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Note

Effect of defect shape and size on the initiation of adiabatic shear bands

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Summary. Backman and Finnegan [1] have pointed out that shear bands initiate from a defect such as a second phase particle, microcrack, or a void. The defect has been modeled as a sinusoidal variation in the thickness of the tubular specimens tested in torsion by Chi [2] and Murphy [3]. Here we simulate their torsional tests numerically and consider different shapes and sizes of defects.

The longitudinal section of the tube by a plane passing through its centroidal axis and shown in Fig. 1 indicates the sinusoidal variation in the tube thickness, viz.,

$$\frac{l(z)}{0.76\ \mathrm{mm}} = \begin{cases} 1 + \dfrac{\varepsilon}{2}\left(\cos\dfrac{2\pi(z-a)}{(L-2a)} - 1\right), & a \leqq z \leqq L-a, \\ 1, \quad 0 \leqq z < a,\ L-a < z \leqq L \end{cases} \tag{1}$$

where ε is the defect parameter, $l(z)$ is the wall thickness at a point distant z from the bottom surface of the tube, a is the distance from the end faces where the tube thickness first begins to decrease (cf. the insert in Fig. 3), and $L = 2.5$ mm is the length of the tube. The thickness variation given by Eq. (1) is depicted in Fig. 1 for $\varepsilon = 0.08$ and $a = 0$. The thickness of tubular specimens tested by Murphy [3] was also given by Eq. (1) with $a = 0$. However, the maximum thickness of 0.76 mm in our simulations is twice that used by Murphy since computations with the tube employed by Murphy indicated buckling of the tube prior to the initiation of a shear band. The

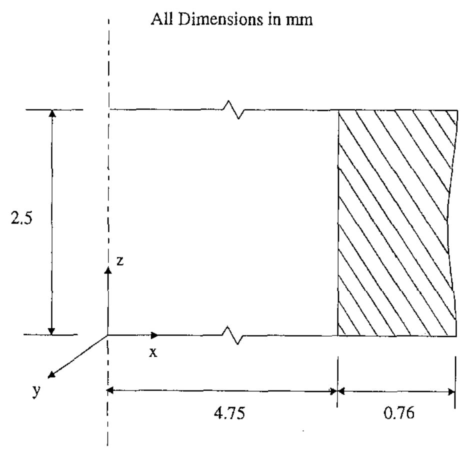

Fig. 1. Geometry of the tubular specimen studied

thermomechanical response of the material (4340 steel) of the tube is modeled by the Johnson-Cook [4] relation, viz.,

$$\sigma_m = \left(792.2 + 509.5\,(\varepsilon_p)^{0.26}\right)\left(1 + 0.014\ln(\dot{\varepsilon}_p/\dot{\varepsilon}_0)\right)\left(1 - T^{1.03}\right)\,\text{MPa},$$
$$T = \frac{\theta - \theta_0}{\theta_m - \theta_0}, \quad \varepsilon_p = \int \dot{\varepsilon}_p\,dt. \tag{2}$$

Here σ_m is the flow stress of the material, ε_p the effective plastic strain, $\dot{\varepsilon}_p$ the effective plastic strain-rate, $\dot{\varepsilon}_0$ the reference plastic strain-rate of 1/sec, T the homologous temperature, θ_m the melting temperature of the material, θ_0 the ambient temperature, and θ the present temperature of a material particle. Equation (2) implies that the flow stress of the material increases because of its hardening due to strain and strain-rate effects and decreases because of its being heated up.

The material is modeled as elastic-viscoplastic and its deformations are regarded as locally adiabatic, i.e. the effect of heat conduction is neglected. All of the plastic work done is assumed to be converted into heat. The two end surfaces of the tube are twisted at an equal and opposite prescribed angular speed that increases linearly from zero to the final value in 20 μs and is then held constant. The steady value of the angular speed is such as to induce the prescribed average strain-rate which is computed by using the mean radius of an end surface of the tube. Both the inner and the outer surfaces of the tube are taken to be traction free, and all bounding surfaces are taken to be thermally insulated. Initially, the tube is taken to be stress free, at rest and at ambient temperature. The aforestated problem was analyzed by using the explicit large scale finite element code DYNA3D (Whirley and Hallquist [5]). Even though the initial and boundary

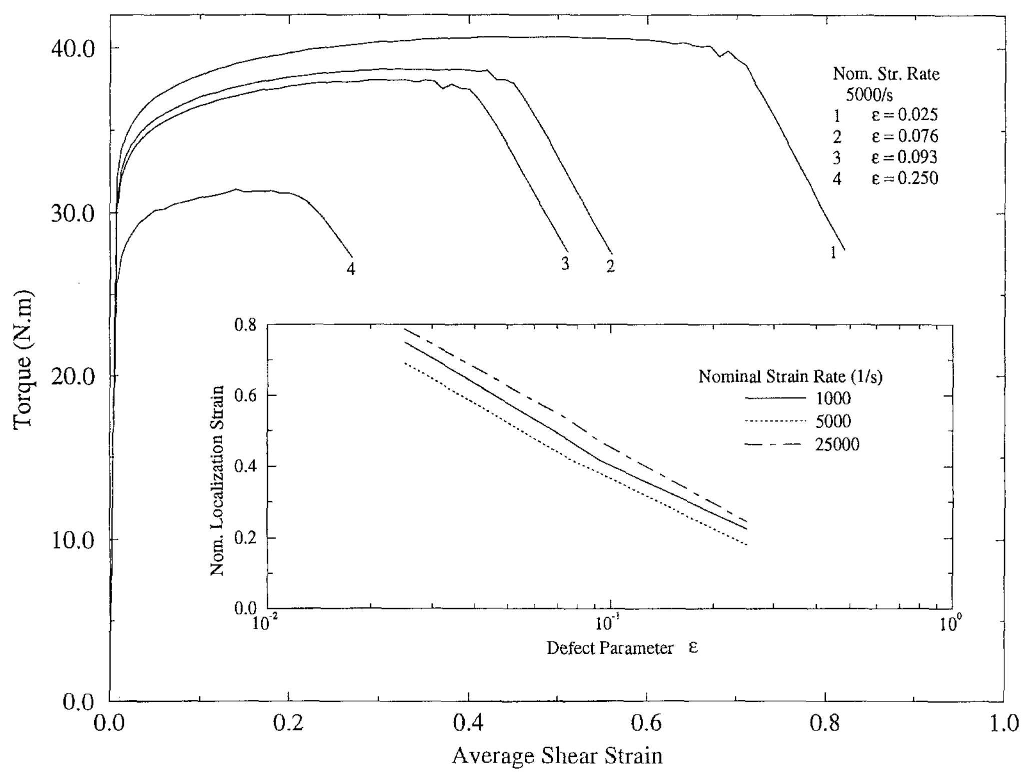

Fig. 2. Time history of the torque required to deform the tube, and the variation of the critical average shear strain with the logarithm of the defect parameter ε for three different values of the nominal shear strain-rate

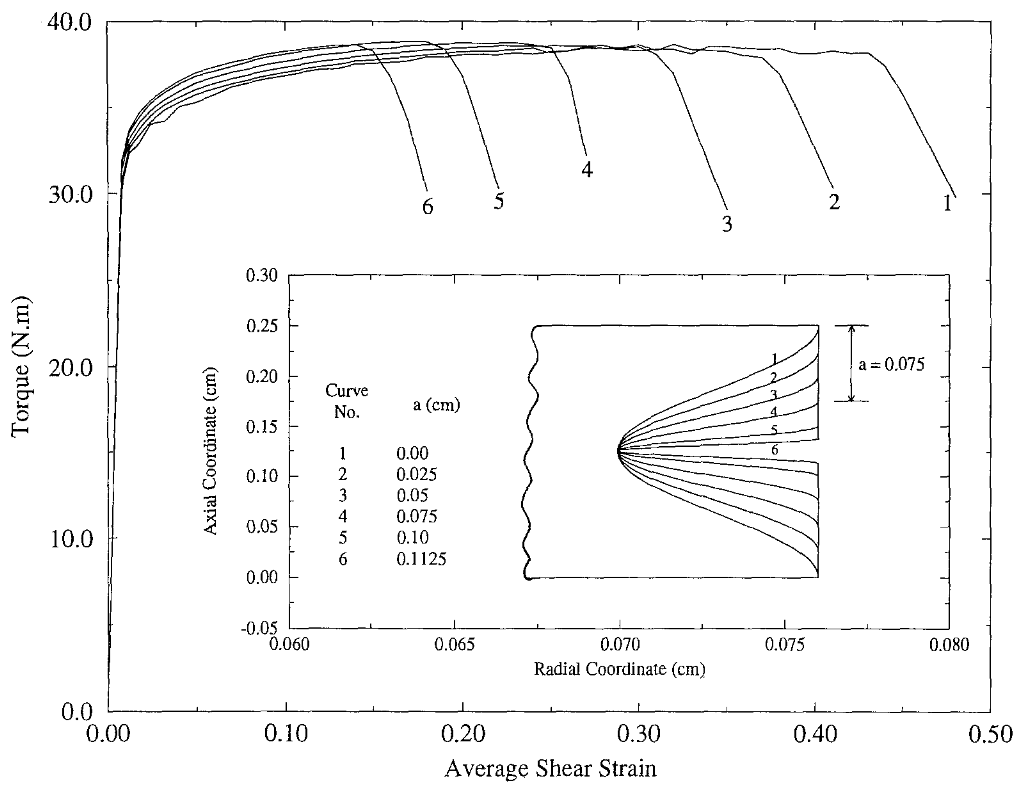

Fig. 3. Time-history of the torque required to deform the tube for six different values of a

conditions suggest that deformations of one-half of the tube can be studied, the way boundary conditions are applied in DYNA3D code precluded this.

The time-history of the torque required to deform the tube for four different values of the defect parameter ε with $a = 0$ in each case and for a nominal strain-rate of 5000/sec is plotted in Fig. 2. Similar results were obtained for nominal strain-rates of $1000\ s^{-1}$ and $25000\ s^{-1}$ and are omitted. A shear band is assumed to initiate when the torque required to deform the tube suddenly drops, and the corresponding value of the average shear strain is hereafter referred to as the critical average shear strain. We note that Marchand and Duffy [6] in the interpretation of their experimental results also used this criterion to decide when a shear band initiates. It is clear that the value of the critical average shear strain decreases with an increase in the value of ε. The insert in Fig. 2 depicts the plot of the critical average shear strain versus the logarithm of the defect size ε for the three different nominal strain-rates studied. These plots reveal that the critical average shear strain decreases exponentially with the defect size ε; the slope of the three curves is nearly the same implying thereby that the rate of change of the critical average shear strain with respect to the defect size ε is independent of the nominal shear strain rate. These results are in qualitative agreement with the test results of Chi [2] and Murphy [3] and analytical results of Molinari and Clifton [7] and Wright [8].

The parameter a in Eq. (1) determines the distance from the tube's ends where the thickness begins to decrease. By changing it, we can alter the defect shape as shown in the insert of Fig. 3. For all values of a, the slope $l'(z)$ equals zero at $z = L/2$; however, the curvature at $z = L/2$ is inversely proportional to $(L - 2a)^2$. Figure 3 depicts the torque versus the average shear strain curve for six different values of a with $\varepsilon = 0.08$ and at a nominal shear strain-rate of 5000/s. It is

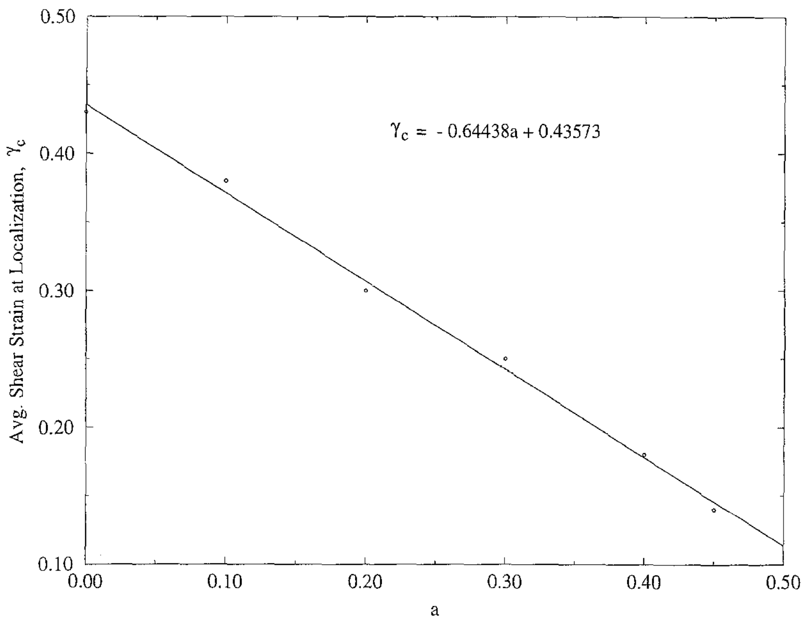

Fig. 4. Dependence of the critical average shear strain upon a

clear that with an increase in the value of a and hence a decrease in the radius of curvature at $z = L/2$ the critical average shear strain decreases; the relation between the two is essentially linear as shown in Fig. 4. We note that the mesh grading in the axial direction was different in each case but the total number of elements was kept fixed. The mesh size near the central section was made smaller with an increase in the value of a. Batra and Adulla [9] have shown that the mesh size has little effect on the value of the critical average shear strain, but does influence the post-localization response.

In summary we conclude that the value of the average shear strain at which a shear band initiates during the twisting of a thin-walled tube depends noticeably not only upon the minimum wall thickness but also upon other factors that characterize the shape of the wall at the point of the minimum wall thickness.

Acknowledgement

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References

[1] Backman, M. E., Finnegan, S. A.: The propagation of adiabatic shear. In: Metallurgical effects at high strain rates (Rhode, R. W., Butcher, B. M., Holland, J. R., Karnes, C. H. eds.), pp. 531–543. New York: Plenum Press 1973.

[2] Chi, Y. C.: Measurement of the local strain and temperature during the formation of adiabatic shear bands in steel. Ph. D. Thesis, Brown University, 1990.

[3] Murphy, B. P.: Shear band formation in a structural steel under a combined state of stress. M. S. Thesis, Brown University, 1990.

[4] Johnson, G. R., Cook, W. H.: A constitutive model and data for metals subjected to large strains, high strain rates, and high temperatures. Proc. 7th Int. Symp. Ballistics, pp. 541–548. The Hague, The Netherlands, 1983.

[5] Whirley, R. G., Hallquist, J. O.: DYNA3D User's Manual (A nonlinear, 'explicit', three-dimensional finite element code for solid and structural mechanics). UCRL-MA-107254, University of California, Lawrence Livemore Laboratory 1991.

[6] Marchand, A., Duffy, J.: An experimental study of the formation process of adiabatic shear bands in a structural steel. J. Mech. Phys. Solids **36,** 251–283 (1988).

[7] Molinari, A., Clifton, R. J.: Analytical characterization of shear localization in thermoviscoplastic materials. J. Appl. Mech. **5,** 806–812 (1987).

[8] Wright, T. W.: Toward a defect invariant basis for susceptibility to adiabatic shear bands. Mech. Materials **17,** 215–222 (1974).

[9] Batra, R. C., Adulla, C.: Effect of prior quasistatic loading on the initiation of dynamic adiabatic shear bands. Arch. Mech. (in press).

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