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# On the shear band spacing in stainless steel 304L

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**Abstract.** In this work we present an analysis of the formation of multiple adiabatic shear bands in stainless steel 304L. Using both analytical criteria and numerical calculations, we analyze instability and shear band spacing in simple shear problems such as under torsional loading of a thin walled-tube. The Zerilli-Armstrong model which successfully describes the deformation response of metals at high strain rates is used. The perturbation approach associated with numerical methods is used to determine the instability modes and their corresponding spacing. The shear band spacing is computed using Molinari's postulate which suggests that the wavelength of the dominant instability mode with the maximum growth rate at a given time determines the minimum spacing between shear bands. The effect of grain size on shear band spacing is discussed. We show that the variation of the Taylor-Quinney parameter as a function of shear strain  $\beta(\gamma)$ , is an important parameter that plays a significant role in the calculation of the shear band spacing.

## 1. INTRODUCTION

The localization of plastic deformation in narrow bands is a major damage mechanism that occurs in ductile metals during high strain rates deformation processes. In some circumstances, many small bands may form throughout a volume of the material [1], in which case a spread weakening occurs with the possibility of multiple failures and a general fragmentation. In other circumstances one band may dominate, and therefore the material failure is restricted to just that one location.

Few numerical studies of the shear band spacing are available in the literature. Grady and Kipp [2] have obtained the shear band spacing by accounting for momentum diffusion due to unloading within bands. Wright and Ockendon [3] have used a perturbation analysis to characterize a dominant mode corresponding to the most probable minimum spacing of shear bands. Thus the wavelength of the dominant instability mode with the maximum initial growth rate will determine the shear band spacing. Molinari [4] has extended the work of Wright and Ockendon [3] to strain-hardening materials and has estimated the error in the shear band spacing due to the finite thickness of a block deformed in simple shear. He showed that the shear band spacing increases with an increase in the strain hardening exponent. Chen and Batra [5, 6] have studied the effect of thermal conductivity on SBS and also showed that it depends on the stress-strain relation used to describe the material behavior. Daridon et al. [7] have shown that the Mechanical Threshold Stress model predicts well the value of the shear band spacing in the case of HY100 steel and Ti-6Al-4V alloy.

Most investigators have employed phenomenological constitutive relations to describe the material response at high strain rate. It was pointed out in the work of Zerilli-Armstrong [8, 9] that these are valid only within the range of data used to calibrate them. These models do not account for the radically different behavior of face-centered-cubic (FCC) and body-centered-cubic (BCC) metals and for the effect of the grain size. In order to better understand the shear band spacing evolution in AISI 304L under high strain rates, the Zerilli-Armstrong model [8], which is based on the physical mechanisms of dislocation motion, is used in the present work. The system of governing equations for one-dimensional simple shearing deformations is formulated. For a given value strain, a perturbation of the fundamental solution is considered and the instability modes are determined. We used the method of Wright

and Ockendon to determine the shear band spacing, assuming a progressive saturation of the stored energy.

## 2. FORMULATION OF THE PROBLEM

Let us consider simple shearing deformation of a plate with a finite thickness  $2h$  in the  $y$ -direction whereas it is infinite in the other two rectangular cartesian directions. At the upper and lower surfaces, constant velocities  $\pm V$  are applied, parallel to the  $x$ -direction. We assume that all physical quantities are uniform along the  $x$  and  $z$  directions so that the deformation depends only on the space coordinate  $y$ , which leads to vanishing of the convection term in the material time derivation. The material is taken incompressible. At large strain and high strain rate, the elastic effects can be ignored and adiabatic conditions can be assumed at the boundaries. Therefore, the governing equations are given by:

$$\rho \frac{\partial v}{\partial t} = \frac{\partial \tau}{\partial y} \quad (1)$$

$$\rho c \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial y^2} = \beta(\gamma) \tau \dot{\gamma} \quad (2)$$

$$\dot{\gamma} = \frac{\partial v}{\partial y} \quad (3)$$

where (1) is the momentum balance equation, (2) the heat equation and (3) the compatibility equation; with  $v$ ,  $\dot{\gamma}$ ,  $\tau$  and  $T$  being respectively, the particle velocity (in the  $y$  direction), the plastic shear strain-rate, the shear stress and absolute temperature. We note that  $t$  represents time in the above equations.

The parameters  $\rho$ ,  $c$ ,  $k$  and  $\beta(\gamma)$  are the mass density, the specific heat, the Taylor-Quinney coefficient which represents the fraction of plastic work converted into heat, respectively. To model the evolution of the fraction of the plastic work converted into heat according to the shear deformation; we propose an empirical formulation:

$$\beta(\gamma) = 1 - \beta_0 e^{-\beta_1 \gamma} \quad (4)$$

Using the experimental results of Chrysochoos [10], obtained for quasi-static loading, the constants  $\beta_0$  and  $\beta_1$  are calculated and are equal respectively to 0.55 and 10.

Among the constitutive models, the Zerilli-Armstrong model represents a more physically-based relationship derived from dislocation mechanics [8]. They also made a distinction between f.c.c. and b.c.c. materials. The Zerilli-Armstrong equation for f.c.c. metals was used to describe the constitutive behaviors of 304L stainless steel:

$$\sigma = C_0 + k_I d^{-1/2} + C_2 \varepsilon^{C_n} e^{(-C_3 T + C_4 T \ln \dot{\varepsilon})} \quad (5)$$

$C_0$  is the athermal portion of the shear stress,  $C_n$  the work hardening exponent,  $d$  the grain size, and  $C_1$ ,  $C_2$ ,  $C_3$ ,  $C_4$ , and  $k_I$  are material parameters. The AISI 304L parameters are given in Table 1 [11].

**Table 1.** Parameters of Zerilli-Armstrong equation for AISI 304L SS [11].

| Parameters | $C_0$ | $k_I$ | $C_2$ | $C_3$  | $C_4$   | $C_n$ |
|------------|-------|-------|-------|--------|---------|-------|
| Value      | -76.9 | 0.75  | 2340  | 0.0016 | 0.00008 | 0.36  |

The axial stress and strain are converted to shear stress and shear strain by the von Mises relations.

For the initial conditions we take the body at rest (stress free) and at a uniform temperature  $T_i = 298$  K. The thermal boundary conditions:

$$\frac{\partial T}{\partial y}(y = -h, t) = \frac{\partial T}{\partial y}(y = +h, t) = 0 \quad (6)$$

### 3. PERTURBATION ANALYSIS

We consider a small perturbation of the homogeneous solution at time  $t_0$  (this gives the average strain  $\gamma^0 = \dot{\gamma}^0.t_0$ ) and evolving with time  $t$ :

$$\delta s(y, t, t_0) = \delta s^0 e^{\eta(t-t_0)} e^{i\xi y}, t \geq t_0 \quad (7)$$

Where  $\delta s^0 = (\delta v^0, \delta \gamma^0, \delta \tau^0, \delta T^0)$

The quantities  $\delta v^0, \delta \gamma^0, \delta \tau^0, \delta T^0$  are small constants that characterize the initial amplitude (at time  $t_0$ ) of the perturbation.  $\xi$  is the wave number of perturbation, and  $\eta$  is related to the initial rate of growth (at time  $t_0$ ). When the real part  $R_e(\eta) < 0$ , this implies that the homogeneous solution is stable at time  $t_0$ , and when  $R_e(\eta) > 0$ , this means that it is unstable.

Substitution of the perturbed solution

$$s(y, t, t_0) = s^0(y, t) + \delta s(y, t, t_0) \quad (8)$$

into the governing equations (1)-(4) and linearization provide, at time  $t_0$ , a linear equation for the amplitude vector  $\delta s^0 = (\delta v^0, \delta \gamma^0, \delta \tau^0, \delta T^0)$ :

$$A(t_0, \eta, \xi). \delta s^0 = 0 \quad (9)$$

This set of equation admits a non-trivial solution only if the determinant of the matrix  $A$  is equal to zero. This leads to a cubic equation for the growth rate  $\eta$  of the perturbation:

$$\begin{aligned} \rho^2 c \eta^3 + \rho \left( c \xi^2 \frac{\partial \tau}{\partial \dot{\gamma}} \Big|_{s^0} + k \xi^2 - \beta^0 \dot{\gamma}^0 \frac{\partial \tau}{\partial T} \Big|_{s^0} \right) \eta^2 + \left( k \xi^2 \frac{\partial \tau}{\partial \dot{\gamma}} \Big|_{s^0} + \rho c \frac{\partial \tau}{\partial \gamma} \Big|_{s^0} + \beta^0 \tau^0 \frac{\partial \tau}{\partial T} \Big|_{s^0} \right) \\ \xi^2 \eta + k \xi^4 \frac{\partial \tau}{\partial \gamma} \Big|_{s^0} = 0 \end{aligned} \quad (10)$$

where partial derivatives are evaluated for the fundamental solution at time  $t_0$  and  $\beta(\gamma^0) = \beta^0$ .

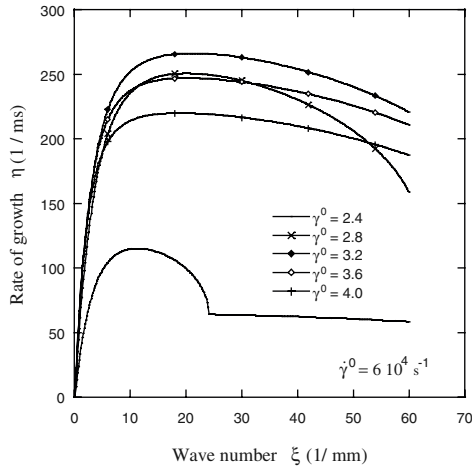
For given values of  $\gamma^0$  and  $\xi$ , the root  $\eta_D$  with the largest positive real part will govern the instability of the homogeneous solution, and is hereafter referred to as the dominant instability mode.

The fundamental solution is such that the strain rate is uniform,  $\dot{\gamma}^0 = \frac{V}{h}$ . The temperature can be obtained by integration of the heat equation (2) where the diffusion term vanishes, and where the constitutive law (4) is used to express the stress  $\tau$ .

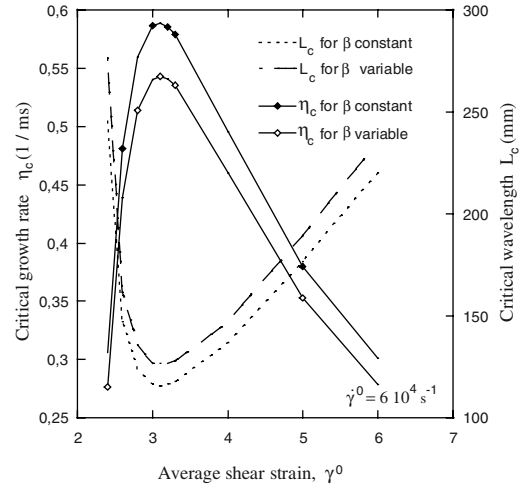
### 4. RESULTS

Figure 1 shows the dominant growth rate,  $\eta_D$ , vs. the wave number,  $\xi$ , for various values of the average strain  $\gamma^0$ . These curves have been computed for a nominal strain rate  $\dot{\gamma}^0 = 610^4 s^{-1}$  and an initial temperature  $T_0 = 298$  K for constant and variable (eq. 5) Taylor-Quinney coefficient. For each value of  $\gamma^0$  the initial growth rate  $\eta_D$  first increases with  $\xi$ , attains a maximum value  $\eta_c$  (corresponding to  $\xi_c$ ) and then decreases for large  $\xi$ . The existence of this maximum is characteristic of the dominant instability mode resulting from the competition of two stabilizing effects: Inertia restrains the growth of long-wavelength modes (small  $\xi$ ) while heat conduction restrains the growth of small-wavelength modes (large  $\xi$ ). In what follows the maximum dominant growth rate at time  $\gamma^0$  for the perturbation is called the critical growth rate  $\eta_c$ , and the corresponding wave number is defined as the critical wave number  $\xi_c$ .

Figure 2 shows the dependence of the critical growth rate  $\eta_c$  and its corresponding wavelength  $L_c = 2\pi/\xi_c$  on the average strain  $\gamma^0$  for Stainless steel 304L. These results are given in both cases



**Figure 1.** Evolution of the dominant instability mode for different values of the average shear strain.



**Figure 2.** Evolution of the critical growth rate and the critical wavelength at the average shear strain.

where the Taylor-Quinney coefficient is supposed to be constant ( $\beta = 0.9$ ) and where it evolves with the shear strain. We observe that the curves of the critical growth rate and the critical wavelength versus average strain have respectively a maximum  $\eta_{cm}$  and a minimum  $L_{cm}$ . These values are obtained for two different values of the average strain,  $\gamma_1^0, \gamma_2^0$ . In the example considered here, since the values of  $\gamma_1^0$  and  $\gamma_2^0$  are very close, we assume  $\gamma_1^0 \cong \gamma_2^0$ . This assumption is in a good agreement with the results obtained by Molinari [4] in the case of XC18 steel with the power law model.

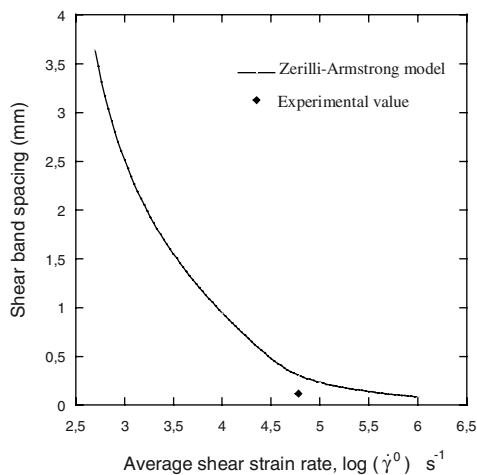
According to Molinari [4], we postulate that the shear band spacing  $L_s$  is given by:

$$L_s = \min L_c(\gamma^0) = \min \frac{2\pi}{\xi_c(\gamma^0)} \quad (11)$$

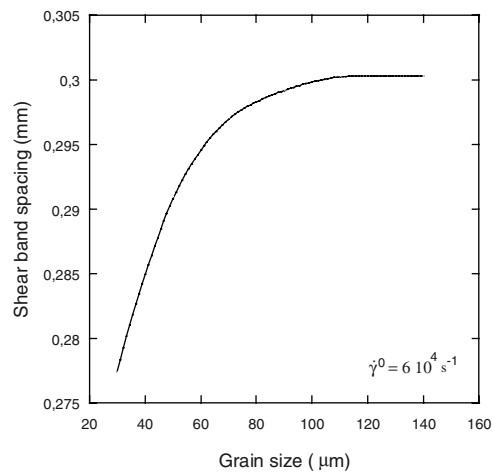
We note that the evolution of the Taylor-Quinney coefficient have an important influence on the shear band spacing  $L_s$ . When it's assumed to be constant, the results lead to significant underestimation of the shear band spacing. Indeed, for the shear strain rate equal to  $6 \cdot 10^4 s^{-1}$ , the shear band spacing is equal to 0.277 mm if we supposed that the coefficient of Taylor is constant whereas by taking account the experiment results which show that the Taylor-Quinney coefficient evolves with the shear strain,  $L_s$  is equal to 0.297 mm. We note that the average shear strain corresponding to the maximum value of  $\eta_c$  is equal to 3.1 for the both case.

In Figure 3, we plotted the dependence of the shear band spacing on the average shear strain-rate. We observe that the shear band spacing decreases rapidly with an increase of the average shear strain-rate, and show a tendency to saturate at high strain rates. We also note that the difference between the theoretical predictions obtained by the Zerilli-Armstrong model and the experimental value is important. But the theoretical predictions are still of the same order of magnitude as the experimental data.

The effect of the grain size  $d$  on the shear band spacing  $L_s$  is illustrated in Figure 4 for  $\dot{\gamma}^0 = 6 \cdot 10^4 s^{-1}$ . One notes that for sizes of grain ranging between 30 and 100  $\mu m$  the shear band spacing increases monotonically with an increasing value of  $d$ , on the other hand for larger values of  $d$   $L_s$  tends towards a state of saturation. Therefore, it can be concluded that there is no significant effect of grain size on the shear band spacing for a grain size more than 100  $\mu m$ . This result is in good agreement with the literature [11].



**Figure 3.** The variation of the shear band spacing with the average shear strain-rate.



**Figure 4.** Shear band spacing as function of grain size.

## 5. CONCLUSION

We studied the thermo-mechanical response of the Stainless steel 304L block deformed in simple shear. The description of the deformation behavior is modeled using the Zerilli-Armstrong constitutive model. The stability of the homogeneous solution is studied by using the perturbation technique.

We have showed that the fraction of plastic work converted into heat may have a significant role in the calculation of the shear band spacing. This result points out the necessity of a fine thermomechanical check of the constitutive equation used in dynamic loading.

We have also showed that the shear band spacing decreases rapidly, towards a saturation value, with increasing of average shear strain-rate.

Lastly, it is shown that the grain size has a limited influence for small grain sizes and this one disappears for grain sizes higher than  $100\mu\text{m}$ .

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