MECHANICAL PROPERTIES—A SCIENTIFIC APPROACH

By

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ABSTRACT

Broadly there are two aspects of what is meant by mechanical properties namely strength and ductility. These properties are measured by various mechanical tests and rather arbitrary values are obtained from these tests. The present conception of true stress and true strain in simple tension test suggests the existence of mechanical equation of state. The article reviews how some of the common properties could be derived from this simple test and how with the progress of our understanding of reactions of forces within metals, a unifying conception of mechanical properties may be developed. It is advocated that in the present state of development many common mechanical properties may be replaced by other values derived from the true stress-strain curve.

Engineers evaluate metal products against certain standards. These standards are the so-called mechanical tests to determine well-defined properties. In other branches of science properties are based on a rigid understanding of requirements. In case of electrical properties for example, the resistance, conductivity, etc., are well defined in units. In mechanical properties the resistance can be a united force, a ratio, as in creep resistance or an amount of energy as in impact resistance. The idea of strength and hardness, toughness and brittleness are often confused What are really the mechanical-properties ? These can be defined as the reaction of the metals and alloys to resist applied forces. It has fallen to the design engineers to devise mechanical tests as short cuts to practical services tests. The resulting trend has been to know the reactions of metals to certain set forces under given conditions, and derive empirical relations thereon.

Let us take the most widely used mechanical property viz., Tensile Strength. This is definied as the maximum load divided by the original minimum cross-sectional area of a test piece. This definition is commonly made use of by designers. But can we find any scientific justification for such a value to be defined as tensile strength ? Ordinarily the results of tensile tests of metals are presented graphically in which the load divided by the original cross-sectional area is plotted as a function of the percentage elongation measured over some specified gauge length. The value of such graphs is limited since the actual stress required to deform the metal at any stage of the tensile deformation is given by the load divided by the 'instantaneous' area rather than the original cross-sectional area of the test piece. Furthermore, each increment of the deformation is performed on metal that has been previously deformed and as pointed out by Ludwik[1] the strain could more effectively be defined as

$\epsilon = \ln \frac{A_o}{A}$ where ϵ is the strain and A_0 and A are respectively the original and instantaneous areas.

For large strain, the change in dimensions due to the change in volume accompanying elastic deformation will be small compared to the change in dimensions arising from plastic flow. If the actual area under load is measured, the plastic strain is equal to $\ln \frac{A_0}{A} - 2\mu(S/\epsilon)$ where A is area under load, μ Poisson's ratio, S the stress and C-Young's modulus.

The results of the tensile tests can more effectively be presented and interpreted if the stress (load divided by the actual instantaneous area) is plotted as a function of the strain as defined above. A schematic curve of this type is presented in Fig. 1.

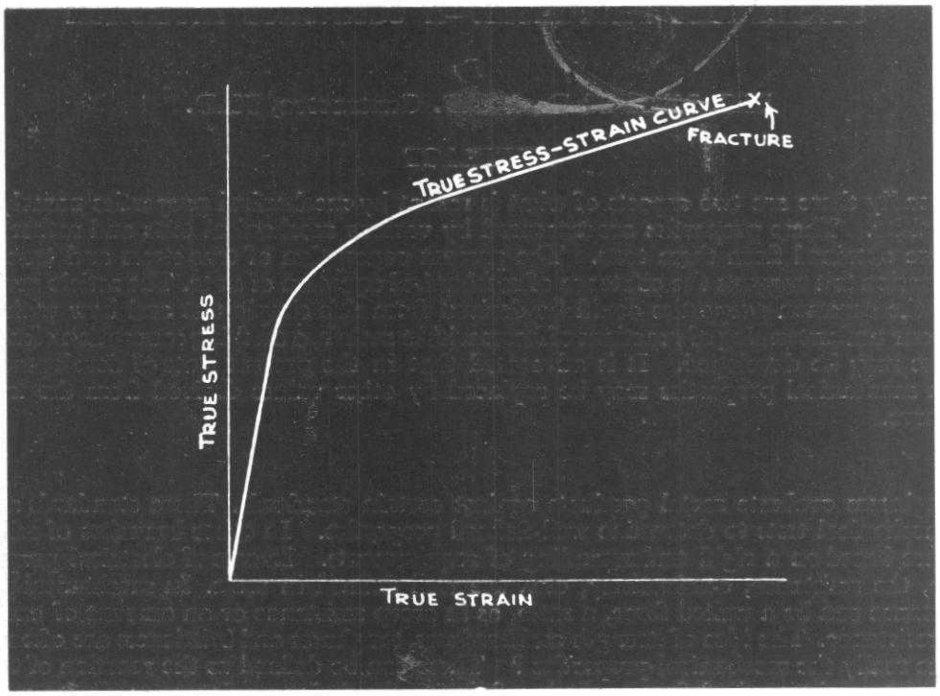

FIG. 1. True stress-True strain Diagram

After necking commences, the stress in the necked region is not strictly uniform or uniaxial. The correction to the average tensile stress necessitated by the non-uniformity of the stress has been developed by Bridgman[2]. In moderately ductile materials, the correction to the average tensile stress as calculated above is found to be small.

If the stress and strains are properly calculated, it then is observed that curves for tension, compression and shear are identical in shape and there is scope for believing that experimental errors and/or purely secondary reasons relatively unimportant are responsible to account for the small differences.

From this scientific basis of stress and strains we can foresee how a 'mechanical equation of state' can be formulated. Hollomon[3] has re-examined and extended Ludwik's conception concerning the nature of the mechanical behaviour of metals and suggested that there exists, atleast under certain conditions, a mechanical equation of state—that the stress required for flow depends upon the instantaneous values of the strain, strain-rate and temperature. It is presumed that under these circumstances the stress does not depend upon the past history of these variables but functions like the temperature of a gas which depends only upon the instantaneous values of pressure and volume.

$S=K(\epsilon)^m$ after the initial yielding where m is the slope of the stress strain curve.

$S=K\epsilon^m$

where S is true stress

ϵ is true strain

and K and m are material constants.

On a log-log plotting the above function represents a straight line of slope m and height log K. Hence m is identified as the strain hardening co-efficient of the material whereas K is related to relative strength and is numerically equal to stress when the strain is unity.

From Hollomon's study it is observed that in under conditions wherein mechanical equation of state is found to apply to plastic deformation, certain general relations between strain rate, temperature, stress and strain could be applied both in case of tensile and creep deformations.

There are, of course, certain conditions when such an equation of state could not apply. If metallurgical changes occur ; within the metal during the deformation the past history of the temperature and strain rate will affect the stress required for flow. For example, if a metal is deformed to the same strain at a low temperature and then heated to an elevated temperature, recrystallisation will not occur until after a finite time at the elevated temperature. The past history does in this case influence expected behaviour. Metallurgical changes such as tempering, precipitation hardening, in fact, any type of phase change many invalidate the application of the equation of state.

If the equation of state describes the mechanical behaviour of metals, the creep behaviour of metals may be directly derivable from their tensile behaviour, that is, the true curve. Hollomon has analysed the tensile and creep data available and confirmed that the qualitative nature of creep may be derived from the behaviour of metals as deforming under a varying load in simple tension. The quantitative derivation is possible not obtained due to secondary creep rate being plotted as a function of temperature or load. Since the strain is not constant when the creep rate is a minimum these relations become extremely complex.

Zener and Hollomon have made a fair case for a single valued functional relationship between strain rate and temperature. If such an equivalence is borne out by more experience, the time required for creep test may be appreciably shortened. For example, a specimen allowed to creep to a given strain and a specimen deformed to the same strain in simple tension, the two should thereafter behave identically. To shorten creep tests therefore, some of the deformation may be introduced by simple tensile stress. Such experiments would also indicate the range of applicability of the relations demanded by the mechanical equation of state.

Vivian[4] has analysed the true stress strain curve to interpret some of the other common properties from the true stress-strain curve.

Toughness : Toughness is the specific reaction in work per unit volumes upto any desired point of stress and strain, extended to the fracture point if desired. Toughness can be calculated from the true-stress (S) and true strain (ϵ) by measuring the area under the true curve thus :

$$\int_{\epsilon=0}^{\epsilon=\epsilon} S \, d\epsilon$$

and if the curve shape is identified by the equation—

$$S = K(\epsilon)^{m}$$

toughness can be calculated

$$K\int_{\epsilon=0}^{\epsilon=\epsilon} \epsilon^{m} d\epsilon \quad \ldots \ldots \ldots \quad \text{which is} \quad \frac{k\epsilon^{m+1}}{m+1}$$

This seems to be an exemplary case.

The true curve denoted by the equation $S=K\epsilon^{m}$ would be varying for particular metal according to temperature and strain rate.

Let us take hardness. We principally use the hardness values which are determined by resistance to penetration—a Brinell ball or a diamond pyramid. But there are also other hardness values as scratch hardness or the rebound hardness. In scratch hardness the width of the microcut made by the ploughing action of diamond is measured while in the latter the principle employed is the drop and rebound of diamond—tipped hammer in which the rebound is a measure of the hardness of the material. In general, these values can be correlated and the relation is rather proportional.

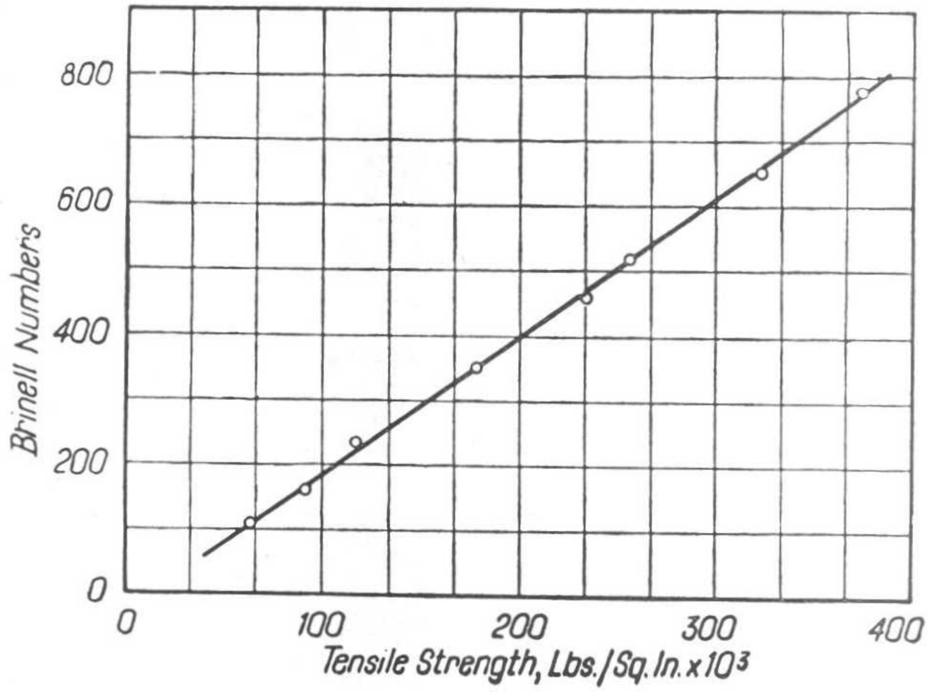

Fig. 2: Relation between hardness and tensile strength.

It will be seen from Fig. 2 that the hardness numbers are proportional to tensile strength, which also makes it possible to see how this value can be synthesized. Reason for hardness values being greater than that of the true curve is the lateral strain restriction characteristics of different materials subjected to local or, central loading. The 'piling up' or 'sinking in' of the material around the edges of this imprint of indentation is a common sight. A recent analysis of the Brinell test shows that under ordinary hardness conditions of lateral strain restriction the ordinary strength is increased by the factor $(\mu-1)/(\mu-2)$ where μ is the Poisson's ratio, even when it is an apparant Poisson's ratio in plasticity. The published values of μ apply to what is known as the elastic range only, as Poisson's ratio is supposed to be an elastic property. It can, however, be argued that since the true curve is also the strain hardening curve; by the time any stress of the plastic range has been induced for a short time, this strain hardening has so altered the stress-strain characteristics of the material that the socalled elastic range has risen upto the value of this plastic stress. The Poisson's ratio values can be applied for this case. So, of the fracture stress of a steel is say 65 tons/sq. in., calculating $(\mu-1)/(\mu-2)$ from the usual Poisson's ratio $3 \cdot 3$ for such steels, the axial stress required under hardening loading conditions to produce fracture would be $65 \times 1 \cdot 77$ or 115 tons/sq. in., or 180 kg/sq. mm. which is the Brinell hardness Number itself for such a steel.

From the foregoing it becomes apparant how a mathematicacal approach to mechanical properties can slowly bring out the unifying conception about mechanical behaviour of metals under load.

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Discussion

Dr. V.G. Paranjpe and Dr. T.V. Cherian, (Tata Iron & Steel Co., Ltd.) :

The authors suggssted that one advantage to be gained by the use of true stress vs. true strain curves was that they could be fitted into the mechanical equation of state. It must be made clear that the basic assumption of this latter relation that the prior mechanical and thermal history has no influence on the flow characteristics of the material, was invalid. We could refer to accurate data on pure aluminium,[1,2] 2S—0 aluminium[1], copper[1,2] 65—35 brass[1], nickel[3], K-Monel[3], plain phosphor bronze[3], leaded phosphor bronze[3], ingot iron[4], 0·12 % C Steel[1], 0·46 % C steel[4], and 18—8 stainless steel[1]. The flow characteristics of none of these materials were in conformity with the mechanical equation of state. Experiments performed before the proposal of this relation on napthalene crystals[5] also gave same result. In the light of this overwhelming evidence the conclusion that the postulated mechanical equation of state was incorrect appeared to be inescapable[6].'

Dr. M.S. Mitra :

Much interest had been aroused about the existence of 'a mechanical equation of state' chiefly because this would be a simplifying assumption in treating the engineering problem of materials. Although this simplifying assumption first made by Ludwik and then by Hollomon had been proven with experiments (1020 steel) there had been likewise, other experiments to disprove it. Ripling and Sachs[5] in a paper published in 1949 confirmed the observation of Hollomon with experiments on mild steel (2.75 % Si). From the discussion of Hollomon on Dorn's paper it was observed that the fight for the equation of state was still on. However, the burden of the present paper lay in its advocacy for adoption of the true stress-strain data for some common engineering properties determined otherwise. In this paper it had been shown how some other physical properties may be derived or substituted by true stress-strain data. Irrespective of the outcome of current controversy concerning the absolute utility or usefulness of the mechnical equation of state, there was no doubt that scientific conceptions introduced thereby, carried far-reaching implications. The present paper was an attempt to emphasize these values to Indian design engineers.

Mr. S. Ramanujam :

It had been suggested that tensile strength at present carried out had no theoretical significance. He would like to know whether there was any practical use for a theoretically correct determination involving considerable time and expense. In practice, every material contained surface scratches. As such, the engineer knew fully well that a false sense of security may be given by basing design or say fatigue results obtained on perfectly polished specimens. He therefore included a factor of safety often known as the "factor of ignorance" to provide for such contingencies in his calculations. Further, the failure of the cable bridges of Mounthope and Ambassador involving millions of dollars had shown the futility of basing design on conventional tests. The failure of war time welded ships had brought out certain as yet undertermined factors

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which had to be taken into account. Steels behaving similarly at ordinary temperatures may not behave similarly at lower temperatures. The only reliable methods was to test materials having the exact size and shape at the temperature range in which these would be finally used. The research metallurgists may prove in the laboratory that welding was better than rivetting but workmanship rivetting may provide relatively greater measure of safety. In this context, was there any purpose in striving to get theoretically accurate data which may involve merely more time and money. Was it not enough to get figures which were reproducible and which were basically sound and adequate to give the practical information a designer required ?

Dr. M.S. Mitra :

Appreciating the remarks by Mr. Ramanujam author stated that laboratory fatigue results, for example, were at best comparative. These results could, however, never be taken for actual values in service. But these results were still used for design after allowing standard factors of safety. The theoretically correct measures were cheaper in the long run as these values were significant and not merely arbitrary.