separation. The slightly altered dislocation energy density can be written as

$$\begin{aligned}H &= H_0 + H_I \\ &= \frac{1}{2} (\sigma_0 \epsilon_0 + \sigma_0 \epsilon' + \sigma' \epsilon_0 + \sigma' \epsilon')\end{aligned}\quad (8)$$

The interaction energy density between the dislocation and the molecular components of the solid responsible for phonon generation is

$$\begin{aligned}H_I &= \frac{1}{2} (\sigma_0 + \sigma') \epsilon' \\ &= \frac{1}{2} \sigma_0 \epsilon',\end{aligned}\quad (9)$$

where terms of the order Δ/r will be neglected.

¹⁸Hirth, J. P. and Lothe, J., "Theory of Dislocations," McGraw Hill Book Co., New York, 1968.

In general, an edge dislocation is constrained to move only along a slip plane. If P' is the initial momentum of the moving dislocation, and P its final momentum after generating a phonon of momentum $\hbar q$, then conservation of momentum requires that

$$P' = P + \hbar q .$$

Furthermore, in its idealized form the edge dislocation is composed of a large (infinite) half plane of extra molecules. This requires that the momentum of the phonon and dislocations be colinear which causes the above momentum conservation relation to reduce to a scalar quantity. Thus for first order processes, the only phonons that can be generated are those that propagate in the direction of the dislocation motion.

In the following analysis, the direction of the dislocation motion will be taken as the x axis. By the above argument only the strain components in the x direction play a role in the first order phonon generation process. These can be written directly, and the interaction energy becomes

$$\begin{aligned} H_I &= \frac{1}{2} \left(\sigma_{rr} \epsilon_r + \sigma_{\theta\theta} \epsilon'_\theta + \sigma_{r\theta} (\epsilon'_{r\theta} + \epsilon'_{\theta r}) \right) \\ &= \frac{x - x_0}{4\pi(1-\nu)} \frac{Gb}{r} \left[(\sin\theta + \cos\theta) \left(\frac{\cos\theta}{d_2} - \frac{\sin\theta}{d_1} \right) \right] . \end{aligned} \quad (10)$$

It is now advantageous to transform to the quantum mechanics point of view. The moving dislocation can be described by a superposition of plane waves, so that a dislocation wave function ψ can be written as

$$\psi = \frac{1}{V^{1/2}} \sum_k a_k e^{i\vec{k} \cdot \vec{r}}$$

and

$$\psi^\dagger = \frac{1}{V^{1/2}} \sum_k a_k^\dagger e^{-i\vec{k} \cdot \vec{r}} , \quad (11)$$

where V is the volume required for normalization. The operators of $a_k^\dagger$ and a_k create and annihilate dislocations of wave number k . Similarly we can write the relative molecular displacement from equilibrium at a distance r from the dislocation as

$$x - x' = \frac{1}{(\rho V)^{1/2}} \sum_q \left(\frac{\hbar}{2cq} \right)^{1/2} \left(b_q + b_{-q}^\dagger \right) e^{i\vec{q} \cdot (\vec{R} + \vec{r})} , \quad (12)$$

where b_q and $b_{-q}^\dagger$ annihilate and create phonons with wave numbers q and $-q$ respectively.

The transition amplitude for the process in which a dislocation of wave vector k' is annihilated and a dislocation of wave vector k is created along with a phonon of wave vector q is given as $\langle \psi_k H_I \psi_{k'} \rangle$. The spatial integrations are straight forward. Integration over R yields the delta function, $\delta(k' - k - q)$. Integration on r involves the limits $r_{\min}$ and $r_{\max}$. The limit $r_{\max}$ produces a rapidly oscillating result which adds little to the value of the integral and consequently can be dropped. The limit $r_{\min}$ is the dislocation core size, and it is convenient to let this approach zero, $r_{\min} \rightarrow 0$. These approximations amount to assuming that only the region near the core of the dislocation is responsible for the lattice perturbations that generate phonons.

The approximate transition probability, $P_{k',k}$, per unit time that a moving dislocation with momentum $\hbar k'$ will emit or absorb a phonon of momentum $\hbar q$ can be determined in the familiar way.¹⁹

$$P_{k',k} = \left(\frac{Gb}{4\pi(1-\nu)} \right)^2 \cdot \frac{1}{2\rho V(2\pi)} \cdot \frac{N_{k'}(N_k+1)}{k'-k} \left[\frac{1-2\cos\theta\sin\theta}{d_2^2 c_T} + \frac{1}{d_1^2 c_L} \right] \left(\sin\theta + \cos\theta - \log \tan \left(\frac{\pi}{4} + \frac{\theta}{2} \right) \right)^2 \quad (13)$$

where c_L and c_T are the longitudinal and transverse sound velocities and d_1 and d_2 are the unstrained longitudinal and transverse molecular separations. $N_{k'}$ and N_k are the number densities of dislocations with wave vector k' and k respectively.

This analysis shows that phonons generated by first order interactions with moving dislocations are emitted only in the direction of the dislocation motion, and with one exception are restricted to regions close to the slip plane. Hot spots can result when these phonons are thermalized, say, by absorption and re-emission by some non-uniformity near the slip plane. The exception to this occurs as $\theta \rightarrow \pi/2$ in the second term of Equation (13). This term represents a compressive wave composed of longitudinal phonons and contains

¹⁹Sakurai, J. J., "Advanced Quantum Mechanics," Addison-Wesley Publ. Co., 1967.

a logarithmic singularity as $\theta \rightarrow \pi/2$ represents a break-down in the approximations used to arrive at Equation (13). However, the analysis does indicate that the probability of longitudinal phonon generation approaches its maximum value of unity as $\theta \rightarrow \pi/2$, and that these phonons are emitted coherently in the x direction over the entire vertical half plane. Physically, this is just what is expected from the classical picture of a moving edge dislocation in which the extra vertical half plane of molecules associated with the edge dislocation advances through the solid in step with the dislocation motion. Thus, not surprisingly, the coherent beam of longitudinal phonons predicted above is just the compressive plane wave produced by the advancing half plane of molecules of a moving edge dislocation.

ACKNOWLEDGMENT

The authors are grateful to S. J. Jacobs and W. L. Elban for many helpful discussions. One of the authors (C. S. Coffey) wishes to acknowledge support from the Naval Surface Weapons Center Independent Research fund for this work. Finally, we want to extend our sincere thanks to Mrs. P. Leahy who expertly typed this report through several revisions.



Fig. 1a

Fig. 1b

Figure 1a,b. Heat sensitive film records of the localized heating generated by impact of a 2.5 kg drop weight on to approximately 4 mg of NaCl crystals. Figure 1a shows the heat pattern produced when the drop weight was released from 2 cm. Figure 1b shows the heat pattern produced when the drop weight was released from 70 cm. The magnification factor is 3.4.

REFERENCES

1. Zener, C. and Hollomon, J. H., J. Appl. Phys., 15, 22, 1944;
Zener, C., "Fracturing of Metals," p. 3, ASM, Cleveland, 1948.
2. Lindholm, U. S., "Mechanical Properties at High Rates of Strain,"
p. 3, Inst. of Physics, London, 1974.
3. a. Eshelby, J. D. and Pratt, P. L., Acta Met. 4, 560, 1956;
b. Nicholas, J. F., Acta Met. 7, 544, 1959.
4. a. Fuller, K. N. G., Fox, P. G. and Field, J. E., Proc. Roy.
Soc. London A., 341, 537, 1975.
b. Doll, W., Eng. Fract. Mech., 5, 259, 1973.
5. Weicher, R. and Schonert, K., J. Mech. Phys. Solids, 26, 151,
1978.
6. Bowden, F. P. and Yoffe, A. D., "Fast Reactions in Solids,"
Academic Press, London, 1958.
7. Afanas'ev, G. T. and Bobolev, V. K., "Initiation of solid
Explosives by Impact," Academy of Sciences of the USSR,
Institute of Chemical Physics, Israel Program for Scientific
Translations, Jerusalem, 1971.
8. Coffey, C. S., Elban, W. L., and Jacobs, S. J., Proc. 16th
JANNAF Combustion Mtg., C.P.I.A., Johns Hopkins Univ.,
Baltimore, 1979.
9. Head, A. K., Phil. Mag., 27, 531, 1973.
10. Armstrong, R. W., Coffey, C. S., and Elban, W. L., submitted
and accepted for publication in Acta. Met., 1981.
11. Heavens, S. N. and Field, J. E., Proc. Roy. Soc. London A,
338, 77, 1974.
12. Cottrell, A. H., Trans TMS-AIME, 212, 192, 1958.
13. Petch, N. J., Phil. Mag., 3, 1089, 1958.
14. Stokes, R. J. and Li, C. H., "Fracture of Solids," p. 289,
Interscience Publ., N.Y., 1963.
15. Armstrong, R. W., Chou, Y. T., Fisher, R. M., and Louat, N.,
Phil. Mag., 14, 943, 1966.

REFERENCES (cont.)

16. Weiner, J. H., "Fundamental Aspects of Dislocation Theory," Nat. Bur. Stand. (U.S.), Spec. Publ. 317, p. 403, 1970.
17. Coffey, C. S., Accepted for publication in the Physical Review, 15 Dec 1981.
18. Hirth, J. P. and Lothe, J., "Theory of Dislocations," McGraw Hill Book Co., New York, 1968.
19. Sakurai, J. J., "Advanced Quantum Mechanics," Addison-Wesley Publ. Co., 1967.

DISTRIBUTION

	<u>Copies</u>		<u>Copies</u>
Chief of Naval Material		Commander	
Attn: MAT-08T222)	1	Naval Sea Systems Command	
Navy Department		Attn: SEA-03B	1
Washington, DC 20360		SEA-033 (W. W. Blaine)	1
		SEA-003	1
Director		SEA-04H (Daugherty)	1
Office of the Secretary		SEA-06D	1
of Defense		SEA-09G32	2
Defense Advance Research		SEA-62B	1
Projects Agency		SEA-62R	1
Washington, DC 20301	1	SEA-62R32	1
		SEA-64E (Beauregard)	1
Director		Washington, DC 20362	
Defense Technical Information		Commander	
Center		Naval Air Systems Command	
Cameron Station		Attn: AIR-350 (E. M. Fisher)	1
Alexandria, VA 22314	12	AIR-350D (H. Benefiel)	1
		AIR-350F	
Commander		(R. J. Wasnewski)	1
Naval Research Laboratory		AIR-5323C	1
Attn: Technical Library	1	AIR-54131	1
Washington, DC 20375		AIR-950D	
		(Technical Library)	1
Director		Department of the Navy	
Lawrence Livermore National		Washington, DC 20361	
Laboratory		Director	
Attn: M. Finger	1	Strategic Systems Project	
J. Kury	1	Office (PM-1)	
Technical Library	1	Attn: SP-273 (R. M. Kinert)	1
University of California		SP-27311	
Livermore, CA 94550		(E. L. Throckmorton	
		Jr.)	1
Director		Department of the Navy	
Los Alamos National Laboratory		Washington, DC 20376	
Attn: J. Shaner	1		
B. Craig	1		
L. Hatler	1		
H. Flaugh	1		
Technical Library	1		
Los Alamos, NM 87544			

NSWC TR 80-499

DISTRIBUTION (cont)

<u>Copies</u>	<u>Copies</u>
Chief of Naval Research Attn: ONR-741 (Technical Library) 1 ONR-473 (J. H. Satkowski) 1 ONR-473 (R. S. Miller) 1 Arlington, VA 22217	Commanding Officer Army Ballistic Research Laboratory Attn: P. Howe 1 Technical Library 1 Aberdeen, MD 21005
Commanding Officer Naval Ordnance Station Attn: Research and Development Department 1 DL (G. B. Stevenson) 1 Technical Library 1 Indian Head, MD 20640	Director Air Force Office of Scientific Research Attn: Library 1 Col. H. Bryan 1 E. Walsh 1 Bolling Air Force Base Building 410 Washington, DC 20332
Director Sandia Laboratories Attn: Technical Library 1 P. O. Box 5800 Albuquerque, NM 87115	Commander Air Force Armament Development and Test Center Attn: Technical Library 1 L. Elkins 1 C. McCulloch 1 Eglin Air Force Base, FL 32542
Director Johns-Hopkins Applied Physics Laboratory Attn: S. Koslov 1 Technical Library 1 Johns-Hopkins Road Laurel, MD 20810	F. J. Seiler Research Laboratory Attn: Technical Library 1 U. S. Air Force Academy Colorado Springs, CO 80840
Goddard Space Flight Center, NASA Attn: Technical Library 1 Glenn Dale Road Greenbelt, MD 20771	Commander Naval Weapons Center Attn: L. Rothstein 1 Yorktown, VA 23491
Commanding Officer U. S. Army Armament Research and Development Command Attn: R. Walker 1 N. Slagg 1 P. Marenkas 1 Technical Library 1 Dover, NJ 07801	Commanding Officer Harry Diamond Laboratory Attn: Technical Library 1 Adelphi, MD 20901 Library of Congress Attn: Gift and Exchange Division 4 Washington, DC 20540

DISTRIBUTION (cont)

Copies

Commander	
Naval Weapons Center	
Attn: A. Adicoff	1
A. Addison	1
T. Joyner	1
D. B. Amster	1
D. Mallory	1
G. Greene	1
Sewell	1
Technical Library	1
China Lake, CA 93555	
New Mexico Institute of	
Mining Technology	
Attn: TERA (M. L. Kempton)	1
Socorro, NM 87801	
Hercules, Inc.	
Attn: Technical Library	1
Allegany Ballistics Laboratory	
P. O. Box 210	
Cumberland, MD 21502	
Commanding Officer	
Naval Ammunition Depot	
Crane, IN 47522	1
ITT Research Institute	
Attn: H. S. Napadensky	1
10 W. 35th Street	
Chicago, IL 60616	