Letters

On the Relation Between Hardness and the Flow Curve of Metals

Many of the mechanical properties of a material are contained in the true stress/true strain curve which is usually obtained using tensile and compression tests. Tabor [1] however, has suggested a method by which the plastic region of the true stress/true strain curve may be determined from indentation hardness measurements. The method, although based to some extent on plasticity theory, is basically empirical. From an analysis of the indentation process Tabor concluded that the true stress, σ, was related to the Meyer hardness, HM, by

$$\text{HM} = 2.8\sigma \quad (1)$$

and that the true strain, ϵ, could be expressed as

$$\epsilon = 0.2\,\frac{d}{D} \quad (2)$$

where d is the diameter of the indentation caused by a ball of diameter D. Thus if the Meyer hardness is obtained for a range of d to D values under conditions of full plasticity, equations 1 and 2 can be used to derive an approximate flow curve.

Tabor found good agreement with the results obtained using his equations compared with values found from a compression test on mild steel, Cu and Al. Lenhart [2] confirmed the agreement for Cu and duralumin but found that the analysis did not hold for Mg and a series of Mg/Al alloys. This was attributed by Lenhart to the high anisotropy of deformation of Mg.

The usefulness of Tabor's correlation is most evident if the material is available in only small amounts. The object of the present investigation was to determine some limitations of the method.

A Hounsfield Tensometer with the appropriate attachments [3] was used to determine the tensile, compression and hardness results. A constant extension rate of 0.0125 in./min (1.0 in. = 2.5 cm) was used.

Compression tests were carried out on cylinders 0.25 in. diameter and 0.3 in. long. The plattens and specimens were polished and PTFE sheet 0.0025 in. thick was used as lubrication [4]. Conditions were selected that gave uniform deformation. Straining was stopped at frequent intervals, the length and diameter of the specimen measured with a micrometer, and the lubrication renewed. Various tests showed that stopping and starting during deformation under the conditions used did not affect the flow curve. Less accurate results from tensile tests were obtained by measuring the specimen diameter with a micrometer before necking, and by the Reduction in Area Gauge after necking had started. The requirements of British Standard 240 [5] was observed during hardness measurements.

Various metals were examined. All were in the fully annealed condition except a cold-worked Cu and a cast Zn. Materials were of commercial purity.

The results presented in fig. 1 demonstrate that the flow curves obtained from tensile,

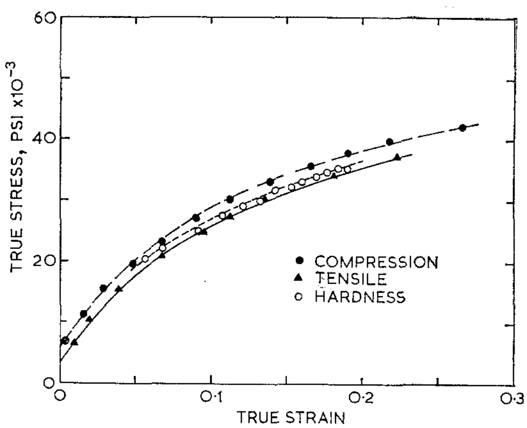

Figure 1 Flow curves of annealed Cu. *Note* psi units are used in this diagram. 1.0 psi = 1.0 lb/in.^{2} = 7.0 × 10^{-2} kg/cm^2.

compression, and hardness measurements are in quite good agreement. The flow curve is frequently expressed as

$$\sigma = K\epsilon^n \quad (3)$$

where K is the stress at $\epsilon = 1.0$ and n is the strain-hardening coefficient. The results of fig. 1 are displayed in a logarithmic form in fig. 2 together with recent results obtained in a precision measurement of the true stress/true

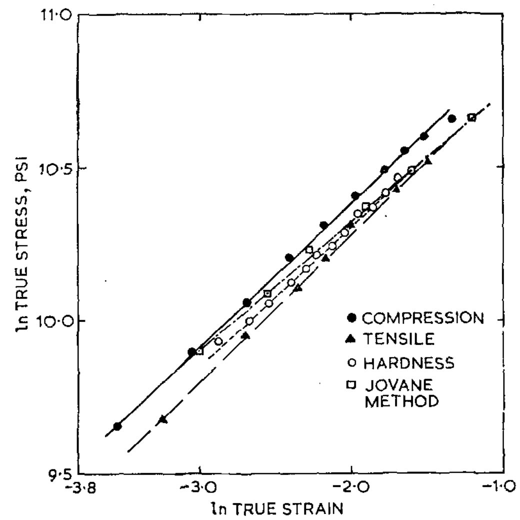

Figure 2 Logarithmic form of the flow curves of annealed copper compared with the results of Jovane [4]. *Note* psi units are used in this diagram. 1.0 psi = 1.0 lb/in.^{2} = 7.0 × 10^{-2} kg/cm^2.

strain curve of Cu [4]. It is seen that the agreement is good and that deformation of the Cu follows closely the logarithmic form of the flow curve. Results obtained with a Cu/15% Zn and Cu/5% Sn alloy also followed closely the pattern of fig. 1. These results are included in the logarithmic form of the flow curve derived from hardness measurements in the general survey presented in fig. 6. It should be noted that all the metals so far discussed are fcc, follow the logarithmic form of the flow

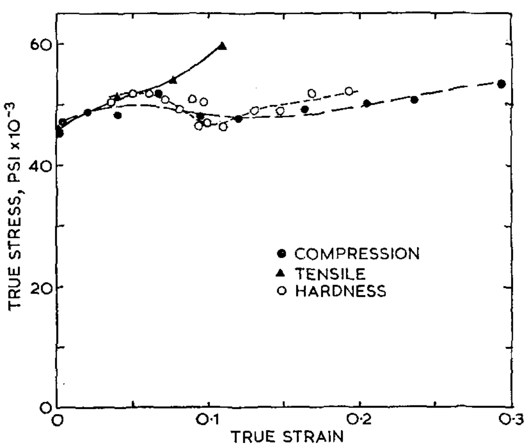

Figure 3 Flow curves of cold-worked Cu. *Note* psi units are used in this diagram. 1.0 psi = 1.0 lb/in.^{2} = 7.0 × 10^{-2} kg/cm^2.

curve, and have a good correlation between the tensile and compression flow curves with that derived from hardness measurements using Tabor's correlation.

In contrast, results obtained with the cold-worked Cu (figs. 3 and 6) and the cast Zn (figs. 4 and 6) show that Tabor's relationships do not hold in this case and that the logarithmic

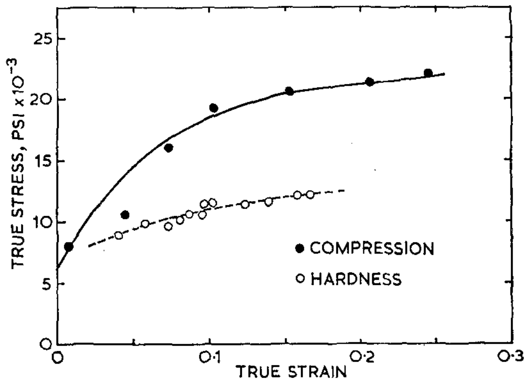

Figure 4 Flow curves of cast Zn. *Note* psi units are used in this diagram. 1.0 psi = 1.0 lb/in.^{2} = 7.0 × 10^{-2} kg/cm^2.

form of the flow curves are not linear. Presumably this is because of the anisotropy of deformation in the preferred orientated Cu and the cph Zn, since the analysis leading to equations 1 and 2 assumed the indented material was plastically isotropic [1]. However, in the case of the cold-worked Cu the Bauschinger effect may also introduce an error as suggested by Lenhart [2]. Fig. 6 indicates clearly that the deformation behaviour of the cold-worked Cu and the cast Zn during hardness testing is complex and non-uniform.

The two-phase Cu/40% Zn alloy was unusual in as much as the results obtained using equations 1 and 2 and the normal flow curves were in good agreement (fig. 5), but the logarithmic form of the hardness flow curve showed a non-linear behaviour as deformation continued. It appears that the overall isotropic nature of the two phase alloy was sufficient to satisfy the assumptions of Tabor's analysis but the influence of the two phases with different plasticity properties was slightly different as deformation proceeded.

It is concluded that it is necessary for a material to deform isotropically during indentation even though the material may be multiphase. A strong anisotropic deformation be-

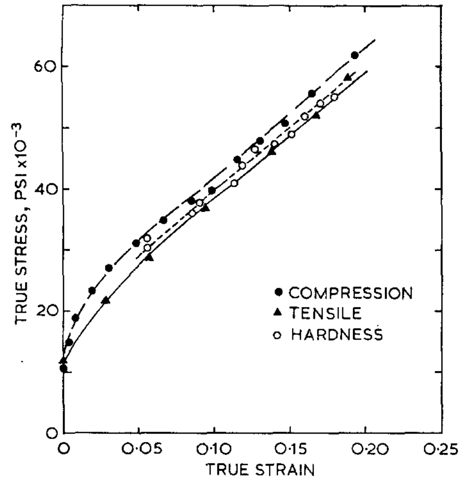

Figure 5 Flow curves of annealed Cu/40% Zn alloy. *Note* psi units are used in this diagram. 1.0 psi = 1.0 lb/in.^{2} = 7.0 × 10^{-2} kg/cm^2.

haviour, whether from the crystal structure or the metallurgical condition, is sufficient to cause the breakdown of Tabor's correlation.

References

1. D. TABOR, *J. Inst. Metals* 79 (1951) 1.
2. R. E. LENHART, WADC Technical Report 55-114 (June, 1955).
3. Hounsfield Tensometer Instruction Manual, Tensometer Ltd, Croydon, Surrey, UK.
4. F. JOVANE, Nat. Eng. Lab., East Kilbride, Glasgow (November, 1963).
5. Brit. Standard 240, Brit. Standards Inst., 2 Park Street, London W1.

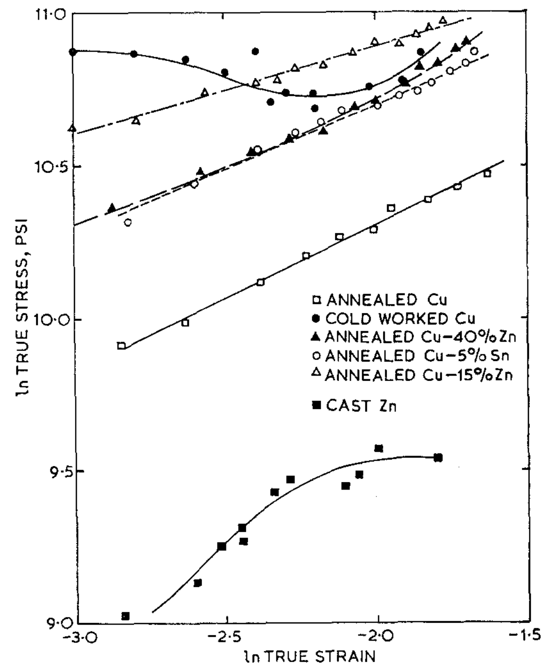

Figure 6 Logarithmic form of flow curves derived from hardness measurements. *Note* psi units are used in this diagram. 1.0 psi = 1.0 lb/in.^{2} = 7.0 × 10^{-2} kg/cm^2.

1 April 1968

W. J. TOMLINSON
K. TALBOT
Rugby College of Engineering Technology
Eastlands, Rugby, UK

Visually Observed Pressure-Induced Transformation Behaviour

The visual observation of temperature-induced phase transformations has been of great assistance in the characterisation of their mechanisms. Similar observations on pressure-induced transformations are limited [1], and in fact, the transformation mechanisms of pressure-induced changes are presently rather obscure. In the present work, a diamond high-pressure cell was used to obtain qualitative descriptions of pressure-induced phase changes in transparent materials; the study indicates that, as in the case of temperature-induced phenomena, both nucleation-and-growth and martensitic-type transformations can occur.

The diamond cell and its utility has been described in detail in the literature [1-7]. Essentially, two diamonds serve as anvils; the smaller diamond has a surface area of approximately 0.16 mm^2. Loading is provided by a hand-operated turn-screw. Desired radiation passes through the diamonds parallel to the