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Chapter 5—Summary

The deformation systems in hexagonal close-packed (hcp) metals are not as numerous and not as symmetrically distributed as in cubic ones. Thus in plastic deformation, twinning competes with slip and may, depending on the deformation conditions, play an essential role. In addition to its effect on the transformation behavior and the corresponding stacking fault energy, the *c/a* axial ratio of the hcp structure also determines which deformation mechanisms are activated. This axial ratio varies from one metal to the other and can reach values both larger and smaller than those for ideal sphere packing. This trait prevents the deformation behavior of hcp metals from being considered en bloc, in contrast to fcc and bcc metals. In order to explain the conditions in zirconium, the well-established relationships of hcp metals are given, and their dependences on the metal-specific parameters of the hexagonal structure are discussed. The interactions between deformation mechanisms and texture formation on the one side and deformation mechanisms and mechanical anisotropy on the other can be likewise transferred to other hcp metals, if one takes into account the differences in dependence of the metal-specific parameters.

In the α structure of zirconium, slip is activated on prism planes in the *a* direction within the temperature range up to 500°C. In the same direction at elevated temperatures also basal slip and in regions of stress concentration slip on $\{10\bar{1}1\}$ planes have been observed at elevated temperatures. Furthermore, pyramidal slip in a $(c + a)$ direction has been observed under restraint conditions and at elevated deformation temperatures. Apart from the pyramidal slip system deformations with a *c* component are normally explained by twinning. Under tensile stresses in a *c* direction, primarily $\{10\bar{1}2\}$ twins and sometimes $\{11\bar{2}1\}$ twins are activated. Under compressive loading in a *c* direction, $\{11\bar{2}2\}$ twinning and $\{10\bar{1}1\}$ twinning at elevated temperatures are observed. In some cases, the less well-defined $\{11\bar{2}3\}$ twinning mode has been also reported.

The effects influencing the deformation mechanisms are discussed generally for hcp metals and particularly for zirconium and Zircaloy. For single crystals under uniaxial loadings, the Schmid factor, the critical resolved shear stress, and the direction of deformation are decisive for the activation of the deformation systems. In addition, for polycrystals under multiaxial loadings, the accommodation conditions and the influence of the texture must be taken into account.

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The low offer of slip systems, with their asymmetrical distribution as well as the strict crystallographic orientation twinning relationships, cause in hcp metals the formation of a strong deformation texture. This is, however, characteristically conditioned by the metal-specific parameters of the hexagonal structure. In zirconium and Zircaloy, the development of a marked deformation texture is caused by the complicated interaction between slip and twinning. By virtue of twinning, even small deformation rates lead to large lattice rotations, which change the orientation of the crystallites where all basal poles align in the direction of the compressive force. The fact that the preferred orientation, which is spread in the transverse direction in zirconium and Zircaloy, is also retained as the final stable position at elevated temperatures is explained by $(c + a)$ pyramidal slip. The decisive factor in texture development is the material flow, whose degree of freedom is low for seamless tube reduction, whereby it determines the reduction in cross-section, wall thickness R_W, and diameter R_D. This permits more precise prediction of the operative forces and the resulting deformation mechanisms.

The experiences gained with tubing can be transferred to sheet rolling and wire drawing. The decisive factor for the development of tube textures is the relative ratio of wall thickness-to-diameter reduction, R_W/R_D. For $R_W/R_D > 1$, the basal poles are preferentially aligned in the radial direction. For $R_W/R_D = 1$, the basal poles are randomly distributed in the radial-tangential plane. For $R_W/R_D < 1$, the basal poles are preferentially aligned in the tangential direction.

The sheet texture is identical to the tube texture for $R_W/R_D > 1$. In both examples, the material flow is characterized by a preponderance of wall thickness reduction.

The fiber texture of wires is identical to the texture of tubes for $R_W/R_D = 1$. One can visualize the wire deformation as corresponding to that of concentric tubes with different diameters to comply with tube reduction rates $R_W/R_D = 1$ under the condition of constant volume. Independent of the fabrication method for the cold-worked semifinished products just mentioned, a $[10\bar{1}0]$ direction always aligns itself parallel to the direction of elongation. When the dependence of the texture development on the reduction parameters is known, it is possible to tailor the texture of Zircaloy tubing in the context of the described extreme alignments, so they can be optimally matched to the requirements.

On the other hand, the deformation mechanisms also account for the pronounced mechanical anisotropy of a textured material. This is discussed using the example of a sheet and a tube of textured Zircaloy under uniaxial loading. The agreement between theoretical prediction and actual experimental behavior also applies to much more complicated loading conditions. For biaxial loading conditions, the anisotropic behavior is normally illustrated by yield loci, creep loci, or burst loci according to the criterion employed, that is yield stress, creep rate, or fracture stress, respectively. Depending on the texture and the loading conditions, an attempt is made to correlate the shape of the loci to the operative deformation mechanism. In this way, it is possible, for instance, to find selection criteria for the desirable texture in Zircaloy cladding tubes.

For an exact estimation, the complex, load-dependent conditions during operation, together with the variously activated long-time or short-time (creep) deformation mechanisms (with or without irradiation), must also be taken into account.