FLOW CURVES RELATED TO CONSTANT STRAIN RATE

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1. Introduction

In designing plastic metalworking technologies, determination of the power and energy requirements of the forming operation demands to know the flow curve of the material to be formed. The flow curve represents the variation in the flow stress (σ_0) of the material, as a function of effective true strain (ε), at a constant temperature (T) and effective true strain rate ($\dot{\varepsilon}$), see [1] and [2]:

$$\sigma_0 = f(\varepsilon). \tag{1}$$

Since a constant effective true strain rate hardly can be provided for during measurements used for the determination of the flow curves, this is often neglected.

There are several methods known for the determination of the flow curve. With the earlier studies conducted for the comparison of these techniques taken into consideration [1, 3, 4, 5], the present paper intends to compare the flow curves of four materials, determined by four selected methods, respectively, and related to constant effective true strain rate, on the basis of the Mises theory. The previous comparative investigations, with the exception of [4], have all neglected the effect of the strain rate.

2. Experimental methods

Four well-known test methods have been used for comparative purposes:

a) *Tensile test*

In course of the tensile test, there will be a uniaxial stress condition existing up to the uniform strain limit and, therefore, the true stress will coincide with the flow stress. Determination of the flow stress concerning the contraction range was based on the measured true mean stress, by making use of the Bridgman equation [6]. The clamp motion speed was constant all along the measurements, thereby the strain rate was changed during this process. Results have been converted, in conformity with the relevant publication by Gillemot [7], to a constant effective true strain rate.

b) *Yield stress measurements on preformed specimens* [8]

Different diameter annealed bars were drawn to identical final size' without intermediate annealing. The yield stress values determined with the specimens thus obtained have rendered the flow stress values pertaining to the previous individual strain figures. Results were converted to constant effective true strain rate [4].

c) *Compression test of cylindrical specimens*

Specimens of identical diameter but different heights were compressed between parallel smooth surfaces with lubrication. Extrapolation to zero friction was according to COOK and LARKE [9]. Compression tests involved intermittent loading [10] and constant die speed. When evaluating results, strain calculation was based upon the height variation of the samples. Because of the strain rate changing in course of the measurements, results were again converted to constant effective true strain rate.

d) *Wedge indentation test of flat specimens*

The wedge indentation test suggested earlier by NADAI and OROWAN was accomplished according to WATTS and FORD [11], [10]. Compression of the flat specimens machined to sheet was by intermittent loading between parallel narrow planes of dimensions corresponding to the specifications of this method. Repeated replacement of the forming tool elements and careful lubrication ensured the dimensional conditions indispensable for plain strain, and permitting to neglect friction. Die speed was again constant, so the data obtained with variable strain rate had to be converted to constant effective strain rate.

3. Conversion to identical strain rate

The common effective strain rate whereto the results of all the four test methods have been converted was $\dot{\varepsilon}_0 = 1 \text{ sec}^{-1}$. Conversion was based on the well-known relation [12, 13]

$$\sigma_0 = \sigma \left(\frac{\dot{\varepsilon}_0}{\dot{\varepsilon}} \right)^n . \tag{2}$$

In Eq. (2) the value $\dot{\varepsilon}_0 = 1 \text{ sec}^{-1} = \text{const}$, thus σ_0 is the flow stress pertaining to the 1 sec^{-1} effective true strain rate, while σ indicates the flow stress measured with the effective true strain rate $\dot{\varepsilon}$. Determination of the material dependent exponent n was by tensile tests performed with different clamp motion speeds.

4. Test materials

Comparative investigations involved Al 99.5 aluminium, Cu E electrolytic copper, Sr 72 brass, and C 10 mild steel; the chemical compositions of these materials are compiled in Table I. Some mechanical properties of the same materials such as static yield stress S_y, static tensile strength S_u, maximum area reduction R, and the value of exponent n required for the application of Eq. (2) are listed in Table II.

Table I

	Al	Si	Fe	Cu	Zn	Ti	C	Mn	P	S	Cr	Ni
Al 99.5	99.67	0.1	0.18	0.006	0.023	0.03						
Cu E				99.91								
Sr 72				74.08	~rest							
C 10		0.02	rest				0.09	0.27	0.10	0.035	0.02	0.04

Note: data in %.

Table II

	S_y kp/mm^2	S_u kp/mm^2	R %	n
Al 99.5	3.2	7.3	96	0.0069
Cu E	8.4	23.6	81	0.0120
Sr 72	10.6	35.7	75	0.0094
C 10	25.8	34.0	65	0.0222

5. Test results

The flow curve of each of the four experimental materials, related to the 1 sec^{-1} effective true strain rate determined in four different ways is shown in Figs 1—4. All measurement data apply to $T = 20$ °C.

In course of earlier comparative tests KRAUSE [1], FROBIN [3], and EBERLEIN [5] found considerable differences between the flow curves of the same material plotted in different ways. These comparisons, however, did not involve curves related to an identical strain rate, and the methods compared have not been identical, either. Gillemot [4] has plotted the flow curves of three materials through tensile test [6], [7] and wire drawing. On the basis of curves measured at an identical effective true strain rate, he has discovered good agreement between the two methods within the measurement accuracy.

Figs 1—4 reveal that, as compared to the measurements by Krause and Eberlein, there is a considerably smaller difference between the methods tested, with the exception of the Sr 72 brass material, where the differences are significant. It should be noted here that brass was not tested in the earlier comparative investigations.

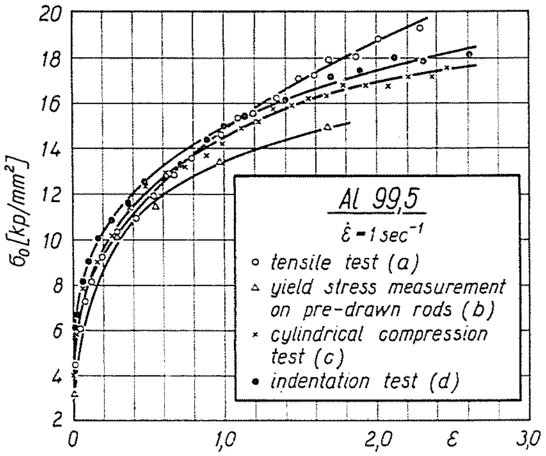

Fig. 1. Flow curves of Al 99.5

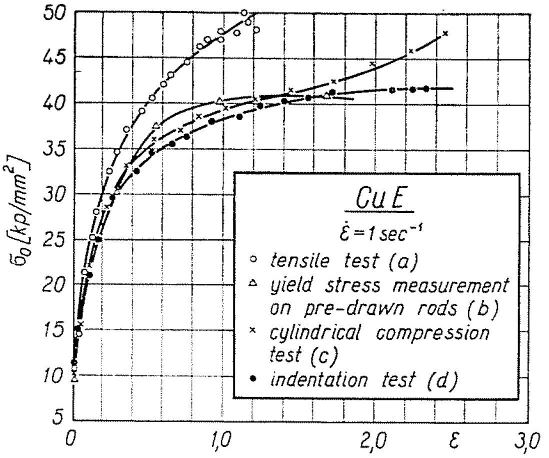

Fig. 2. Flow curves of Cu E

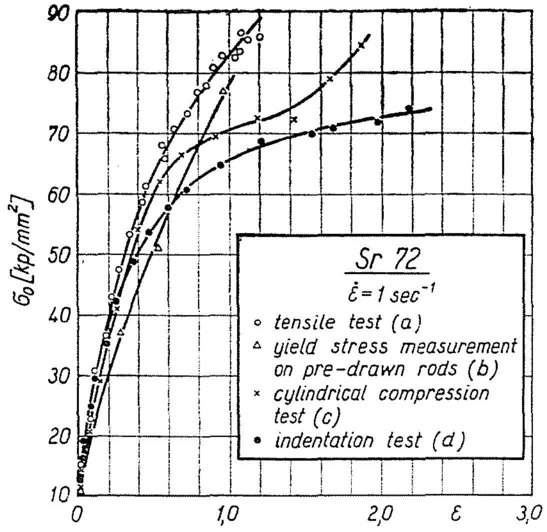

Fig. 3. Flow curves of Sr 72

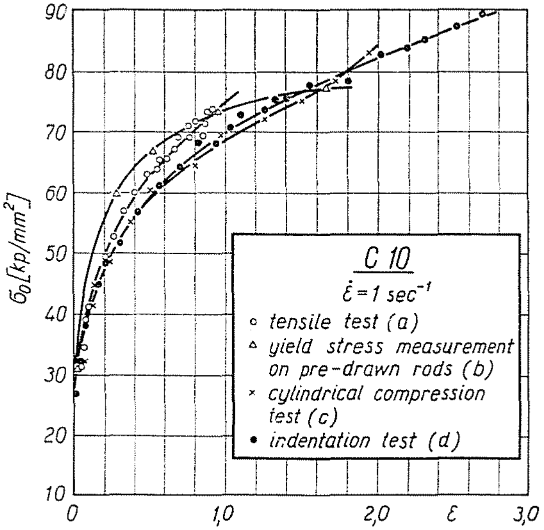

Fig. 4. Flow curves of C 10

Testing the other three materials will reveal that the compression test of cylindrical specimens performed with intermittent loading, and the wedge indentation test of flat samples similarly under intermittent loading conditions show a good agreement up to a strain of $\varepsilon = 1.4$ to 1.6, whereafter the curves of the cylindrical compression test deviate in function of the material. A similar deviation was observed by **Frobin** in connection with Al 99.5 during compression by conical dies. This phenomenon is probably due to the fact that the elimination of friction effects cannot be solved in case of major strains either by extrapolation or by the application of conical dies.

In case of small strains ($\varepsilon < 0.3$), curves obtained by tensile test will hardly differ from those of the compression tests but this deviation may be quite significant if greater strains are involved (e.g. Cu E).

Although the curves obtained from preforming by rod drawing do not coincide with either the curves obtained from tensile or compression tests, but they differ from the latter to only a lesser extent. Thus in case of $\varepsilon = 1$, the difference is 7.5 per cent with Al 99.5, while 4.2 per cent with Cu E and 6 per cent with C 10.

When evaluating the small differences between the results of cylindrical compression, wedge indentation, and rod drawing, respectively, it must be taken into account that each technique involves more or less hypotheses, and conversion to $\dot{\varepsilon} = 1$ sec^{-1} had been on the basis of empirical correlations. Thus the differences observed could be caused by the errors of these hypotheses proper.

Summary

Based on flow curves plotted with four different methods for Al 99.5, Cu E, Sr 72 and C 10, then converted to 1 sec^{-1} effective true strain rate, the following statements may be made:

1. Sr 72 renders considerably different flow curves if compared to those of the other three materials.

2. As for the flow curves of Cu E, C 10 and Al 99.5:

a) The curve obtained from a tensile test according to Bridgman offers, particularly in case of greater strains, significantly higher values than the other methods. The maximum strains thus realized do not satisfy practical requirements.

b) The difference between the curves obtained through the intermittent compression of cylindrical specimens, the intermittent wedge indentation test, and samples preformed by rod drawing, respectively, is less than 8 per cent.

3. For engineering practice in case of the latter three materials, any of the methods under 2b will supply an acceptable flow curve. Still the intermittent wedge indentation test should be preferred because of the following reasons:

a) maximum strain can be achieved;
b) measurement is simpler and faster than with the two other techniques;
c) the specimen required is the simplest, with a minimum material demand; and
d) evaluation of the measurement results is again simpler and faster.

4. With Sr 72, the flow curve obtained by the method best approximating the character of the loading encountered during plastic formation should be employed.

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