MASTER

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

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Eindstudieopdracht W.H. Sillekens.

Begintijdstip	: September 1986.
Begeleider	: Dr.ir. J.H. Dautzenberg.
ONDERWERP	: Vloeikrommen van metalen bij een niet-rechte spanningsweg.
TOELICHTING	: Uit de praktijk is bekend dat bij het afwijken van de rechte spanningsweg een verandering in de vloeikromme optreedt. Het is duidelijk dat bij een spanningsafname een instabiliteit kan optreden. Bij de overgang van trek naar druk is dit fenomeen bekend als het Bauschinger effekt. De verklaring kan gezocht worden in de grotere bewegingsvrijheid van de dislokaties bij het omkeren van de spanningsrichting. Eenzelfde effekt, misschien minder uitgesproken, moet ook optreden bij de overgang van een trek- naar een torsiebelasting. Het is duidelijk dat de grootte van het effekt beïnvloed wordt door de grootte van de deformatie voor de spanningsomkeer.
OPDRACHT	: Ga dit effekt na bij verschillende technische metalen, voor verschillende veranderingen van de spanningstoestand, verschillende deformaties voor de spanningsverandering en bekijk of dit effekt voorspelbaar is.
VERSLAG ETC.	: Het memorandum "Aanwijzingen voor het afstuderen" is bij de secretaresse verkrijgbaar.

10 september 1986
Dr.ir. J.H. Dautzenberg

Prof.ir. J.A.G. Kals

SAMENVATTING

Het plastisch gedrag van materialen kan worden vastgelegd in een vloeikromme. Een vloeikromme (spanning-rek kromme) wordt meestal bepaald met behulp van een materiaalproef waarbij de gevolgde rekweg recht is (trekproef, stuikproef). In veel industriële omvormprocessen echter is de gevolgde rekweg niet recht. Een afwijking van de rechte rekweg leidt, algemeen gesteld, tot veranderingen in de vloeikromme. Afwijkingen die leiden tot een vloeispanningsafname zijn van bijzonder belang omdat deze de oorzaak kunnen zijn van instabiliteit.

Om meer informatie te krijgen over het vloeigedrag van metalen bij abrupte veranderingen in de rekweg zijn twee typen veranderingen onderzocht: de overgang van stuik- naar trekbelasting ("Bauschinger effect") en de overgang van trek- naar torsiebelasting. Dit werd gedaan aan de hand van experimenten met als proefstukmateriaal staal C45. De rek vòòr de overgang ("voorrek") werd gevarieerd. Veranderingen in de opgenomen vloeikrommen zijn vastgelegd in drie zogenaamde "karakteristieken". Eèn karakteristiek is gebaseerd op de initiële verandering, de tweede op de permanente verandering en de derde op een tussenwaarde. Het blijkt dat er eenvoudige relaties bestaan tussen de karakteristieken en de voorrek. Metaalkundige achtergronden worden besproken aan de hand van de resultaten.

SUMMARY

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.

CONTENTS

1. INTRODUCTION

In forming technology the plastic behaviour of materials often is represented graphically by a flow curve. Such a flow curve (or stress-strain curve) can be determined by performing a material test. The most well known tests are the tension test and the compression test on solid cylindrical test pieces. Typical of these tests 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 strain 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 of this behaviour it is necessary to examine the changes in flow curve which occur as a result of well-defined changes in 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 the group which is concerned with changes in flow curve resulting from a total reversal in straining direction; these changes generally are indicated as "Bauschinger effect". A number of workers [1-4] has tried to quantify the Bauschinger effect in terms of the observed yield stress drop, for example as a function of the strain before reversal. 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 on the topic of the Bauschinger effect (microscopic and macroscopic) are reviewed.

The second group of articles in this field is mainly concerned with other changes in strain path. A first example of this is [8], which 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 criterion 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 are the changes resulting from a total reversal in straining direction: compression-to-tension. The second are the changes resulting 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". From these characteristics a comparison is made between the two types of changes investigated. Considerations on the metallurgical backgrounds also 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.

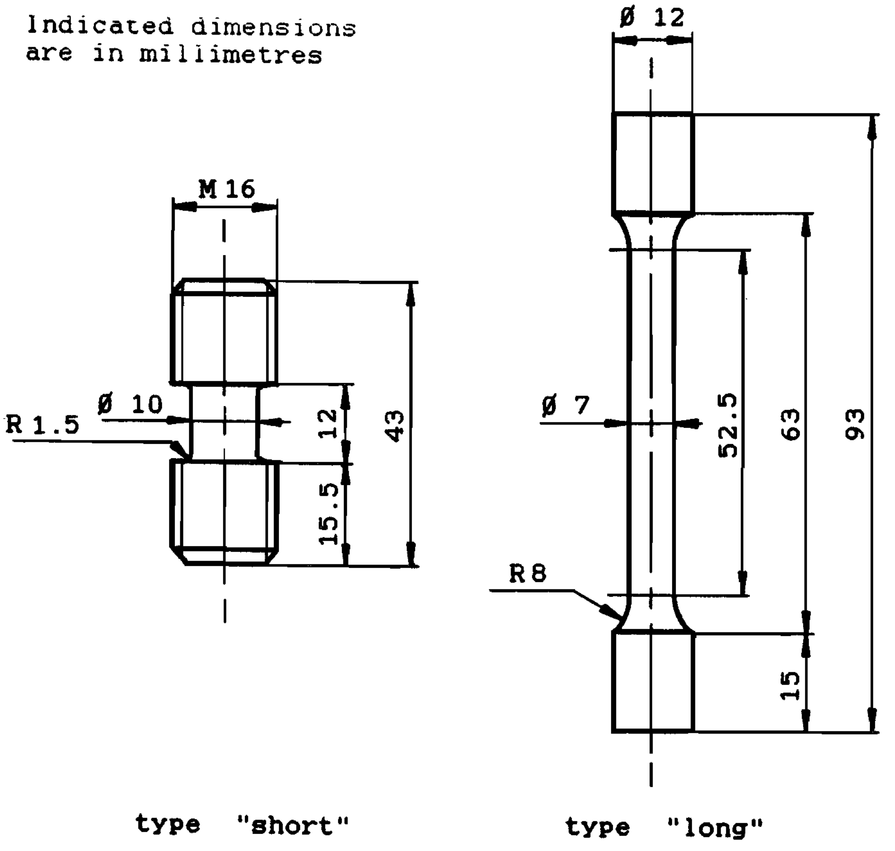


Fig. 1 Test specimens

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 (in compression) 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 of these tests 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;
* the test piece contour-radius, in case of a barreled or necked test piece.
  Contour-radii are determined using a measuring microscope.

From these measured quantities effective strains and effective stresses can be calculated; the used method is discussed in appendix A.

Specimens of the "long" type are used in the tension-torsion tests. The tensile part of these tests is performed on the Mohr&Federhaff press in an intermittent way. Measured quantities are the tensile force and the test piece diameter. 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; the used method is discussed in appendix B.

In compression and tension, as well as in torsion, the implemented strain-rates are low. The obtained flow curves therefore can be considered as representing the quasi-static flow behaviour. The tests are performed at room temperature. As test material a plain carbon steel was chosen (indication: C45, materialnumber 1.0503 according to DIN 17200). All test specimens were machined from the same bar and were annealed in vacuum for 1½ hour at 700 °C.

3. RESULTS

3.1. Compression-tension (the Bauschinger effect)

Experimentation

The Bauschinger effect is examined in terms of flow curve changes resulting from a compression-to-tension change in deformation mode. A set of 10 compression-tension tests was performed. Amounts of strain before strain reversal ("pre-strains", "$\bar{\varepsilon}_o$") were varied from 0.02 up to 0.20 [-] with a step increment of 0.02 [-]. In addition two tension tests (also on "short" specimens) were done to attain a reference from which the other experiments could be interpreted.

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

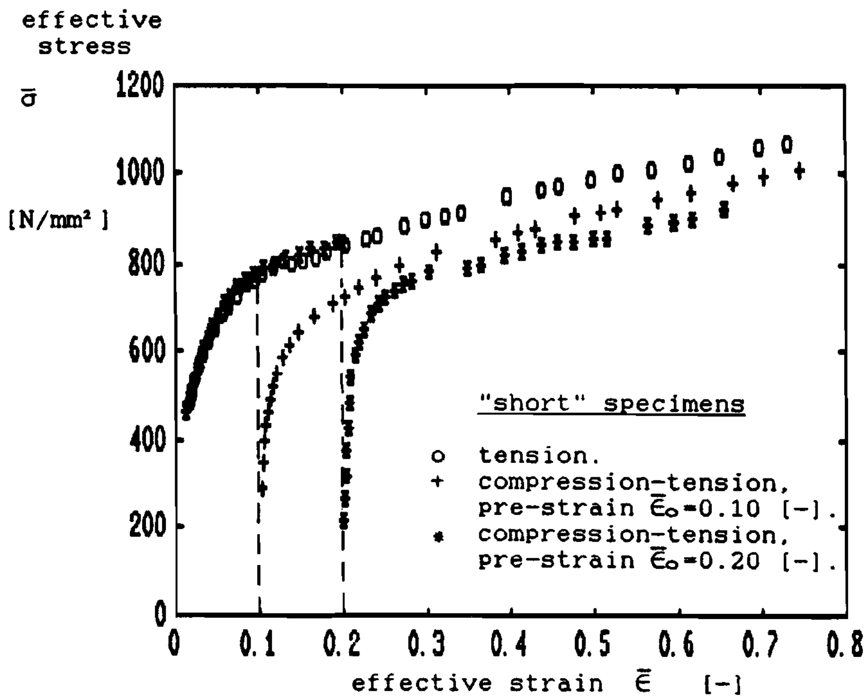


Fig. 2 Flow curves for C45 steel from tension and compression-tension experiments

In this figure one curve represents a tension test. The other curves follow from compression-tension tests with a pre-strain in compression of 0.10 and 0.20 [-] respectively. The "compression-parts" of these curves nearly coincide with the tension curve, as could be expected. The "tension-parts" however are significantly lower positioned compared to the tension curve, especially in the first stages of reverse deformation.

Characterization

From the compression-tension flow curves characteristics can be derived that describe the flow curve changes. Many possible characteristics can be thought of. 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 $\bar{\epsilon}_B$.
   It is the strain in reverse direction, needed to attain the original flow stress level in forward direction (fig.3).

In figure 3 curve 1 is a tension flow curve; curve 2 is the flow curve branch after a change from compression-to-tension.

The experimentally determined 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:

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

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

This characteristic can be interpreted as being a comparison between forward and reverse yield behaviour of the pre-strained material. The stresses used in determining this characteristic consequently must have a "yield" character: fix the transition from elastic to plastic deformation. In the absence of a pronounced yield point at the strain reversal this is done 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:

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

, 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 }.

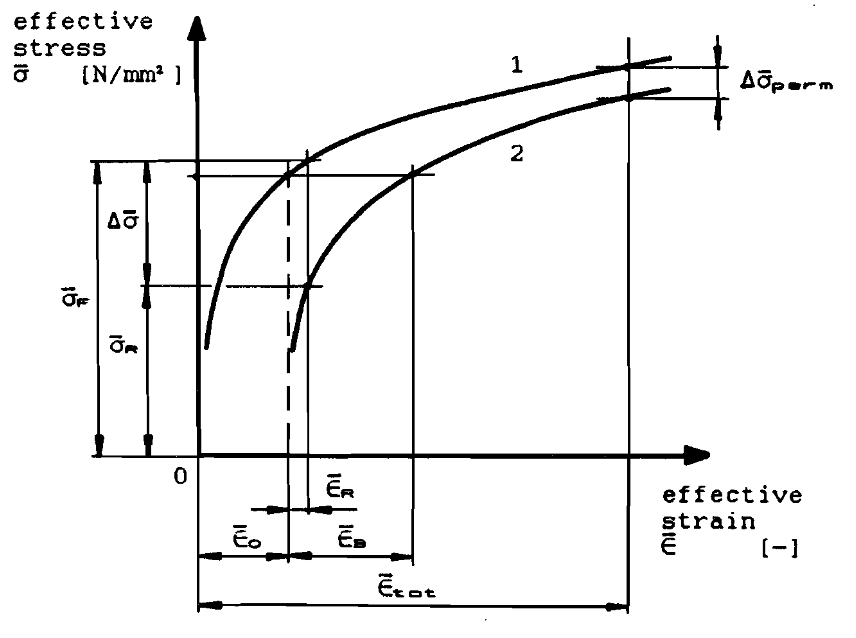
The plotted values of the permanent softening in figure 4b are determined at a total effective strain of 0.70 [-]. When total strain levels of 0.50 and 0.60 [-] are adopted similar results are obtained. It means that the curves 1 and 2 in figure 3 nearly run parallel to each other at large strains: "softening" can be considered "permanent".

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

$$\bar{\varepsilon}_B \approx k_3 \cdot \bar{\varepsilon}_o \quad \{ \text{ or } (\bar{\varepsilon}_B/\bar{\varepsilon}_o) \approx k_3 \} \quad [-] \qquad (3)$$

, 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,
$\bar{\varepsilon}_o$ 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

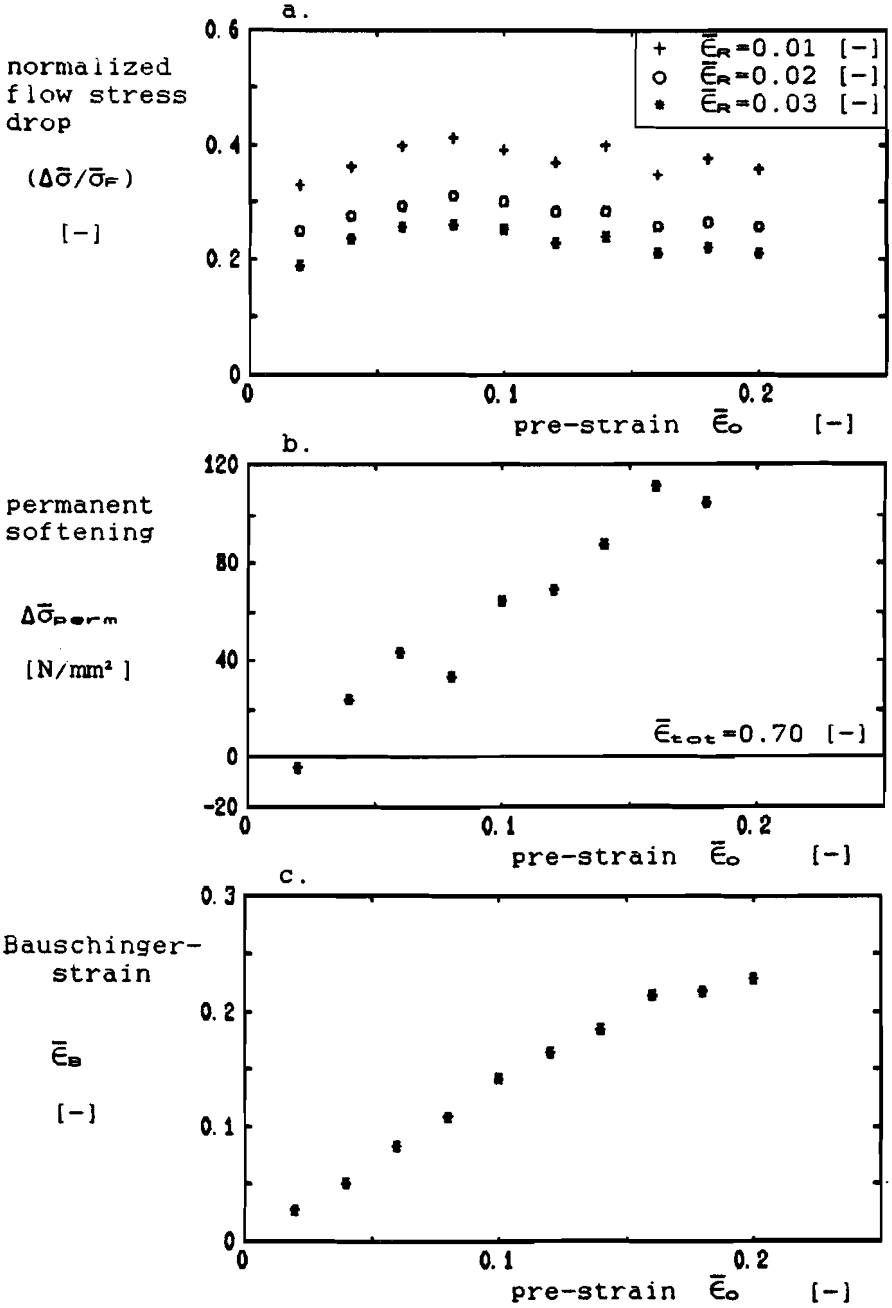


Fig. 4 Bauschinger effect characteristics for C45 steel as a function of pre-strain

3.2. Tension-torsion

Experimentation

The second type of flow curve changes that have been examined are the changes resulting from a tension-to-torsion transition in deformation. 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 one tension and two torsion tests (also on "long" specimens) were carried out in order to get a reference from which the results could be interpreted.

Flow curves can be derived from these experiments, some examples are given in figure 5.

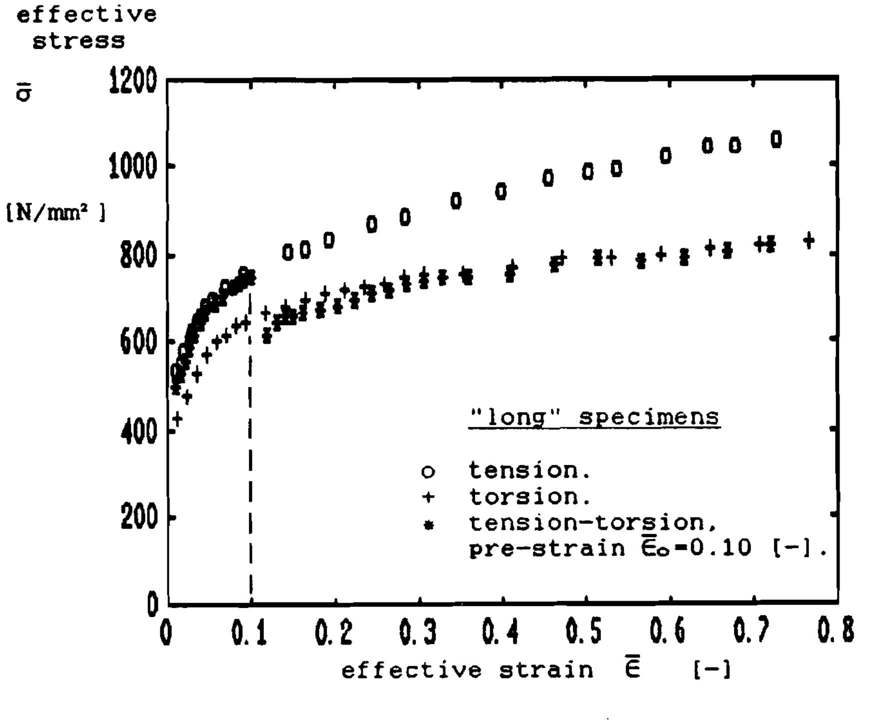


Fig. 5 Flow curves for C45 steel from tension, torsion and tension-torsion experiments

In this figure one curve represents the tension test, the second a torsion test and the third the tension-torsion test with a pre-strain in tension of 0.10 [-].

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. [12].

The tension-torsion curve in figure 5 is a typical example of the observed flow behaviour in the performed experiments. This behaviour can be characterized as follows. The change from a tensile into a torsional deformation leads to a reduced flow stress, initially flow stresses even are smaller than those obtained from a torsion test. As torsional deformation proceeds however the resulting curve quickly converges on the torsion flow curve.

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. In this figure curve 1 is a tension flow curve, curve 2 is the flow curve branch after a change from tension to torsion and curve 3 is a torsion flow curve.

The experimentally determined values for the characteristics are represented as a function of pre-strain in figure 7.

Interpretation

* The normalized flow stress drop seems to be independent of pre-strain, or at least no pronounced dependency can be concluded from figure 7a.
This is written as:

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

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

The averages of the measurement points:
k_4=0.188 [-] at $\bar{\varepsilon}_B$=0.02 [-] and k_4=0.167 [-] at $\bar{\varepsilon}_B$=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 $\bar{\epsilon}_{tot} = 0.70$ [-]).
When a total strain level of 1.00 [-] is adopted a similar result is obtained.

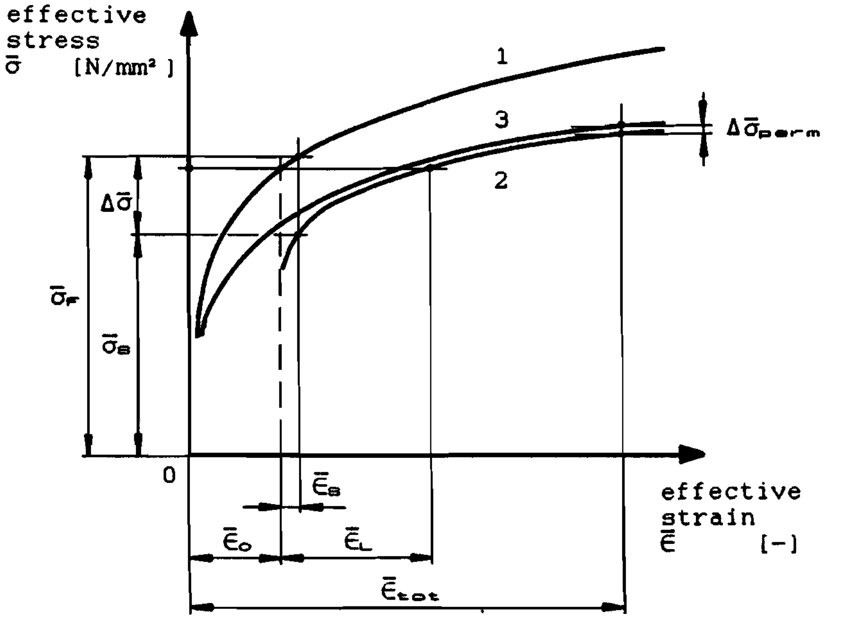
It can be concluded that no structural permanent softening exhibits in the tension-torsion experiments.

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

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

, with k_6 as a constant.

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



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

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

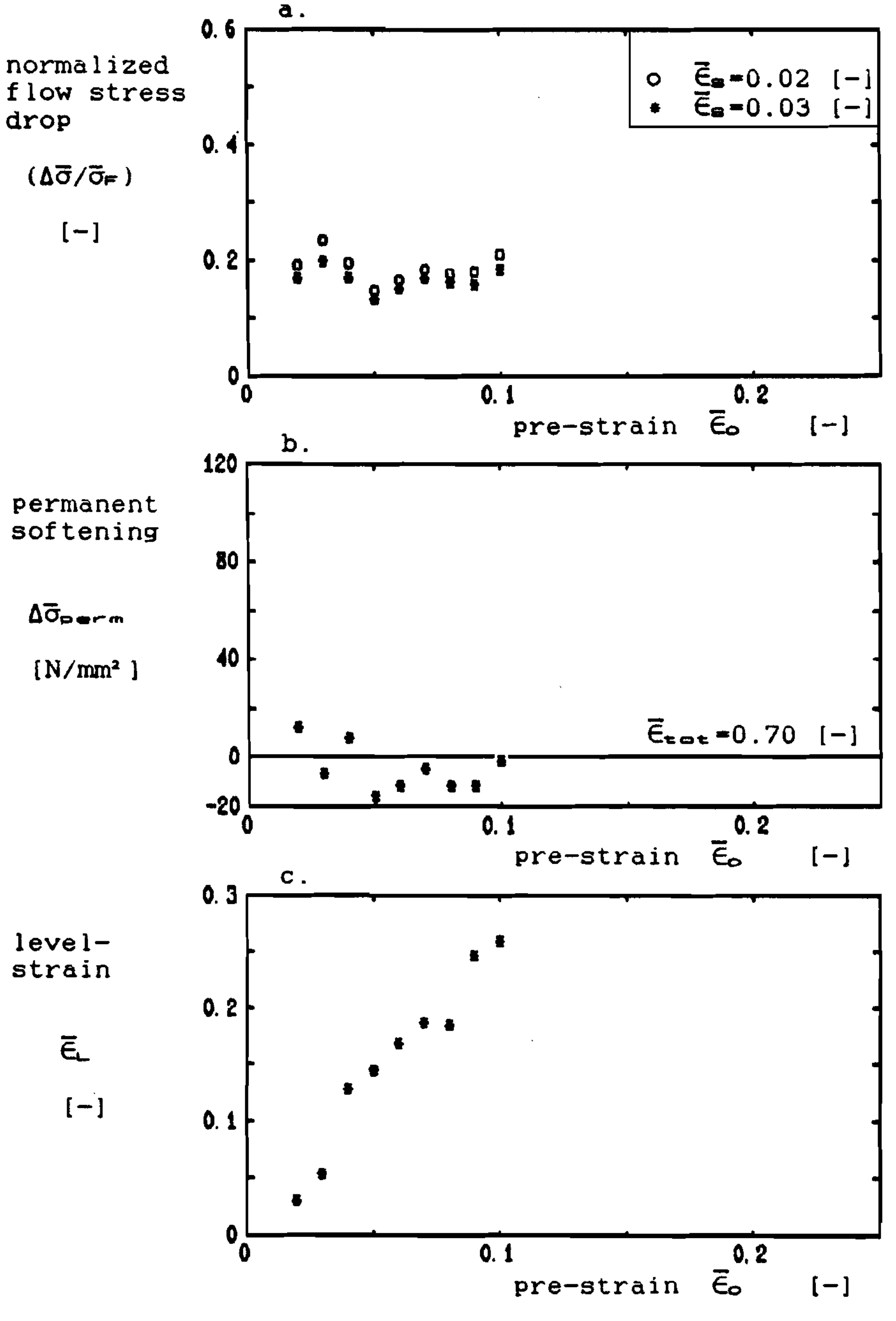


Fig. 7 Tension-torsion characteristics for C45 steel as a function of pre-strain

4. DISCUSSION

According to Sowerby, Uko and Tomita [7], the Bauschinger effect "...is manifested by the reverse flow curve exhibiting [firstly:] a reduced elastic limit, [secondly:] a well-rounded appearance of the initial plastic portion and [thirdly:] permanent softening vis à vis the forward hardening curve".
A connection can be found between these (qualitative) features and the (quantitative) Bauschinger effect characteristics:

* the first feature is expressed by the normalized flow stress drop;
* the second feature can be brought in connection with the Bauschinger-strain, or to be more exact: with the quotient of Bauschinger-strain and pre-strain [This needs some elaboration. From the experiments it is found that this quotient can be considered a constant (k_s), with a value bigger than unity. Thus the initial plastic portion of the reverse flow curve must be "more rounded" than its comparable part in the forward curve!];
* the third feature, of course, is related to the permanent softening characteristic.

From the performed compression-tension and tension-torsion experiments a comparison can be made between the respective flow curves.

A strain reversal from compression to tension leads to a considerable lowering in flow stress. As straining in reverse direction proceeds the flow stress drop decreases (compared to the tension flow curve) but does not disappear; at large strains a stabilization of the softening is observed. This is in contrast with the results from the tension-torsion experiments. While in the first stages of torsional deformation (after tension) a limited flow stress drop is observed (compared to the torsion flow curve), continued deformation leads to a recovery; at larger strains the curves coincide.

The comparison between compression-tension and tension-torsion can be specified by using the derived flow curve change characteristics.

* The above mentioned differences at large strains find expression in the permanent softening characteristic. A Bauschinger effect as it appears in compression-tension leads to a permanent softening proportional to the amount of pre-strain. In tension-torsion on the other hand no permanent softening exhibits.

* Flow curve changes immediately after the change in deformation mode are expressed by the normalized flow stress drop. The results suggest a pre-strain independency of this characteristic for both types of strain path changes. At compression-tension a flow stress decrease of 28 [%] is observed, at tension-torsion a decrease of 19 [%]. These values are determined at 0.02 [-] strain in the second direction. It can be concluded that the flow stress drop in compression-tension is more drastic.
* The Bauschinger- and level-strain give an impression of the flow behaviour between the initial and the permanent effects, as expressed in the two other characteristics. Experimental results indicate a proportionality between the Bauschinger- or level-strain and the pre-strain. Derived proportionality factors are 1.3 [-] in the compression-tension experiments and 2.6 [-] in the tension-torsion experiments. The large value of the latter one is not surprising; at the change to torsion a transition to the significantly lower positioned torsion flow curve takes place.

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 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 [13]:

$$\bar{\sigma} = M_T \cdot \tau_{crit} \quad [N/mm^2] \qquad (7)$$

$\bar{\sigma}$	:	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.

From this a next consideration on the flow behaviour in the tension-torsion experiments can be made. At all implemented pre-strains (from 0.02 up to 0.10 [-]) a similar behaviour was observed: at the transition from tension to torsion a small flow stress drop and at further torsional straining merging into the torsion curve. It is improbable that at these pre-strains a tensile texture is developed so far that it can exert substantial influence on subsequent torsional deformation. The observed initial flow stress drop therefore is believed to be connected with the change in dislocation arrangement. Apparently the arrangement developing in tension can be altered easily to a torsion conforming arrangement (considering the low accompanying flow stresses and the quick recovery).

This discussion of the experimental results is concluded with some final remarks.

Values for the "normalized flow stress drop" were determined at strains in second direction of 0.01, 0.02 and 0.03 [-]. Background of this characteristic is to be an indication of the "fractional loss of strenght" resulting from the change in deformation mode. This background will be better expressed when smaller re-strain values are adopted, for instance 0.001 or 0.002 [-]. Used measurement methods however were not suitable for such small strains. A more accurate strain measurement method can be of use in putting this characteristic in a proper perspective. Then also a better picture of the pre-strain (in)dependency of this characteristic may be obtained.

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.

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APPENDIX A

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

Basic assumption is that a tension and a compression test lead to (approximately) the same flow curves [14]. Consequently a compression-tension and a tension-compression test must lead to an approximately same result (same material and pre-strain assumed).

Used test pieces take on a barrel-shape at larger compressive deformations. This influences the stress-state, not only in compression but also in subsequent tensile deformation. A calculation method is applied which accounts for the deviation from the uni-axial stress-state in a compression-tension test. This method implies that the in the centre-plane of the test piece existing strains and stresses are calculated (by centre-plane is ment: the largest cross-section in a barreled and the smallest cross-section in a necked test piece).

Evidence for the validity of this method was obtained by comparing calculated compression-tension flow curves with the flow curves from the equivalent tension-compression experiments.

* <u>Pre-straining in compression.</u>

$$\bar{\varepsilon} = 2 \cdot \ln(d/d_i) \qquad [-] \qquad \text{(A1)}$$

$$\bar{\sigma} = \frac{4 \cdot F_c}{\pi \cdot d^2} \qquad [N/mm^2] \qquad \text{(A2)}$$

$\bar{\varepsilon}$:	effective strain	[-]
d_i :	initial test piece diameter	[mm]
d :	test piece diameter (at largest cross-section)	[mm]
$\bar{\sigma}$:	effective stress	[N/mm²]
F_c :	compressive force	[N]

Straining in compression is done until the pre-strain ($\bar{\varepsilon}_o$) is reached. For the implemented pre-strains a satisfying correspondence with the tension flow curve is concluded using the formula for the uni-axial stress-state (A2). It has been indicated that, in stress calculation, the barreling effect is largely compensated by another friction effect: the development of a "friction hill" ([15] pp. 33-35 and 55-57).

* <u>Straining in tension.</u>

$$\bar{\varepsilon} = 2 \cdot \ln(d_o/d) + \bar{\varepsilon}_o \qquad [-] \qquad \text{(A3)}$$

$$\bar{\sigma} = \frac{4 \cdot F_t}{\pi \cdot d^2} \cdot C_B \qquad [N/mm^2] \qquad \text{(A4)}$$

Correction factor:

$$C_B = \frac{1}{(1+[4 \cdot R]/d) \cdot \ln(1+d/[4 \cdot R])} \qquad [-] \qquad \text{(A5)}$$

d_o :	test piece diameter (at largest cross-section) at the pre-strain	[mm]
$\bar{\varepsilon}_o$:	pre-strain	[-]
F_t :	tensile force	[N]
C_B :	Bridgman correction factor	[-]
d :	test piece diameter (at largest, or smallest cross-section)	[mm]
R :	contour-radius	[mm]

In case $\bar{\varepsilon}_o \geq 0.14$ [-] test pieces are measurable barreled (R<60 [mm]). In tensile testing of barreled test pieces the Bridgman correction is used, applying a minus sign in the contour-radius containing terms (thus $C_B > 1$). At continued tension R increases (barreling decreases); for R>60 [mm] no correction is used. At larger tensile strains test piece necking appears, then the Bridgman correction is used in the normal way ([16] pp. 9-32).

APPENDIX B

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

* Pre-straining in tension.

A uni-axial stress-state is assumed: no test piece necking. Used formulas:

$$\bar{\epsilon} = 2 \cdot \ln(d_i/d) \qquad [-] \qquad (B1)$$

$$\bar{\sigma} = \frac{4 \cdot F_t}{\pi \cdot d^2} \qquad [N/mm^2] \qquad (B2)$$

$\bar{\epsilon}$:	effective strain	[-]
d_i :	initial test piece diameter	[mm]
d :	test piece diameter	[mm]
$\bar{\sigma}$:	effective stress	[N/mm²]
F_t :	tensile force	[N]

Straining in tension is done until the pre-strain ($\bar{\epsilon}_o$) is reached.

* Straining in torsion.

Assuming a homogeneous torsional deformation and the von Mises yield criterion, the next formulas can be derived:

$$\bar{\epsilon}_T(r) = \frac{r \cdot \alpha}{\sqrt{3} \cdot L} \qquad [-] \qquad (B3)$$

$$M = \frac{2 \cdot \pi}{\sqrt{3}} \cdot \int_{r=0}^{\frac{1}{2}d_o} \bar{\sigma} \cdot r^2 \, dr \qquad [Nmm] \qquad (B4)$$

$\bar{\epsilon}_T$:	torsional strain distribution	[-]
r :	radial coordinate	[mm]
L :	test piece length	[mm]
α :	twisting angle	[rad]
M :	twisting moment	[Nmm]
d_o :	test piece diameter	[mm]

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

$$\bar{\sigma} = C \cdot (\bar{\varepsilon}+\bar{\varepsilon}_o)^n \qquad [N/mm^2] \qquad (B5)$$

C :	characteristic stress	[N/mm²]
n :	strain hardening exponent	[-]
$\bar{\varepsilon}_o$:	pre-strain	[-]

When the formulas B3, B4 and B5 are combined the integral can be elaborated. The twisting moment thus can be expressed as a (complicated) function of the other quantities, simply represented as:

$$M = M(\alpha,\bar{\varepsilon}_o,L,d_o,C,n) \qquad [Nmm] \qquad (B6)$$

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:

$$\bar{\varepsilon} = \bar{\varepsilon}_T(r=\tfrac{1}{2}d_o) + \bar{\varepsilon}_o \qquad [-] \qquad (B7)$$

The two points of measurement both are substituted in equation B6, from this two equations with two unknown parameters (C and n) result. These are solved in a numerical way (no analytical solution available). Substituting the obtained C and n value together with the respective strains (calculated from equation B7) in the Ludwik relationship (B5) results in two accompanying values for the effective stress.