PLASTIC DEFORMATION OF METALS

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I. Introduction

Deformation is widely dealt with in the technical literature, but the scope of the various studies has to a great extent been restricted to elaborations of various empirical formulae. One of the possible ways of examining the process of deformation is the tensile test. There are at least two reasons to justify the application of this test: 1) it is relatively simple and 2) it can provide data both on the strength of the material and on its plastic characteristics.

According to the generally accepted views, the process of deformation in a tensile experiment can be divided into two stages: i) stage of uniform elongation, and ii) the stage of necking. The transition from one stage to the other is thought to occur at maximum force. However, the existence of a stage of completely uniform elongation is still open to question. Certain researchers [1—6] have claimed to show experimentally that a definite stage of uniform elongation occurs. Others [7, 8], however, maintain that the idea of uniform elongation is even theoretically wrong.

The latest investigations [9, 10] have proved that the generally accepted views are wrong, since the deformation in a tensile test cannot be simply characterized as a process consisting only of two stages. Recently CZOBOLY [11] using cylindrical tensile specimens, and KATOR [12] using sheet tensile specimens discovered that the curve of elongation and necking consisted of three stages. The first stage can be regarded macroscopically as that of uniform elongation. The deformation curve was divided into three stages also by IVANOVA and VOROBJEV [13].

At present, it is similarly unsettled whether the onset of necking coincides with the point of maximum load. According to LUDWIK [14], necking begins before maximum load is obtained. SACHS and FICK [1] maintain that uniform elongation ends only after maximum force has been reached. KUNTZE [8], KRUPKOWSKY et al. [3] and KRISCH [15] maintain that uniform elongation stops at maximum force.

Even this short survey verifies that one can doubt both the existence and the value of uniform elongation. It is uncertain whether the final point of uniform elongation coincides with the point of maximum force. The present paper is intended to contribute to answer these questions.

II. Principle and method of examination

The basis of the examination is that during plastic deformation part of external work is transformed into heat. The changes in temperature are in accord with the internal structural alterations. The changes in microstructure are indicated by the slopes and inflection-points of the temperature-strain curves. In order to examine the processes of deformation occurring during the tensile test, the changes in diameter and the temperature of the tensile specimen were measured. To measure the diameter a strain-gage tensometer was used. The tensile specimen was scanned at full length by an apparatus of high sensitivity, used at the same time to measure the diameter, so the point of minimum diameter could be established. The values of the diameter were continually recorded by a plotting apparatus at 40 times magnification. At the same time the changes in force were plotted. In the cross-section where the diameter was measured, a thermo-couple was placed on the surface of the tensile specimen. The temperature was measured, by means of a mirrored galvanometer, with 0.01°C accuracy.

OFHC copper, high purity nickel, Cu—Ni solid solutions and mild steel were examined. These materials were hot forged, hot rolled, and finally drawn to bars of 8 mm diameter, which were then machined and polished to produce test specimens of 6 mm $\times$60 mm test length.

III. Experimental results

When evaluating the results, we extracted the changes in force (F) and in temperature (T) as functions of true elongation (Figs. 1—6). Two inflection-points on the temperature-curve of copper were obtained (Fig. 1). Neither of these points coincides with the point of maximum force, the first occurs before maximum force is reached, and the second after the force has started to decrease. The temperature-curve is thus divided into three stages. Changes in temperature in the various stages differ from each other by their characteristics and in absolute magnitude. In the first stage the temperature increases exponentially with the increase in deformation. The curve is exponential in the second stage as well, but the increase in temperature for the same strain is smaller than in the first stage. The third stage is linear. There are three inflection-points on the temperature-force curve of nickel (Fig. 2). None coincides with the maximum force, the first being before maximum force and the second after it, just as with copper. The temperature curve consists of four stages. In copper only three stages were discovered. This may be due to the very large differences in true elongation values between the last and last but one measuring points of copper. At rupture the elongation (λ) equals 5,218, whereas at the preceding measuring point the value of λ was only 1,472.

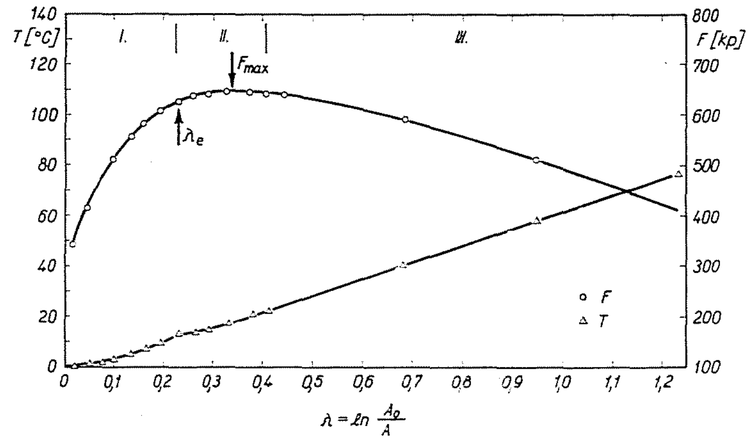

Fig. 1. Change in force and temperature for copper as a function of elongation

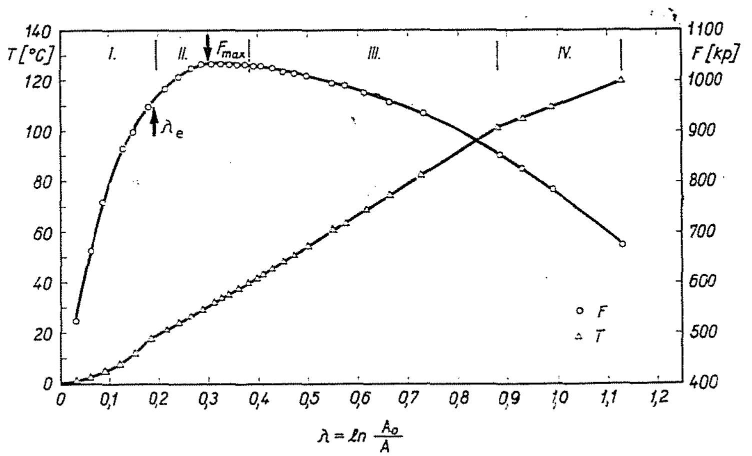

Fig. 2. Change in force and temperature for nickel as a function of elongation

The change in elongation between the two measurements is more than a factor of three. On account of the shortness of time, in this large elongation interval no reliable measurements could be carried out, therefore in the period immediately preceding the rupture no examinations of changes in temperature were made. In nickel, also, the first stage of the temperature curve depends exponentially on true elongation. The changes at the third and fourth stages are the same as those at the third stage of the curve of copper. In nickel, during the second stage, the oscillation of temperature is great. In this stage the relation between temperature and true elongation is well approximated by a straight line.

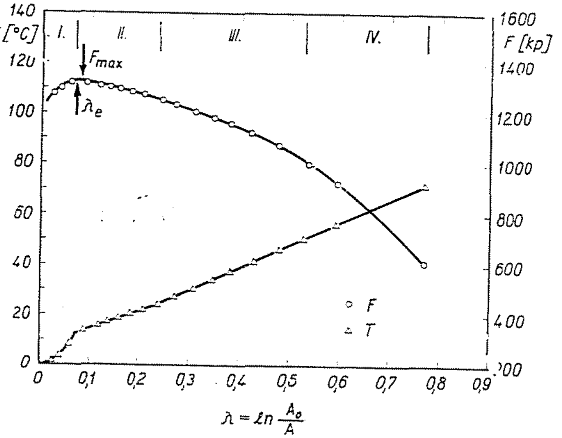

Fig. 3. Change in force and temperature for 75.53 per cent Cu, 24.28 per cent Ni alloy as a function of elongation

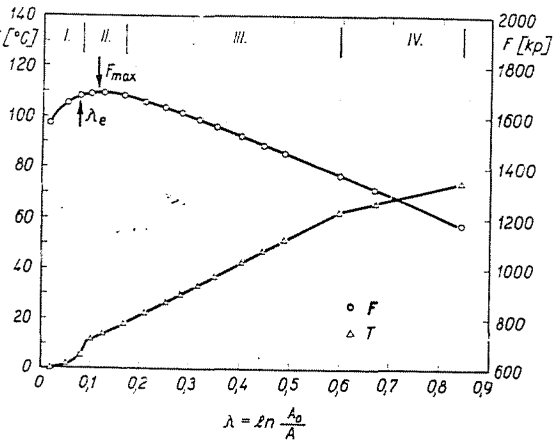

Fig. 4. Change in force and temperature for 47.50 per cent Cu, 52.40 per cent Ni alloy as a function of elongation

For Cu—Ni solid solutions the temperature-elongation curves consist of four stages (Figs. 3, 4, 5). The changes of relations in the identical stages in these alloys are the same as they are in nickel. In the first stages of the curves the relation is exponential, but their area of effectiveness is small. In the other stages the characteristics of the increases in temperature are identical, but they differ from each other in magnitude. Differences in the increase of temperature are indicated by the divergent slopes of the straight lines. Increases in temperature are different in alloys with varying copper content, i.e. not only in different stages of individual materials, but also in individual materials. This fact seems to prove that changes in temperature are dependent on the chemical composition of materials.

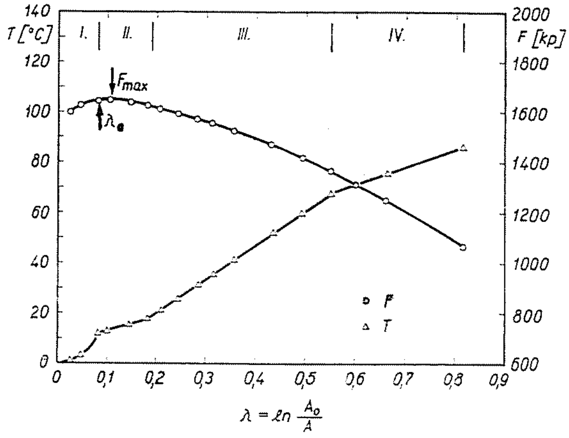

Fig. 5. Change in force and temperature for 22.30 per cent Cu, 77.52 per cent Ni alloy as a function of elongation

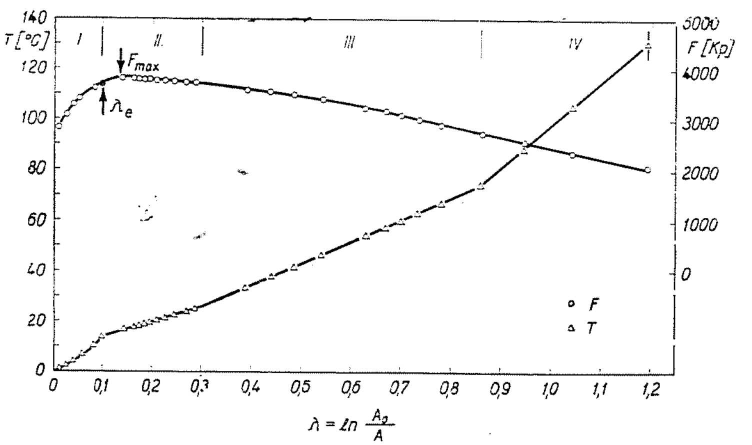

Fig. 6. Change in force and temperature for mild steel as a function of elongation

The curves of mild steel (Fig. 6) do not show any hitherto undiscussed characteristics. Here, too, there are four stages of the temperature curve. If we compare the individual stages of temperature curves after the onset of necking with the identical curves of nickel and copper, we discover that the slopes of the curves of steel are greater even than the values measured for nickel.

Discussion

When examining the deformations of single crystals three stages of deformation were observed. Deformations of polycrystaline materials generally have four stages. The first two stages correspond to the stage of easy glide of single crystals, whereas the third stage corresponds to the second stage of single crystals and the fourth corresponds to the third stage of single crystals. It was stated earlier [11, 12] that in tensile tests of polycrystaline materials the relation between elongation and necking is exponential up to the limit of uniform elongation. While carrying out the measurement discussed here, we found that the increase in temperature was also an exponential function of true elongation up to the limit of uniform elongation. Uniform elongation stops before maximum force is reached. Examination of temperature versus force curves reveals that maximum force is obtained in the second stage of temperature curves. With pure metals this point is closer to the end of the second period; with alloys it is at the onset of the second stage, close to the first one. This may have led to the opinions maintained by 1, 3, 8 and 15. After extending the curves of the first and third stages the volume of true elongation at the intersection of the two curves corresponds to the elongation, where maximum force is present.

Conclusions

On the basis of this examination we can state that.

1. From the onset of deformation to rupture the temperature-elongation curves generally consist of four parts.

2. It is characteristic of the first stage that the temperature increases exponentially with the increase in deformation. The first stage ends before maximum force is reached. This stage can be regarded macroscopically as that of uniform elongation.

3. In contradiction to the generally accepted view, the necking stage does not immediately follow that of uniform elongation. Instead, they are separated by a transitional stage.

4. In the third and fourth stages the relation between temperature and elongation is linear.

Summary

This paper discusses the parts the process of deformation in tensile tests consists of, and the area of effectiveness of the relevant steps. It attempts to answer the question whether there is a sort of uniform elongation in plastically deformed metals and where are its limits. The examinations were carried out in Cu and Ni, and Cu—Ni solid solutions, and in mild steel. The stages of deformation were determined through the changes in temperature measured at the surface of the tensile specimen.

References

1. SACHS, G.—FICK, G.: "Der Zugversuch" Leipzig, Akademische Verlagsgesellschaft, M. B. H. 1926).
2. SACHS, G. — Mitt. Materialprüfungsamt K. W. Inst. für Metallforschung, Sonderheft **2**, 114—126 (1926).
3. KRUPKOWSKI and WANTUCHOWSKI: Annales de l'Académie Polonaise des Sciences Techniques **7**, 10—40 (1939—1945).
4. TRUSKOWSKI, W.: Bulletin de l'Académie Polonaise des Sciences et des Lettres **4**, 375—410 (1952).
5. JÄNICHE, W.—PUZICHA, W.: Arch. f. d. Eisenhüttenwesen **25**, 589—593 (1954).
6. SIEBEL, E.: "Die Prüfung der metallischen Werkstoffe" Berlin, Springer Verlag (1955).
7. BACH, C.—Mitt. über Forschungsarbeit **29**, 69—74 (1905).
8. KUNTZE, W.—Mitt. Materialprüfungsamt, K. W. Inst. für Metallforschung **42**, 25—28.
9. ODING, I. A.—LIBEROV, J. P.: ...
10. ODING, I. A.—Liberov, J. P.: ...
11. CZOBOLY, E.: Periodica Polytechnica **4**, 395—404 (1964).
12. KATOR, L.: Periodica Polytechnica **4**, 405—416 (1964).
13. IVANOVA, V. S.–VOROBJEV, N. A.: Lecture given in 1966 at the Technical University of Budapest.
14. LUDWIK, P.: "Elemente der technologischen Mechanik", Berlin, Springer Verlag (1909).
15. KRISCH, A.: Arch. f. d. Eisenhüttenwesen **25**, 595—598 (1954).

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