Flow curves for C45 steel at abrupt changes in the strain path

Citation for published version (APA):
Sillekens, W. H., Dautzenberg, J. H., & Kals, J. A. G. (1988). Flow curves for C45 steel at abrupt changes in the strain path. *CIRP Annals*, *37*(1), 213-216.

Document status and date:
Published: 01/01/1988

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 05. Oct. 2023

Flow Curves for C45 Steel at Abrupt Changes in the Strain Path

W. H. Sillekens, J. H. Dautzenberg (2) and J. A. G. Kals (1); Laboratory for Forming Technology,
Eindhoven University of Technology
Received on January 18, 1988

Many industrial forming processes involve a non-straight strain path. In general, a deviation from a straight strain path is accompanied by a change in the flow curve. The deviations that lead to a reduced flow stress are especially important because they may lead to instability.
In order to get more information about flow stress behaviour at abrupt changes in the deformation mode, two types were examined: the first for compression-to-tension ("Bauschinger effect") and the second for tension-to-torsion. Experiments were performed with C45 steel. The amount of strain before the change ("pre-strain") was varied.
The observed flow curve changes are recorded in three so-called "flow curve change characteristics". One is based on the initial change, the second on the permanent change and the third on an intermediate value. These three characteristics display simple relationships with the pre-strain. The results are discussed from a metallurgical point of view.

KEY WORDS: Flow curves, non-straight strain path, deformation mode change, compression- tension test, Bauschinger effect, tension-torsion test, C45 steel.

1. INTRODUCTION

In forming technology the plastic behaviour of materials often is represented graphically by a flow curve. A flow curve (stress-strain curve) can be determined by performing a material test; the most well known are the tension and the compression test. Typical of these is that the followed strain path is straight; this means that the principal strain components stay proportional to each other while the principal strain axes retain the same direction with regard to the material.

From practice it is known that a deviation from the straight strain path leads to changes in the flow curve. This is an important information because many industrial forming processes involve a non-straight path. Consequently a flow curve derived from one of the mentioned tests can not represent the flow behaviour in such a process. To obtain a better understanding it is necessary to examine the changes in flow curve which occur as a result of well-defined changes in the strain path. Special attention must be paid to any changes that lead to a reduced flow stress because this may cause unstable material flow, strain concentration and even material failure.

The literature about this subject [1-11] can be divided into two groups. The first is concerned with changes resulting from a total reversal in straining direction; these generally are indicated as "Bauschinger effect". A number of workers [1-4] has tried to quantify the observed yield stress drop. Their approach can be called fenomenological, macroscopic. Others [5-6] have tried to explain the Bauschinger effect from a microscopic point of view. Their aim was to give the observed effect a metallurgical background. In [7] many of the developed models are reviewed.

The second group of articles is mainly concerned with other changes in strain path. A first example of this is [8]. It deals with the deformation behaviour of brass undergoing a strain path with one or two corners. Amounts of strain before a corner were small: two percent at maximum. Also research has been done about the derivation of a yield criterion including a strain history in a certain deformation mode [9-10]. From this the yield stress in any direction in the pre-strained material can be determined; flow curves however can not be derived. In [11] the tensile flow behaviour of pre-torsioned steel bars is examined. Complications arose from the non-uniform distribution of the torsional pre-strain over the cross-section of the bars.

The question can be raised if it is possible to predict the changes in deformation behaviour resulting from a change in deformation mode. In answering this question however first some quantitative measurements have to be made.

In the present study two types of flow curve changes are examined. The first result from a total reversal in straining direction (compression-to-tension); the second from a tension-to-torsion transition. These changes are examined on the basis of experiments. The amount of strain before the transition ("pre-strain") is varied. Observed changes are quantified and interpreted by introduction of three "flow curve change characteristics". Considerations on the metallurgical backgrounds form part of the discussion.

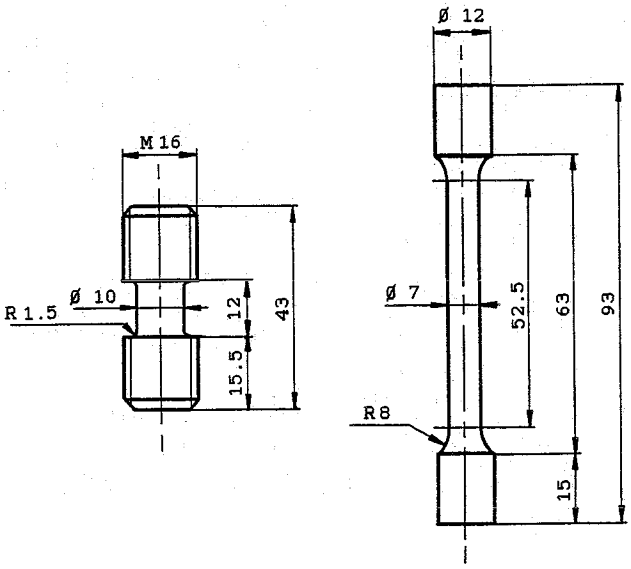
2. EXPERIMENTAL SET-UP

Two types of tests are used: compression-tension and tension-torsion tests. Figure 1 shows the geometry of the specimens.

Specimens of the "short" type are used in the compression-tension tests. A compressive force can be imposed on the face surfaces, a tensile force by means of the screw threads. To avoid specimen-buckling the height-to-diameter ratio of this specimen type has been chosen small. Besides that the face surfaces have been machined accurately perpendicular to the central axis. The compressive and the tensile part both are performed on the same testing machine (Mohr&Federhaff hydraulic press). Testing is done in an intermittent way. After every deformation step the following quantities are measured: the compressive or tensile force; the test piece diameter and the test piece contour-radius, in case of a barreled or necked test piece. From these quantities effective strains and effective stresses can be calculated (for barreled or necked test pieces the usual Bridgman correction is used [12]).

Specimens of the "long" type are used in the tension-torsion tests. The tensile part is performed on the Mohr&Federhaff press, in a way already discussed. Testing in torsion is done on an Amsler torsional testing machine in a continuous way. The moment needed to twist the test bars is registered as a function of twisting angle. From the measured quantities effective strains and effective stresses can be calculated [appendix A].

All tests are performed at room temperature, implementing low strain rates. As test material a plain carbon steel was chosen (C45, according to DIN 17200). All test specimens were machined from the same bar and were annealed in vacuum for 1½ hour at 700 °C.



type "short" type "long"

Fig. 1 Test specimens (dimensions are in mm)

3. RESULTS

3.1. Compression-tension (the Bauschinger effect)

Experimentation

A set of 10 compression-tension tests was performed. Amounts of strain before strain reversal ("pre-strains", "$\bar{\varepsilon}_0$") were varied from 0.02 up to 0.20 [-] in steps of 0.02 [-]. In addition two tension tests were done to obtain a reference.

From each of the experiments a flow curve is derived, some examples are given in figure 2.

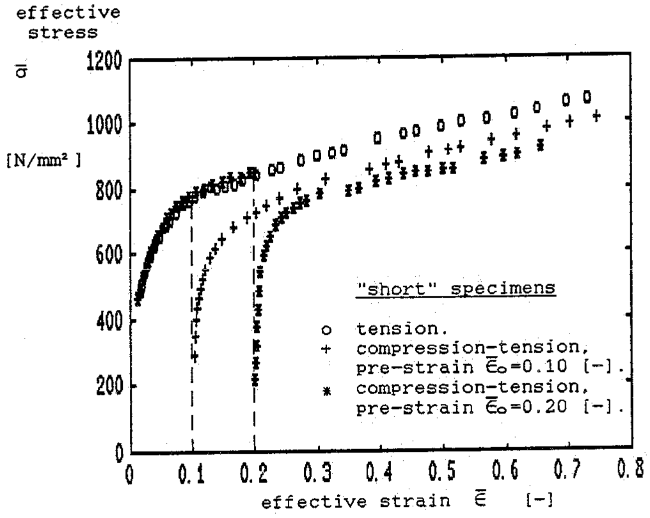


Fig. 2 Flow curves for C45 steel from tension and compression-tension experiments

Characterization

From the compression-tension flow curves characteristics can be derived that describe the flow curve changes. The following seem to be successful in quantifying the changes in relation to the amount of pre-strain:

1. "normalized flow stress drop", indicated by $(\Delta\bar{\sigma}/\bar{\sigma}_F)$.
   It is the reconstructed difference of forward and reverse flow stress ($=\Delta\bar{\sigma}$) at the strain reversal, divided by the forward flow stress ($\bar{\sigma}_F$) (Fig.3).
2. "permanent softening", indicated by $\Delta\bar{\sigma}_{perm}$.
   It is the difference of forward and reverse flow stress at large total strains (Fig.3).
3. "Bauschinger-strain", indicated by $\bar{\varepsilon}_B$.
   It is the strain in reverse direction, needed to attain the original flow stress level in forward direction (Fig.3).

The values for the characteristics are represented as a function of pre-strain in figure 4.

Interpretation

* From figure 4a it follows that the normalized flow stress drop as a first approximation can be considered independent of the pre-strain.
This is written as:

$$(\Delta\bar{\sigma}/\bar{\sigma}_F) \approx k_1 \quad [-] \qquad (1)$$

Whereas k_1 is independent of $\bar{\varepsilon}_0$, it depends on $\bar{\varepsilon}_R$.

In the absence of a pronounced yield point at the strain reversal this characteristic is fixed by adopting a certain strain value at which accompanying stresses are determined. Reverse strains of 0.01, 0.02 and 0.03 [-] are used; smaller values lead to inaccurate results, larger values obscure the background.

Values for the constant k_1 are obtained by averaging the 10 measurement results. This leads to:
$k_1=0.376$ [-] at $\bar{\varepsilon}_R=0.01$ [-]
{estimator of variance: $(\sigma_{n-1})^2=7.12\cdot10^{-4}$},
$k_1=0.279$ [-] at $\bar{\varepsilon}_R=0.02$ [-] {$(\sigma_{n-1})^2=4.04\cdot10^{-4}$},
$k_1=0.232$ [-] at $\bar{\varepsilon}_R=0.03$ [-] {$(\sigma_{n-1})^2=5.45\cdot10^{-4}$}.

* From figure 4b it can be seen that the permanent softening (in approach) is proportional to the pre-strain, or formulated:

$$\Delta\bar{\sigma}_{perm} \approx k_2\cdot\bar{\varepsilon}_0 \quad [\mathrm{N/mm^2}] \qquad (2)$$

, with k_2 as a constant.

Regression of the measurement results according to this formula, using the method of the least squares, gives: $k_2=613$ [N/mm²] {coefficient of determination: $R^2=0.9819$ [-]} (at $\bar{\varepsilon}_{tot}=0.70$ [-]).

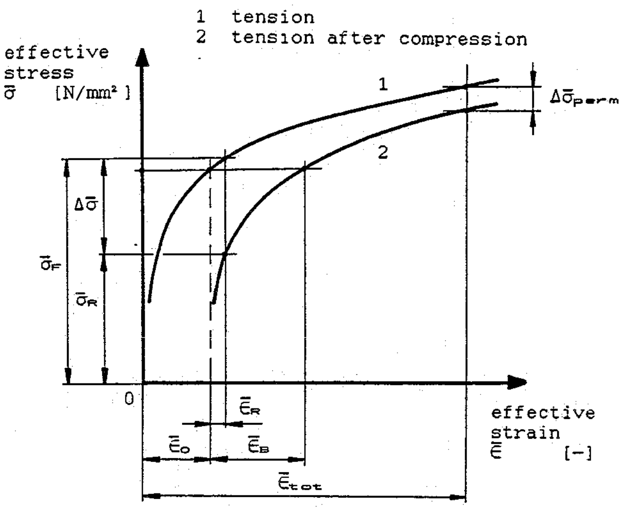
When total strain levels of 0.50 and 0.60 [-] are adopted similar results are obtained.

* The Bauschinger-strain is obviously proportional to the pre-strain (Fig.4c). This is formulated as:

$$\bar{\varepsilon}_B \approx k_3\cdot\bar{\varepsilon}_0 \quad [-] \qquad (3)$$

, with k_3 as a constant.

Regression of the measurement results (as above) leads to: $k_3=1.27$ [-] {$R^2=0.9945$ [-]}.



$\bar{\sigma}_F$	stress in the forward direction,
$\bar{\sigma}_R$	stress in the reverse direction,
$\bar{\varepsilon}_0$	pre-strain,
$\bar{\varepsilon}_R$	reverse strain,
$\bar{\varepsilon}_{tot}$	total strain.

Fig. 3 Schematic drawing of flow curve changes resulting from a strain reversal

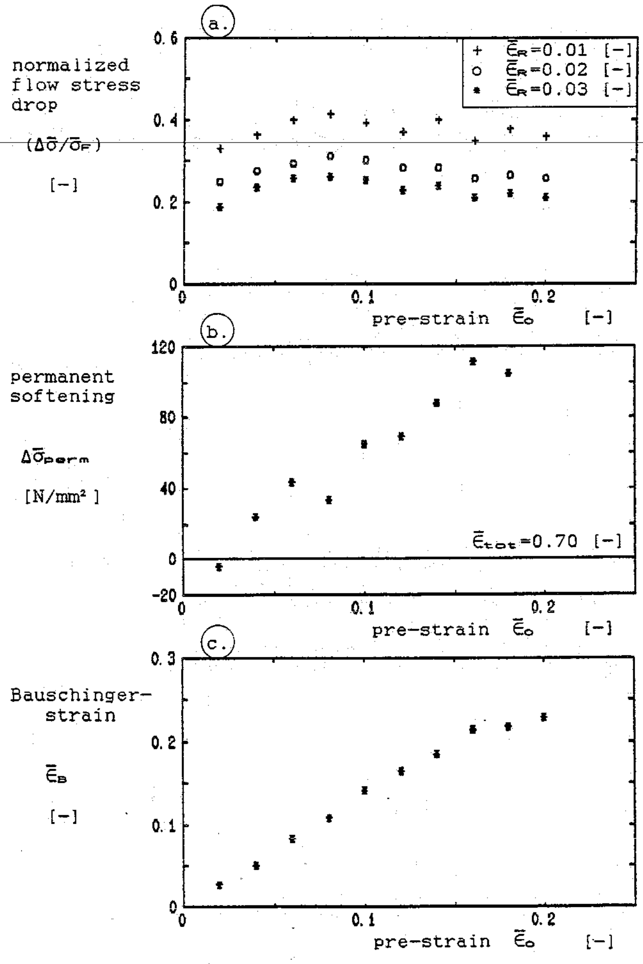


Fig. 4 Bauschinger effect characteristics for C45 steel as a function of pre-strain

3.2. Tension-torsion

Experimentation

Nine tension-torsion tests were performed. Pre-strains (in tension) were varied from 0.02 up to 0.10 [-] in steps of 0.01 [-]. An experiment with 0.01 [-] pre-strain could not be done because of the discontinuous yielding behaviour of the material. Pre-strains exceeding 0.10 [-] were not used because of the initiation of necking; as a result subsequent torsional deformation is inhomogeneous. In addition to the tension-torsion experiments a tension and two torsion tests were carried out to get a reference.

Flow curves are derived from the experiments, some examples are given in figure 5. A first observation that can be made is that the torsion curve is positioned below the tension curve. Similar observations have been made by Canova et al. [13].

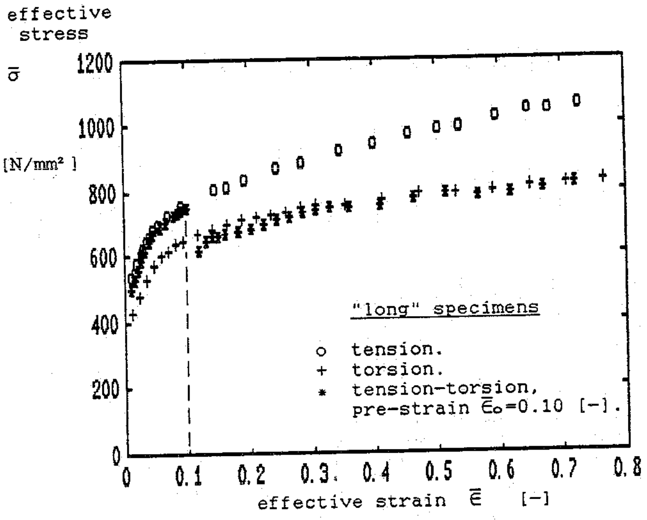
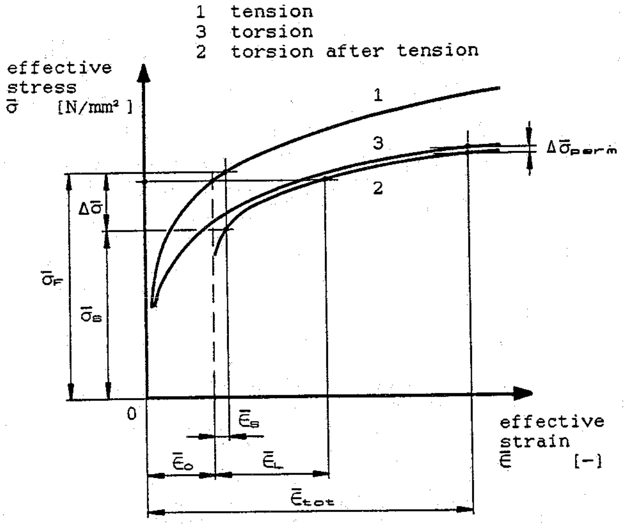


Fig. 5 Flow curves for C45 steel from tension, torsion and tension-torsion experiments

Characterization

Similar characteristics as introduced for describing the compression-tension behaviour are applied here. The same indications are used except for the Bauschinger-strain; its tension-torsion equivalent is indicated by the term "level-strain" and the symbol $\bar{\varepsilon}_L$. The characteristics ($\Delta\bar{\sigma}/\bar{\sigma}_F$; $\Delta\bar{\sigma}_{perm}$ and $\bar{\varepsilon}_L$) for the tension-torsion flow behaviour are indicated in the schematic drawing of figure 6. The values for the characteristics are represented as a function of pre-strain in figure 7.



$\bar{\sigma}_F$ stress in the first direction,
$\bar{\sigma}_S$ stress in the second direction,
$\bar{\varepsilon}_o$ pre-strain,
$\bar{\varepsilon}_S$ strain in the second direction,
$\bar{\varepsilon}_{tot}$ total strain.

Fig. 6 Schematic drawing of flow curve changes resulting from a tension-to-torsion transition

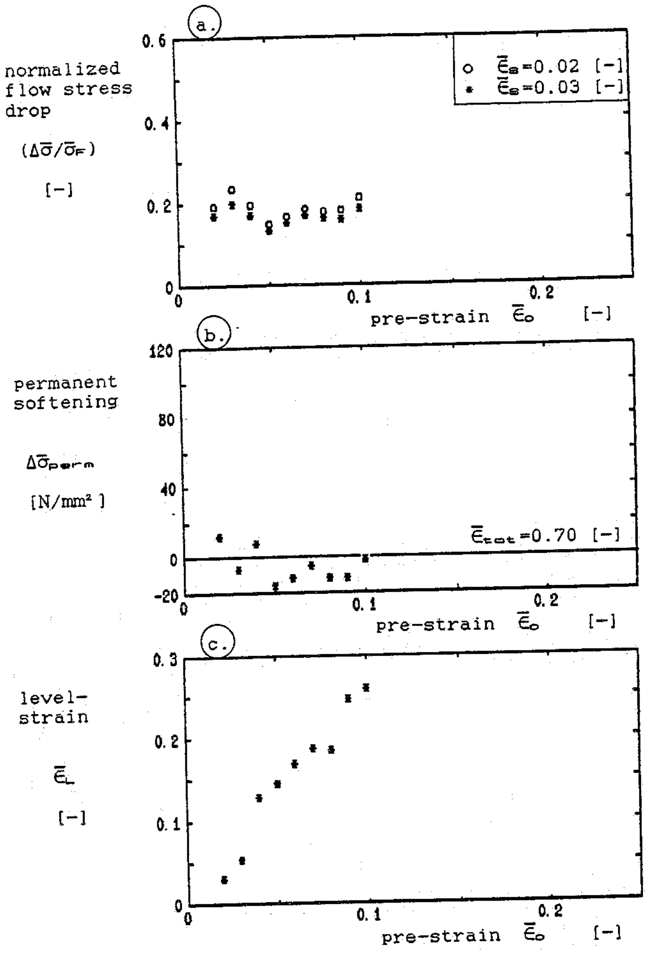


Fig. 7 Tension-torsion characteristics for C45 steel as a function of pre-strain

Interpretation

* The normalized flow stress drop seems to be independent of the pre-strain (Fig.7a).
This is written as:

$$(\Delta\bar{\sigma}/\bar{\sigma}_F) \approx k_4 \quad [-] \qquad (4)$$

Whereas k_4 is independent of $\bar{\varepsilon}_0$, it depends on $\bar{\varepsilon}_S$.

The averages of the measurement points: k_4=0.188 [-] at $\bar{\varepsilon}_S$=0.02 [-] and k_4=0.167 [-] at $\bar{\varepsilon}_S$=0.03 [-], {$(\sigma_{n-1})^2=6.18\cdot10^{-4}$ and $(\sigma_{n-1})^2=3.59\cdot10^{-4}$ respectively}.

* Figure 7b suggests that there exists no pre-strain dependency of the permanent softening. Formulation:

$$\Delta\bar{\sigma}_{perm} \approx k_5 \quad [N/mm^2] \qquad (5)$$

, with k_5 as a constant.

By averaging the nine measurement points we obtain: k_5=-4.8 [N/mm²] {$(\sigma_{n-1})^2$=89.68} (at $\bar{\varepsilon}_{tot}$=0.70 [-]).

When a total strain level of 1.00 [-] is adopted a similar result is obtained. It can be concluded that no structural permanent softening exhibits.

* The level-strain is obviously proportional to the pre-strain (Fig.7c).
This is formulated as:

$$\bar{\varepsilon}_L \approx k_6\cdot\bar{\varepsilon}_0 \quad [-] \qquad (6)$$

, with k_6 as a constant.

Regression leads to k_6=2.63 [-] {R^2=0.9895 [-]}.

4. DISCUSSION

Until now the experiments are interpreted on the basis of macroscopic observations. The question of the metallurgical backgrounds however is also of interest. In the next some considerations in this context are presented.

About the principles causing a Bauschinger effect a general agreement exists. These can be summarized as follows.

Plastic straining occurs when dislocations displace in their slip-plane under the influence of a shear stress, caused by an external stress. Continued displacement however can be obstructed by obstacles such as grain boundaries, second phase particles et cetera. When dislocations can not pass they pile up in front of the obstacles. Continued straining then requires an increase in shear stress and thus in the external stress.

At a reverse in straining direction the same slip-systems are applied, but in reverse direction. Dislocation accumulations can unpile when a shear stress in reverse direction is introduced, assisted by the repulsion between the (piled) dislocations. Therefore the required stress for straining in reverse direction is smaller than the stress for straining in forward direction. In the first stages of reverse deformation the dislocations will not encounter other obstacles. Thus it is plausible that a strain reversal influences the entire (reverse) flow curve. Another conclusion is that the magnitude of the Bauschinger effect will depend on the number of dislocations accumulated at the obstacles and therefore will increase with increasing pre-strain.

Metallurgical backgrounds leading to the discrepancy between tension and torsion flow curve are discussed by Witzel and Haeßner on the basis of the Taylor equation [14]:

$$\bar{\sigma} = M_T \cdot \tau_{crit} \qquad (7)$$

$\bar{\sigma}$: flow stress in a polycrystalline metal [N/mm^2]
M_T : factor, determined by the orientation distribution of the crystals (Taylorfactor) [-]
τ_{crit} : critical shear stress in the individual slip systems of a crystal [N/mm^2]

Two effects are distinguished:

* The texture developing in tension differs from that in torsion. This finds expression in a Taylorfactor increase in tension and a decrease in torsion by a proceed of deformation.
* The dislocation arrangement developing in tension differs from that in torsion. Thus the critical shear stress developes differently. It is indicated that the increase in critical shear stress (strain hardening) is larger in tensile deformation than in torsional deformation.

These effects lead to a deviation between tension and torsion flow curve that increases with strain.

The Bauschinger effect was examined by means of compression-tension tests. Some former studies investigated this effect using torsion- reverse torsion tests on thin tube specimens [1],[2],[10]. As observed, the torsion flow curve differs significantly from the tension curve. Therefore it can be doubted whether the obtained results from the different types of tests can be exchanged directly.

It would be of interest performing similar experiments on other materials. Then a comparison can be made between the responses of different materials to the same changes in deformation mode. Such a comparison may be made on the basis of the introduced flow curve change characteristics. In this context the question arises whether or not other materials show same relationships between characteristics and pre-strain.

5. CONCLUSIONS

* At a strain reversal from compression to tension considerable flow curve changes exhibit. These changes are expressions of the Bauschinger effect. They can be characterized roughly as a drastic flow stress drop at the reversal, that can not be neutralized entirely by the strain hardening resulting from continued (reverse) straining. The amount of strain before the strain reversal appears to be an influencing factor.

* At a change from tension to torsion a quick transition from the tension flow curve to the lower positioned torsion curve is observed. Only at initial re-straining a small drop in flow stress (compared to the torsion curve) is perceived.

* There appear to exist simple mathematical relationships between the pre-strain and the "flow curve change characteristics" for both types of flow curve changes investigated.

* The Bauschinger effect can be explained on the basis of a metallurgical model, from which also influencing factors can be derived.

* On the observed flow behaviour in tension-torsion some considerations, concerning the metallurgical backgrounds, can be made. A good insight however is still lacking.

REFERENCES

[1] Jamieson R.M., Hood J.E., 1971, Bauschinger Effect in High-Strength Low-Alloy Steels, J. Iron Steel Inst., 209:46-48.
[2] Kishi T., Gokyu I., 1973, A New Relationship Between Pre-strain and Yield Stress Drop Due to Bauschinger Effect, Met. Trans., 4:390-392.
[3] Pugh J.W., 1980, The Bauschinger Effect in Tungsten Lamp Wire, Met. Trans., 11A:1487-1489.
[4] Ibrahim N., Embury J.D., 1975, The Bauschinger Effect in Single Phase b.c.c. Materials, Mater. Sci. Eng., 19:147-149.
[5] Moan G.D., Embury J.D., 1979, A Study of the Bauschinger Effect in Al-Cu Alloys, Acta Met., 27:903-914.
[6] Hasegawa T., Yakou T., Kocks U.F., 1986, A Unified Representation of Stress-Strain Curves in Reversed Direction of Prestrained Cell-Forming Metals, Trans. JIM, 27:425-433.
[7] Sowerby R., Uko D.K., Tomita Y., 1979, A Review of Certain Aspects of the Bauschinger Effect in Metals, Mater. Sci. Eng., 41:43-58.
[8] Ohashi Y., Tokuda M., Itoh S., Miyake T., 1980, Experimental Investigation on History-dependence of Plastic Behaviour of Brass under Combined Loading, Bull. JSME, 23:1305-1312.
[9] Williams J.F., Svensson N.L., 1970, Effect of Tensile Prestrain on the Yield Locus of 1100-F Aluminium, J. Strain Anal., 5:128-139.
[10] Kishi T., Tanabe T., 1973, The Bauschinger Effect and its Role in Mechanical Anisotropy, J. Mech. Phys. Solids, 21:303-315.
[11] Brown G.G., Watson J.D., 1982, The Tensile Properties of Pretorsioned Steel Bars, Met. Forum, 5:195-209.
[12] Bridgman P.W., 1952, Studies in Large Plastic Flow and Fracture, McGraw-Hill, NewYork-London.
[13] Canova G.R., Shrivastava S., Jonas J.J., G'Sell C., 1982, The Use of Torsion Testing to Assess Material Formability, Formability of Metallic Materials - 2000 A.D., 189-210.
[14] Witzel W., Haeßner F., 1987, Zur Vergleichbarkeit von Werkstoffzuständen nach Dehnen, Stauchen und Tordieren, Z. Metallk., 78:316-323.

APPENDIX A

Calculation method for effective strains and effective stresses in the tension-torsion test.

At pre-straining in tension the formulas for the uni-axial stress-state are used.

Assume, for straining in torsion, a homogeneous torsional deformation and the von Mises yield criterion. Then the next formulas can be derived:

$$\bar{\varepsilon}_T(r) = \frac{r \cdot \alpha}{\sqrt{3} \cdot L} \qquad (A1) \quad ; \quad M = \frac{2 \cdot \pi}{\sqrt{3}} \cdot \int_{r=0}^{\frac{1}{2}d_0} \bar{\sigma} \cdot r^2 \, dr \qquad (A2)$$

$\bar{\varepsilon}_T$: torsional strain distribution [-]
r : radial coordinate [mm]
L : test piece length [mm]
α : twisting angle [rad]
M : twisting moment [Nmm]
d_0 : test piece diameter [mm]
$\bar{\sigma}$: effective stress [N/mm^2]

Additionally a Ludwik stress-strain relationship is assumed, expressed as:

$$\bar{\sigma} = C \cdot (\bar{\varepsilon} + \bar{\varepsilon}_0)^n \qquad (A3)$$

C : characteristic stress [N/mm^2]
n : strain hardening exponent [-]
$\bar{\varepsilon}$: effective strain [-]
$\bar{\varepsilon}_0$: pre-strain [-]

When the formulas A1, A2 and A3 are combined the integral can be elaborated. The twisting moment thus can be expressed as:

$$M = M(\alpha, \bar{\varepsilon}_0, L, d_0, C, n) \qquad (A4)$$

The calculation procedure is as follows. Two points of measurement (twisting angle - twisting moment) are adopted: α_1, M_1 and α_2, M_2. Accompanying total strains in the outer radius of the test piece are calculated from:

$$\bar{\varepsilon} = \bar{\varepsilon}_T(r = \tfrac{1}{2}d_0) + \bar{\varepsilon}_0 \qquad (A5)$$

The two points of measurement both are substituted in equation A4, from this two equations with two unknown parameters (C and n) result. These are solved in a numerical way. Substituting the obtained C and n value, together with the respective strains, in the Ludwik relationship (A3) results in two accompanying values for the effective stress.