INVESTIGATION OF THE PLASTIC STRAIN AND FRACTURE OF METALS BY THE METHOD OF THE CHANGE OF SPECIFIC INTERNAL ENERGY

By

L. KATOR

Department of Mechanical Technology, Technical University, Budapest

(Received January 13, 1971)

Presented by Prof. Dr. L. GILLEMOT

I. Introduction

In general, structural materials do not undergo brittle failure but a major plastic strain precedes the failure. The local, plastic strain continues up to failure. It is a longstanding endeavour to elaborate a method for following up the changes in the structure of the material during deformation. This is possible — among others — by studying the changes in the internal energy of the metal.

Due to the fact that soft materials absorb much energy prior to failure, a major amount of mechanical work is necessary for plastic strain. In general, a major plastic strain can be observed in the vicinity of the failure, once again necessitating much energy. Thus in failure problems of highly plastic materials principles and methods relating the energy necessary to failure to unit surface, are likely to be inefficient. As the energy is consumed for the deformation of a certain volume, parameters indicating the changes in energy values referred to a unit volume have to be found.

According to the first main law of thermodynamics, the relation between the energy components is

$$W_M = W_S + W_T \tag{1}$$

where:

W_M mechanical (external) work

W_S part of mechanical work retained in the metal

W_T part of mechanical work transformed into heat.

A part of the mechanical work necessary for plastic strain is used for increasing the internal energy of the metal, while another part is transformed into heat.

In recent years more and more research has been done on the relationship between internal energy changes and strain. WOLFENDEN [1, 2] undertook low temperature tensile stress experiments on copper, aluminium and silver single crystals. For measuring the internal energy, he used a calorimeter. The relationship between strain and internal energy was determined in case of major strain, by working between two hammers, once again using a calorimeter [3]. For the case of major strain in even elongation, no uniform method for determining the internal energy is available. Internal energy may be calculated on basis of e.g. relationship (1), if the external work and its part transformed into heat is known. A method has to be elaborated, for determining the needed mechanical work and its part transformed into heat, from the start of strain up to failure.

2. Determining the mechanical work

In a cylindrical test specimen, the work of external forces referred to unit volume, is

$$W_M = \int \frac{F \cdot dl}{V} = \int \frac{F \cdot dl}{A \cdot l} = \int \sigma' \, d\lambda \tag{2}$$

where:

- F acting force
- dl elongation
- V volume undergoing strain
- σ real stress

Using the symbols in Fig. 1, relationship (2) can be written in a general form as:

$$W_M = \int \sigma_1 \, d\lambda_1 + \int \sigma_2 \, d\lambda_2 + \int \sigma_3 \, d\lambda_3 \, . \tag{3}$$

On the surface of a circular symmetrical specimen under tensile stress, at the lowest compressive stress, $\sigma_1 = k_f$ in the greatest cross section, where k_f is the Yield strength, $\sigma_2 = \sigma_3 = 0$. In the same cross section, for $r = r_0$, the main elongation λ_1 equals the comparative elongation $\lambda_{\ddot{o}}$.

Under the above conditions of external forces apply work

$$W_M = \int_{\lambda_0}^{\lambda_t} k_f \cdot d\lambda_{\ddot{o}} \ [\mathrm{mkp/cm^3}] \, . \tag{4}$$

on the cylindrical specimen.

From the known yield curve of a certain material $k_f = f(\lambda)$ the mechanical work for arbitrary strains can be obtained from the area beneath the curve.

The strain rate greatly influences the amount of external work. Its impact has to be taken into consideration.

The $k_f - \lambda$ curves were plotted in case of tensile stress with BRIDGMAN's method [4] in case of compressive stress with that of WATTS and FORD [5]. The effect of strain rate has been considered according to the relation suggested by ALDER and PHILLIPS [6].

Working has been carried out with gradual tensile and compressive stress, respectively, in small stages, by selecting suitable fine stages. The diameter was measured optically, in the cross section of the test specimen fitted with a thermocouple.

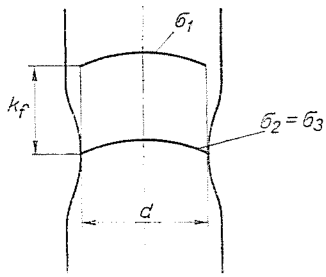

Fig. 1. Symbols of stress

3. Temperature determination alongside the specimen strain

For measuring the heat released during strain, thermocouple of copper—constantan wires 0.08 mm ∅ was used. The wires were welded on the specimen surface with their junction within the material to be examined. The energy transformed into heat can be computed if the physical constants of the material and the released heat are known, by the following relationship:

$$W_T = \frac{c_v \cdot \gamma \cdot \Delta T}{1000} 427 \quad [\mathrm{mkp/cm^3}] \tag{5}$$

where:

c_v specific heat of the studied material [kcal/kg °C]

γ density of the studies material [kg/dm³]

T temperature variation in the studied material [°C]

Temperature determination is done by recording a rapidly changing, low voltage signal (thermo-electric voltage). In the different working stages temperature change amounts to a few centigrades corresponding to a signal of 50 to 200 μV. To amplify these small signals, interrupter-type, transistor amplifier was used, with an interrupting-frequency of 720 Hz. The amplified signal of the interrupter was lead directly to the oscilloscope and photographically recorded.

4. Test materials

Both tensile and compressive tests were done on a C10-type, unalloyed polycrystal steel with a carbon content of 0.1%. The tensile specimens were produced with a 20 mm long and 7 mm diameter shank, with a threaded clamping head. The diameter of the compressive specimens was 100 mm, its length 15 mm.

5. Test results

The changes in mechanical work as a function of strain are illustrated in Fig. 2. Tensile and compressive stress require for an identical amount of strain different amounts of mechanical work over the limit of even elongation. Up to this limit, however, the amount of external work is independent from the kind of stress. In tension the specimen failed at $\lambda = 1.42$ true strain, where the mechanical work was $W_M = 80$ mkp/cm³, while in $\lambda = 2.4$, no failure occurred even for compression and $W_M = 140$ mkp/cm³.

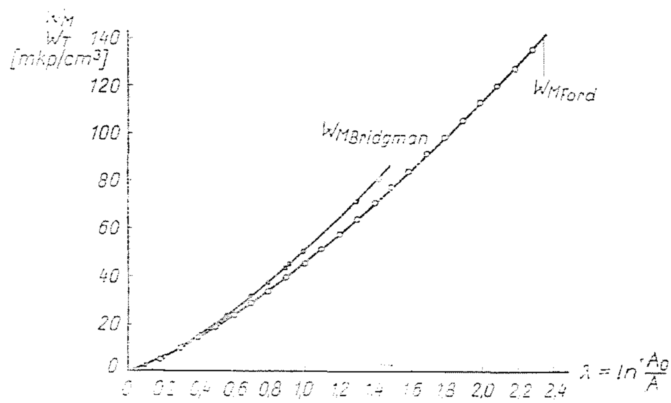

Fig. 2. The changes in mechanical work as a function of strain

Similarly to mechanical work the part of external work transformed into heat (Fig. 3) is independent of the kind of stress up to the limit of even elongation. Over this limit, however, up to a certain strain, more heat is released in tension (W_{Th}), than in compression (W_{Tny}). The curve of mechanical work transformed into heat has pronounced breaks (indicated by fingers in Fig. 3) at true strains of $\lambda = 1.0$ and $\lambda = 1.2$ in tension and in compression respectively. After these break points, the part of mechanical work transformed into heat decreases in case of tensile stress and increases in that of compressive stress.

In Fig. 4 the curves of mechanical work absorbed by tension and of the drawing energy transformed into heat were plotted according to BRIDGMAN. The part of mechanical work retained in the metal equals the segment between the two curves. The energy absorbed at the break point in the curve of the energy transformed into heat is $W_S = 12.5$ mkp/cm³. At the same point the mechanical work amounts to $W_M = 51$ mkp/cm³.

The curves for mechanical work spent to compression and for the energy released in compression are plotted in Fig. 5. The energy consumed at the

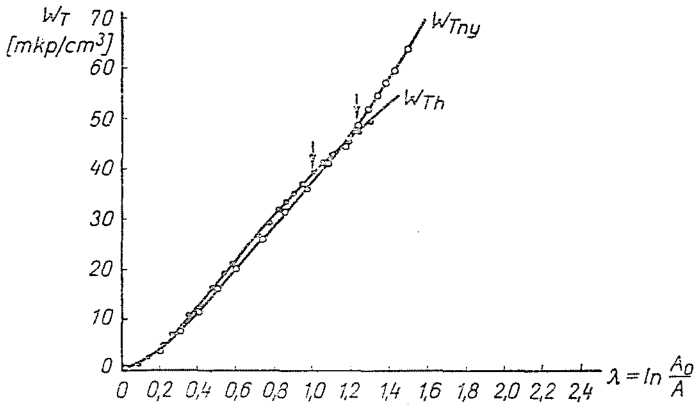

Fig. 3. The part of external work transformed into heat

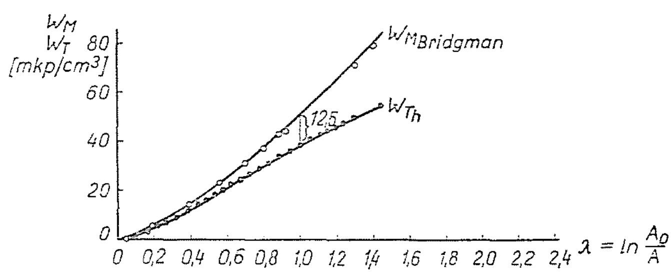

Fig. 4. The curves for tensile stress according to the mechanical work assumed by Bridgman and of the energy transformed into heat while drawing were plotted

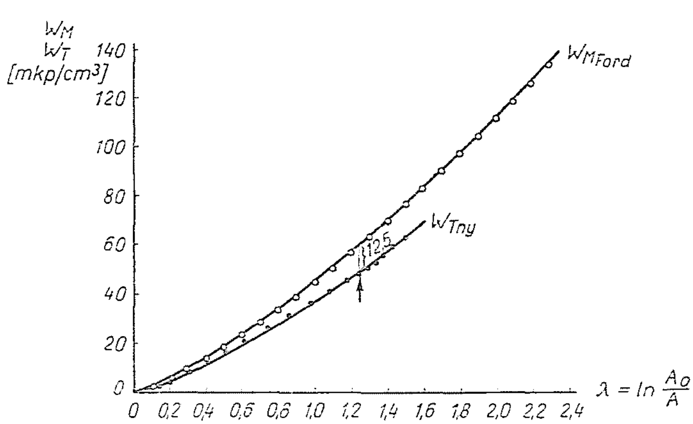

Fig. 5. The curves for mechanical work in case of compressive stress and for the energy releas-ed while compressions were plotted

break point of the curve for energy transformed into heat is $W_S = 12.5$ mkp/cm^3 just as was in tension, in spite of mechanical work $W_M = 60$ mkp/cm^3.

In tensile and compressive tests on solid cylindrical bars, it was observed that beyond even elongation the amount of mechanical work necessary for working depended on the kind of stress just as did the part of mechanical work transformed into heat. The mechanical work linearly increased with the increase in true strain, while the continuously ascending curve of the energy transformed into heat exhibited a pronounced break at a major strain. This break point was observed at a smaller elongation in case of tensile than of compressive stress, and also the mechanical work spent up to the break point

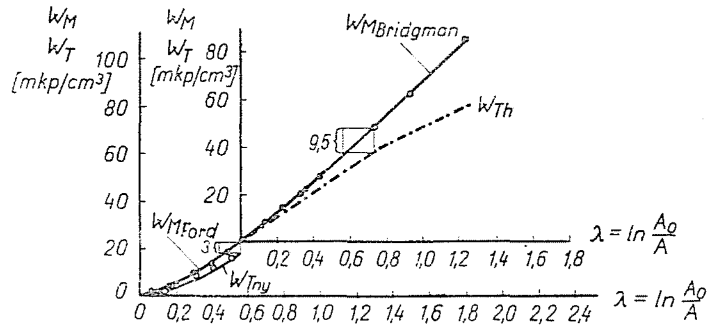

Fig. 6. The curves for mechanical work in case of compressive-tensile stresses and for the energy released while compressive-tensile were plotted

was less in tension than in compression. The amount of internal energy absorbed at the break point was the same in both cases independently of the kind of stress, the value of true strain and of the mechanical work.

To support these results, the tests were extended to combined tensile-compressive stresses. The tests were carried out in a way that great diameter, cylindrical test specimens were first compressed to different rates and the released heat and the mechanical work were determined as indicated above. Compressed blocks have been processed to tensile specimens of the previously indicated geometry. In tensile tests on these specimens of already compressed material the values of released heat and of mechanical work necessary for strain, measured at the point of contraction are shown in Fig. 6. True strain $\lambda = 0.57$ was due to compression. This strain is about twice the even elongation. The part of mechanical work retained in the metal following compression is $W_S = 3$ mkp/cm^3. In Fig. 6 the tensile strain and the amount of mechanical work are indicated separately. Combined effect of compressive and tensile stress produced a total strain $\lambda = 1.8$ up to failure, which exceeded that in tension alone ($\lambda = 1.42$). The total amount of mechanical work up to failure was $W_M = 108$ mkp/cm^3, as compared with the 80 mkp/cm^3, necessary in pure tension to failure. Again, a pronounced break point in the curve for the energy transformed into heat appeared, where the total amount of mechanical work was $W_M = 70$ mkp/cm^3, as compared to that for tension and for compression alone (51 mkp/cm^3) and (60 mkp/cm^3) respectively. At this point the energy transformed into heat was $W_S = 9.5$ mkp/cm^3, in tension. The amount of internal energy $W_S = 12.5$ mkp/cm^3, absorbed in combined compression and tension equals the energy absorbed at the break point of the curve of the energy transformed into heat in tension and in compression.

The main data of these tests are compiled in Table 1.

Table 1

Kind of stress	W_M mkp/cm^3	λ_{real}	W_M mkp/cm^3 (at the break point of the curve for the energy transformed into heat)	λ (at the break point of the curve for the energy transformed into heat)	W_S mkp/cm^3 (at the break point of the curve for the energy transformed into heat)
Tensile stress	80 up to failure	1.42 up to failure	51	1.0	12.5
Compressive stress	140 no failure	2.4 no failure	60	1.2	12.5
Tensile-compressive stress	108 up to failure	1.8 up to failure	70	1.3	12.5

According to these data, the energy (W_S) absorbed at the break point of the curve for the energy transformed into heat is independent of the kind of stress, as against the mechanical work and the true strain.

These observations are likely to impose more detailed tests on energy changes.

From the external work spent to plastic strain, the part retained in the metal is composed of energy absorbed for lattice defects and in crack surfaces

$$W_S = W_D + W_A \tag{6}$$

where W_D = the energy of lattice defects and W_A = the surface energy. The surface energy is negligible in plastic failure, compared to the energy of lattice defects. The lattice defect density is higher at crack edges than throughout the material (Fig. 7). The Burgers vector for lattice defect aggregated at crack ends is not dependent on the crystal structure alone. If these aggregated lattice defects are treated as a continuous plane, the Burgers vector is infinitely small. In this case the total Burgers vector of all lattice defects within the distance x to $x + dx$ equals $b(x)dx$. This is the case where the total stress (loading stress σ_0 + the stress of lattice defects σ_D) equals zero at any point of the rupture tip.

The lattice defect shifts if the stress of the lattice defects is lower than or equal to the imposed stress. To start a plastic strain, an energy equalling

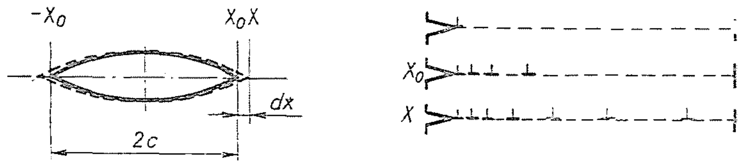

Fig. 7. The lattice defect density

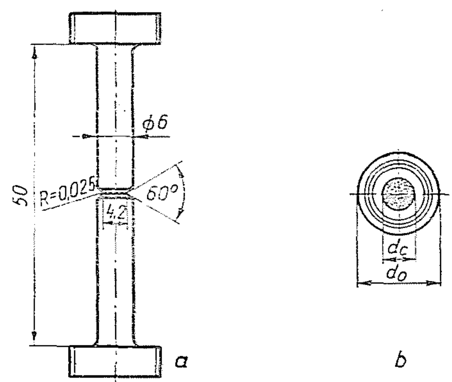

Fig. 8. a) Tensile stress test specimen, *b)* Fractured test specimen cross section

or exceeding the elastic energy is necessary. In all formed metals the elastic energy is increased by the mechanical work applied for strain and retained in the metal. For a formed metal:

$$W_S = \frac{\sigma^2}{2E} \quad \text{mkp/cm}^3 \tag{9}$$

thus the stress at the edge of the rupture necessary to move the lattice defects is

$$\sigma_D = \sqrt{2EW_S}\,. \tag{10}$$

Substituting into Eq. (10) the internal energy values absorbed at the break point of the curve for the energy transformed into heat yields $\sigma_D =$ 750 kp/mm², this stress arising at the tip of fracture where the absorption of internal energy begins to follow a different law. This must be true also for strain.

ARTINGER [7] undertook tests to determine the stress σ_D at the critical point. Tensile specimens of the geometry indicated in Fig. 8a were used. Force and elongation were determined in tension. In the failure cross section at such a sharp notch, a cracked and a granular surface developed. Fig. 8b is the schematic diagram of such a fracture. The acting force referred to the granular fractured surface, yields a stress $\sigma = 700-800$ kp/mm². According to the fracture pattern in the notched tensile specimen fissural plastic strain passes into fibrous breaking at a stress of 700—800 kp/mm² at the crack tips. This is in agreement with the stress value calculated from the internal energy.

Tests on sharply notched tensile specimens seem to prove the assumption that the strain mechanism changes at the break point of the curve for the energy transformed into heat. The fissural fracture preceding this point passes into granular fracture, thus plastic failure is replaced by brittle failure.

The transition between plastic and brittle failure is at the break point of the curve for energy transformed into heat.

To prove the above similar tests were made on high purity aluminium, copper and nickel and on copper-zinc alloys, as well as on hardened and refined, unalloyed structural steels. These tests proved the conclusions drawn from tests on low carbon steels.

6. Summary

Plastic strain and fracture were studied by testing the change in energy referred to unit volume, by experimentally determining the mechanical work necessary for forming and its part transformed into heat. The part of mechanical work retained in the metal was calculated according to the first main law of thermodynamics: $W_S = W_M - W_T$.

In the course of these tests the following were observed:

1. The amount of external work needed to failure is independent of the kind of stress.
2. The internal energy absorbed up to the transition from plastic to brittle failure is constant, independently of the kind of stress.
3. The transition from plastic to brittle failure occurs at different strain values, depending on the stress kind.
4. The stress at the transition from plastic to brittle failure of drawn metals is obtained from relationship $\sigma = \sqrt{2\,EW_S}$, if the amount of internal energy is known.

References

1. WOLFENDEN, A.: The ratio of stored to expended energy during the deformation of copper and aluminium single crystals at 78° K. Acta Met. **16**, 975—980 (1968).
2. WOLFENDEN, A.: The energy stored in silver single crystals. Acta Met. **17**, 585—593 (1969).
3. WILLIAMS, R. O.: Stored energy and release kinetics in lead, aluminium, silver, nickel, iron and zirconium. Trans. Metal Soc. AIME **223**, 719—726 (1962).
4. BRIDGMAN, P. W.: Studies in large plastic flow and fracture. Mc Graw-Hill, New York 1952, pp. 9—38.
5. WATTS, A. B., FORD, H.: On the basis yield stress curve for a Metal. Proc. I. Mech. Eng. **169**, 1141—1149 (1955).
6. ALDER, J. F., PHILLIPS, V. A.: The effect of strain rate and temperature on the resistance of aluminium, copper and steel to compression. J. Inst. Metals **83**, 80—86 (1954—55).
7. ARTINGER, I.: Candidate's Thesis. Manuscript.

Dr. Lajos KATOR, Budapest XI., Bertalan Lajos u. 4. Hungary