Textures and Microstructures, 1991, Vols 14–18, pp. 139–144
Reprints available from the publisher
Photocopying permitted by license only
© 1991 Gordon and Breach Science Publishers SA
Printed in the United Kingdom

TEXTURE AND DEFORMATION MECHANISMS ACTING UNDER DIFFERENT LOADING PATHS IN ZRY 4

A.A. POCHETTINO, C. VIAL EDWARDS* and R. PENELLE+
Dpto. Ciencia de Materiales, Gcia. Desarrollo, CNEA, Av. del Libertador 8250, 1429 Buenos Aires, Argentina.
* Escuela de Ingeniería, Pontificia Univ. Católica de Chile, Vicuña Mackenna 4860, Santiago de Chile, Chile.
+ Lab. Metallurgie Structurale, UA CNRS 1107, Univ. Paris Sud, 91405 Orsay Cedex, France.

INTRODUCTION

Zr alloys have a highly anisotropic plastic behaviour, related to the crystallographic textures and to the active deformation mechanisms in grains: $\{10\bar{1}0\}\langle 1\bar{2}10\rangle$ prismatic and $\{10\bar{1}3\}\langle 1\bar{2}13\rangle$ pyramidal slip and twinning. Microstructural observations indicate that prismatic slip is the most active deformation mode in these materials[1]. Pyramidal slip, $\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ tensile twins and $\{\bar{2}112\}\langle\bar{2}113\rangle$ compressive twins allows to accommodate grain strains along the $\vec{c}$ axis, but the activation conditions and the amount of activity on these deformation modes is actually in discussion[2-3]. The aim of this work is to contribute to the analysis of the active deformation mechanisms under three different loading paths: uniaxial tension, equibiaxial expansion (bulge test) and tension with restricted transverse deformation (Wagoner type specimen).

EXPERIMENTAL

Materials:

Two different Zircaloy-4 (Zry-4) sheets presenting different crystallographic textures -named PO and PC- were tested. PO had *c* axes concentrated around the plane defined by the Normal (ND) and the Transverse (TD) Directions of the sheet with reinforcements of the components $\{10\bar{1}3\}\langle 1\bar{2}10\rangle$ and $\{\bar{2}115\}\langle 10\bar{1}0\rangle$. These components placed the $\bar{c}$ axes at approximately 30° from the ND. PC had a high concentration of [0001] poles around the ND of the sheet. The PC material had a considerably higher Oxygen content than the PO material (0.135 and 0.072 wt% respectively).

Mechanical Tests:

Uniaxial tension tests were peformed with standard specimens cut at 0, 45 and 90 degrees to the Rolling Direction (RD). A 100 KN Instron machine was used to apply and to measure the load. An initial strain rate of 5.10^{-3} s^{-1} was used. Longitudinal and transverse strains were measured on photographs of a printed grid with a tool maker's microscope. Strain ratios were determined with the same tests.

Tensile tests with restricted transverse deformation were performed with specimens similar to those utilized by Wagoner et al.[4], which are shown in Fig. 1. The tensile axis was parallel to the transverse direction. This specimen was designed to produce plane-strain conditions in approximately 75% of the width; but in the present experiments the ratio of the transverse to the longitudinal deformation varied between -0.37 and -0.61 in the central region of the specimens. These results will be discussed in next sections. Flow stress was computed dividing the applied force by the instantaneous transverse section. This section was determined using an average value of the longitudinal strain across the width of the specimen. The longitudinal and width strains were measured on photographs of a printed grid of circles, whose diameter was 10 mm.

Biaxial tension tests were performed using the Bulge test. Details of the experimental setup can be seen in reference[5].

RESULTS

True stress-true strain curves for Zry-4 PO and PC samples are presented in Fig.2a-b. Tables 1 and 2 show the results of the different mechanical tests when the true stress-true strain curves are fitted by the power law $\sigma=C\epsilon^n$ in the range of strains given in the table. RD and TD indicate that tensile axis was parallel to the rolling direction and to the transverse direction respectively.

The values of the contraction coefficients ($q=-E_{22}/E_{11}$) in uniaxial tension and Wagoner specimen tests and the Lankford coefficients (uniaxial tests) at true strains around $\epsilon\approx0.06$ for both samples are reported in table 3.

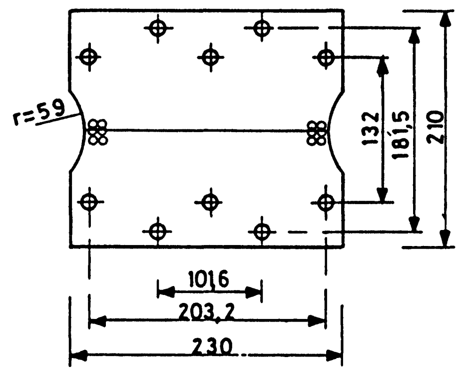

Figure 1: Wagoner test specimen used in this work. Dimensions are given in mm.

Table 1: True strain-true stress results in Zry-4 PC

Tests	C(Mpa)	n	Range strains	Corr.coeff.
Uniax.Tension (RD)	715	0.127	0.006-0.142	0.972
Uniax.Tension (TD)	699	0.124	0.012-0.110	0.989
Biaxial Tension	1587	0.224	0.006-0.113	0.998
Wagoner specimen	895	0.105	0.010-0.090	0.993

Table 2: True strain-true stress results in Zry-4 PO

Tests	C(Mpa)	n	Range strains	Corr.coeff.
Uniax.Tension (RD)	727	0.178	0.010-0.178	0.984
Uniax.Tension (TD)	553	0.102	0.008-0.087	0.997
Biaxial Tension	2332	0.391	$\epsilon < 0.05$	0.920
	1453	0.236	$\epsilon > 0.05$	0.991
Wagoner specimen	779	0.114	0.007-0.105	0.999

Table 3: strain ratios in uniaxial tension and Wagoner type tests.

Sample	Test	q	R
Zry-4 PC	Uniaxial Tension (RD)	0.74	2.9
	Uniaxial Tension (TD)	0.76	3.0
	Wagoner specimen	0.42	---
Zry-4 PO	Uniaxial Tension (RD)	0.70	2.4
	Uniaxial Tension (TD)	0.86	6.0
	Wagoner specimen	0.51	---

DISCUSSION

Zry-4 PO samples present lower levels of flow stresses than Zry-4 PC under the three different loading paths. In uniaxial tension, the properties of both materials are similar to those already reported in the literature[3]. It is important to remark the following: when the transverse strain is restricted as in Wagoner type specimen or it is imposed as in biaxial tension tests, the flow stresses increase drastically.

For biaxial expansion tests, the higher yield stress presented by PC samples can be explained by the analysis of the active deformation mechanisms. Microstructural observations indicate that very limited twinning activity has been observed in biaxial expansion of PC with similar Oxygen content[6]. Then, pyramidal slip becomes the principal mechanism for the accomodation of plastic deformation in the transversal direction of these samples. The activation of pyramidal slip requieres the application of high stress levels in order to reach the high values of the associated CRSS[1]. The hardening law for this material will be controlled by the interaction between <c+a> dislocations associated to pyramidal slip with other <c+a> and <a> dislocations[7]. Therefore, the strain hardening exponent of PC samples in biaxial expansion ($n=0.224$) can be associated to the hardening of pyramidal slip. The value of this coefficient presents a clear difference with that corresponding to uniaxial tension tests ($n \approx 0.12$-0.13). For these tests, in-plane anisotropy behaviour of the Lankford coefficient and the strain hardening coefficient was determined. The high values of the Lankford coefficients can be explained considering that, during uniaxial tension tests, deformations occur principally by prismatic slip[2].

There are experimental evidences of considerable twinning activity during biaxial expansion tests of PO samples[6], whose Oxygen content is lower than the one observed in PC. Twinning, combined with probable prismatic slip in reoriented grains facilitates plastic deformation, explaining a lower flow stress for $\epsilon<0.05$. The experimental stress-strain curves induce us to believe that as deformation increases, the activity of the twinning mechanisms decreases, leaving the pyramidal slip as the main deformation mode for the accomodation of plastic deformation along ND. These concepts are confirmed by the evolution of the strain hardening exponent and the stress levels with plastic deformation. In fact, the initial stresses are similar to those corresponding to uniaxial tensile tests and the strain hardening exponent presents a high value ($n=0.391$ for $\epsilon<0.05$) which shows the increasing difficulty to accomodate plastic deformations. When pyramidal slip becomes the main mechanism

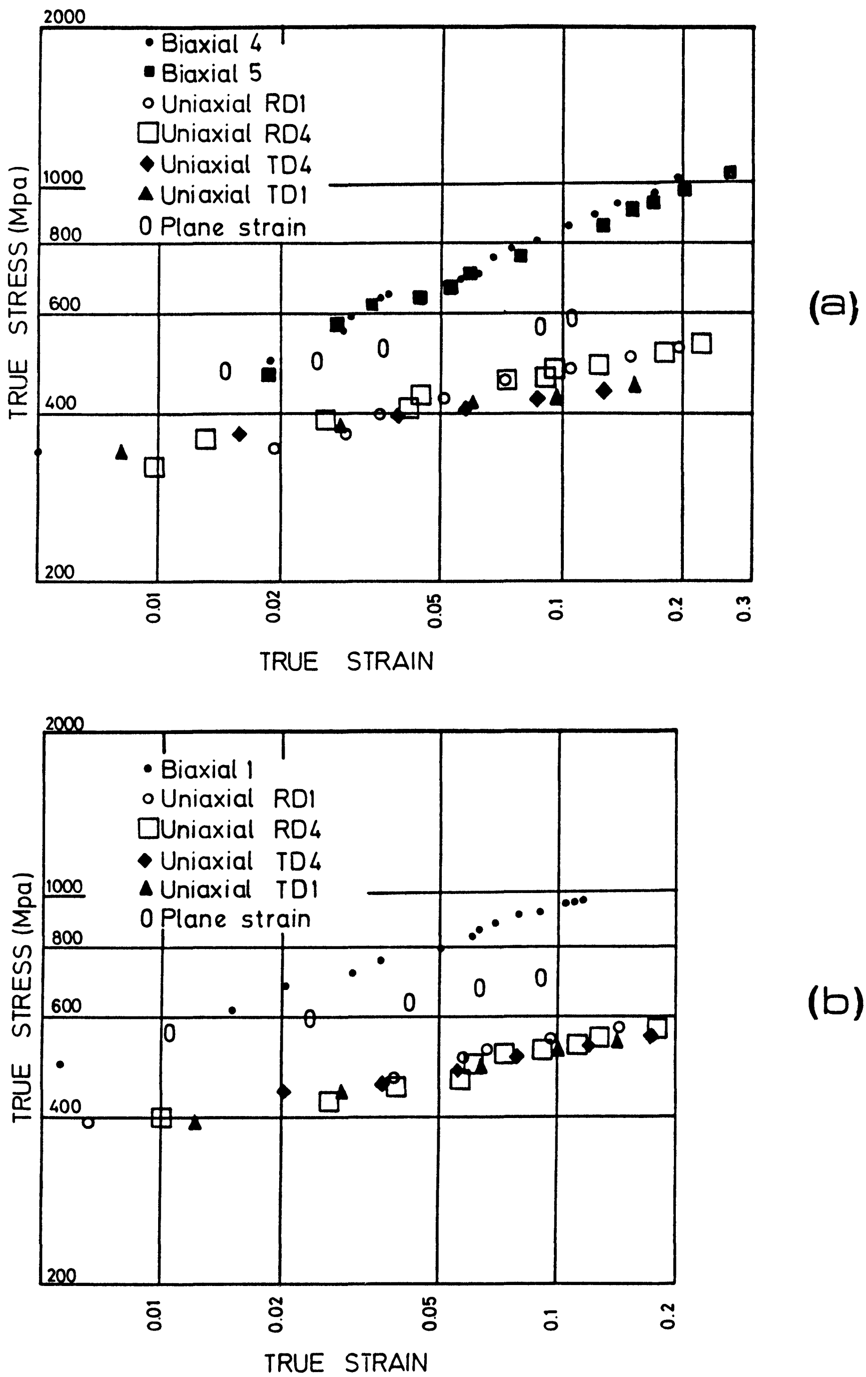

Figure 2: True stress-true strain curves for (a) Zry-4 PO and (b) Zry-4 PC samples.

of deformation, the stress and the strain hardening exponent reach values similar to those observed in the PC material (n=0.236 for ϵ>0.05 in table 2).

Tensile tests with the Wagoner's type specimens give approximate plane strain conditions in bcc and fcc materials[8]. However, in Zry 4 samples the plane strain condition was not reached. Table 3 shows important q values very different from q=0 for both materials. These results are consistent with the high strength of the through-thickness direction of the studied materials. This fact is consistent with the high measured values of the Lankford coefficient (R > 2 in all Zry-4 samples), which is directly related to the difficulty presented by Zry-4 samples to accommodate deformation along the c axis of the hcp crystal and to the crystallographic texture[1]. Similarity of n values for Wagoner tests and uniaxial tension tests along TD indicate that the same deformation nechanisms are acting in both deformation paths.

Independently of the Oxygen effect on twins activity, which can affect the mechanical behaviour at low deformations, it can be concluded that the plastic constitutive equation for the studied Zry-4 is controlled principally by pyramidal slip in biaxial expansion tests and by prismatic slip (PO-PC) and twinning (PO) during uniaxial tensile tests.

AKNOWLEDGEMENTS: This work was partially supported by a grant under the agreement Conicet (Argentina)-Conicyt (Chile) and by the PMM (American States Organization).

REFERENCES

1. A.A. Pochettino, P. Vedoya and R. Penelle, *Constitutive Equations and their Physical Basis* (RISO Nat. Lab.,1987), p.485.
2. C. Tomé, A.A. Pochettino and R. Penelle, *ICOTOM 8* (The Metall. Soc., 1988), p.985.
3. P. Vedoya, A.A. Pochettino and R. Penelle, *Textures and Microstructures*, 8-9, 601 (1988).
4. R.H. Wagoner. *Metall. Trans.*, A 11, 165 (1980).
5. C. Vial, *Int. Journal of Mech. Sciences*, 30, 137 (1988).
6. M.J. Phillipe, F. Wagner and C. Esling, *Icotom 8* (The Metall. Soc., 1988), p.837.
7. A.A. Pochettino, N. Gannio and R. Penelle, to be published.
8. C. Vial, N. Weinstein and J. Laso, *Revista Asoc. Española de Ing. Mecánica*, 2, 341 (1984).