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CONF-8908128--71

LA-UR--89-3018

DE90 000535

TITLE: TWINNING, TEXTURE AND CONSTITUTIVE RELATIONS FOR EXPLOSIVELY FORMED JETS

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SUBMITTED TO: 1989 APS TOPICAL CONFERENCE ON SHOCK COMPRESSION OF CONDENSED MATTER, 14-17 AUGUST 1989, ALBUQUERQUE, NM

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TWINNING, TEXTURE AND CONSTITUTIVE RELATIONS FOR EXPLOSIVELY FORMED JETS

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We have used crystallographic-texture calculations to simulate the evolution of preferred grain orientations, and the corresponding changes in anisotropic plasticity, during explosively-driven liner collapse in metallic shaped-charge jets. For hcp metals, twinning tends to be an important deformation mechanism, and twinning is known to be strongly influenced by shocks. We consider cases of enhanced and inhibited twinning for titanium and titanium-alloys; the consequences of these treatments for the evolution of plasticity in early jet formation are discussed.

1 INTRODUCTION

There have been a number of studies investigating anisotropic plasticity under shock and high-strain-rate conditions. Much of this work has focussed on properties of composites. We consider a different kind of anisotropy here: the directional properties of single-phase materials resulting from crystallographic texture. We also consider the changes in anisotropy as these materials deform. This approach has been used previously to investigate the mode of action of initial texture on the subsequent behavior of shaped-charge jets.[1]

Crystallographic texture refers to preferred orientation of the single-crystal grains in a polycrystalline solid. If the orientations are not random, the material will tend to be anisotropic, since single crystals are typically anisotropic. The bulk anisotropies due to texture can be quite large: in zirconium,[2] for example, the ratio of yield strengths in different directions can be > 2:1. Plastic strain anisotropies can be even larger. For metal sheet, the Lankford coefficient R, is defined as the ratio of (plastic) width strain to thickness strain in a tensile test. For isotropic materials, R = 1. For titanium[3], typical R values range from 3-7, and indicate significant resistance to thinning. In contrast, copper sheet[1] gives R = .6 - .9.

A strong preferred orientation is typically the result of large deformation (>50%), random materials can become textured, and textured materials can evolve new preferred orientations. It is important to note that the patterns of deformation textures depend on both the crystal structure and the deformation path.

The two basic mechanisms involved in deformation texturing are crystallographic slip and twinning.[4] Both mechanisms involve shear in a crystal along certain planes and in certain directions, and both mechanisms rotate the crystal lattice. In twinning, only part of the crystal shears. In addition, the twinning shear is unidirectional and accompanied by a slight shuffle in atom positions. The twinned material is effectively rotated relative to the untwinned matrix. Twinning in hcp (hexagonal-close-packed) materials is particularly interesting as a source of texture change, since this effective rotation can be very large (the "hard" direction rotates by ~85° for a common type of tensile twin), and a significant volume of material can be twinned during very small strains. Moreover, twinning is encouraged by shock and high-strain-rate conditions. It is inhibited by small grain size, certain initial dislocation structures, impurities, and some kinds of alloying.[5]

Our system of interest is the early collapse (the first few microseconds of deformation) of a hemispherical metal liner in a shaped-charge jet. Collapse involves a shock compression, followed by large deformation at high (~10^5 sec^{-1}) strain-rate. Under these conditions, plastic flow can be largely accommodated by slip and twinning. Deformation texturing, rather than crystal growth or recrystallization, would be the major source of any changes in preferred orientation.

To calculate changes in texture, we simulate the mechanisms of slip and twinning in a collection of grains for a particular deformation path. We consider the activation of any system to require a certain critical-resolved-shear stress (CRSS); the relative CRSSs depend on the material and the conditions. The numerical scheme used to simulate texture evolution has been described elsewhere;[1] we note that each grain rotation includes both the ordinary continuum rotation plus a second term depending on the texture.

In the present work we investigate specifically the effects of twinning during shaped-charge liner collapse. We use properties typical of α-titanium (hcp) and some of its alloys, and two different material models, one with enhanced twinning, and the other with inhibited twinning. The initial texture has a strong preferred orientation and strong anisotropy. The results of our calculations indicate that twinning (or the lack of twinning) can play a very important role in the evolution of yield anisotropy in these systems. Profuse twinning can effectively destroy a strong texture in a very short time; inhibition of twinning can make a strong texture even stronger.

2. PROCEDURE

Our method, to compare the effects of enhanced and inhibited twinning on constitutive relations for a shaped-charge liner, involves two connected simulations. The first simulation uses a continuum code to produce a deformation path. The second uses the deformation path as input to a texture code to calculate texture evolution and yield surfaces.

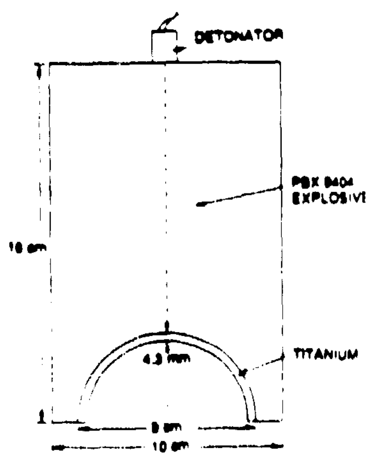


Fig. 1. Schematic of titanium shaped charge.

The jet design is shown in Fig. 1. Liner collapse was simulated with TEWA, an explicit 2-D finite-difference Lagrangian code incorporating high-explosive burn. The liner equation-of-state was obtained from a fit to Hugoniot data, and the constitutive behavior was approximated by a high strain rate isotropic model.[6] From the simulation results, we constructed a time series of deviatoric distortion tensors for a liner element initially located at 3° from the jet axis, using successive positions of the corners of its corresponding Lagrangian cell, plus the cell compression, at simulation time intervals of 0.25 μs. Each tensor was further divided, if necessary, so that the equivalent von Mises strain of any deformation step was < 2.5%.

Texture evolution calculations were then performed for a sample of 3000 grains, using the set of distortion tensors. We employed two different material models: the first model allowed considerable twinning; the second model allowed no twinning. Our models used single-crystal properties of pure titanium at moderately high temperatures (a few 100°C) and very high strain-rates (> 10^5 sec^{-1}). The dominant form at ordinary temperatures and pressures is α–titanium, with an hcp crystal structure and c/a = 1.59. For the purposes of this study, we assume there are no phase transitions. The slip and twin systems characteristic of α–Ti at various temperatures, plus CRSSs for these systems, have been summarized by Conrad.[5]

We modified the system activity for shock and high-strain-rate conditions, according to Meyers and Murr.[7] They report that the general effect of high strain-rates is to shift the dominant systems from higher-temperature to lower-temperature modes. Hence, we modeled our system activity on low to moderate-temperature systems.

TABLE I.
Deformation Modes and Critical-Resolved-Shear Stresses

Designation	Plane	Direction	CRSS[a]
Prism slip	$(10\bar{1}0)$	$\langle 11\bar{2}0\rangle$	1
Pyramidal slip	$(10\bar{1}1)$	$\langle 11\bar{2}0\rangle$	2
Basal slip	(0001)	$\langle 11\bar{2}0\rangle$	3
Tensile Twin	$(10\bar{1}2)$	$\langle \bar{1}011\rangle$	2.5
Compressive Twin	$(11\bar{2}2)$	$\langle 11\bar{2}\bar{3}\rangle$	3.75
Pyramidal <c+a> slip	$(10\bar{1}1)$	$\langle 11\bar{2}3\rangle$	4

[a] Normalized to the CRSS for prism slip.

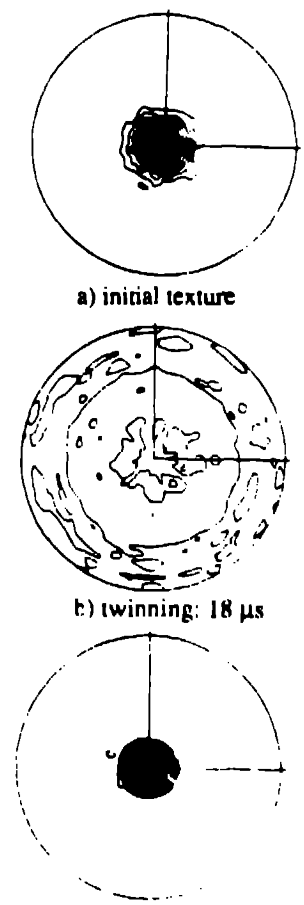
Our active systems, and the CRSS for each kind of system, are given in Table I. The first three systems listed are generally agreed to be the easy slip systems for a wide range of conditions. None of these systems accommodates deformations in the c axis direction. The two principal modes of c-axis deformation for low and moderate temperatures are the twinning systems listed in the table. For our twinning model, we use systems 1-5. For inhibited twinning, we replace the twinning systems by the sixth system. This secondary slip system becomes important in c-axis deformation at high temperatures, where twinning becomes more difficult.[8]

The initial liner texture was modeled from the general features of cross-rolled titanium sheet.[9] We idealize the compression texture by clustering the (0002) poles (c-axes) around the normal direction of the sheet; the pole angles from the sheet normal are assigned from a Gaussian distribution with $\sigma = 18°$. This texture gives an R-value of 9, and a yield strength ratio $z/x = 2.25$, where z is the compressive yield normal to the sheet, and x is the average compressive yield in the plane of the sheet. To make a textured hemispherical liner, for simplicity we map the sheet texture separately onto each computational element of the shell. A liner element whose center is at the angle θ from the axis contains all of the grain orientations in the sheet, but with each orientation rotated by θ.

3. RESULTS AND DISCUSSION

The changes in texture and the corresponding anisotropies resulting from collapse of a hemispherical titanium shaped-charge liner are shown in Figs. 2-3, for two different material models, one allowing considerable twinning, the other no twinning. The deformation path corresponds to that of a liner element initially located at $\theta = 3°$ from the jet axis. For this section of liner, the shock arrives at ~ 13.75 μs. The early deformation is a compression approximately along the jet axis, followed by tension along the axis.

Figure 2 shows the evolution of texture in this cell. All three diagrams are (0002) pole figures; the density contours indicate the directions of the c ("hard") axes. The center of each pole figure corresponds to c-axes pointing out of the page; the top corresponds to c-axes pointing vertically, etc. The second and third pole figures indicate the textures for the enhanced-twin and inhibited-twin models, respectively, at 18 μs, after 7% compression followed by ~ 50% tension (von Mises equivalent strains)



a) initial texture

b) twinning: 18 μs

c) no twins: 18 μs

Fig. 2 (0002) pole figures for deforming liner element. Intensities in multiples of a random distribution (m.r.d.); contours are 1, 2, ...m.r.d. Stereographic projection; projection plane is normal to the jet axis.

Figure 3 shows deviatoric yield surfaces corresponding to the textures in Fig. 2. There are two yield surfaces for the initial texture, since the yielding for the two models is different. The unequal yields in the S_1 and $-S_1$ directions in Fig. 3(a) are due to the unidirectional nature of twinning; this effect is seen experimentally.

The different texture evolution, and the different plastic anisotropies for enhanced and inhibited twinning are quite clear. In the former case, profuse twinning (~80% of the grain volume has twinned by 18 μs) produces a drastic reorientation of the crystals. The c-axes move from a strong concentration in the axial direction to a clustering around the radial direction (a weak extrusion type texture). A large fraction of the reoriented grains can now deform by primary slip, which is generally easier than twinning. The changes in yield anisotropy reflect the texture changes. The axial direction starts out "hard" and the radial direction "soft". This relation reverses, albeit weakly. The final yield anisotropy is ~ 5%. For inhibited twinning, there is no reorientation. Instead, the strong preferred orientation (and yield anisotropy) becomes stronger.

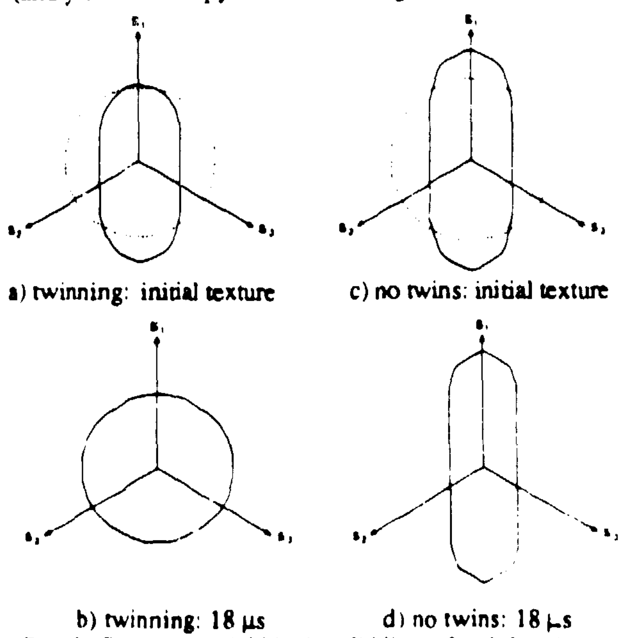


Fig. 3. Deviatoric yield loci (solid lines) for deforming liner element. The [1] direction is parallel to the jet axis. Dashed lines indicate loci for isotropic texture.

The main discrepancies in these results are in the simplified twinning model, and the neglect of temperature dependence in the CRSS for the secondary slip system. In the first case, the radial preferred orientation should be stronger. The weakness of the evolved twinning texture is partly due to the initial compression, but also due to unrestricted higher-order twinning. This causes some of the twin orientations to shuttle back and forth. In the second case, the CRSS for the <c+a> slip is treated as a constant. However, this slip mode is a major deformation mechanism for c-axis deformation at high temperature, and becomes easier as the temperature increases. This will reduce the yield anisotropy as the liner collapses. Nevertheless, the pattern of yield anisotropy will remain, since primary slip will still be easier than <c+a> slip.

We have concentrated here on typical slip and twinning systems for titanium and its alloys, and on the effect of conditions that promote or inhibit twinning. From our results, we can conclude that a strong compression texture, and strong yield anisotropy, can be essentially destroyed by deformation twinning in a short time. In the absence of twinning, the anisotropy remains and can even be strengthened. The matter of correct twinning systems for jets and explosively-formed projectiles needs to be studied further. We note, however, that liner materials can be processed, not only to discourage twinning, but pre-twinned[10] under some conditions to encourage particular twins under other conditions. Texture studies, as a prescription for constitutive models, can help provide insights into material behavior in many of these cases.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Defense and the Department of Energy, through the Joint DoD/DOE Munitions Technology Development Program.

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