from axial heat flow out uninsulated ends. The interfacial resistance between the two copper cylinder surfaces and the test material was only half as important (only one interface) for the EPDM as in other tests, but that effect must always produce a lower effective thermal conductivity, rather than the higher value measured here. Similarly, the tube removal resulted in no more than a one to two percent uncertainty in diameter and that error should not have exceeded the diametral uncertainty.

Two other insulation materials, designated HTPB and SIPB, which were peculiar to the Jet Propulsion Laboratory solid rocket motor program were also tested. They represented an additional fifty tests and the inner and outer cylinders were both present. The mean thermal conductivity values for the HTPB and SIPB were 0.1214 W/m K and 0.1135 W/m K, respectively. While no standard measurement data are available for those materials, the measured values were consistent with the observed performance of those materials in the test program. Currently, the authors are awaiting verification of those data by the National Bureau of Standards.

The results of these preliminary tests have been very encouraging. The small standard deviation for measurements taken over a relatively long time interval indicates that the system behaves very reproducibly. An optimum sized apparatus can be developed which has a predictable end loss correction, combined with a convenient test cylinder size, in terms of casting requirements and accuracy.

The system can be modified readily for investigating temperature dependent thermal conductivity or the thermal conductivity of explosive materials. Different insulation temperatures can be examined by either using a pressurized steam system or by using heating fluids with different boiling temperatures—thereby varying $T$, and the mean insulation temperature. The test cylinder can be isolated electrically for measurements of explosives if the thermocouple temperature transducers are removed and the surface temperature of the two cylinders are monitored using an infrared scanning system.

This work represents one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract NAS7-100, sponsored by the National Aeronautics and Space Administration. The authors would like to thank Robert L. Ray for his assistance in performing these experiments, and Warren L. Dowler and Richard L. Bailey for their suggestions and support.

A goniometer for cutting single crystals

G. L. Price

School of Mathematical and Physical Sciences, Murdoch University, Murdoch, 6153, Western Australia

(Received 22 October 1979; accepted for publication 21 March 1980)

A simple, compact and robust goniometer is described which is suitable for aligning and cutting metal single crystals with a slow speed saw.

PACS numbers: 06.60.Ei

This goniometer was designed for the orientation and the cutting of metal single crystals with a slow speed saw. The principle of operation is shown in Fig. 1. The relative rotation of two wedges of angle $\alpha$ gives an angular range of 0 to $2\alpha$, while rotating the crystal in the top wedge brings the desired plane parallel to the saw and perpendicular to the x-ray beam. The crystal is first aligned by Laue diffraction with the arm clamped to the x-ray generator. It is then transferred to the slow speed saw.

The advantages of this device are that it is compact and light but extremely robust; and it has a high precision even though small, because a 180° relative rotation of the wedges corresponds (for $\alpha = 23^\circ$) to a range of 0° to 46° and hence a 0.2° precision can be obtained without a vernier scale. (The choice of angular range will be determined by the crystal structure, the planes required and the crystalline orientation of the ingot.) The disadvantage is that the rotations are not simply related to the angles measured by a Greninger chart. However these equations are derived below, and in practice the use of a small programmable calculator bypasses this difficulty.

The geometry of the goniometer is shown in Fig. 2. A, B, C and D lie in the plane of the photographic plate.
with AO along the incident x-ray beam and normal to the plate; OD is the normal to the crystal plane and is to be brought to coincide with OA; OB is the axis around which the top wedge rotates and OC is the axis of the crystal ingot. The saw arm is clamped so that AB (which lies parallel to the saw arm and in the plane of Fig. 1) is parallel to the edge of the film. Thus $\delta = \angle DOA$ and $\epsilon = \angle DAB$ can be determined with a Greninger chart and $\phi$ and $\theta$ are the angles engraved on the goniometer. The angles $\omega = \angle DOC$ and $\gamma = \angle AOC$ are used in the calculation and $\epsilon, \phi$ and $\theta$ are measured in planes normal to their corresponding axes.

It is easily shown that for a pyramid with two sides perpendicular to the base, the angle subtended by these two sides in the basal plane is

$$F(x,y;z) = \arccos \left( \frac{\cos z - \cos x \cos y}{\sin x \sin y} \right), \quad (1)$$

where $x, y$ and $z$ are the angles at the apex of the pyramid in the planes of the two perpendicular sides and the third side respectively. The convention

$$\arccos(t) = \pm \arccos(t) + 2k\pi, \quad (2)$$

where $k$ is an arbitrary integer, has been used.

This equation can be applied to Fig. 2 in the following manner: the apex angles of the pyramid with base ABC are used to find $\phi$; the sum of the adjacent $\angle CAB$ and $\angle CAD$ of the pyramids of bases ABC and ACD give $\epsilon$; and a similar procedure with these same pyramids gives $\theta$. Hence

$$\phi = F(\alpha, \alpha; \gamma), \quad (3)$$

$$\epsilon = F(\alpha, \gamma; \alpha) + F(\gamma, \delta; \omega), \quad (4)$$

$$\theta = F(\alpha, \gamma; \alpha) + F(\gamma, \omega; \delta), \quad (5)$$

where $\delta$ and $\phi$ are known, $\gamma$ can be found from (3), $\omega$ from (4) and $\theta$ from (5).

The new values of $\theta$ and $\phi$ which make DO and AO coincident occur when $\delta = 0$ and $\gamma = \omega$. The change in $\theta$ and $\phi$ required is then

$$\Delta \theta = F(\alpha, \omega; \alpha) - F(\alpha, \gamma; \alpha) - F(\gamma, \omega; \delta) \quad (6)$$

$$\Delta \phi = F(\alpha, \alpha; \omega) - \phi. \quad (7)$$

The multiple solutions arising from Eq. (2) make this general method cumbersome. A simpler procedure is to take the first Laue photograph with $\phi = 0$. Since OC is then normal to the photographic plate, $\theta$ and $\omega$ can easily be found from the indexed pattern. Hence

$$\Delta \theta = \arccos \left( \frac{\cos \alpha - \sin \alpha \sin \omega}{\cos \alpha \cos \omega} \right) - \theta \quad (8)$$

$$\Delta \phi = \arccos \left( \frac{\cos \omega - \sin ^2 \alpha}{\cos ^2 \alpha} \right). \quad (9)$$

This goniometer has been used successfully to cut a number of different metal single crystals over the past two years. It has been found to be extremely robust and if necessary its size could be reduced without affecting its performance.

Valuable comments by S. Thurgate, a suggestion by H. J. de Bruin and the skillful craftsmanship of M. Lindau are gratefully acknowledged.

\* Present Address: Telecom Australia, Research Laboratories, 770 Blackburn Road, Clayton, Victoria.