# SOME NEW ASPECTS OF FRACTURE MECHANICS OF POLYMERS

G. M. Kerch*

It is shown that negative linear thermal expansion coefficient, evolution of heat under stretching and positive weight changes as a result of fracture of an oriented polyethylene may be associated with crystalline structure characterized by *c*-axis orientation of crystallites and positive linear thermal expansion coefficient, absorption of heat under stretching and weight losses as a result of fracture of oriented polyethylene may be associated with crystalline structure characterized by *a*-axis orientation of crystallites. Relativistic mechanisms of internal energy and weight changes during processes of deformation and fracture are discussed.

## INTRODUCTION

It has been shown (Frenkel and Kontorova (1), Frank (2) and Eshelby (3)) that equations of motion of crystal dislocations can be brought into a form analogous to those of a particle in special relativity. Dislocations suffer Lorentz contraction in the direction of motion and the total energy is also given by the relativistic equation. But what is essentially a limiting velocity is equal to the velocity of sound. It is very likely that movements of kinetic units on the microscopic scale in solids are governed by the principle of relativity but in relativistic equations velocity of light must be substituted by velocity of sound.

The purpose of this paper is to demonstrate relativistic nature of some physical phenomena in solids including processes of thermal deformation and fracture of oriented polymers.

* Centre of Science and Engineering ECOTRA, Nicgales Str. 4-235, LV-1035, Riga, Latvia

## RESULTS AND DISCUSSION

Let us consider a finite system of elements. The interaction by means of exchange of signals between the elements ensures the co-operative movement of all parts of the system. It is impossible for the elements of the system to move with velocity greater than velocity of propagation of the signals. So it is obviously that the rate of propagation of the signals is the limiting velocity for mechanical movement of the elements within the system. For example the top velocity for mechanical displacements in solids is velocity of sound. The displacement of one part of the solid will cause the displacements of the other parts of the solid after a some time interval. The value of this time interval is equal to the distance between the parts of the solid divided by velocity of sound. The consequence of the speed limit is that "rigid" bodies and "incompressible fluids" have become impossible objects. For, by definition, they would transmit signals instantaneously. One can conclude that rigidity of a body will increase with increasing the speed limit. It is consistent with well known formula

$$E = \rho c^2 \tag{1}$$

where $E$ is elasticity modulus, $\rho$ is density and $c$ is velocity of sound.

The relativity principle is universal principle which cannot be restricted by application only to light propagation. The relativity principle should be valid also for systems where top speed differs from velocity of light. Lorentz transformation should describe the physical behaviour for such systems. All results of special theory of relativity are valid for such systems but instead of velocity of light in all formulae we must substitute another velocity, for example velocity of sound. Let us now consider consequences of the use of velocity of sound in relativistic formulae to describe some physical phenomena in solids.

The value of linear thermal expansion coefficient is given by

$$\beta = \frac{L_2 - L_1}{L_1 \cdot \Delta T}. \tag{2}$$

Taking into account Lorentz formula for length contraction one obtains the following relation

$$\beta = \frac{L_0 (1 - v_2^2/c^2)^{1/2}}{\Delta T \cdot L_0 (1 - v_1^2/c^2)^{1/2}} - \frac{1}{\Delta T}. \tag{3}$$

Substituting in eq. (3) $v^2 = kT/m$ we can rewrite (3) as

$$1 + \beta \cdot \Delta T = \frac{(1 - kT_2/mc^2)^{1/2}}{(1 - kT_1/mc^2)^{1/2}} = \left(1 - \frac{k \cdot \Delta T}{mc^2 - kT_1}\right)^{1/2}. \tag{4}$$

Since $\beta << 1$ and $mc^2 >> kT_1$ we obtain

$$\beta \approx - \frac{k}{2mc^2}. \tag{5}$$

Eq. (5) can also be derived from another nonrelativistic assumptions. Nonlinear dependence between force $F$ and displacement $\varepsilon$ given by

$$F = -f\varepsilon + g\varepsilon^2 \tag{6}$$

where $f$ and $g$ are constants, leads to the following relations (1)

$$\beta \approx \frac{gk}{R_0 \cdot f^2} \approx \frac{-k}{2R_0^3 \cdot E} \tag{7}$$

where $R_o^3$ is the volume of atom. After substitution of eq. (1) in eq. (7) we obtain expression (5). So one can suppose that nonlinearity in dependence (6) (the unharmonicity of vibrations of atoms) is a consequence of relativistic effects.

It has been shown by Kerch and Irgen (4) that negative linear thermal expansion coefficient and evolution of heat under stretching of an oriented polyethylene may be associated with crystalline structure characterized by $c$-axis orientation of crystallites and positive linear thermal expansion coefficient and absorption of heat under stretching of an oriented polyethylene may be associated with crystalline structure characterized by $a$-axis orientation of crystallites.

If an amount of energy $\Delta U$ be given to a body, the inertial mass of the body increases by an amount $\Delta U/c^2$. It was found that inertia is

not a fundamental property of matter but a property of energy. In the case if $\Delta U$ is internal energy changes of a solid the $c$ should be equal to velocity of sound. So comparatively large changes of the weight of polymers are expected to be observed under the comparatively small changes of internal energy. Analytical balance was used to measure weights of polymer samples before and after stretching and fracture with accuracy 0.05 mg. The following samples were used:

— low density polyethylene sheets produced by compression molding;
— oriented low density polyethylene films;
— polyvinylchloride, compression molded plates.

The results are shown in Table 1. The values of mass decrease or increase depend on the changes of internal energy of a body after stretching and fracture. The increase of weight has been observed for

TABLE 1 - Weight changes in polymer samples

| No. | Sample | Weight before fracture, $10^{-6}$ kg | Weight after fracture, $10^{-6}$ kg | Weight changes, $10^{-6}$ kg |
|---|---|---|---|---|
| | Low density polyethylene (compression molded sheets) | | | |
| 1 | | 5590.6 | 5589.6 | -1.0 |
| 2 | | 5491.3 | 5490.6 | -0.7 |
| 3 | | 5488.2 | 5487.2 | -1.0 |
| 4 | | 5439.5 | 5438.3 | -1.2 |
| 5 | | 5444.1 | 5443.3 | -0.8 |
| | Poly(vinyl chloride) | | | |
| 6 | | 3170.4 | 3166.3 | -4.1 |
| 7 | | 3164.7 | 3161.2 | -3.5 |
| 8 | | 3180.2 | 3175.9 | -4.3 |
| 9 | | 3083.9 | 3079.7 | -4.2 |
| | Low density polyethylene films | | | |
| 10 | | 195.6 | 196.1 | +0.5 |
| 11 | | 206.0 | 206.8 | +0.8 |
| 12 | | 173.6 | 174.4 | +0.8 |
| 13 | | 182.2 | 183.3 | +1.1 |
| 14 | | 194.2 | 195.1 | +0.9 |

polymer with negative linear thermal expansion coefficient. The comparatively great changes of masses are due to low value of limiting velocity. The value of weight changes is too high to be attributed to the absorption or desorption of gases or to other experimental errors. One can calculate from the data of Table 1 internal energy changes $\Delta U = \Delta m \cdot c^2$, which vary between -0.5 and 2.0 J. These values are consistent with experimental data reported by Godovsky (5).

One can expect arising of high mechanical forces in solids when velocity of kinetic units approaches velocity of sound. High mechanical forces in conductors have been observed in experiments including wire exploding into fragments when subjected to a short current pulse of several thousand amperes (Nasilowski (6)). It has been concluded from the studies of optical and scanning electron micrographs that observed wire fragmentation was the result of tensile fracture in the solid state.

We can calculate the values of current which causes mechanical displacements with velocity of sound $5 \cdot 10^3$ m/sec in copper wires for various cross-sectional areas of conductors. For a wire with cross-sectional area $10^{-10}$ m$^2$ (the case of exploding wires) the velocity of mechanical displacements will be equal to velocity of sound when the value of current will be $6 \cdot 10^3$ amperes. It is very likely that high mechanical stresses in wires are due to relativistic effects.

## SYMBOLS USED

$c$ = velocity of sound

$E$ = elastic modulus

$F$ = force

$L_i$ = length at temperature $T_i$

$m$ = mass of atom

$T_i$ = absolute temperature

$\Delta U$ = internal energy changes

$v_i$ = velocity of atom at temperature $T_i$

$\beta$ = linear thermal expansion coefficient

$\varepsilon$ = displacement

$\rho$ = density

## REFERENCES

(1) Frenkel, J.I., "Vvedenie v teoriju metalov", Nauka, Leningrad, 1972.

(2) Frank, F.C., Proc. Phys. Soc., Vol. 62, No. 350A, 1949, pp. 131—134.

(3) Eshelby, J. D., Proc. Phys. Soc., Vol. 62, No. 353A, 1949, pp. 307—314.

(4) Kerch, G. M. and Irgen, L. A., Mehanika polimerov, No. 3, 1975, pp. 547—550.

(5) Godovsky, J. K., "Teplofizika polimerov", Chimija, Moscow, 1982.

(6) Nasilowski, J., "Exploding wires". Edited by W. G. Chase and H. K. Moore, Plenum, New York, U.S.A., 1964.