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EFFECTS OF ANISOTROPY ON DYNAMIC TENSILE BEHAVIOR

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A stability analysis for an anisotropic stretching rod is presented. We consider the particular case of a rapidly stretching titanium jet using a continuum code to examine anisotropic plastic response in the finite-neck regime. It was found that the classical analysis (yield strength is inversely proportional to stability) is insufficient; anisotropic jets can be more or less stable than their maximum or minimum yield strengths, depending on initial perturbations and the orientation of the anisotropy. One particular anisotropy—with the weak direction along the jet axis—appears to be generally stabilizing.

1. INTRODUCTION

When a metal rod is stretched, the material becomes unstable in the sense that one or more necks eventually will appear and grow until the rod breaks. We will consider this stability problem for a particular dynamic case: the neck-down of a shaped-charge jet, with strain rates of the order of 10^4 – 10^5 s⁻¹, for an anisotropic material. The necking problem first was treated for a nonstretching capillary jet by Rayleigh,¹ and the general fluid problem has been treated extensively in the literature. Rayleigh's expression for perturbation growth has two parts: a parameter, $\Phi = T/\rho a^3$, and a factor depending on the perturbation wavelength. Here, T is the surface tension, ρ is the density, and a is the radius; Φ has units of (time)⁻². Early work on the stability problem for a stretching solid rod, which has some mathematical similarities to the fluid case, was done by Chou and Carleone² and Walsh³ using both analytical and computer simulation methods. An initial radial velocity gradient was added by Romero.⁴ If T is replaced by Y , where Y is the yield strength, and the stability parameter, Γ , is made dimensionless,⁵ we obtain

$$\Gamma^2(\dot{\epsilon}) = \sqrt{3}\rho\dot{\epsilon}^2(a^2)/Y,$$

where $\dot{\epsilon}$ is the axial strain rate. Note that the lower the yield strength and the higher the density (and strain rate), the more stable the jet. As the jet stretches, Γ decreases. For $\Gamma < 1$, perturbations become unstable.⁴ The stability is important for the penetration of a jet into a target; the slower the growth of perturbations, the longer the final jet fragments—and longer fragments penetrate deeper.

The above phenomena have been seen in jet simulations, and all but certain density effects correspond to experimental data. Density effects are hard to isolate because changing the density generally means changing the jet material, and factors not treated by the above analysis may be equally important. In particular, jets of zirconium and titanium (materials with a hexagonal-close-packed (hcp) crystal structure) appear to be more stable than their (low) densities would indicate. One possible stabilizing factor is anisotropy, and plastic anisotropies for hcp materials

can be very large. For example, yield anisotropies can be greater than 2:1, and R values (the ratio of plastic width strain to thickness strain in a tensile test) typically range from 3–7.⁵ The source of this anisotropy is crystallographic texture, the preferred orientation of single-crystal grains in a polycrystalline solid. If the orientations are not random, the material will tend to be anisotropic because single crystals are normally anisotropic. A strong preferred orientation is typically the result of a large deformation ($\epsilon > 50\%$)—and jet deformations are extraordinarily large.

Our system of interest is the stability of an axisymmetric, anisotropic jet with the properties typical of (hcp) α -titanium and some of its alloys, where the preferred orientations are results of a high-speed tensile deformation. If the material can twin (the usual case), the well-developed jet will have a typical extrusion texture,⁶ with the "hard" directions (c -axes) of the grains pointing radially. This produces a plastic anisotropy in the extruded rod (or jet), with the weak direction along the axis and the strong direction radial. For comparison, we also evaluate the opposite anisotropy with the strong direction along the axis (typical of cross-rolled sheet).

In the present work, we investigate the effects of these two different anisotropies on jet stability. We use a texture code to calculate the anisotropy resulting from a set of preferred orientations. Essentially, such a calculation "samples" an oriented collection of grains and models the single-crystal mechanisms of slip and twinning to produce a set of stress points that together define a yield surface.⁷ We use continuum calculations to simulate neck growth and to follow the effect of initial perturbations into the nonlinear, finite-neck regime. The results of our calculations indicate that anisotropy can have significant effects on neck growth, either to stabilize or to destabilize, depending on the nature of the anisotropy and of the initial perturbations. Moreover, anisotropic stability is not just a matter of the magnitude of the yield strength.

2. PROCEDURE

Our investigation of jet stability consists of two parts: (1) a comparison of isotropic and anisotropic response and (2) a study

of the effects of different initial perturbations. Both isotropic and anisotropic material models were incorporated into a modified version of EPIC2-88,⁸ an explicit Lagrangian 2D finite-element code. The code modifications are described elsewhere.⁷

The anisotropic material was modeled from the general features of heavily cross-rolled (transversely isotropic) titanium or zirconium sheet.⁹ This sheet gives an R value of ~ 6.5 , which corresponds to an anisotropy ratio of $\sigma_y/\sigma_x = 1.95$, where z is the through-thickness direction and x is in the plane of the sheet. Details of the yield surface, including shear strength, were obtained with a texture simulation using single-crystal properties of hcp titanium at moderately high temperatures and relatively high strain rates. The yield surface was normalized by applying the texture code to a randomly oriented collection of grains, and setting the (isotropic) average yield stress to 200 MPa, a value characteristic of annealed sheet. The two strong anisotropies described in Sec. 1 were fitted to a standard quadratic anisotropic yield function.¹⁰ Our two anisotropies correspond to two different initial material orientations of the same yield function: 0° (weak direction axial) and 90° (strong direction axial), where the strong, weak, and shear components are $Y = 239, 123$, and 217 MPa, respectively.

Along with the anisotropic functions, we used two isotropic models, with $Y = 123$ and 239 MPa, corresponding to the anisotropic weak and strong directions. Both isotropic and anisotropic materials were treated as elastic-perfectly-plastic. The constant yield surface should be applicable to the late stages of jetting, where hardening and thermal softening compete. In addition, the first stages of necking, at least, probably would not alter the anisotropy significantly.

A section of the stretching jet was modeled as a cylinder fixed at one end and with the other end moving at a constant velocity. Necking was initiated by imposing small perturbations in the outer surface of the bar. The perturbed surface was stress-free, and the end surfaces were free from shear stresses. For initial conditions, we imposed linear velocity distributions in both radial and axial directions.

The initial jet dimensions and strain rate were within the normal range for jets at the time when necks are first visible: the axial strain-rate, $\dot{\epsilon}$, was $6.1 \times 10^4 \text{ s}^{-1}$, the unperturbed radius, r_0 , was 2.13 mm ,² and the initial segment length, L_0 , was 8.52 mm . If the density is 4.5 g cm^{-3} (titanium), the stability parameter, Γ , ranges from 0.74 – 1.0 , indicating conditions slightly unstable for neck growth. The initial radial velocity was calculated to be $\dot{r}/2$ by assuming plastic incompressibility.

We set up two different kinds of disturbances in the free surface of the jet. The first kind is a superposition of cosine waves:

$$r(z) = r_0 + \sum_{n=1}^8 a_n \cos(2\pi z/\lambda_n)$$

where $r(z)$ is the radial coordinate and $\lambda_n = L_0/n$. We constructed two different cosine series. For the first, we used only four waves ($a_n = 0.026 \text{ mm}$ for $n = 1, 2, 4, 8$; $a_n = 0$ otherwise). This series corresponds to Chou and Carleone's² initial perturbation and spans their most unstable wavelengths. For the second series, we used all eight waves ($a_n = 0.026 \text{ mm}$ for all n). The second kind of initial disturbance is a set of random perturbations:

$$r(z) = r_0 + \alpha \lambda \text{ RAN}$$

where $\alpha = 0.013 \text{ mm}$ and RAN is a random number between -1 and 1 . A different seed was used to generate each set of random perturbations. These axisymmetric calculations were performed with 600 rectangular finite elements: 6 radial elements $\times$ 100 axial elements. This spatial resolution was well-converged when compared with a doubly fine case (12×200).

Finally, to follow the necking process, we define a growth function:

$$f(t) = \frac{r_{\max}(t) - r_{\min}(t)}{R(t)}$$

where R is the undisturbed radius. The growth function was calculated at $1\text{-}\mu\text{s}$ intervals.

3. RESULTS AND DISCUSSION

The results for necking of both isotropic and anisotropic jets for different kinds of initial perturbations are shown in Figs. 1–6. For each of these simulations, we compare neck growth for four material models: two anisotropic models, the first with the strong direction along the axis (90°) and the second with the weak direction along the axis (0°) and two isotropic models, one with a yield strength of 239 MPa (the same as the anisotropic strong direction, and the maximum anisotropic strength) and one with a yield strength of 123 MPa (the same as the anisotropic weak direction). From the classical stability analysis, the two isotropic cases should bracket the anisotropic results because the anisotropic yield strength varies between 123 and 239 MPa . Thus, the anisotropic jet should be, in general, more stable than the 239-MPa jet and less stable than the 123-MPa jet.

Our simulations show that the classical analysis is insufficient for anisotropic effects. Figures 1 and 2 show the neck growth and jet shapes, respectively, for the four-wave cosine perturbation. The 0° anisotropy is more stable than the 123-MPa isotropic case, even though the anisotropic yield strength equals 123 MPa for axial tension and is greater than 123 MPa for the stress states "near" tension encountered in the necked region. This extra stability must be a result of anisotropy, not overall yield strength differences. The neck distribution is also different for isotropic and anisotropic jets.

Figures 3 and 4 show neck growth and jet shapes for the eight-wave perturbation. Here, both anisotropic cases are generally more stable than the 123-MPa isotropy. The anisotropic

Fig. 1. Growth functions for four-wave perturbation.

Fig. 3. Growth functions for eight-wave perturbation.

Fig. 2. Element plots for neck configuration at 40 μ s; four-wave perturbation.

Fig. 4. Element plots for neck configuration at 40 μ s; eight-wave perturbation.

Fig. 5. Growth functions for random perturbations (Set 1).

Fig. 6. Growth functions for random perturbations (Set 2).

stability has changed significantly, whereas the isotropic neck growth is not affected significantly. (However, it is clear from Figs. 2 and 4 that the isotropic neck distribution is sensitive to initial perturbations.)

Figures 5 and 6 show neck growth for two sets of random perturbations. In the first case, the 90° anisotropy is considerably more stable than the 239 MPa isotropy. In the second case, in contrast, the 90° anisotropy is less stable even though the maximum anisotropic yield is 239 MPa. The 0° anisotropy is more stable than the 123 MPa isotropy for both random sets. We have calculated other random sets, and the increased stability for the 0° anisotropy was repeated. In addition, the 0° case takes longer to begin necking than the isotropic cases.

These results suggest several special characteristics of anisotropic response. First, the classical argument of "lower yield strength, more stability" is not sufficient to describe anisotropic response in necking. Second, initial perturbations have a significant effect on the neck growth of anisotropic (but not isotropic)

jets. (These perturbations do have a large effect on the neck distribution of both isotropic and anisotropic jets). Finally, an anisotropic orientation with the weak direction of the material along the axis (the usual rod texture for a twinning hcp material) appears to significantly stabilize against necking, compared with an isotropic material having the same yield strength as in the anisotropic weak direction. This may be part of the extra stability seen in jets of hexagonal materials.

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