Comment by M. T. Lilburne on a Letter by Dr J. J. Bikerman

Bikerman has raised four points.

Firstly, it is not assumed that there is zero elastic strain around a gas filled bubble in a solid, but that the strain present is negligible at equilibrium compared with the surface energy term for the particular size of bubbles considered. This was discussed in the paper and reference should be made also to the work of Lidiard and Nelson [1]. Elastic strain produces contrast in an electron microscope (see Brown and Mazey [2] for example) and was observed. This phenomenon only occurs when copper foils are annealed for short times at low temperature, say 400° C. Obviously, equilibrium has not been established.

Secondly, although it can be shown that $P = 2\gamma/r$ for faceted bubbles by using a virtual work argument, results were not used for such bubbles. (P is the gas pressure within a bubble and γ is the surface energy. The exact value assigned to r must be an average of the shortest distance from the centre of the bubble to the planes of the facets.) As was stated in the paper, faceted bubbles were thought to be severely contaminated by oxygen. Bubbles with clean surfaces were essentially spheres and thus exhibited little anisotropy of surface energy. Any error in considering these bubbles as spheres is within experimental error.

The third point, marked 2 in Bikerman's letter, has no relevance to this work.

The final sentence of Bikerman's comment is a generalisation which apparently dismisses the rigorous and accepted theoretical work of Herring [3] and of Mullins [4] and a large body of experimental evidence.

References

1. A. B. LIDIARD and R. S. NELSON, *Phil. Mag.* **17** (1968) 425.
2. L. M. BROWN and D. J. MAZEY, *ibid* **10** (1964) 1081.
3. C. HERRING, "Structure and properties of solid surfaces", edited by R. Gomer and C. S. Smith (The University of Chicago Press, 1953) p. 5.
4. W. W. MULLINS, "Metal Surfaces" (The American Society for Metals, 1963) p. 17.

Received 3 September and accepted 14 October 1970

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Validity of Kovacs and Nagy Equation

Kovacs and Feltham [1] and Kovacs and Nagy [2] derived an equation for the total equivalent mean shear strain $\bar{\gamma}$ of a wire plastically twisted about its axis at constant tensile load. In this equation, $\bar{\gamma}$ consists of the torsional shear strain ND/L and the shear strain component equivalent to the associated tensile strain $\Delta L/L_0$ as follows:

$$\bar{\gamma} = \alpha\pi ND/L + \beta\Delta L/L_0 \qquad (1)$$

where N is the number of turns of twist, D is the diameter of the wire, and L_0 and L are initial and instantaneous lengths of the wire. α and β are constants. The numerical values of α and β were taken to be 1/3 and 2.24 respectively [1]. Kovacs and Feltham [1] also indicated that these values were underestimated because the mean torsional strain was evaluated on the assumption that the wire was purely elastic. They pointed out that the assumption of ideal plasticity of Gaydon [3] would be more appropriate. Recent work [4, 5] has also indicated that the values of α or β are $2\pi/3$ and 3 respectively.

Equation 1 could be written in the form:

$$\begin{aligned} \Delta L/L_0 &= -(\alpha/\beta)\, ND/L + \bar{\gamma}/\beta \\ \epsilon &= -(\alpha/\beta)\,\theta + \bar{\gamma}/\beta \end{aligned} \qquad (2)$$

or

where $\epsilon = \Delta L/L_0$ and $\theta = ND/L$.

By partial differentiation of ϵ with respect to θ at constant $\bar{\gamma}$ and substituting for the values of α and β we get:

$$\begin{aligned} \left(\frac{\partial\epsilon}{\partial\theta}\right)_{\bar{\gamma}} &= -(\alpha/\beta) \\ &= -2\pi/9 \\ &= -0.698 \end{aligned} \qquad (3)$$

Equation 3 shows that the rate of change of tensile strain per unit torsional strain at constant $\bar{\gamma}$ has a constant value of -0.698. Since the value of $(\partial\epsilon/\partial\theta)\bar{\gamma}$ could be determined experimentally, the validity of the Kovacs-Nagy equation (equation 1) and the ratio α/β could be determined. The purpose of this work is to use this approach for determining the validity of Kovacs-Nagy equation (K-N).

Al wires of 0.05 cm diameter and 15 cm long were used. The composition of the material was: Fe 0.25, Si 0.05, Mg 0.02, and Cu 0.005 (wt %). The wires were annealed in vacuum before use. The specimens were subjected to uniform twisting in a conventional twisting machine [6] at room temperature. Axial tensile loads were applied during twisting. The magnitudes of the stresses varied from 0.75 to 2.25 kg/mm². The associated change in sample length was measured up to fracture with an accuracy of 10^{-3} cm.

Fig. 1 shows that the tensile strain $\Delta L/L_0$ accompanying torsional strain (ND/L) increases as the magnitude of applied stress is increased. If $\Delta L/L_0$ is plotted against $\bar{\gamma}$ (determined from equation 1), similar results are obtained.

To calculate the values of $(\partial\epsilon/\partial\theta)\bar{\gamma}$, the values of $\Delta L/L_0$ at various $\bar{\gamma}$ were obtained from fig. 2, then using the *independent experimental information* shown in fig. 1 $(\partial\epsilon/\partial\theta)\bar{\gamma}$ were determined using the least squares method. These values are given in table I and are plotted against $\bar{\gamma}$ in fig. 3. The average value of $(\partial\epsilon/\partial\theta)\bar{\gamma}$ over the whole range of $\bar{\gamma}$ is approximately equal to the

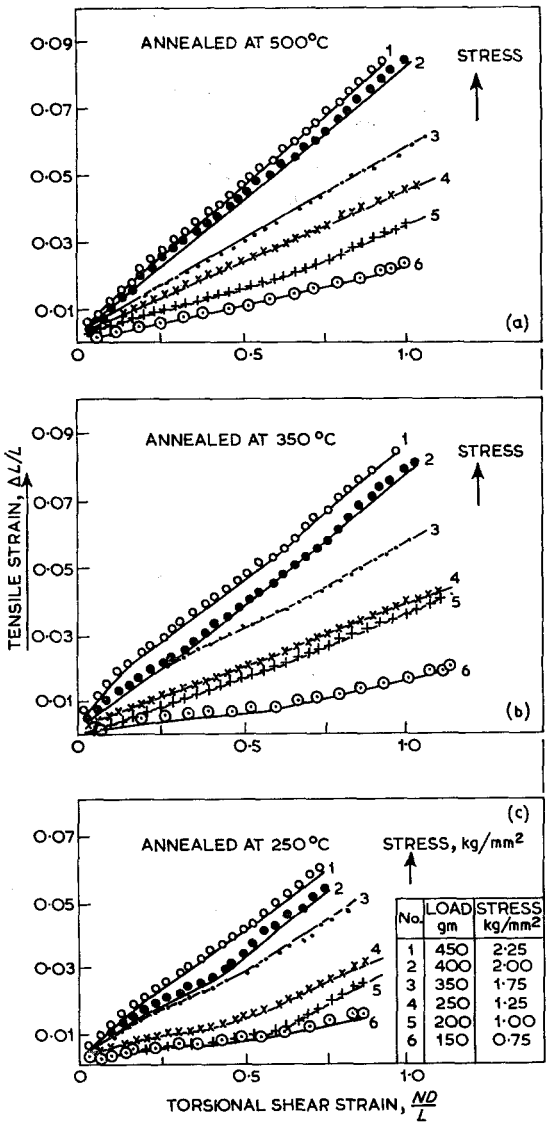

Figure 1 Effect of torsional shear strain ND/L at various applied loads on the tensile strain $\Delta L/L_0$.

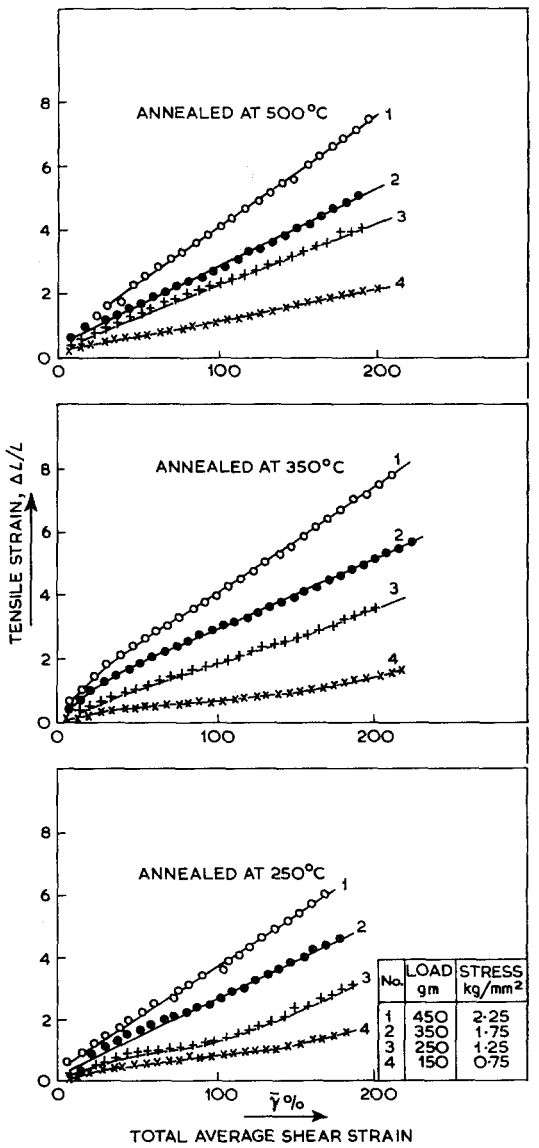

Figure 2 Relationship between tensile strain $\Delta L/L_0$ and total average shear strain $\bar{\gamma}$ at various applied loads.

TABLE I

$\bar{\gamma}$	$\left(\frac{\partial\epsilon}{\partial\theta}\right)_{\bar{\gamma}}$ 250° C	350° C
0.435		− 0.65
0.440		
0.450	− 0.68	
0.480		
0.500	− 0.80	
0.600		
0.620		
0.630		− 0.70
0.640	− 0.82	
0.700	− 0.65	− 0.40
0.800		
0.920		− 0.50
1.000	− 0.70	
1.200	− 0.63	− 0.70
1.400	− 0.72	− 0.65
1.500		
1.600	− 0.67	− 0.63
1.700	− 0.82	
1.790		−0.76
1.800	− 0.80	
1.880		
2.000		− 0.60

constant $-\alpha/\beta = -0.7$. The resemblance of the experimentally determined values of α/β to that given by equation 3 indicates that the Kovacs-Nagy (K-N) equation is valid.

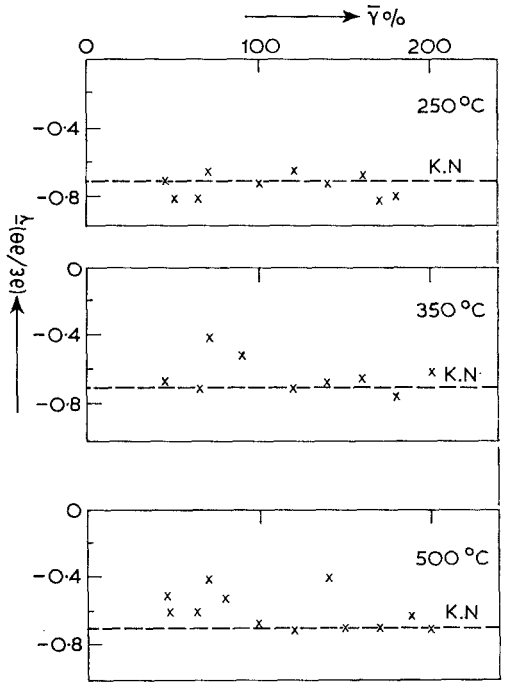

Figure 3 Variation of the relative change of tensile strain with plastic torsion $\partial\epsilon/\partial\theta$ vs. $\bar{\gamma}$.

References

1. I. KOVACS and P. FELTHAM, *Phys. Stat. Sol.* **3** (1963) 2379.
2. I. KOVACS and E. NAGY, *ibid* **8** (1965) 795.
3. F. A. GAYDON, *J. Mech. Appl. Math.* **5** (1952) 29.
4. S. HOWE and C. ELBAUM, *Phil. Mag.* **6** (1961) 37.
5. P. FELTHAM, *ibid* **8** (1963) 989.
6. T. H. YOUSEF, Ph.D Thesis, Cairo University (1967).

Received 29 September
and accepted 12 October, 1970

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D.C. Hall Current Measurements on Organic Crystals

Hall voltage measurements of mobility against temperature normally used in the studies of conduction processes in semiconductors have serious limitations for high resistivity materials, such as organic solids. It is often impossible to separate surface and bulk effects for crystals of bulk resistivities greater than $10^2\ \Omega$m. Resistivities greater than $10^8\ \Omega$m present difficulties associated with input impedance and sensitivity requirements of the detection system. The Hall current measurement technique first described by Dobrovolskii and Gritsenko [1] can overcome these difficulties if single crystals of suitable dimensions can be prepared.

Hall current measurements on anthracene have been reported [2] previously and here the technique is detailed. The basic outline of the measuring circuit and the geometry of the specimen and electrodes are given in fig. 1. With this geometry the Hall field normally generated in the Hall voltage technique, is short circuited by the electrodes: one half of the resultant Hall current is detected across the split electrode $A_1 - A_2$. The surface effects are eliminated by the guard ring.

Measurements made in this laboratory on single crystal silicon specimens indicated that the accuracy of the Hall current technique depended critically on the contact resistances of the broad area electrodes. For silicon it was not possible to use the technique for material having resistivities over 1 Ωm, because satisfactory low resistance ohmic electrodes could not be fabricated with available equipment. The normal practice for conductivity measurements on