Comparison of the Equivalent Flow Curves in Tension and Shear at Low and High Strain Rate for AISI 316 and ARMCO Iron

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ABSTRACT

Stress strain characteristics in tension and in shear of AISI 316 and ARMCO iron have been measured up to very high strain rates, including the study of the necking phase in tension following the Bridgman analysis. Very large strain values at fracture have been obtained; they were in the range of those attained in metal forming and cutting processes. It has been shown that the tension flow curves and the equivalent Von Mises flow curves from shear tests diverge; their prediction requires constitutive equations implementing anisotropy effects.

1 INTRODUCTION

Modern finite element codes are capable to perform reliable calculations of rapid metal forming and cutting processes and of penetration of missile impact in metal shields, provided that the implemented material models describe the response of the unit metal volume up to large strains, at very high strain rates, under multiaxial loading, taking into account the different deformation modes and straining paths.

Most of the viscoplastic material models used in the finite element codes are generalized to multiaxial stress states by means of the yielding criteria of classical plasticity (e.g. Von Mises). Such yielding criteria are based on the concept of the unique equivalent flow curve whatever the deformation mode, presuming that at microscopic level the deformation mechanism is the same for each deformation mode. Nevertheless, few authors in the far (Ludwik, 1925) and recent past (Hecker et al., 1981) have shown that it is not possible to obtain a unique equivalent flow curve by applying the Von Mises yielding criterion to the tensile and shear flow curves of the same material (e.g. aluminium, copper, austenitic stainless steels, iron alloys). Such demonstrations have mainly been performed by deforming the materials at low strain rate, while the present paper extends the comparison to the tensile and shear tests of austenitic stainless steel AISI 316 and of ARMCO pure iron, which were performed at low, medium and high strain rates (e.g. from 10^{-3} to 10^{3} s^{-1}).

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2 EXPERIMENTAL PROCEDURE AND ANALYSIS

The tensile tests were performed using the specimen of Figure 1, which was tested with a Hounsfield tensometer at low strain rate (10^{-3} s^{-1}), with a hydropneumatic apparatus at medium strain rate (1 s^{-1}) and with a modified Hopkinson bar at high strain rate (10^{3} s^{-1}), described in Albertini et al. (1977). The tensile specimens were filmed during testing by high speed cameras to record all the parameters needed to characterize the necking zone. The shear tests were performed using the specimen of Figure 2, where the gauge part consists of a thin circular crown built up by means of a slight difference between the outer diameter of the smaller cylindrical part and the inner diameter of the larger cylindrical part. The detailed development of the shear specimen has been described by Albertini et al. (1990a,b).

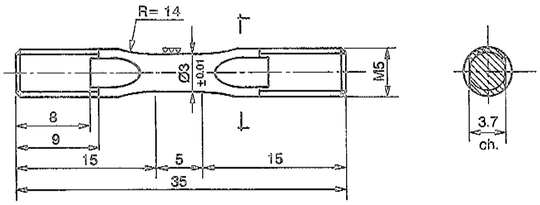

Fig.1: Tension specimen.

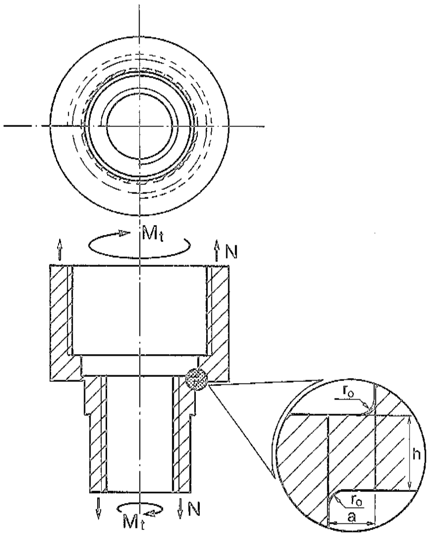

Fig.2: shear specimen.

The actual shear specimen was constructed with a short gauge length, a = 0.25 mm, which allows a homogeneous stress distribution along the gauge length even in the case of very high strain rates. In the shear test the strain rate was increased up to 3×10^{4} s^{-1}. The apparatus for the shear test was the same as that used for the tensile tests. The stress strain strain rate curves in shear are shown in Figures 3 and 4 for AISI 316 and ARMCO iron, respectively. The comparison of the true stress strain curves in tension with the equivalent stress strain curves obtained from the shear test is shown in Figures 5 and 6 for AISI 316 and ARMCO iron, respectively. In Figures 5 and 6 the parts of the true stress strain curves in tension of AISI 316 and ARMCO iron, traced with discrete points, correspond to necking and have been reconstructed following the analysis of Bridgman (1952) where true stress and strain are given by (1) and (2):

$$\sigma = \frac{\sigma_{AVG}}{(1+2R/a)\left[\ln(1+a/2R)\right]} \qquad (1)$$

σ_{AVG} = load divided by minimum cross section;
R = radius of curvature of the neck:
a = radius corresponding to the minimum cross section;

$$\varepsilon = 2 \ln \frac{D_o}{2a} \qquad (2)$$

D_o = initial diameter of the specimen.
The equivalent stress strain curves in shear of Figures 5 and 6 have been obtained by calculating the equivalent stress by (3) (Von Mises model):

$$\sigma_{EQV} = \sqrt{3}\, \tau \qquad (3)$$

τ = shear stress;
and by calculating the equivalent strain by (4) as suggested by Polakowski and Ripling (1966):

$$\varepsilon_{EQV} = \frac{2}{\sqrt{3}} \ln \left[\left(\sqrt{1 + \frac{y^2}{4}} \right) + \frac{y}{2} \right] \qquad (4)$$

y = shear strain.

3 DISCUSSION OF THE RESULTS

The flow curves in shear at low and medium strain rate for AISI 316 and ARMCO iron (Figures 3 and 4) show strain hardening up to strain values of about 2, after which there is saturation of flow stress (zero strain hardening); at high strain rate the saturation of flow stress is reached much earlier, at a strain of 1 for AISI 316 and immediately after initial yielding for ARMCO iron, and is followed by a sharp strain softening.

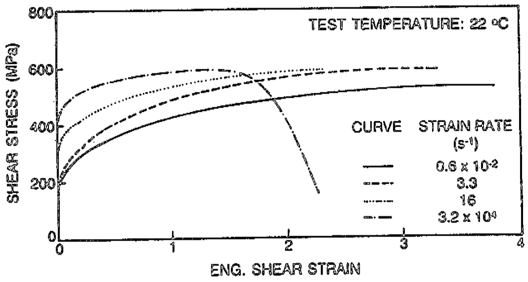

Fig.3: Shear stress-strain curves at different strain rates of AISI 316 stainless steel.

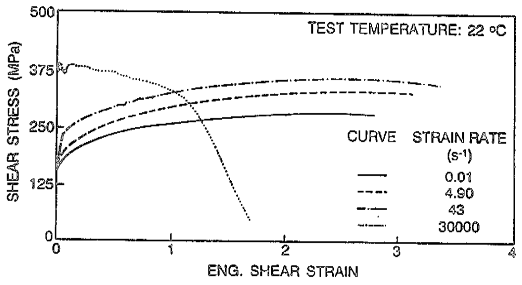

Fig.4: Shear stress-strain curves at different strain rates of ARMCO iron.

The reason for these differences of the shear flow curves at low to medium and very high strain rate is probably due to the presence of strain concentrations at a very high strain rate, as reported by Albertini et al. (1990a). Nevertheless, the shear flow curves of both materials at low, medium and high strain rate reach very high values of fracture strains comparable with those reached in metal forming and cutting operations and in penetration problems.

The true stress strain curves in tension of AISI 316 and ARMCO iron in Figures 5 and 6 show that the necking instability arises very early and gives rise to premature fracture strains. Therefore, the tension test is not appropriate for the study of large strain phenomena in metals. However, the necking phase of the tension test on AISI 316 and ARMCO iron has been studied following the Bridgman (1952) analysis, using the photographic records and all the true stress strain curves in tension have been compared with the equivalent stress strain curves from shear tests (Figures 5 and 6). From this comparison it follows that:

- The tension curves by the Bridgman (1952) analysis of both steels show strain hardening up to fracture, while the equivalent curves from the shear tests show saturation of flow stress. This phenomenon is present at each strain rate.
- As a consequence of the above phenomenon, the true flow curve in tension and the equivalent flow curve in shear show a modest agreement at low strain, while at large strain they diverge, particularly at high strain rates.
- The fracture strain of the tension curves by the Bridgman (1952) analysis and of the equivalent curves from the shear tests are comparable.
- The above-mentioned observations are valid also taking into account that during necking the strain rate is about ten times higher than during uniform straining.

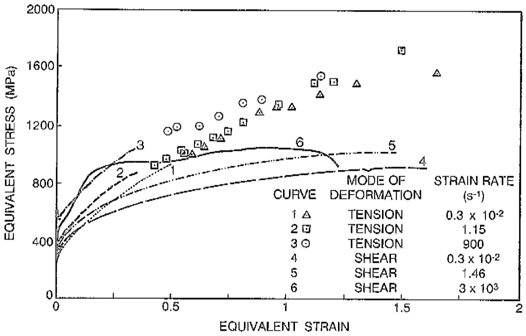

Fig.5: Equivalent stress strain curves of AISI 316 stainless steel from tension and shear tests at different strain rates.

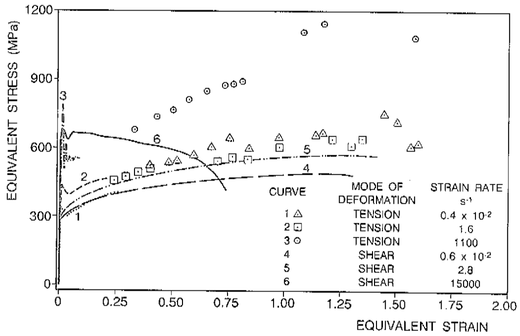

Fig.6: Equivalent stress strain curves of ARMCO iron from tension and shear tests at different strain rates.

The reasons for such discrepancies between the curves in tension and the equivalent curves from shear tests were ascribed by Jonas et al. (1981) to:

- yield criterion differences by microscopic anisotropy;
- different texture development at large strains in tension and shear;
- effect of strain path on the microscopic rate of strain hardening.

It follows that stress and strain characteristics depend on the deformation mode and that it is not possible to obtain a unique equivalent flow curve from tension and shear tests, as claimed in classical plasticity, because the physical phenomena are more complex than those included in the classical material models.

As a consequence of the results reported here and of own results on the same research subject, Eleiche et al. (1991) attempted to predict more accurately the tensile response of AISI 316 as well as the torsional shear response by modifying the Von Mises criterion used in the Chaboche unified theory of viscoplasticity by means of a Hill-type anisotropic tensor.

4 CONCLUSIONS

Shear testing of AISI 316 and ARMCO iron allowed us to obtain very large fracture strains at low and high strain rates, which makes such tests important for studying large structural strains due to metal forming and cutting or accidental impact loading. Nevertheless, shear tests showed saturation of flow stress at low and medium strain rates, together with strain concentration at a very high strain rate.

Tension testing of the same materials showed strain hardening (except ARMCO iron at a high strain rate)up to the necking instability which arises very early, which makes this test inappropriate for the study of the large strain capability of structures and materials. However, the application of the Bridgman analysis to the necking phase of the tension test shows strain hardening up to fracture (no saturationof flow stress as in the shear test) and large values of plastic strain at fracture, comparable with those reached in the shear test.

The different phenomena shown by the flow curves in tension and shear are caused by differences in yield criteria, texture development and straining path dependence of microscopic strain hardening. Comparison of the tension flow curves with the equivalent flow curves of the shear tests following the classical plasticity models (e.g. Von Mises) showed unavoidable discrepancies from the concept of the unique flow curve whatever the deformation mode, because the model assumes a unique microscopic deformation mechanism at each deformation mode. Material models need to be modified in order to represent the material response in tension and shear.

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