

of about  $5 \times 10^{-4}$  radian is satisfactory for the type of experiments to be described. Various investigators have used different means to achieve the precisely aligned impact, and the technology for achieving this is reasonably widespread although principally utilized for the measurement of mechanical properties.<sup>5</sup> If provisions for securing low values of tilt are not made, meaningful measurements are not possible in the particularly important low-velocity (low stress) region. Further, it is important to compare shock-wave measurements in their low-pressure limit to atmospheric pressure values. Thus, exclusion of the low-stress region is a serious experimental limitation.

To prevent air-pressure buildup between the rapidly closing surfaces of the facing and specimen, it is necessary to evacuate the space between the projectile and specimen to a pressure of about  $10^{-3}$  torr. The high pressure driving the projectile is sealed from the vacuum by O-ring seals on the projectile.

As will be demonstrated later, one of the most useful measurements made in an impact experiment is that giving the velocity of the impacting surface. For the impact of like materials, this velocity measurement gives additional data to that which can be obtained in an explosive loading experiment, and much of the effectiveness of the impact experiment is lost if the provision for velocity measurements is not made. The most precise measurements are made with electrical discharge contact pins which may protrude either through the side of the gun bore (17) or through the plane of the specimen toward the projectile (18). The velocity of the impacting disk at the instant of impact typically can be measured to  $\pm 0.5$  percent.

Measurements of the electrical behavior of the specimen usually require a conducting electrode at the impact surface. To maintain precise alignment and provide minimum distortion to the shock wave, the electrode is normally a thin vapor-deposited layer of aluminum or silver.

Although not absolutely essential, the effectiveness of the experiment is greatly enhanced if a preselected impact velocity can be achieved within about 5 percent of the desired velocity. Even though the velocity is to be precisely meas-

<sup>5</sup> Impact techniques also are effectively employed for the measurement of mechanical properties. Since many of the alignment techniques and other experimental problems are similar, a supplementary list of references on mechanical property measurements by impact techniques is included at the end of the individually cited references.

ured on each experiment, there are numerous instances for which experiments are required in the neighborhood of a critical point. Further, this control results in the capability of achieving virtually continuous values of stress over a range of stress which can be quite large.<sup>6</sup>

In summary, an impact experiment suitable for well-defined physical property measurements has the following general features:

- 1 Precise alignment of the impacting surfaces of facing and specimen disks.
- 2 Provisions for impact in vacuum.
- 3 Precise measurement of velocity at impact.
- 4 Capability of obtaining a preselected impact velocity.

#### The Impact Relationships

If the impact of two flat surfaces is achieved under the conditions described in the foregoing, the particle velocity imparted to the specimen as a result of the impact can be precisely determined. The relations that specify the impact conditions follow from the consideration that for all times when the impacting and impacted surfaces are in contact, the stress and particle velocity must have the same values across the interface. Thus, it follows that

$$U_0 - u_a = u_b \quad (3)$$

and

$$\sigma_a = \sigma_b \quad (4)$$

where  $U_0$  is the impact velocity,  $u$  is the particle velocity, and  $\sigma$  is the stress in the impact direction imparted to the facing. The subscript,  $a$ , refers to the sample and the subscript,  $b$ , refers to the specimen. Combining these relations with equation (1) results in the relation

$$u_b = \frac{Z_a}{Z_a + Z_b} U_0 \quad (5)$$

where  $Z$  represents the shock-wave impedance ( $\rho_0 U$ ) for the stress and particle velocity of the experiment.<sup>7</sup> Thus, if the properties of the facing and specimen are known, the particle velocity can be computed from the measured impact velocity. In general, however, these properties are unknown

<sup>6</sup> The author has performed experiments from 2.5 to 450 kbar with the gun described in Reference 11.

<sup>7</sup> In general, the impedance of the solid will depend upon the stress; thus, a graphical solution would be employed for the particle velocity rather than the analytical method implied by equation (5) (2-p179).

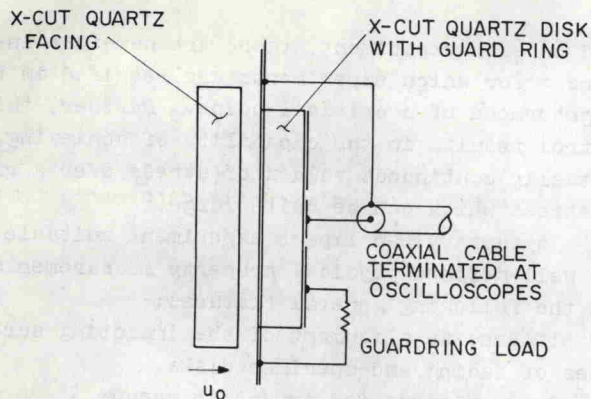


Fig. 3 Experimental arrangement for the measurement of the piezoelectric coefficient. The guard ring geometry is employed to obtain one-dimensional conditions

or not known with sufficient precision so that it is difficult to perform precise experiments with dissimilar materials impacting upon each other.

However, if the facing and specimen are the same material, equation (5) is greatly simplified, since

$$u_a = u_b = u = \frac{1}{2} U_0 \quad (6)$$

For this condition, the particle velocity imparted to the target is precisely known, regardless of the material used or whether its properties are known. The impact of identical materials, termed the symmetric impact, is clearly the best defined condition for use in impact experiments and is utilized in the major portion of the work to be presented.

#### PHYSICAL PROPERTY MEASUREMENTS

Impact techniques are best illustrated by describing specific methods employed for various measurements. Some of these measurements are reported here for the first time while others are reported in more detail elsewhere and are shown here only to illustrate particular features of technique.

##### Piezoelectric Properties of X-cut Quartz

The most extensive measurements accomplished to date have been made to determine the piezoelectric properties of X-cut quartz (19-23) under shock-wave compression. As illustrated in Fig. 3, both facing and specimen are disks of X-cut quartz. For a given experiment, the velocity of the impacting disk is measured along with the short-circuited current which results from the shock wave traversing the specimen disk. Previously it was demonstrated (23) that this cur-

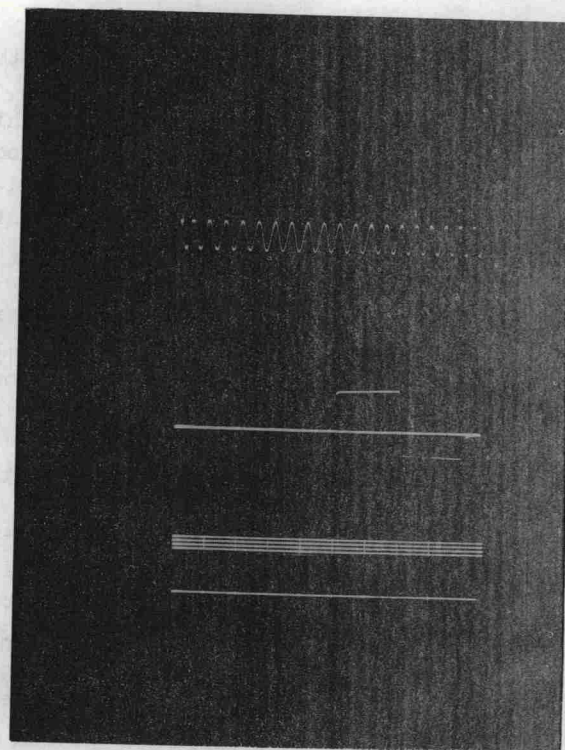


Fig. 4 Typical current-time record from impact-loaded quartz. A timing wave of 10 Mc is shown at the top, and the amplitude calibration is below the signal. Time increases from right to left. The positive signal corresponds to transit of wave through the crystal. Negative signal is that due to reflected wave from rear of specimen

rent,  $i$ , produced by the piezoelectric effect is

$$i = f_{11} \frac{\sigma A U}{\ell} \quad 0 < t < \ell/U \quad (7)$$

where  $f_{11}$  is the piezoelectric coefficient relating the component of stress to the resulting charge on the x-face;  $A$ , is the area of the disk;  $\sigma$  is the x-component of stress;  $\ell$  is the thickness of the disk, and  $t$  is the time. In the low signal limit,  $f_{11} = e_{11}/c_{11}$ , where  $e_{11}$  is the piezoelectric stress constant and  $c_{11}$  is the elastic stiffness constant. It is apparent from equations (6), (7), and (1) that measurements of  $U$  and  $U_0$  along with the resulting current and pre-determined dimensions of the disk are sufficient to determine the piezoelectric coefficient.

A typical current-time oscilloscope trace is shown in Fig. 4. The record not only shows the current amplitude but also the time taken for the shock wave to traverse the known thickness of the specimen disk. From this measured transit time and the measured impact velocity, the particle velocity and shock velocity are specified precisely on each experiment. This method of measuring