THE INFLUENCE OF THE STRAIN RATE ON METAL CHARACTERISTICS

By

L. GILLEMOT

Department of Mechanical Technology, Polytechnical University, Budapest

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1. Introduction

During the last 10 years a number of metalworking technologies have been developed where the rate of deformation would exceed that of the conventional technologies by a few orders of magnitude. Such are, for example, explosion type metalworking or pneumatic press-forging and extrusion. Pneumatic forging facilities and their various structural problems have been dealt with by the literature in detail [1—9]. There have been forging facilities constructed which operate by evaporating liquid nitrogen [10] or by burning liquid fuel [11]. Applying high-speed metalworking for extrusion is dealt with by a number of papers [12—13], and explosion is similarly employed for extrusion purposes [14]. With these methods, the rate of tool movement amounts to 18—40 m/sec, and the specific strain rate varies within the 10^4 to 10^5 order of magnitude range. Due to the high rate of deformation, work temperature will vary to a similarly great extent [15—17]. Naturally, temperature variations also exert a considerable influence on material characteristics. BÜCHLER and MÜLLER [8], therefore, claim that high-speed metalworking does not transform material characteristics to a significant degree. However, high-speed extrusion experiments revealed that the yield point of the metal worked on was much higher than if formed to the same reduction in a slower rate. For this reason, it seems necessary to study the effect of the phenomenon in question on the characteristics of the material. Through the research work by KÁRMÁN and others [18—20], the velocity (v) of the plastic wave propagating within the material under impulsive load conditions has been understood

$$v = \sqrt{\frac{\frac{d\sigma}{d\varepsilon}}{\varrho}} \tag{1}$$

just like the elongation or tension produced in the material as due to the impulse of a (u) velocity

$$u = \int_0^{\varepsilon_m} \sqrt{\frac{\frac{d\sigma}{d\varepsilon}}{\varrho}} \cdot d\varepsilon. \tag{2}$$

Here ϱ is the material density, σ represents the engineering stress, and ε indicates the engineering strain.

The above formulae apply only to very thin and long bars, and the velocity effect was entirely neglected in the calculations. Thus, under tensile test conditions, it is possible to arrive at such a velocity whereupon the specimen would exhibit brittle fracture. According to the critical velocity [18] in case of copper this would amount, if calculated theoretically from the formulae, to 45 m/sec. In our experiments 99.5 per cent aluminium, 0.1 per cent carbon content carbon steel, and electrolytic copper have been made use of. Their critical rate of velocity were: aluminium 42 m/sec, for copper the figure given above, and mild carbon steel 60 m/sec. In order to make the omission of the plastic wave effect permissible, the velocity employed for the experiments described below never exceeded 5.6 m/sec.

The experiments to be described here represent part of an experimental series the objective of which is to determine the variation of the material characteristics in the velocity range where the effects of plastic deformation waves may be yet neglected. A later task will be to further study that velocity range where the action of plastic deformation waves must also be taken into consideration.

2. Experimental objectives

One objective was to determine the most suitable method for plotting the yield curve under high velocity conditions, and to decide how to calculate from the results of low speed experiments the yield curve applying to high velocities. Another objective of the experiments was to study the effects of high-speed metalworking on the strength characteristics of the material tested, and to find out how the expected characteristics could be calculated with an approximation acceptable for practical purposes.

Omitting the detailed calculation techniques, the present paper deals only with the experimental results since the empirical formulae required for numerical calculations do not apply to each material alike although they might be well used in first approximation.

Quite a number of methods are suggested by literature for yield curve determination. The more important ones are as follows:

(a) *Yield curve determination by tensile test.* In course of tensile test, a uniaxial stress condition will prevail only up to the uniform strain limit. Determination of the yield stress within the contraction range requires calculation the hitherto most accurate formula of which was presented by BRIDGEMAN [21]. In course of the tensile test, however, the rate of elongation also will vary within the contraction phase. For this reason, test should be performed with a constant strain velocity instead of the application of a constant clamp-motion rate [22]. This, however, requires an extremely complex test method and, therefore, it seems more appropriate to conduct the experiment with a constant clamp rate followed by a numerical correction of the rate effect [23]. The rate of elongation will increase considerably within the contraction area as compared to its initial value. Consequently, the figure measured at a constant rate of elongation will be some σ_0 value lower than the mean true stress measured with a constant clamp-motion rate. This can be calculated according to formula (3)

$$\sigma_0 = \sigma - a \cdot e^{\varepsilon - \varepsilon_m} \cdot (\varepsilon - \varepsilon_m) \tag{3}$$

where a is the constant depending on the material tested,
ε is the true strain at the point of contraction, and
ε_m is the true strain value in the moment of maximum force application.

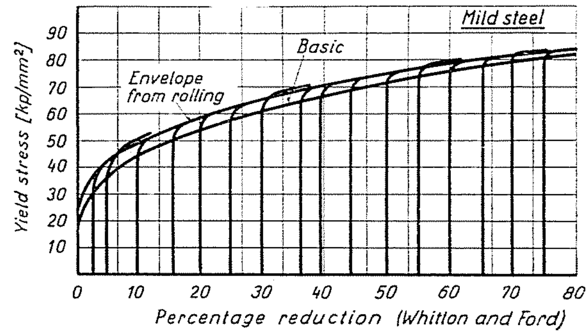

Fig. 1. Yield stress, determined by rolling

(b) *A usual yield curve determination* is to work on the material with continuous rolling in conformity with a given technological method and, following various reductions, the yield point after formation is then determined by means of a tensile test. WHITTON and FORD [24] measured the yield point of rolled sheets this way, and compared the results to yield curves obtained through other methods such as the wedge indentation test. As shown by Fig. 1, the yield curve of rolled sheets is considerably higher than that measured with static methods. KRAUSE [25] measured the yield curve by using a similar technique.

(c) *For low-speed measurements*, the wedge indentation test suggested by NÁDAY seems most suitable which has been successfully employed and further developed ever since [26—28]. However, the application of this experimental method under high-speed conditions will encounter certain difficulties.

(d) *A very simple experimental method is represented by the compression test* where, nevertheless, it must be taken into consideration that, due to the friction produced, a multiaxial stress condition will be created, and the rate of elongation will vary to a considerable extent. This experimental method was recently employed by HEINEMANN [29].

(e) *Torsion test* — This test type appears very suitable for yield curve plotting. In case of excessive plastic deformations, however, the correlation between shear stress and deformation must be calculated again. Recently, many authors conducted experiments by using this method.

The methods described above have been compared lately by KRAUSE [30]. His data reveal that the yield curves measured with the different techniques do not entirely agree under low-speed conditions, either (Fig. 2).

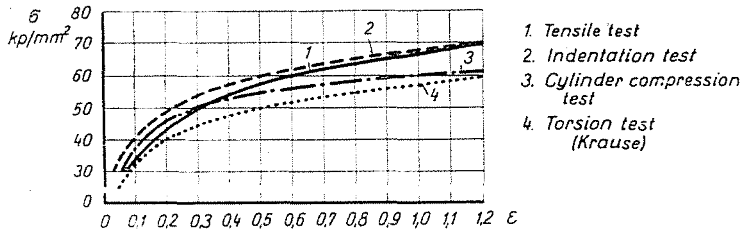

Fig. 2. Comparison of different methods

3. Yield curve plotting under low-speed conditions

In our experiments the tensile test (a) and wire-draw test have been selected for yield curve determination purposes. Three different experimental material types (aluminium, copper, and mild steel) have been used to compare the yield curve rendered by tensile test data to those obtained through wire drawing performed with the same rate. The technological processes, either wire drawing or rolling, show a considerably higher specific rate of elongation than that shown by the tensile test, and most likely this is the reason why the yield curves plotted by using metalworking technologies do not agree accurately with those determined by using any other method (see Fig. 1). Wire drawing, however, seems most appropriate since, due to the small diameter of the material tested, the effect of temperature increase could be reliably eliminated by cooling.

A further advantage of the adaptation of wire drawing is the possibility of rate variations within a very wide range. Although the distribution of the strain rate in the wire draw die varies from one point to the other in a direction normal to the axis of the die, it may be considered as approximately uniform.

According to the diagram presented by Fig. 3, if — in a drawing test series — the pre-draw diameter of the wire is r_0 whereas that after drawing is r_1, then the reduction in the first die is

$$\varepsilon_1 = \ln \frac{r_0^2}{r_1^2} \tag{4}$$

If the rate of drawing behind the die is u_1, then in any point characterized by co-ordinate (y) it will be

$$u_y = \frac{u_1 \cdot r_1^2}{x^2} \tag{5}$$

whereas the strain rate in cross section (y) is

$$c_y = \frac{d\varepsilon}{d\iota} = \frac{d\varepsilon}{dr} \cdot \frac{dr}{dy} \cdot \frac{dy}{dt} = \frac{2}{x} \cdot \text{tg}\, \alpha_1 \cdot u_1 \cdot \frac{r_1^2}{x^2} \tag{6}$$

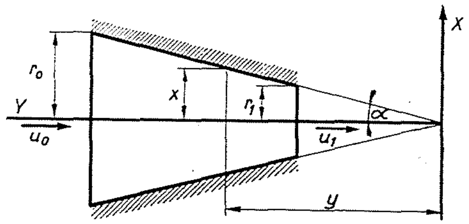

Fig. 3. Strain-rate in the die

Thus the specific strain rate of the wire when entering the first die is

$$c_1^x = \frac{2\text{tg}\, \alpha_1 u_1}{r_0} \cdot \frac{r_1^2}{r_0^2} \tag{7}$$

and when leaving it

$$c_1 = \frac{2\, \text{tg}\, \alpha_1 u_1}{r_1}\,. \tag{8}$$

The strain rate value may be similarly written for entering and leaving, respectively, the second die

$$c_2^x = \frac{2\, \text{tg}\, \alpha_2 u_2}{r_1} \cdot \frac{r_2^2}{r_1^2} \tag{9*}$$

and

$$c_2 = \frac{2\, \text{tg}\, \alpha_2 u_2}{r_2}\,. \tag{10*}$$

The indices in the formulae show always the serial number of the draw die, and (x) the entrance side.

Considering (n) dies, the rate variation in course of wire drawing may be expressed, as compared to the c_0 rate of the tensile test, thus:

$$\frac{c_n}{c_0} = \frac{c_1^x}{c_0} \cdot \frac{c_1}{c_1^x} \cdot \frac{c_1^x}{c_2^x} \cdot \ \ldots \ \frac{c_n}{c_n^x} =$$

$$= \left(\frac{2 \operatorname{tg} \alpha_1 \, u_1 \, e^{-\varepsilon_1}}{c_0 \, r_0} \right) (\varepsilon^{\frac{3\varepsilon_1}{2}}) \cdot \left(\frac{\operatorname{tg} \alpha_2 \, u_2}{\operatorname{tg} \alpha_1 \, u_1} \cdot e^{-\varepsilon_2} \right) (e^{\frac{3\varepsilon_2}{2}}) \tag{11}$$

The $u_1, u_2, \ldots u_n$ rate of the individual drawing phases can be selected in such a manner so as to make the $\frac{c_n}{c_0}$ ratio approximately constant during the entire test period. However, it cannot be maintained at an absolutely constant value as the strain rate will necessarily vary at both the inlet and outlet edges of each die.

A further problem to be solved is presented by the requirement, according to which specific strain rate in course of drawing should vary at least in an identical order of magnitude to that of the specific strain rate observed at tension test, apart from the fluctuation referred to above. The strain rate of comparative tensile tests amounted to $c_0 = 2 \times 10^{-1}$/min. In order to have the wire drawing rate vary within this order of magnitude, such a draw bench was constructed where drawing rate could be varied between 1 mm/min and 10^4 mm/min order of magnitude figures. For experimental purposes seven dies of different drawing angle have been employed, with a minimum of $\alpha = 3°$ and a maximum of 16°. In course of the successive drawing tests, variation of the drawing angle and of the rate succeeded to make the specific strain rate maintain, all along the experiment, an order of magnitude identical to that of the tensile test strain rate. However, with the equipment available at present, this can be achieved only up to a limited extent of deformation. The difficulties encountered may be explained by the following simple example:

If, in course of the tensile test, the die angle as well as the rate of drawing are constant in each successive drawing phase, that is, $u_1 = u_2 = u_n$, then — by substituting these values into Equation (11), — it follows that

$$\frac{c_n}{c_0} = \frac{2 \operatorname{tg} \alpha \cdot u_1}{r_0 \cdot c_0} \cdot e^{\frac{\varepsilon_1 + \varepsilon_2 + \varepsilon_n}{2}} \tag{12}$$

The strain rate will exponentially increase with the increasing specific deformation. For this reason, the condition of maintaining an at least approximately constant strain rate during the drawing process could be satisfied only up to about $\varepsilon = 2$.

For plotting the yield curve, experiments of constant strain rate have been conducted with mild steel, 99.5 per cent aluminum, and electrolyte copper. The true stress/true strain curve was plotted for each of these materials with a constant clamp-motion rate, then this curve was corrected to conform to the

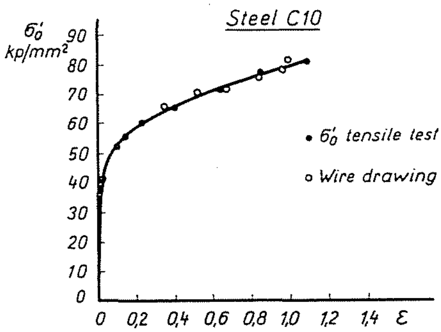

Fig. 4

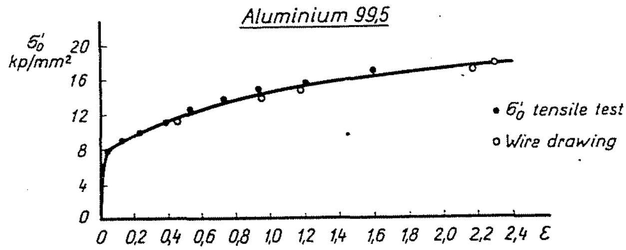

Fig. 5

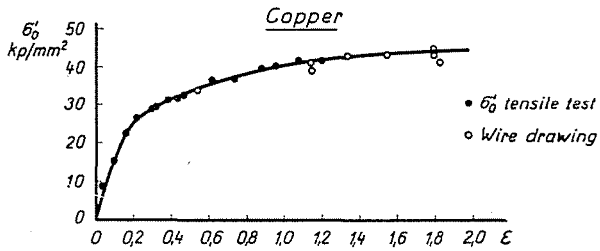

Fig. 6

Figs 4—6. Yield-curve of different metals

constant strain rate while the resistance to formation was calculated according to the Bridgeman method.

The same material samples were reduced by drawing with a constant strain rate, then the yield point was determined by sampling after each reduction phase. The results obtained are illustrated by Figs 4, 5 and 6. The diagrams reveal that the drawing points and the corrected tensile test points coincide within the measurement accuracy range. In general, therefore, it may be assumed that the considerable scatter observed by KRAUSE when comparing different techniques can be traced back to the occasional omission of the strain rate effect.

On grounds of these results, comparative experiments have been conducted with 99.99 per cent purity aluminum and electrolyte copper. With respect to the considerable deformations applied, the strain rate could not be main-

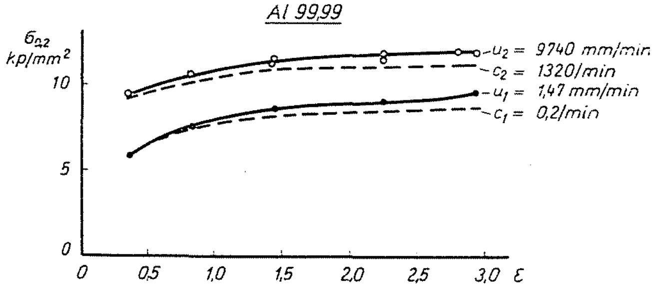

Fig. 7

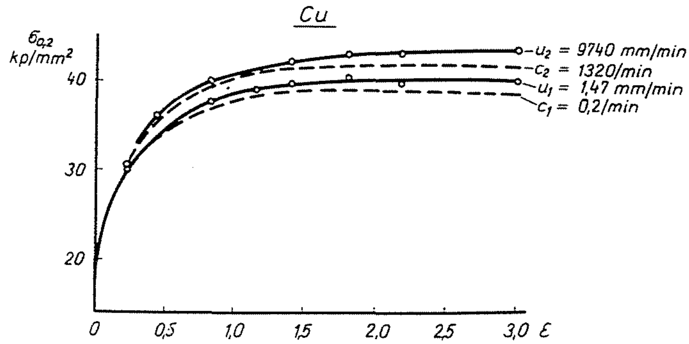

Fig. 8

Figs 7—8. Effect of strain-rate on yield-curves

tained at a constant value all along the experimental period and, therefore, the comparative studies involved the employment of a constant drawing rate which meant a continuous increase of the strain rate during reduction, as compared to the initial value. The maximum drawing rate employed amounted to 9740 mm/min which was much less than that used by the industry for wire drawing purposes. Since, however, the effect of heat production on the measurement data was to be avoided, no higher drawing rate was selected for the time being. The measurement results are illustrated by Figs 7 and 8. Thus Fig. 7 displays the measurement results obtained with 99.99 per cent aluminum. The full lines indicate the test results arrived at by using a constant drawing rate. Although the strain rate changed during the experiment in function of the specific strain, the ratio of the strain rates pertaining to identical specific strains was $\frac{c_2}{c_1} = \frac{u_2}{u_1}$ in each point of the curves. Within the measurement scatter the two curves are parallel which seems to verify the validity of the PRANDTL law. According to PRANDTL [31]

$$F_2 = F_1 + m \cdot \ln \frac{c_2}{c_1} \tag{13}$$

which, divided by the initial cross section, renders the following rate formula:

$$\sigma_2 = \sigma_1 + \alpha \cdot \ln \frac{c_2}{c_1} \tag{14}$$

Accordingly, for example, the aluminum rate constant is $\alpha = 0.66$ with an about ± 10 per cent deviation.

Considering the strain rate according to Equation (12), the measurement results were corrected to a constant strain rate by using the PRANDTL formula again. The corrected curves are plotted by means of dotted lines.

The electrolyte copper test exhibits quite similar results (Fig. 8). Both figures reveal that, subsequent to a certain deformation ($\varepsilon = 1.4 - 1.5$), the yield curve may be considered as constant within the measurement scatter range, if the specific strain rate is constant.

However, it is extremely remarkable that, although the drawing rate affected the 0.2 proof stress of the material types tested, within the limitations studied, the strain rate did not exert a significant effect on any other material property like, for example, contraction. Thus the contraction of the 99.99 per cent purity aluminum amounted, in each drawing phase, to 96—97 per cent regardless of the strain rate, and although the contraction of the copper decreased in course of drawing from 0.74 to 0.68, the samples tested with two different drawing rates did not display any difference.

Summary

The few measurement results described above represent only a fraction of the entire experimental series. However, the findings disclosed so far seem to verify that

1. in technological processes, an increased metalworking rate would increase the yield point of the material without a significant reduction of plasticity;

2. the rate effect is determined in a limited range, at least for engineering approximations, by the PRANDTL formula with a satisfactory accuracy;

3. following extensive formation carried out with a constant strain rate, the yield point of the material would change only to a minor extent, and might be considered as constant in practice.

The work performed by an external force in the solidbody may be divided into two parts according to the first principal thesis of thermodynamics. One is the energy content variation of the body (ΔE), and the other is the heat produced by deformation (Q). Consequently, $W = \Delta E + Q$.

Figs 7 and 8 lead to the conclusion that, beyond a deformation of given extent, the internal energy of the body would not vary anymore, since neither aluminum nor copper did exhibit any further hardening in case of ε exceeding the 1.5 value. This means at the same time that, beyond the deformation of a given extent, the internal energy content would not vary anymore, if the formation was carried out with a constant strain rate.

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Prof. Dr. László GILLEMOT, Budapest XI., Bertalan Lajos u. 7. Hungary