



Shear Band Interaction In 1D Torsion

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ABSTRACT

When two shear bands are formed at close distance from each other, they interact, and further development of one of them may be quenched down. As a result, there should be a minimum distance between shear bands. In the literature there are at least three analytical models to estimate this minimum distance. Predictions of these models do not generally agree with each other and with test results. Recently we developed a 1D numerical scheme to predict the formation of shear bands in a torsion test of a thin-walled pipe. We validated that scheme by reproducing the results of the pioneering experiments of Marchand and Duffy [9], and then used it to investigate the mechanics of shear localization and shear band formation. We describe our shear band code in a separate publication [8], and here we use it only as a tool to investigate the interaction between two neighboring shear bands during the process of their formation. We trigger the formation of those shear bands by specifying two perturbations in the initial strength. We vary the perturbations in term of their amplitude and/or their width. Usually, the stronger perturbation triggers a faster developing shear band, which then prevails and quenches the development of the other shear band. We change the distance between the two shear bands and find, that up to a certain distance between them, one of the shear bands becomes fully developed and the other stays only partially developed. Beyond this distance between them the two shear bands are both fully developed. Finally, we check the influence of certain material parameters and loading parameters on the interaction between such two neighbouring shear bands, and compare the results to predictions of the above-mentioned analytical models from the literature.

INTRODUCTION

Modeling of shear band formation in metals in a 1D configuration was performed, with various levels of success, by several researchers [1-7]. We review those publications, together with a detailed description of our own numerical model, in a separate publication [8]. Here we only outline briefly the equations to solve when using our own model, and how this model works. We simulate the torsion deformation of a thin-walled pipe, similar to the specimen used in the pioneering experiments of Marchand and Duffy [9]. We assume that there is no deformation in the circumferential direction and in the radial direction, so that the problem is 1D in the z (length) direction. Our gauge length is 5 mm, and our computational cell size is $1\mu\text{m}$, so that we have 5000 cells. The pipe is loaded by specifying the circumferential boundary velocities in opposite directions on its both ends. The equations to be solved by the code are:

$$\begin{aligned}
\dot{u} &= -\frac{1}{\rho} \frac{d\tau}{dz} ; \dot{\gamma} = -\frac{du}{dz} \\
\dot{\gamma}_{\text{eff}}^p &= A(\tau_{\text{eq}} - \tau_{\text{qs}}) ; \tau_{\text{eq}} > \tau_{\text{qs}} \\
\dot{\gamma}_{\text{eff}}^p &= 0 ; \tau_{\text{eq}} \leq \tau_{\text{qs}} \\
\dot{\gamma}^p &= \dot{\gamma}_{\text{eff}}^p \text{sign}(\tau) ; \tau_{\text{eq}} = |\tau| \\
\dot{\gamma} &= \dot{\gamma}^e + \dot{\gamma}^p ; \dot{\tau} = 2G \dot{\gamma}^e \\
\tau_{\text{qs}} &= (\tau_0 + h \gamma_{\text{eff}}^p) \left(\frac{T_m - T}{T_m - T_0} \right)^\alpha \\
\dot{T} &= \frac{1}{\rho C_p} \left(k \frac{d^2 T}{dz^2} + \beta |\tau \dot{\gamma}_{\text{eff}}^p| \right)
\end{aligned} \tag{1}$$

where: u =circumferential particle velocity, τ =shear stress, ρ =density (unchanging), γ =shear strain, G =shear modulus, C_p =constant pressure heat capacity, h =strain hardening coefficient, T =temperature, k =coefficient of heat conduction, β =Taylor-Quinny coefficient=1, A =Plastic flow coefficient. We're using the overstress approach to viscoplasticity [10], $\varepsilon_{\text{eff}}^p$ =effective plastic strain, the index e means elastic, the index p means plastic, the index eff means=effective, the index eq means equivalent, the index qs means quasistatic, and the index 0 means initial value.

We express the z derivatives in each computational cell by finite differences, and obtain a system of $5n$ ODEs, where n is the number of cells, and where the $5n$ unknowns are: u_i , τ_i , T_i , γ_i , γ_{pi} . The boundary conditions are: u is given on both boundaries, and the temperature gradient is zero on the boundaries. In all the computations we use $u_0=10\text{m/s}$ and $u_n=-10\text{m/s}$. We solve the system of $5n$ ODEs with a standard ODE solver. We use the 4th order Runge-Kutta solver. The perturbations that we apply are in terms of the initial quasi-static yield stress τ_0 , and their nominal value is 0.2%.

COMPUTATIONS AND RESULTS

We first show results from a computation with a single perturbation in the middle of the flow field. In Fig. 1 we show $T(z)$, the temperature profile along the sample, at $t=20\mu\text{s}$, and in Fig. 2 we show $T(t)$, the temperature history in the perturbed cell. We see from these figures that it takes the shear band about $15\mu\text{s}$ to begin forming and less than 5 more μs to become fully developed. The shear band reaches a peak temperature of about 2000K. We move now to runs with two shear bands. In Fig. 3 we show a temperature profile from two symmetric and equal perturbations, 2 mm apart. In Fig. 4 we doubled the strength of the right perturbation of Fig. 3, in Fig. 5 we moved the two equal perturbations of Fig. 3 by 0.5mm to the left, and in Fig. 6 we doubled the width of the right perturbation of Fig. 3. From Figs. 4 to 6 we see that any

asymmetry of the two perturbations causes one of the shear bands to start forming earlier, thereby inhibiting the development of the other shear-band. Next, we go back to the configuration of Fig. 3, increasing symmetrically the distance (d) between the two perturbations. We choose the temperature difference between the two shear bands (ΔT) at $20\mu s$, as a measure of the intensity of their interaction. In Fig. 7 we show our results for $\Delta T(d)$.

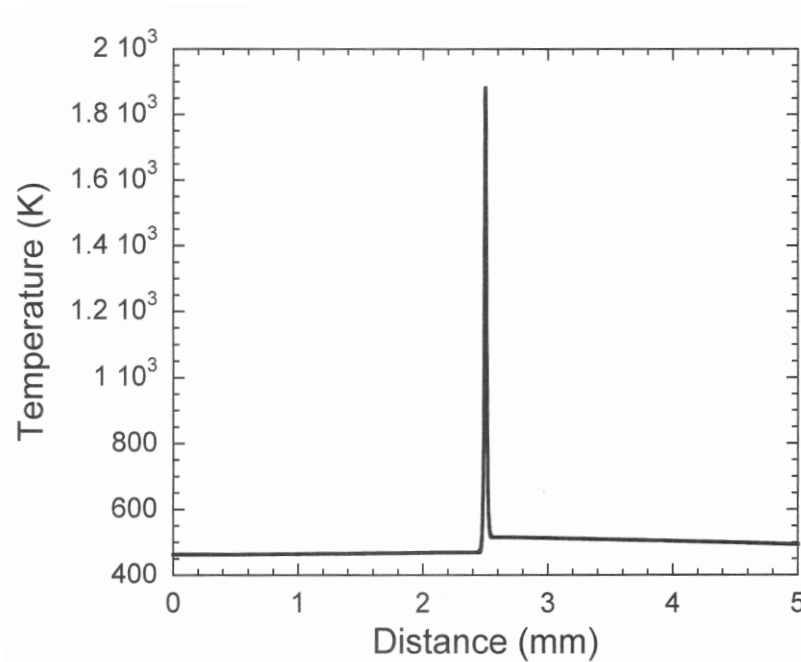


Figure 1. Temperature profile for a single shear band at $20\mu s$.

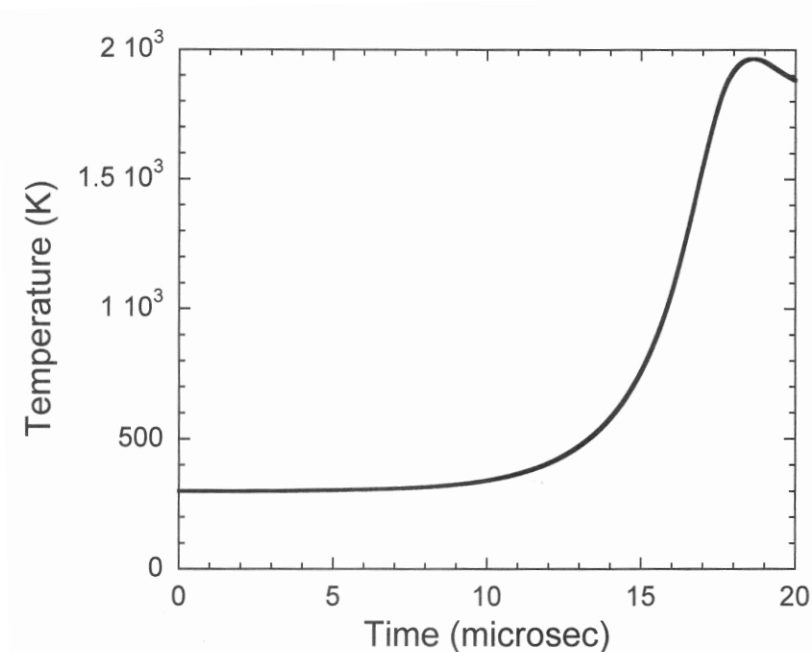


Figure 2. Temperature history of the shear band.

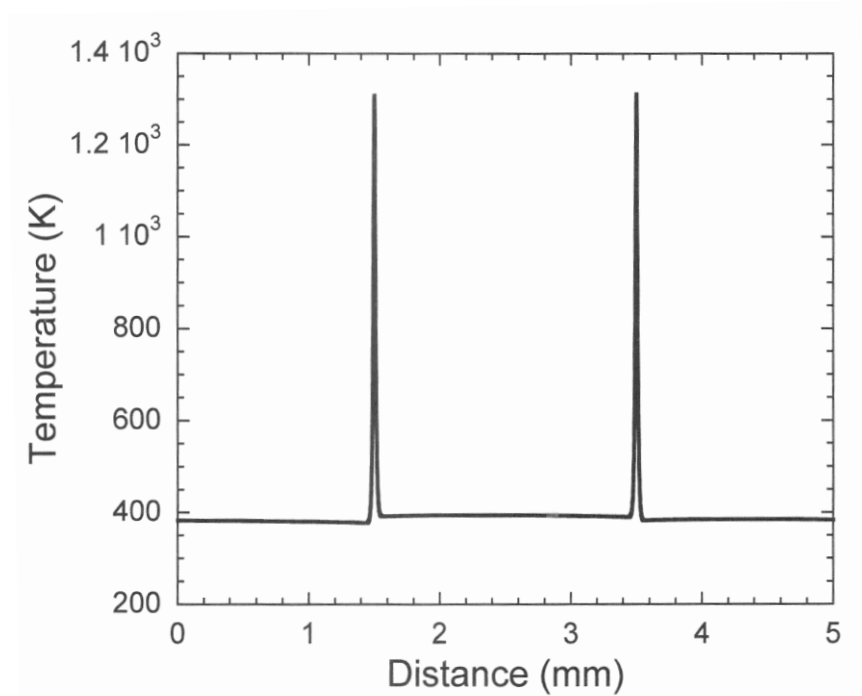


Figure 3. Temperature profiles of two symmetric shear bands, 2mm apart, at $20\mu\text{s}$.

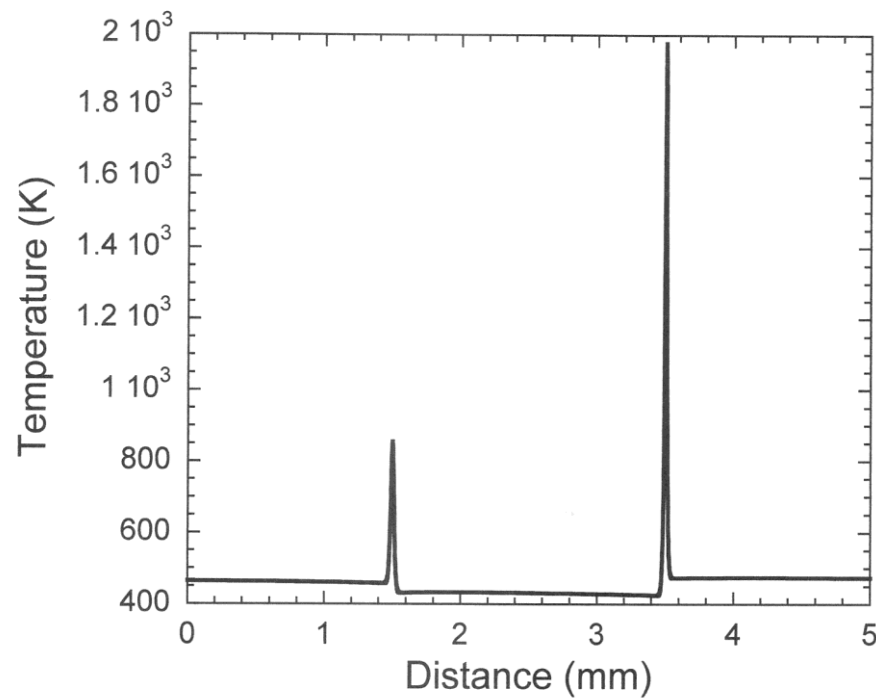


Figure 4. As in Fig. 3, but the perturbation on the right is of double strength.

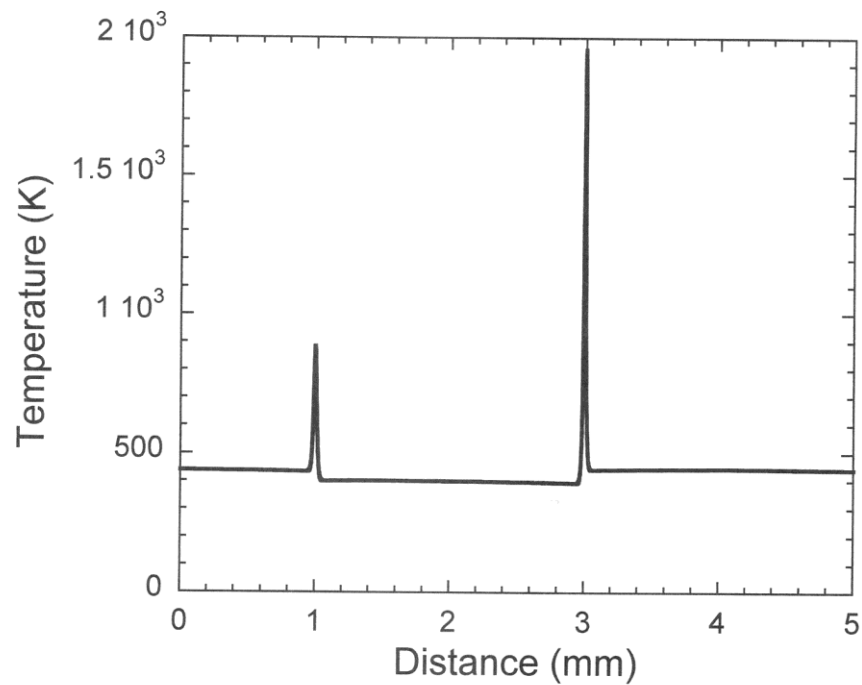


Figure 5. As in Fig. 3, but with the two perturbations shifted to the left by 0.5mm.

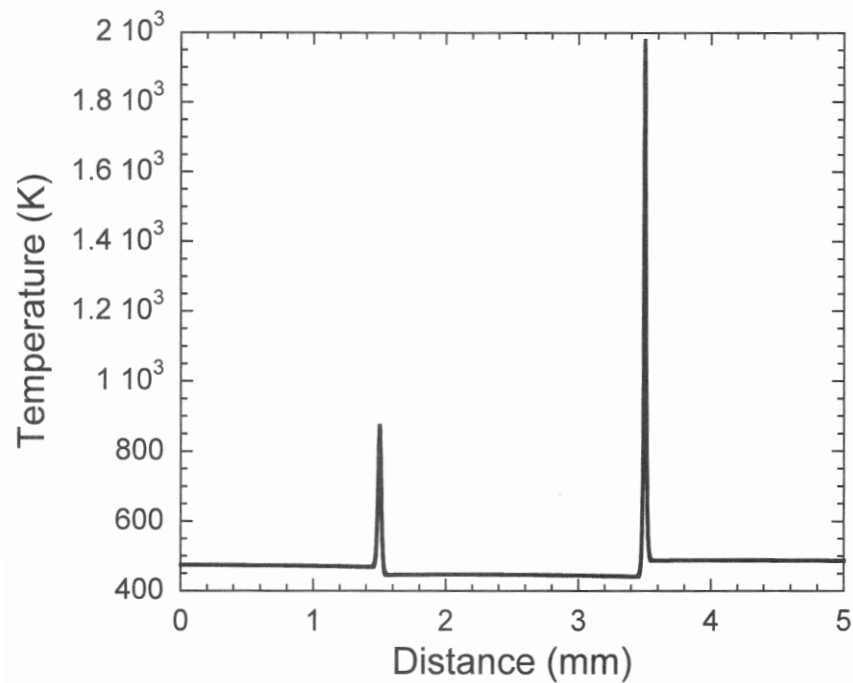


Figure 6. As in Fig. 3, but the perturbation on the right is of double width.

We see from Fig. 7 that the degree of interaction between the two shear bands decreases gradually as their distance increases. Extrapolating to zero temperature difference, we get no

interaction at a distance of 5.4mm. For decreasing distance there is an increasing degree of interaction.

Next, we check the influence of several material and loading parameters on the degree of interaction between two shear bands that are 2mm apart. All the parameters except the one that we change are the same as in Fig. 3.

The parameters and the amount of their change are:

- Average strain rate – decrease by 50%.
- Coefficient of heat conduction – decrease by 50%.
- Heat capacity – decrease by 50%.
- Initial strength – increase by 50%.
- Shear modulus – increase by 50%.
- Average softening curve slope ($d\tau_0/dT$) – increase by 57%.

In Fig. 8 we show the results of these checks (the black points underneath the curve). We see from Fig. 8 that the changes in all six parameters decrease the temperature difference by different amounts. Assuming a similar change with distance as for the nominal case, the distance of no interaction also decreases for the above changes. These results are generally not in agreement with the predictions of the analytical models in the literature [11-13].

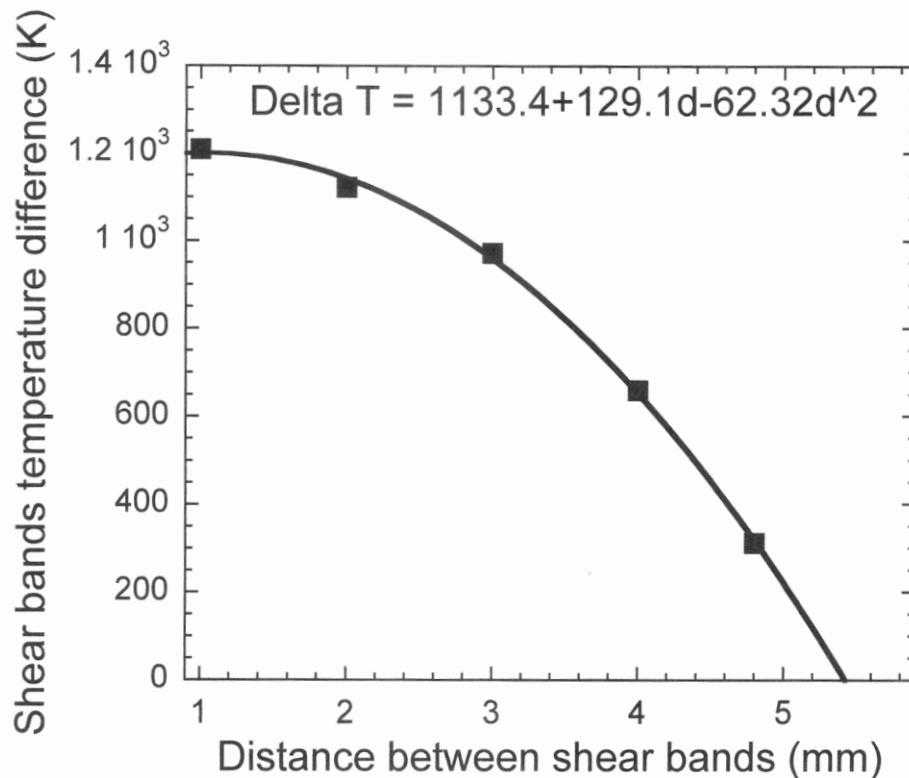


Figure 7. Temperature difference between the two shear bands at $20\mu s$ (ΔT) as function of their distance (d).

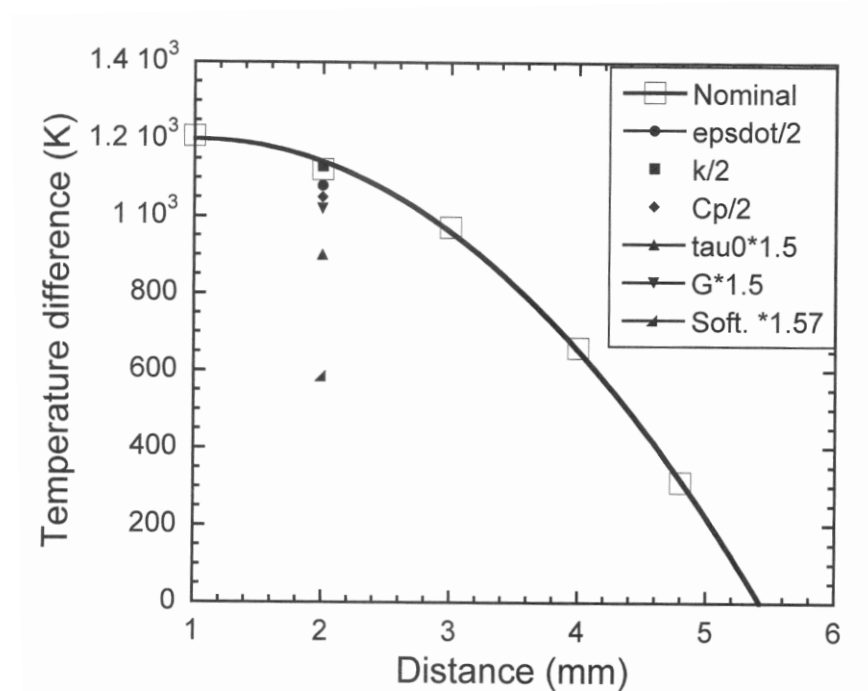


Figure 8. Temperature difference between the two shear bands at $20\mu\text{s}$ (ΔT) as function of their distance (d) (from Fig. 7), and ΔT for 2mm distance and for several parameter changes.

SUMMARY

We developed a 1D simulation code to predict the formation of shear bands in torsion of a thin metal pipe. We describe this simulation code in a separate publication [8]. Here we use this code to investigate the degree of interaction between shear bands. First, we show the development of a single shear band from a perturbation on the initial strength. Then we demonstrate the interaction between two shear bands 2mm apart. We show that when the perturbations are not symmetric in terms of their location their strength or their width, one of the two shear bands develops faster, and then dominates and quenches down the other shear band to some degree. Next, we check the influence of the distance between the initial perturbations on the degree of interaction between the shear bands that they trigger. We find that the degree of interaction decreases with distance between the shear bands, and that beyond some distance there is no interaction. Finally, we check the influence of six material and loading parameters on the degree of interaction between two shear bands 2mm apart. We find that the influence is generally not in agreement with predictions of analytical models from the literature.

References

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