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Shear Fracture in Zirconium and Its Alloys

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SHEAR FRACTURE IN ZIRCONIUM AND ITS ALLOYS

Introduction

Fracture by localization of flow into shear bands is common and practically important. A background for understanding how this happens, and how it relates specifically to zirconium and its alloys, was given in the Report of last year.

The general view is that distributed flow becomes localized when conditions are satisfied that embody chiefly plastic properties. In principle, continued flow in such a collapsed volume could lead to a sliding apart, which is one kind of fracture. It is probably more usual, however, for ductility to enter now, and when that is exceeded the plastically unstable flow ends in fracture.

Flow confined to bands means, implicitly, shear or plane-strain deformation. Therefore, in an experimental study it is a good plan to feature such deformation, as this has been in the work now going on. Basic flow properties, and especially their temperature dependence, are no less important, and these are established by more conventional tension testing; it is remarkable that practically no data of the kind needed for treating this problem are in the literature.

Tensile Deformation

Sheet specimens of Zircaloy-4 with a width no more than four times the thickness, were pulled at $\sim 100^\circ\text{C}$ intervals from 25°C to 800°C ; at and above

200°C, tests were done in a helium atmosphere. Many results are summarized in Fig. 1. The yield stress, σ_Y , is for 0.2% "offset" strain; as a measure of its temperature dependence, $d\sigma_Y/dT$ is also plotted. The fracture strain, ϵ_f , is $\ln (A_0/A_f)$, with A_0 and A_f initial and final cross-sectional areas, respectively. On logarithmic coordinates, true-stress/strain plots were essentially linear, and the slope, $n = d \log \sigma / d \log \epsilon$, is a measure of over-all strain-hardening rate; it showed practically no strain-rate dependence. The measure of strain-rate hardening capacity is $m = d \log \sigma / d \log \dot{\epsilon}$ and comes from tests at different strain rates for fixed temperature; this was independent of strain.

A general pattern shows up in the results. At lower temperatures, certain indices favor plastic instability after small strains, e.g. large $d\sigma_Y/dT$ and small m coupled with only limited n . At the same time, ϵ_f is so small that fracture ought to follow any tendency towards flow localization. At higher temperatures, however, more resistance to both developments might be expected, especially because of rising m and rapidly increasing ϵ_f ; the "transition" temperature here is in the neighborhood of 400°C.

Plane-strain Deformation

The compression of strips has continued to be the means for imposing such deformation. It is a realistic prototype of the operations and applications in which shear cracking is a problem. Also, it is an

excellent means for forcing flow into shear bands, for these are geometrically necessary when only part of the total volume deforms in plane strain.

Tests have again been made in 100°C intervals, to 800°C with Mo S₂ as an extremely effective lubricant over the whole temperature range. The friction-hill pressure correction was < 10%.

To date, three kinds of observations have been made: macroscopic and conventional metallographic cracking patterns, stress-strain relationships, and fractographic detail from scanning electron microscopy.

The cracking observations are summarized in the upper part of Fig. 1, and are in general agreement with the flow and fracture data given there. Above 400°C, there was no cracking up to the heaviest reduction of ~ 50%, although shear zones were apparent. At lower temperatures, however, and depending upon reduction, cracks did appear at the edges of the strip. At still lower temperatures and heavier reductions, there was extensive fracture with an abrupt load drop.

Systematic measurements of local-shear strains have not yet been made. In cold-rolled zirconium, however, after heavy plane-strain compression at room temperature, it was metallographically apparent that grains traversed by the shear band were displaced a distance of about 6 times the band width, for a shear strain of ~ 6, under an imposed strain of ~ 2.

An edge-cracking analysis is available for strip rolling and has been applied with some success to a number of materials.* Basically, it relates

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* M.G. Cockcroft, in Ductility, ASM, p. 199, 1968.

crack initiation at the edges to the fact that hydrostatic compression is necessarily lost there. The reduction for cracking is fairly successfully related to ϵ_f (in Fig. 1). In Zircaloy-4, however, cracking appears to occur at lower reductions than those predicted from tensile ductility. This indicates again that flow can become unstable, concentrate into shear bands and lead to fracture at lowered apparent strains.

Scanning electron microscopy has been used to examine both shear-fracture surfaces and the prepolished edges of strained and broken specimens. At room temperature, there were two principal details in shear-fracture surfaces: flat and relatively featureless areas plus other areas covered by elongated dimples. The latter, covering about 30% of the total area, is typical of ductile-shear fracture; the former is somewhat puzzling but may prove to be nothing more than the effect of rubbing across the fracture surface. The rubbing complication was particularly severe at 100°C and 200°C. Microscopy on as-deformed surfaces at the edges of the specimens clearly revealed the transgranular nature of cracking. There was some indication of cracking along crystallographic features, but because of the fine grain size (25 to 30 μ) and heavy deformation in the shear bands it was difficult to distinguish between slip-lines and fine twins and between twin boundaries and grain boundaries.

Fig. 1. Mechanical Properties of Zr - 4