Reprinted from THE REVIEW OF SCIENTIFIC INSTRUMENTS, Vol. 32, No. 12, 1308–1313, December, 1961
Printed in U. S. A.

Technique for Studying Piezoelectricity under Transient High Stress Conditions*

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(Received August 9, 1961; and in final form, September 11, 1961)

An experimental technique is described which is being successfully used to study the transient high stress piezoelectric behavior of synthetic alpha-quartz. Short, flat-faced cylinders of quartz are impacted upon each other at high velocity to produce the desired transient stress in the range from 5–70 kilobar. Precision is maintained in the alignment of the flat impact surfaces so that the Hugoniot conservation of momentum and the relationship governing the impact of flat cylinders may be used to compute the stress imparted to the target cylinders of quartz. Electric charge release data are taken in conjunction with the initial passage of the stress wave produced by impact.

INTRODUCTION

SINCE the discovery of the piezoelectric effect by Pierre and Jacques Curie in 1880, considerable application of the effect has been made utilizing a number of piezoelectric materials.[1] Most of the applications involve the use of the material in an environment of low pressure and low electric field. Within this low signal range the properties of many piezoelectric materials have been very extensively investigated. Because of the experimental difficulties involved and since little application has been found for piezoelectric materials under high stress, high field conditions, only a meager amount of experimental data is available describing the mechanical and piezoelectric properties of piezoelectric materials when they are subjected to these "high signal" conditions. Interest in high pressure research in general has been steadily increasing and considerable interest has been shown in equation of state studies of metals when they are subjected to high transient stress.[2] In conjunction with free surface velocity techniques Goranson *et al.*[3] used the piezoelectric effect in a tourmaline crystal as a quantitative measure of a Hugoniot elastic limit for steel of 15.7 kilobar.[4] Pressure measurements were also reported as high as 324 kilobar. Minshall[5] used tourmaline to indicate arrival times of the various waves but did not attempt to use the piezoelectric effect as a quantitative indication of stress. Interest in the use of alpha-quartz for a continuous record of the details of the elastic wave structure in metals was shown in discussion periods at the Technical Conference on Response of Metals to High-Velocity Deformation.[6] Neilson, Benedick, and Halpin[7] have obtained very encouraging results in using quartz for this purpose. The use of quartz under these high stress, transient conditions clearly emphasizes the necessity of investigating the properties of quartz itself under similar conditions before it can be used with confidence in this unusual environment. It is the object of this paper to describe a technique which is being successfully applied to study the piezoelectric behavior of synthetic alpha-quartz when subjected to high transient stress.

IMPACT OF PROJECTILES

In order to vary the applied stress from low stress to the high stress region in small increments, the stress produced by the impact of flat-faced projectiles fired by a gun offers many advantages. If high enough impact velocities can be achieved, stress can be produced which is as high as the lower end of the pressure range which can be conveniently achieved with the detonation of high explosives in intimate contact with a metal (say about 70 kilobar). The general procedure used in the technique reported upon here is to impact two very short flat-faced cylinders of quartz upon each other and measure the electric charge produced in one of the cylinders due to the initial transit of the stress wave produced by impact. The relationships given below may be utilized to define the stress produced by the impact.

THE HUGONIOT CONSERVATION RELATION

The conservation relations of a stress wave front were first derived by Rankine and Hugoniot and are given by Rice *et al.*[2] From Newton's law of conservation of momentum it can be shown that the following relation describes a time-independent, one-dimensional stress profile,[8]

$$\sigma=\rho_0 u_s u_P, \tag{1}$$

where σ=stress imparted by the wave front, ρ_0=mass

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* This work was done under the auspices of the U. S. Atomic Energy Commission.

[1] See, for example, W. P. Mason, *Piezoelectric Crystals and Their Application to Ultrasonics* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1950); W. G. Cady, *Piezoelectricity* (McGraw-Hill Book Company, Inc., New York, 1946).

[2] See M. H. Rice, R. G. McQueen, and J. M. Walsh, "Compression of Solids by Strong Shock Waves," *Solid State Physics* (Academic Press, Inc., New York, 1958), Vol. VI.

[3] R. W. Goranson, D. Bancroft, B. L. Burton, T. Blechar, E. E. Hudson, E. F. Gittings, and S. A. Landeen, J. Appl. Phys. **26**,1472 (1955).

[4] 1 kilobar=982.92 atmospheres=14 504 psi=10^9 dynes/cm^2.

[5] S. Minshall, J. Appl. Phys. **26**, 463 (1955).

[6] Technical Conference on Response of Metals to High-Velocity Deformation held at Estes Park, Colorado, July 11–12, 1960, sponsored by Physical Metallurgy Committee, The Metallurgical Society, AIMMPE.

[7] F. W. Neilson, W. B. Benedick, and W. J. Halpin, Sandia Corporation, Albuquerque, New Mexico (private communication).

[8] Stress profile as used here refers to the relation between stress and space as viewed at a given time or the relation between stress and time as viewed at a given point.

density of the undisturbed material, u_s=propagation velocity of the wave front, u_P=particle velocity imparted by the wave front.

Stress and velocity are relative to the medium into which the stress wave is moving.

Let

$$z=\rho_0 u_s,$$

called the "acoustic impedance" by many investigators, when u_s is the elastic stress wave velocity. Then

$$\sigma=z u_P.$$

Since the stress is related to the particle velocity by the acoustic impedance characteristic of the stress profile being considered, a determination of particle velocity in a situation where the acoustic impedance is known leads immediately to the stress. It is assumed in our analysis that the stress wave propagation velocity is constant for all stress amplitudes within the elastic range and is equal to the low signal value. An experimentally determined particle velocity and the elastic acoustic impedance are sufficient for elastic stress determination. This assumption is consistent with the condition of the experiments if the stress range investigated extends from previously confirmed elastic regions into higher elastic stress regions. The assumption is also verified experimentally.

MECHANICS OF FLAT CYLINDER IMPACT

Consider now the case of a flat-faced cylinder moving at a velocity v_0 and impacting upon a stationary flat-faced target cylinder. At any time in which the surfaces of the two cylinders are in contact, the forces between the two surfaces are equal by virtue of Newton's third law. To maintain contact, the velocity of the two surfaces must also be equal. Taking the two cylinders to be of the same material, it follows that the particle velocity imparted to the stationary target by impact is

$$u_P=\tfrac{1}{2}v_0. \tag{2}$$

For an experiment meeting the requirements given in developing Eqs. (1) and (2), a measured impact velocity may be used to compute the particle velocity imparted by the impact. Knowing the particle velocity and acoustic impedance of the wave front, the stress due to impact may be computed.

In order to subject the specimen to a uniform input, it is necessary that the entire face of the specimen be impacted at the same instant. This places the requirement on any experiment which utilizes these relationships that instantaneous closure be achieved between the entire contacting surfaces of the two cylinders, that is the cylinders must be aligned at impact such that there is negligible "angle of tilt" between the two flat surfaces.

EXPECTED CHARGE RELEASE CHARACTERISTICS

Neilson and Anderson[9] have derived relations which describe the electrical characteristics of a piezoelectric medium in which a stress wave is propagating. The idealized one-dimensional situation is shown in Fig. 1. The expected behavior of the medium may be considered the same as that of two time-varying capacitors, C_1 and C_2, in series. This model is descriptive if the electric displacement D_1 is continuous across the stress wave front, that is $D_1=D_2=D_0$. As the stress wave enters the quartz, a quantity of charge $Q=PA$ is released, producing a potential V_1 on C_1. "P" here is the polarization produced due to the application of the stress and "A" is the electroded area normal to the direction of stress application. For short circuit conditions

$$V_1=V_2$$

or

$$Q_1(l-X_{(t)})/\epsilon_1=Q_2X_{(t)}/\epsilon_2,$$

where ϵ is the dielectric permittivity.

Since

$$Q_1+Q_2=Q_0=PA$$

and

$$X_{(t)}=u_s t,$$

it follows that

$$Q_2=PAu_s t/l \qquad \text{for} \quad \epsilon_1=\epsilon_2$$

$$i=dQ/dt=PAu_s/l. \tag{3}$$

As shown in Fig. 2, Eq. (3) predicts a current pulse constant with time during the transit of the wave. From a current versus time record obtained under short circuit conditions, several observations can then be made. If we are interested in relating an experimentally observed charge to a known applied impact stress, we may integrate the current versus time record to obtain the charge released due to the transit of this stress. If there is no tilt in the wave front, the transit time of the wave is indicated by the time from the initial indication of current to the abrupt

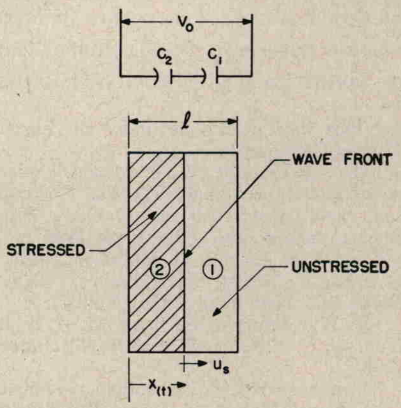

FIG. 1. Stress wave in a piezoelectric medium.

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[9] F W. Neilson and G. W. Anderson, Sandia Corporation, Albuquerque, New Mexico (private communication).