Cyclic strength of metals at impact strain rates

A.M.Eleiche

Department of Engineering, American University in Cairo; on leave from Department of Mechanical Design and Production, Cairo University, Guiza, Egypt

M.M.El-Kady

Department of Mechanical Design and Production, Cairo University, Guiza, Egypt

1 INTRODUCTION

Rigorous understanding of the effects of impact loading on the mechanical response of materials and structures is essential for the optimum design and safe operation of many sophisticated engineering systems and components, such as industrial high-energy-rate fabrication processes and nuclear reactor containments.

Extensive data are available at present on the dynamic behaviour of most metals in uniaxial tension, compression, torsion and pure shear, when they are subjected to diversified loading conditions, ranging from those characterised by monotonic constant rates, to those involving forward or reverse strain-rate jumps of several orders of magnitude. What appears to be missing in the current material data banks, however, is detailed information concerning the mechanical response under cyclic loading at impact strain rates. Such data are needed for engineering design purposes on one hand, and for the formulation of proper constitutive equations and the accurate modeling of deformation processes on the other.

Conventional type apparatus, in which the stress may vary considerably along the length of the specimen due to inertia effects, cannot be used in the impact range of strain rates. The most popular experimental device which can successfully meet the high-speed test requirements is the split Hopkinson bar (SHB) apparatus. Moreover, generation of relevant material data under cyclic loading at impact strain rates usually requires: (a) the use of a testing system capable of both forward and reverse loading at fairly constant strain rates and up to large values of strain, and (b) the capability of subjecting the same specimen to load reversals at small or large pre-strains within a reasonable amount of elapsed time. To this end, the torsion of thin-walled tubes stands as the ideal mode of loading (Eleiche, 1986).

Therefore, all test requirements can be satisfied by twisting a tubular specimen in a torsional SHB, modified as shown in Figure 1, up to a given prestrain, and unloading. The same specimen can then be retwisted in the reverse direction, after a dwell time of five minutes maximum, by simply reversing the direction of the loading torsional wave propagating in the system from clockwise to anticlockwise or vice-versa. This procedure may then be repeated again and again on the same specimen until fracture. Details of the system components, testing procedure and data analysis have been previously reported (Eleiche and El-Kady 1983, Eleiche 1984).

In the present paper, typical stress-strain characteristics at ambient temperature for copper, mild steel and titanium are first exhibited. The application of the unified Bodner-Partom constitutive theory to these data is then presented and discussed.

2 EXPERIMENTAL RESULTS AND DISCUSSION

2.1 Stress-strain characteristics

Materials tested were: (a) oxygen-free high-conductivity (OFHC) copper (99.97 Cu, 0.03 Fe and

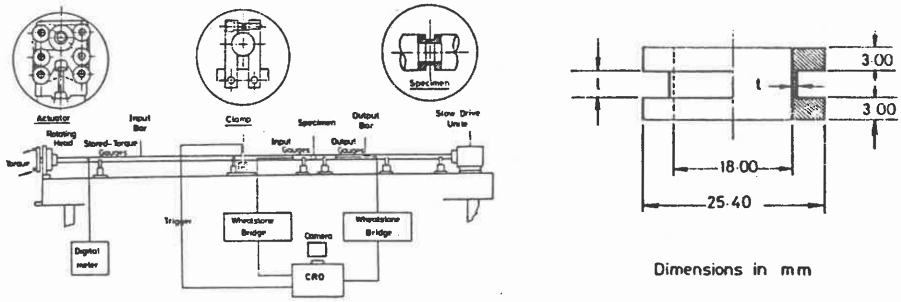

Figure 1. Schematic drawing of torsional SHB and specimen.

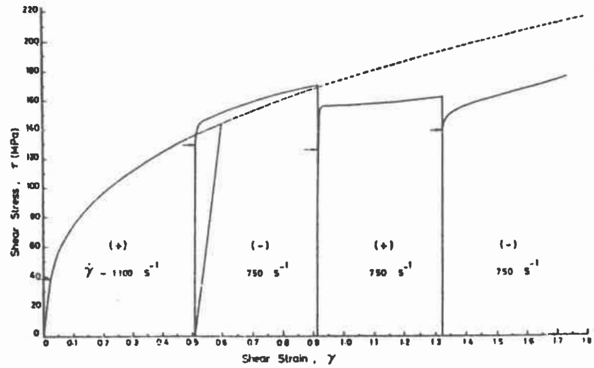

Figure 2. Stress-strain curves for copper under sequential reverse loading at $\dot{\gamma} \sim 1100\ s^{-1}$ for a constant strain amplitude $\gamma_0 \sim 0.60$.

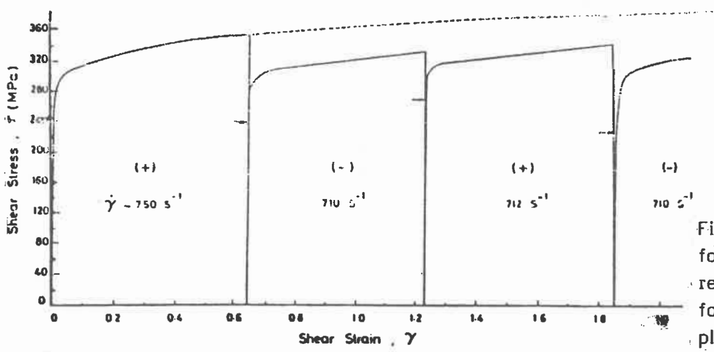

Figure 3. Stress-strain curves for steel under sequential reverse loading at $\dot{\gamma} \sim 760\ s^{-1}$ for a constant strain amplitude $\gamma_0 \sim 0.65$.

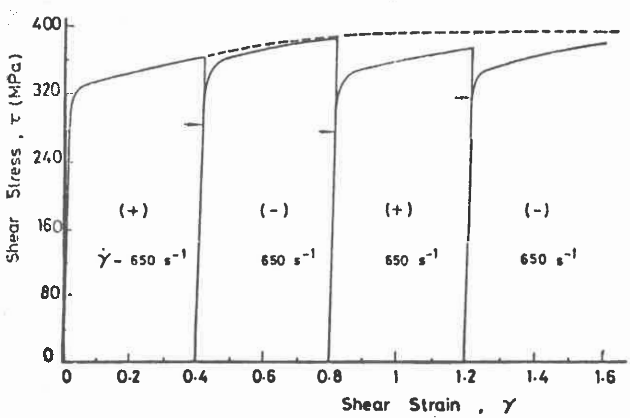

Figure 4. Stress-strain curves for titanium under sequential reverse loading at $\dot{\gamma} \sim 600\ s^{-1}$ for a constant strain amplitude $\gamma_0 \sim 0.4$.

$<$0.01 other elements; (b) a mild stell (0.23 C, 0.50 Mn, 0.25 Si, 0.04 S and 0.025 P); and (c) commercially-pure titanium IMI 130 (of standard composition).

Specimens used (Figure 1) had a nominal gauge length of 1.0, 2.0 or 3.0 mm depending on the strain rate desired, and a nominal wall thickness of 0.5 mm for copper, and 0.3 mm for mild steel and titanium. Copper and titanium specimens were annealed in a vacuum of 10^{-3} to 10^{-4} torr for 1.5 hr at 370 and at 700 $^{\circ}$C, respectively. Mild steel specimens were used without heat treatment.

Each metal was tested (at room temperature) at one quasi-static and two impact strain rates. For each case, three different cyclic strain amplitudes were considered. Typical results are shown in Figures 2, 3 and 4 for copper, steel and titanium, respectively. Four loading sequences are shown; the elapsed time between any two consecutive loadings being five minutes, at most. Note that the curves resulting from reverse loading (-) are plotted in the figures upward, instead of downward, for ease of comparison with the curves resulting from forward loadings (+). It is clear that the behaviour of copper shows signs of strain ageing caused by the elapsed time between loadings. Nevertheless, for all three metals, sequential loading causes the flow curve to flatten out and to ultimately reach saturation, thus continuously deviating from the unidirectional flow curve (shown extrapolated in dashed lines in Figures 2 to 4). All results obtained at the three strain rates are plotted in the collective plots of Figures 5, 6 and 7 for copper, steel and titanium, respectively. The same trend is exhibited irrespective of the strain rate. Nevertheless, detailed analyses of the data in terms of various Bauschinger effect parameters (Eleiche 1986, El-Kady 1986) indicate that sequential reverse loading at large plastic strains progressively weakens the material, more seriously so at impact strain rates than at the quasi-static ones. These conclusions should be accounted for in the design of structural engineering components, as well as in the planning of metal forming operations.

2.2 Fitting of Bodner-Partom model to results

The constitutive equation developed by Bodner and his co-workers (1975, 1979) can generally satisfy the requirements of predicting a wide variety of mechanical responses including tensile, shear, creep, stress relaxation and cyclic behaviour. The representation is fully three dimensional, and has also been extended to include anisotropic response (Stouffer and Bodner 1979). This model is adopted in the present study to describe and predict the reverse-loading behaviour of the three metals at various strain rates (El-Kady 1986). Space limitations prohibit even a short description of the model here. Details have been presented by Bodner et al (1975, 1978, 1979), and followed subsequently by many other investigators.

In the theory, five viscoplastic constants are needed to model the material behaviour. These are: D_0 which is a scale factor representing the limiting value of the inelastic strain rate and usually taken as 10^4 s^{-1}; Z_0 which is a reference state for the history-dependent internal

Table 1. List of material constants fitting Bodner's model

Constant	Material		
	Copper	Steel	Titanium
D_0 (s^{-1})	10^4	10^4	10^4
Z_0 (MPa)	155	723	780
$\bar{Z}$ (MPa)	332	901	930
n	3.2	2.69	2.62
m $(MPa)^{-1}$	0.037	0.009	0.009
G (MPa)	10000	24000	40000
q	0.7	0.65	0.55

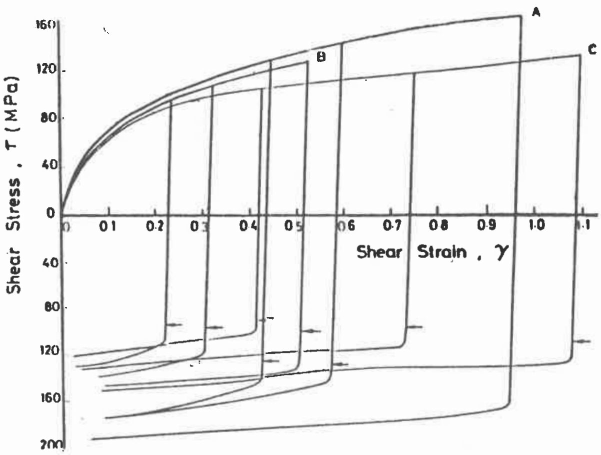

Figure 5. Stress-strain curves for copper under reverse loading at different prestrain for three different strain rates.

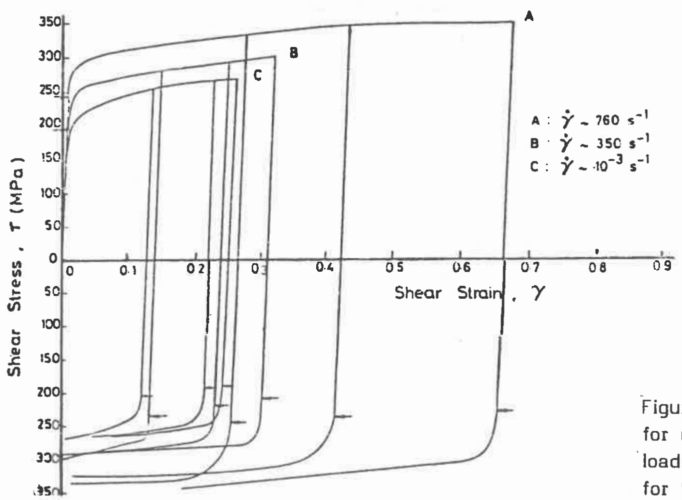

Figure 6. Stress-strain curves for mild steel under reverse loading at different prestrains for three different strain rates.

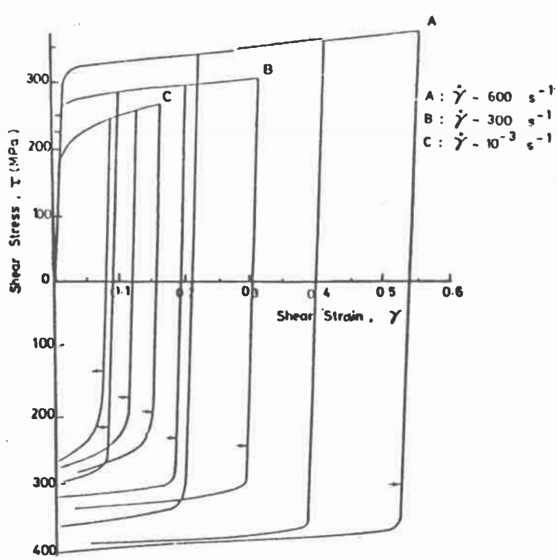

Figure 7. Stress-strain curves for titanium under reverse loading at different prestrains for three different strain rates.

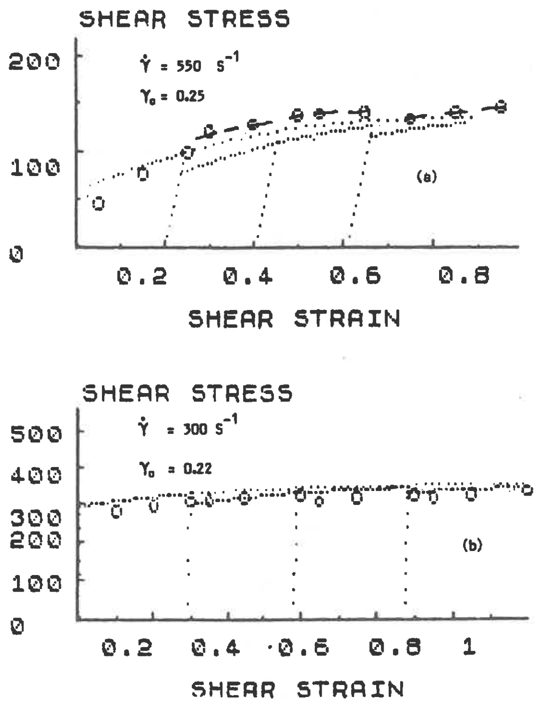

Figure 8. Calculated and experimental cyclic stress-strain curves for: (a) copper, (b) titanium.

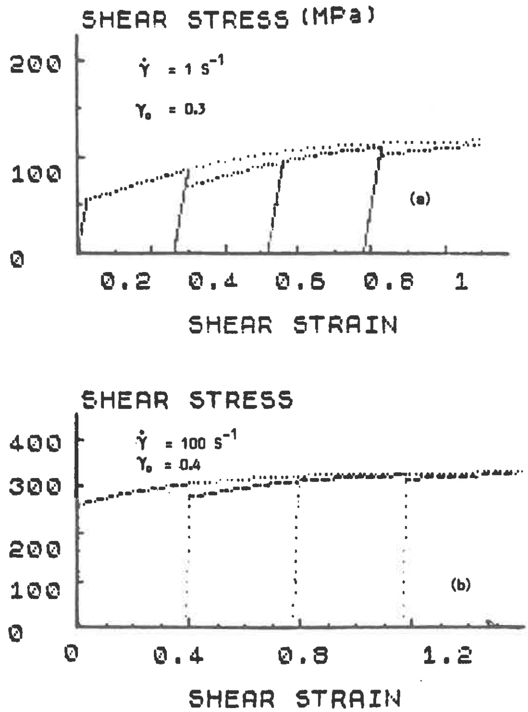

Figure 9. Calculated cyclic shear stress-strain curves for: (a) copper, (b) mild steel.

state variable; $\bar{Z}$, the asymptotic value of the variable; n, a constant controlling strain-rate sensitivity; and m controlling the rate of hardening. In addition, the shear modulus G is needed for elastic behaviour description, while another constant q ($\leqslant 1$) is necessary for representing either cyclic hardening or softening.

In general, a pair of stress-strain curves at two constant strain rates (preferably belonging to two extreme regimes), with three sets of data points (τ,γ) in the plastic range on each curve, are necessary and sufficient to provide essentially unique values for all viscoplastic constants. Table 1 lists average values of all constants for the three materials of interest.

The model was first calibrated by the monotonic stress-strain curves collected at steady constant strain rates. It was then used to calculate the response under sequential reverse torsional shear, for various cyclic strains and strain rates. Figure 8 (a) and (b) show sample of the results obtained, together with experimental data points for comparison. Overall agreement is observed.

As a final exercise, the model was also used to predict material behaviour under different other conditions (El-Kady 1986). For illustration, Figure 9 (a) and (b) show typical cyclic response predicted for copper and mild steel.

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