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A PRELIMINARY EXAMINATION OF THE FORMATION AND UTILIZATION OF TEXTURE AND ANISOTROPY IN ZIRCALOY-2

M. L. Picklesimer

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ABSTRACT

The anisotropy of mechanical properties in Zircaloy-2 due to preferred orientation developed during manufacture has caused many difficulties in the fabrication and utilization of mill products. While many have become more aware of the problems and the promises of anisotropy in manufacturing and engineering applications, little effort has been spent in examination, analysis, or control of the development of preferred orientation in Zircaloy-2. The promise of an appreciable increase in permissible design stresses in structures made of this material requires that a thorough study be made of the problem. This paper presents a preliminary examination of the development and utilization of texture preparatory to an experimental study of anisotropy in Zircaloy-2 tubing.

The development of preferred orientation during manufacture of Zircaloy-2 plate, strip, and tubing is qualitatively analyzed in terms of the plastic strain undergone, the modes of deformation operative, the existing anisotropy of flow strengths, and the effects of forming forces of the rolls or dies. The problem of forming structural shapes from anisotropic mill products is discussed and the utilization of the anisotropy of mechanical properties to ease manufacture and to strengthen structures is considered.

INTRODUCTION

The importance of the anisotropy of mechanical properties of sheet metal during forming of structural shapes has been recognized as a major problem for many years. By empirical methods and research on preferred orientation, the more immediate problems in the control of texture in cubic metals during fabrication have been solved. In some cases, preferred orientation has been sought deliberately to take advantage of the anisotropy of some property, such as the high magnetic permeability of the silicon-iron transformer sheet when the $\langle 001 \rangle$ direction is oriented in the rolling direction. Similar, but frequently much more severe, problems are encountered in all phases of the manufacture and utilization of products of the close-packed-hexagonal metals such as beryllium, magnesium, titanium, and zirconium. This has not been adequately realized. Indeed, it has not been recognized that the mildest anisotropy of mechanical properties obtainable in these materials is much more severe than the maximum anisotropy that can be produced in cubic metals. Further, few designers have been aware that the very great anisotropy of yield strengths present in these materials when highly textured can either seriously limit their use or can be of considerable advantage in strengthening parts and structures.

It is the purpose of this paper to qualitatively analyze the effects of anisotropy of mechanical properties of Zircaloy-2 upon the fabrication of plate, sheet, and tubing, and upon the forming of parts and structural shapes from them. Several advantageous applications of anisotropy will be presented and discussed. Finally, the approach of a current research program to the analysis, prediction, production, control of texture, and influence of texture on the strain behavior in Zircaloy-2 tubing will be presented.

The Anisotropy of Mechanical Properties in Plate and Sheet

In a recent study[1] of the effect of fabrication variables on the preferred orientation and anisotropy of mechanical properties in Zircaloy-2 plate it was found that the yield strengths varied, in highly textured polycrystalline material, from a minimum of 52,000 psi to a maximum of 71,000 psi in tension and from 63,000 to 122,000 psi in compression, as shown in Table 1. Further, it was found that the yield strength was 70,000 psi in tension and 101,300 psi in compression for the transverse direction specimens of one lot of material (sched J in Table 1). The proportional limits were found to vary correspondingly. The tensile and compressive stress-strain curves for two of the twenty materials studied are presented in Fig. 1. Also presented are polar plots of the variation of mechanical properties with specimen orientation in the plane of the sheet for these two materials. Such anisotropy of mechanical properties must be considered in the fabrication of mill products, in the forming of shapes, and in the design of structures.

This study has shown that the textures and resulting anisotropy can be modified by control of the fabrication variables, and especially by intermediate beta heat treatments. It has also shown that the three-dimensional anisotropy in plate material may be determined from an analysis of two fractured round tensile specimens. (This measurement allows the purchaser to set specifications of anisotropy and gives the manufacturer a method of quality control.) The change in shape from the original round cross section to a very elliptical one at the fracture is shown in Fig. 2 for a typical longitudinal tensile specimen cut from sched-8 material of Table 1. Both polished ends at the fracture are shown with one rotated 90° relative to the other to show that the ellipticity is not photographic distortion. Wherever plastic flow had

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[1] P. L. Rittenhouse and M. L. Picklesimer, Metallurgy of Zircaloy-2 Part I. The Effects of Fabrication Variables on the Anisotropy of Mechanical Properties, ORNL-2944 (Oct. 13, 1960); Metallurgy of Zircaloy-2 Part II. The Effects of Fabrication Variables on the Preferred Orientation and Anisotropy of Strain Behavior, ORNL-2948 (Jan. 11, 1961).

Table 1. Anisotropy of Mechanical Properties in Two Lots of Zircaloy-2 Plate

Schedule[a]	Specimen Orientation[b]	0.2% Yield Strength Compression 10^3 psi[c]	0.2% Yield Strength Tension 10^3 psi[d]	Ultimate Strength Tension 10^3 psi	Elongation % in 1 in.	R.A.[e]	Strain Ratio[f]
8	RD	66.7	54.9	67.8	24.2	46.8	0.13
	22 1/2 deg		53.7	66.5	22.5	51.1	0.13
	45 deg		56.2	66.6	25.0	48.8	0.13
	67 1/2 deg		55.8	65.3	25.0	50.1	0.13
	TD	62.7	58.3	68.0	19.5	43.6	0.13
	ND	122.0					
J	RD	65.6	52.0	74.9	22.0	33.6	2.29
	22 1/2 deg		63.2	75.8	18.5	36.2	0.55
	45 deg		66.1	74.3	18.0	41.5	0.81
	67 1/2 deg		71.0	76.6	18.7	44.0	0.59
	TD	101.3	70.0	78.1	21.5	44.8	0.67
	ND	72.5					

[a]Schedule 8 — alpha worked (1475 to 1000°F) from forged plate; Schedule J — rolled from 1850°F, 12-in.-diam ingot to 3/4-in. plate with reheat, rolled to 7/16 in. from 1450°F, heated to 1832°F 30 min, water spray quenched, rolled to 5/16 in. at 1000°F, ingot axis in transverse direction. Both materials annealed 30 min at 1450°F.

[b]Angle of specimen axis relative to rolling direction. RD = rolling direction; TD = transverse direction; ND = normal direction.

[c]Compression test specimen — 0.160-in. diam × 0.160 in. long. S. H. Bush, Compression Testing of Zircaloy-2, HAPD, personal communication (1961).

[d]Tensile test specimen — 0.125-in. diam × 1-in. gage section, duplicate specimens.

[e]R. A. = reduction of area calculated from area of fracture ellipse.

[f]Ratio of natural contractile strain in normal direction to the natural contractile strain in the plane of the plate. For truly isotropic material, the strain ratio = 1.0 for all specimen orientations.

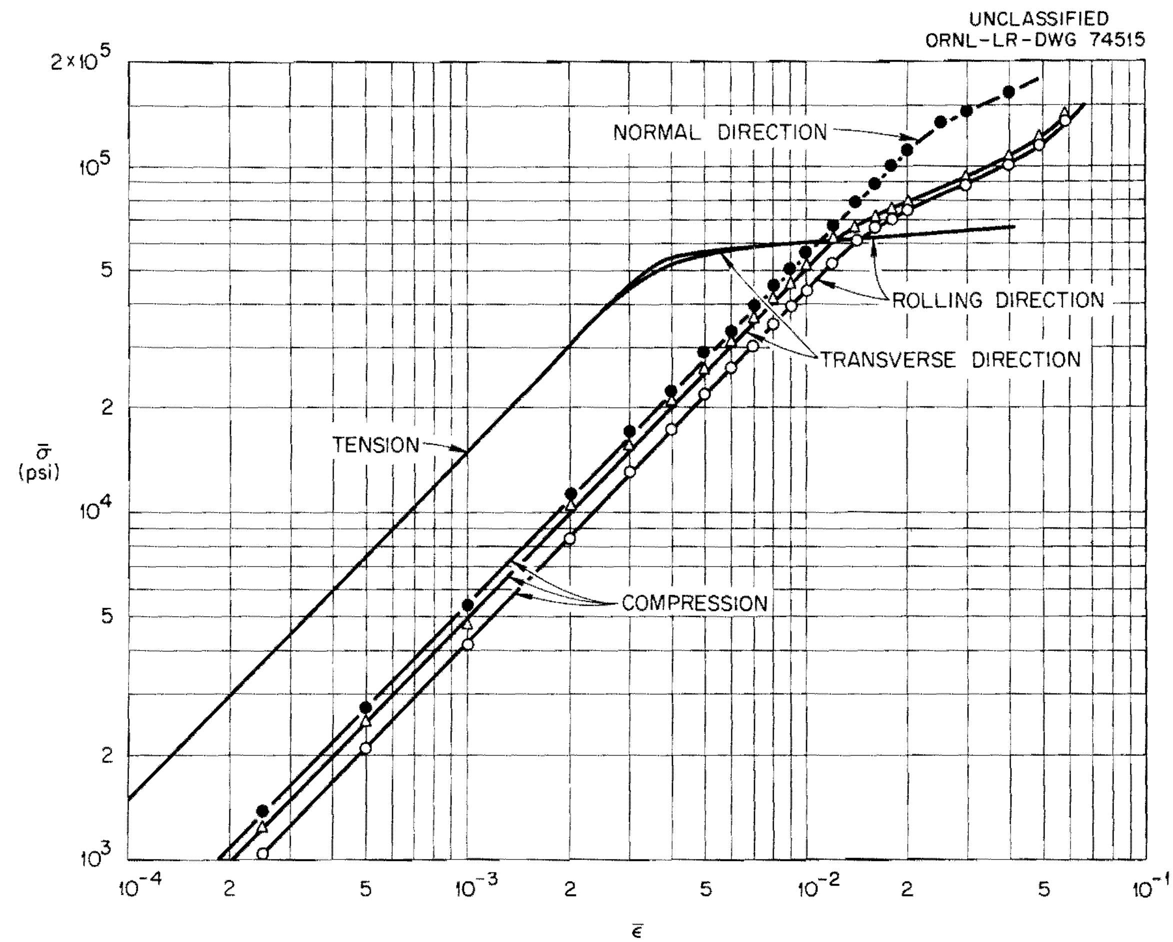

Fig. 1a. Tensile and Compressive True Stress-True Strain Curves for Sched-8 Zircaloy-2.

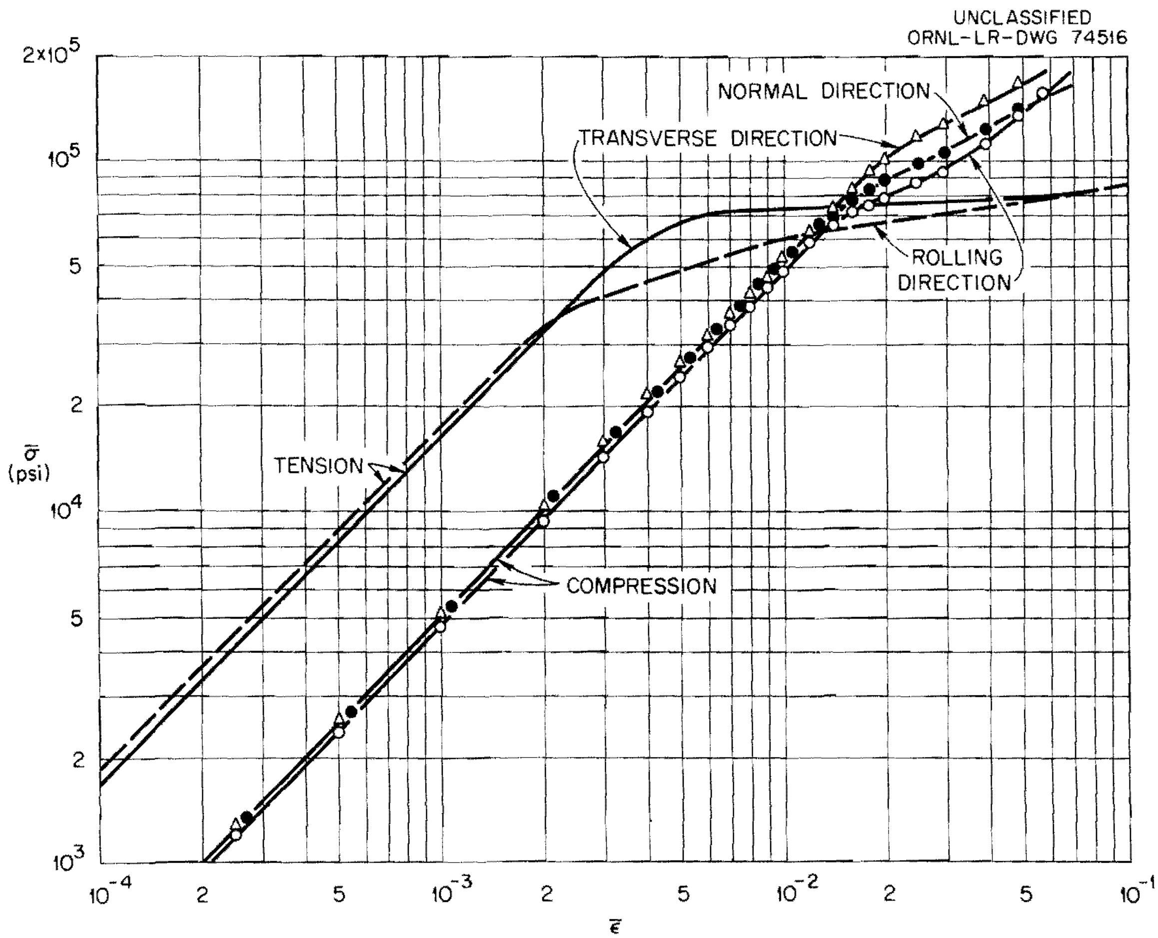

Fig. 1b. Tensile and Compressive True Stress-True Strain Curves for Sched-J Zircaloy-2.

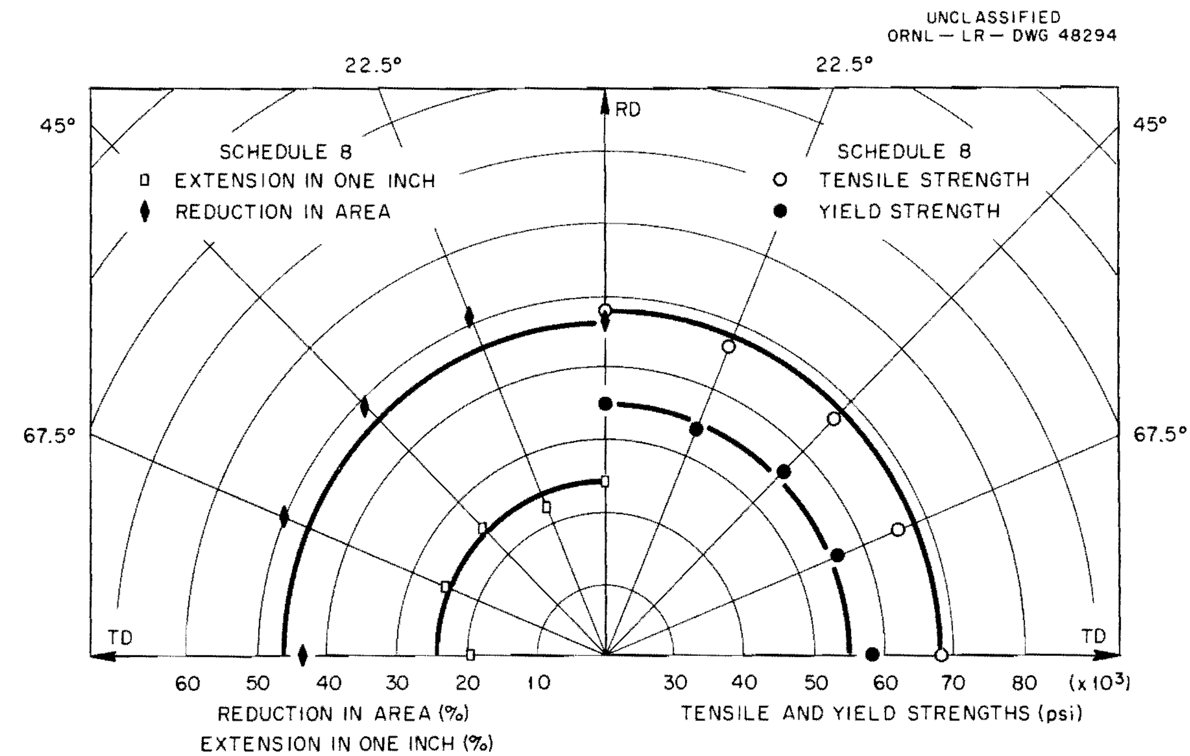

Fig. 1c. Tensile Properties of Sched-8 Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate.

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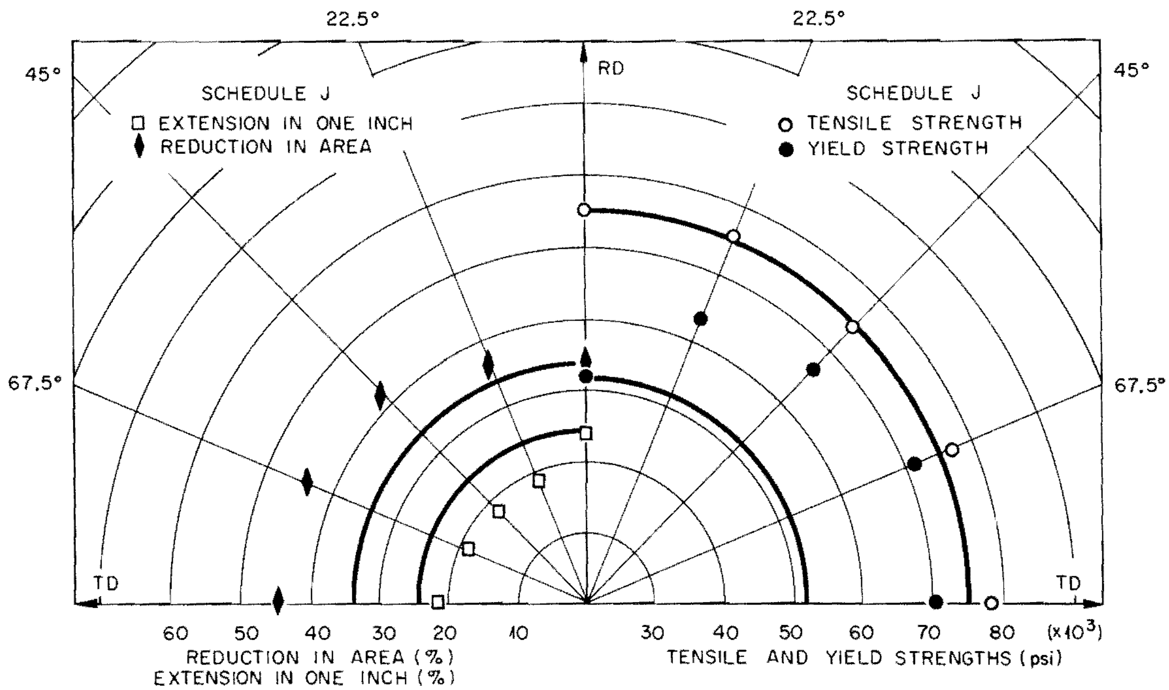

Fig. 1d. Tensile Properties of Sched-J Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate.

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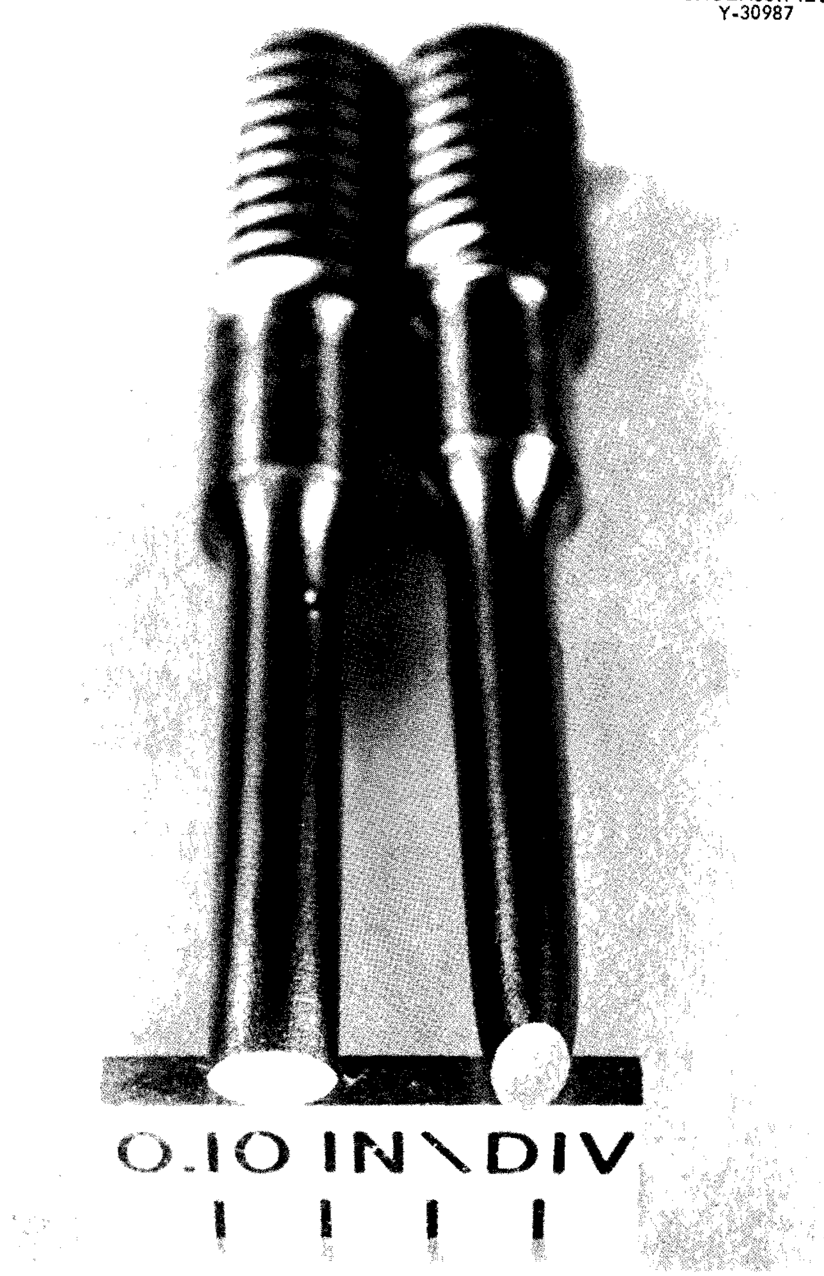

Fig. 2. Photograph of the Ellipticity of Cross Section Developed in Sched-8 Zircaloy-2 Round Tensile Specimen. One end is rotated 90° to show that the ellipticity is not photographic distortion.

occurred in this specimen, the shape had changed from round to elliptical. The ratio of plastic strain in the cross section was 0.13 for the normal-to-transverse directions for all values of axial plastic strain. The compression yield strengths for these two directions (Table 1) were 62,700 and 122,000 psi, respectively, while the tensile yield strength in the rolling direction was 54,900 psi. Most of the sheet and strip Zircaloy-2 produced today have essentially these properties. It is hardly surprising that many problems arise in the fabrication of mill products and in the forming of shapes from them. Changing the working temperature will not help appreciably (except to increase the ductility) since, from tensile test data,[1,2] it has been shown that the strain anisotropy is essentially constant from −190 to 540°C for a given lot of Zircaloy-2.

Deformation Systems in Zircaloy-2

The deformation systems operating in Zircaloy-2 have not been reported but have generally been assumed to be those reported for zirconium[3,4] (see Fig. 3). No evidence to the contrary has been reported and experiments by Reed-Hill[5] have tentatively confirmed them to be the same. These systems are $(10\bar{1}0)[\bar{1}2\bar{1}0]$ slip, $\{10\bar{1}2\}$ and $\{11\bar{2}1\}$ twinning in tension along the basal pole, and $\{11\bar{2}2\}$ twinning in compression along the basal pole. The $\{11\bar{2}3\}$ twinning mode for tension along the basal pole has been reported[4] also but the data are neither conclusive nor complete. It is possible that other twin systems may operate when there is sufficient restraint in one of the principal stress directions.

An examination of these deformation systems shows that, in simple tension along the basal pole, the first plastic flow occurs by $\{10\bar{1}2\}$

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[2]R. E. Reed-Hill, "An Evaluation of the Role of Deformation Twinning in the Plastic Deformation of Zirconium," Monthly Progress Letter for July, 1962, Contract AT(38-1)-252, Metallurgical Research Laboratory, University of Florida to USAEC, Savannah River Operations Office.

[3]E. J. Rapperport, Room Temperature Deformation Process in Zirconium, NMI-1199 (Feb., 1958).

[4]E. J. Rapperport and C. S. Hartley, Deformation Modes of Zirconium at 77°K, 300°K, 575°K, and 1075°K, NMI-1221 (Aug., 1959).

[5]R. E. Reed-Hill, "An Evaluation of the Role of Deformation Twinning in the Plastic Deformation of Zirconium," Second Quarterly Progress Report, Jan., 1962; Third Quarterly Progress Report, April, 1962; Fourth Quarterly Progress Report, July, 1962; Contract AT(38-1)-252, Metallurgical Research Laboratory, University of Florida to USAEC, Savannah River Operations Office.

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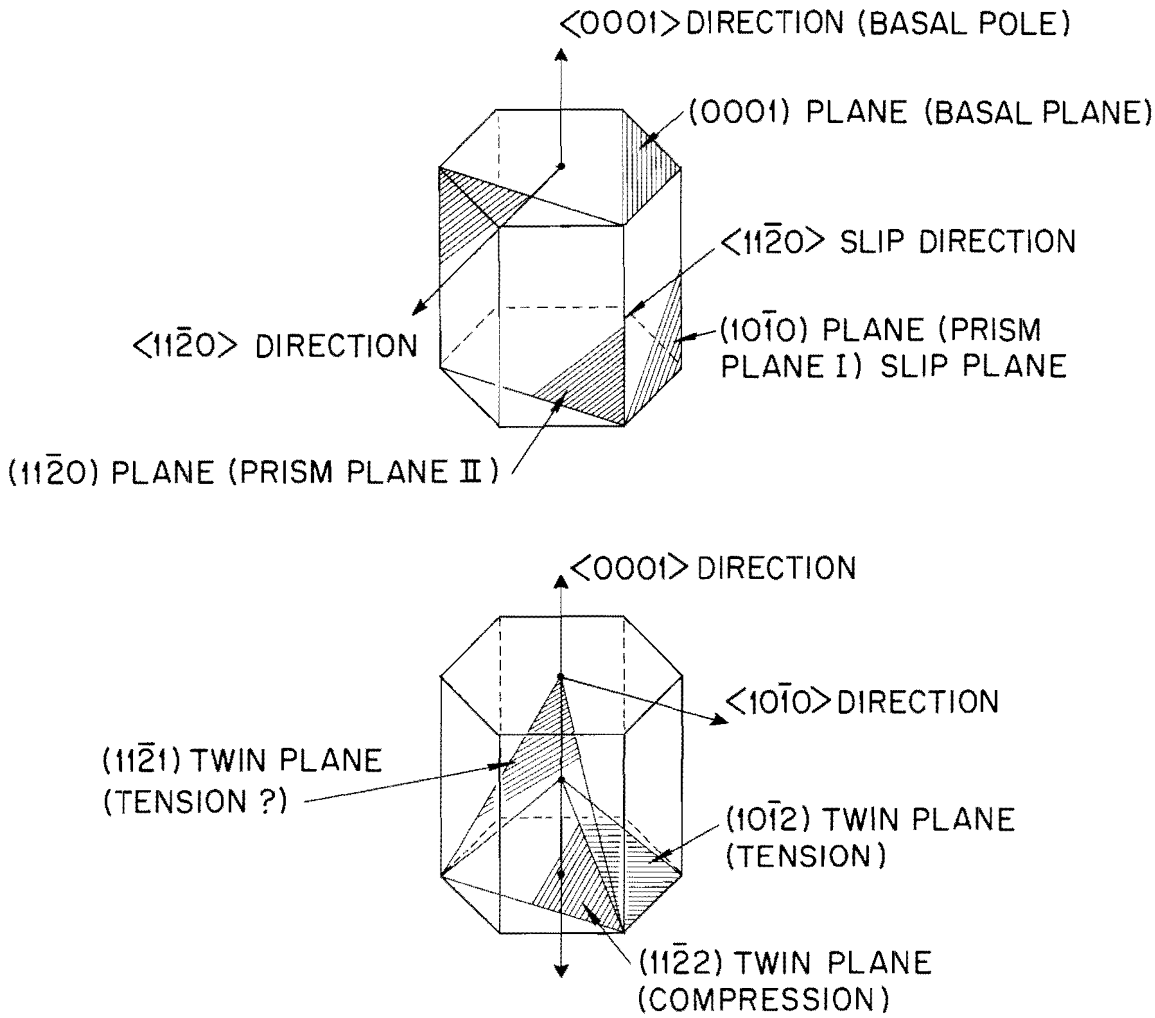

Fig. 3. The Orientation of a Number of Crystallographic Planes with Respect to the Close-Packed-Hexagonal Unit Cell.

twinning. The twinned material is then so oriented relative to the stress axis that it can flow readily by slip. Work-hardening apparently occurs rapidly enough to prevent confinement of the strain to the twinned material, forcing more material to twin. When there is compression along the basal pole, all of the deformation takes place by twinning, through a complicated sequence involving $\{11\bar{2}2\}$, $\{10\bar{1}2\}$, and $\{11\bar{2}1\}$ twinning, until a stable texture is reached. In this stable texture (stable to continued flow in the original compression direction), the basal poles are concentrated in a $\pm 40°$ spread about the compression axis. Once this texture is established, all further deformation takes place by $\{11\bar{2}2\}$ and $\{11\bar{2}1\}$ twinning. While the $\{11\bar{2}1\}$ twin system operates for tension along the basal pole, it can produce thinning of the specimen whenever the basal pole of the particular grain or segment being considered is more than about 18° away from the compression axis. The exact sequence of twinning operations required to produce and keep the stable texture has not yet been worked out. Such a sequence must exist since experiment demonstrates that the final texture is stable to continued deformation. Little, if any, of the required deformation can have occurred by slip (after the stable texture is reached) because none of the twinning modes that can produce the required strains simultaneously orients both the slip plane normal and the slip direction in the plane of strain. If the plastic flow is confined to plane strain and the basal pole is oriented in the direction of the normal to the plane of strain, all of the deformation will take place by slip.

Textures Produced by Fabrication

Conventional mill practice in the production of plate, sheet, and strip Zircaloy-2 involves major reductions at temperatures where the alpha phase is stable. Intermediate and final annealing is usually performed in the range of 1200 to 1550°F, depending on the grain size desired. The material may or may not be given a finishing cold reduction of 10 to 15%. The worked texture produced[1] is that of $[10\bar{1}0] \parallel$ RD, $[11\bar{2}0] \parallel$ TD, and $[0001] \parallel$ ND or within a 30 to 40° transverse spread about the normal direction. The intensity of the texture in the rolling and transverse directions is moderately strong; that about the normal direction is quite strong. Alpha annealing sharpens the texture and rotates it approximately 30° about the basal pole, usually putting $[11\bar{2}0] \parallel$ RD and $[10\bar{1}0] \parallel$ TD.

The textures found in tubing vary considerably, seemingly according to the exact details of the sequence of fabrication steps and the fabrication methods. They do have one common feature, a complete absence of basal poles in the axial or longitudinal direction. In various lots of tubing,[6–9] the basal pole concentrations have been found to be (1) in the radial direction, (2) in the tangential direction, (3) at 30 to 40° to the radial direction, (4) in both the radial and tangential directions, and (5) randomly distributed between the radial and tangential directions. The methods of manufacture have been (1) drawing with plug or mandrel, (2) tube sinking, (3) swaging, and (4) tube reducing. All the manufacturers started with extruded tubes, but the extrusion ratio varied. The texture found in extruded tubing is apparently influenced by the extrusion ratio in a manner which cannot yet be understood, in part, because the processing variables have not been reported in sufficient detail. The texture of the finished product has been reported for tubing made by the several processes, but the manufacturing steps have not been given in sufficient detail to permit an analytical examination or correlation. Such an examination requires knowledge of die angles, amount of sinking before plug or mandrel is encountered, whether the drawing operation is performed with plug or mandrel or with neither, reductions at each operation, lubrication conditions, etc. Without such data, it appears impossible to analyze the development of the textures reported in the literature.

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[6]R. H. Tuxworth, A Study of Preferred Orientation in Extruded Zircaloy-2 Pressure Tubes, CRMet-901, AECL-1174 (Nov., 1960).

[7]V. Nerses, Texture of Extruded Zirconium and Zircaloy-2 Tubing, NMI-1222 (July, 1960).

[8]J. J. Laidler, Preferred Orientations in Extruded Zircaloy-2 Tubing, HW-64815 (April, 1960).

[9]E. F. Sturcken and W. G. Duke, Measurement of Preferred Orientation of Thin-Walled Zircaloy-2 Tubes, DP-607 (Nov., 1961).

The formation of texture during mill fabrication can be interpreted, in a simple manner, by examining the changes in texture accompanying plastic flow in a sheet-tensile specimen. Three situations are diagrammed in Fig. 4. The texture of the material represented in Fig. 4a is typical of that produced by conventional rolling mill practice, a strong texture consisting of basal poles ($< 0001 >$ directions in the hexagonal cell) normal to the rolling plane. In the necked region of the sheet specimen, it is found that the thickness of the specimen has decreased very little but that the width of the specimen has decreased quite appreciably. In this region the basal poles are still in the original alignment but the "cell" may have been rotated to put a different prism direction in the direction of plastic flow. The strains that have occurred are tensile along the axis of the specimen, compressive in the width direction, and essentially zero in the thickness direction. The specimen will fail by narrowing in the width direction even for a specimen having a width-to-thickness ratio of 8 to 1. By contrast, a sheet-type specimen made of an isotropic material will fail by localized thinning along two lines approximately 55° to the stress axis.[10] The behavior of these Zircaloy-2 specimens can be partially understood by an examination of the yield strengths in compression presented in Table 1, noting that the sched-8 material has the texture under consideration. The compressive yield strength in the normal (thickness) direction (122,000) is twice that in the transverse (width) direction (62,700 psi). The compressive stress-strain curves presented in Fig. 1a show that the work-hardening produced by the strain in the width direction will never cause the flow strength to increase to the point that appreciable flow will occur in the thickness direction. The plastic flow occurs entirely by slip. Flow in the thickness direction would have to occur by $\{11\bar{2}2\}$ twinning requiring (from the compressive yield data) nearly twice the stress as flow in the width direction. If one interprets the tensile properties (Fig. 1c) conventionally, this material would be called

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[10] A. Nadai, Theory of Flow and Fracture of Solids, pp 316–27, vol I, 2d ed., McGraw-Hill Book Company, Inc., New York, 1950.

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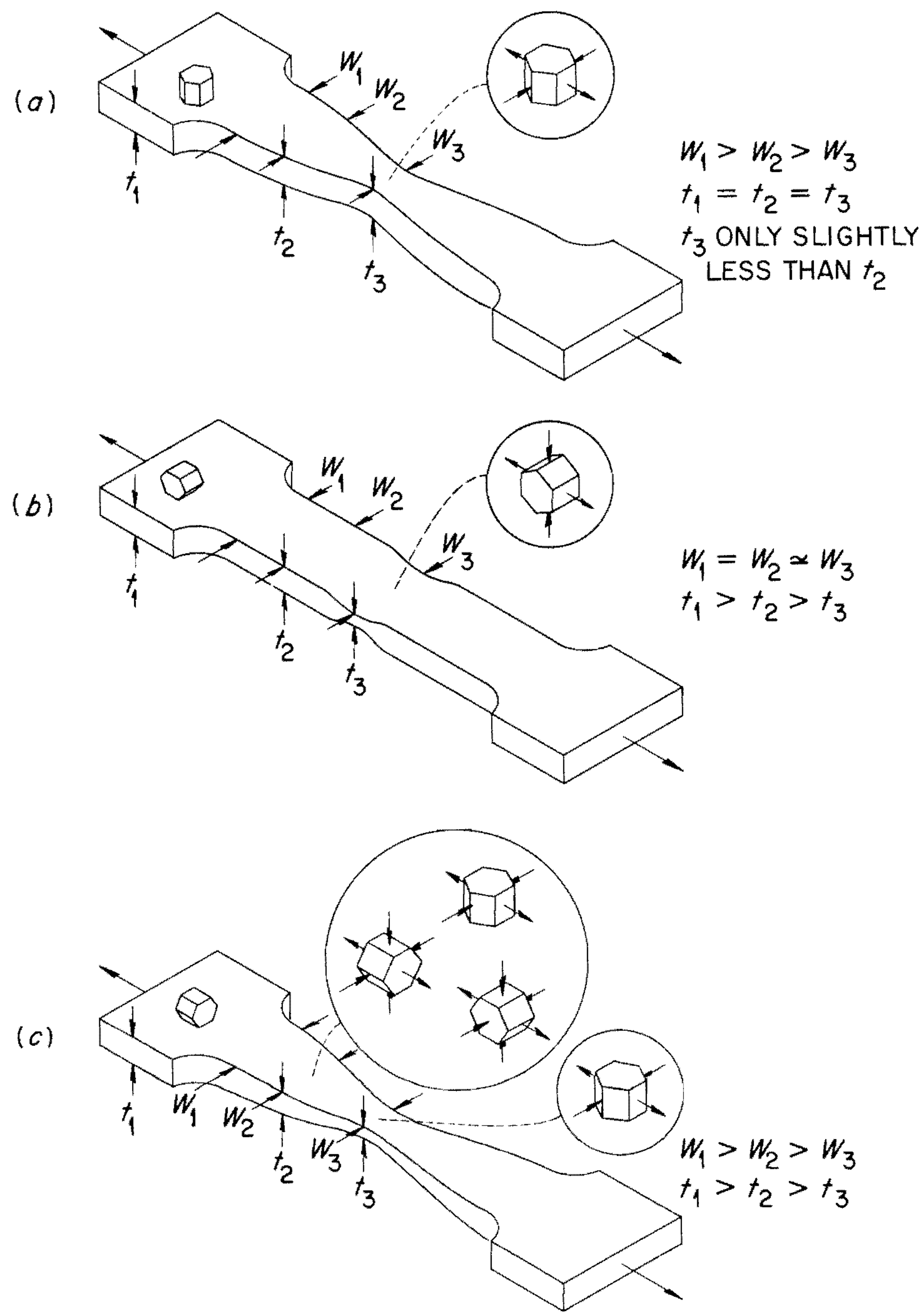

Fig. 4. Texture Cells and Strain Patterns in Sheet Tensile Specimens of Zircaloy-2.

"isotropic" since the mechanical properties in all directions in the plane of the sheet are essentially the same. Yet, few modern structural materials can be more truly anisotropic. This anisotropy can, however, be quite useful in many applications if it is considered as part of the design problem.

Figures 4b and 4c represent the textures encountered in longitudinal and transverse direction tensile specimens for the sched-J material of Table 1. The longitudinal direction specimen will fail by thinning in the thickness direction and will have a large value of "uniform elongation"; but the fracture will be perpendicular to the tensile stress axis, rather than at 55° to it as for an isotropic material. The texture will not change during straining. The transverse direction specimen (Fig. 4c) will fail much like the specimen of Fig. 4a; but, prior to fracture, it will experience appreciable flow in the thickness direction. In this case, the basal pole is parallel to the direction of tensile strain with the result that the strain can occur only by $\{10\bar{1}2\}$ twinning. The twinned material becomes favorably oriented for slip to occur and the specimen lengthens along the tensile axis and thins in the thickness and width directions. It is probable that some of the twinned material will have basal poles aligned in the width direction as well as in the thickness direction. Either alignment will produce the required strains and both of the resulting orientations are stable under further straining. It is difficult to say what the texture in the fracture area will be, since highly localized heterogeneous strain can occur in this region.

Thus, the initial texture will be:

1. Stable if there is compression along the basal pole.

2. Stable if there is a state of plane strain such that the strain can be accomplished by slip and the basal pole is normal to the plane of strain.

3. Unstable if the strain is produced by tension along the basal pole, in which case twinning and rotation to one of the above conditions will occur. If, then, the directions of strain can be defined in the region of plastic flow, the stability of the entering texture (that just before the deforming process) can be stated and the emerging texture (that just after the deforming process) can be predicted.

The examination of the plastic behavior of the sheet-type tensile specimens (Fig. 4) also allows the prediction of the plastic behavior and load carrying capacity of fabricated shapes having various textures. This, in turn, will permit the selection of the sequence of fabrication operations that uses the anisotropy of the material to maximum advantage during fabrication and yet produces the desired final texture. Finally, an approach such as this is a start toward accurate use of anisotropy in the design of structural members.

Consider the production of plate, sheet, and strip by warm or cold rolling. The forming operation is essentially that of forcing compressive strain to occur in the thickness direction of the material as shown in Fig. 5a. There will also be a tensile strain in the rolling direction and a small tensile strain in the transverse direction which can, for present purposes, be neglected. If the starting texture is completely random but a major reduction in thickness is required, all grains that are oriented with basal poles near the normal direction will maintain their alignment (within 30 to 40° about the normal) since compressive strain by twinning does not produce a rotation of texture. All grains with basal poles oriented near the rolling direction will undergo tensile strain by $\{10\bar{1}2\}$ twinning and the twinned material will have its basal poles near the normal or transverse direction. All grains having basal poles oriented near the transverse direction will be stable in their orientation unless transverse tensile strain occurs, either generally or locally, due to heterogeneous deformation. If transverse tensile strain does occur, it will be by $\{10\bar{1}2\}$ twinning, and the twinned material will have its basal poles in the normal or rolling direction. The latter will again be deformed by twinning to finally align the basal pole in the normal direction. Thus, after a sufficient amount of reduction in thickness, almost all grains will have their basal poles oriented near the normal direction of the sheet. It has generally been found that the texture which is stable during extensive plastic flow is that which allows duplex deformation. This requirement can be fulfilled only if the basal poles are oriented approximately 30 to 40° each side of the sheet normal and a $\langle 10\bar{1}0 \rangle$ direction is near

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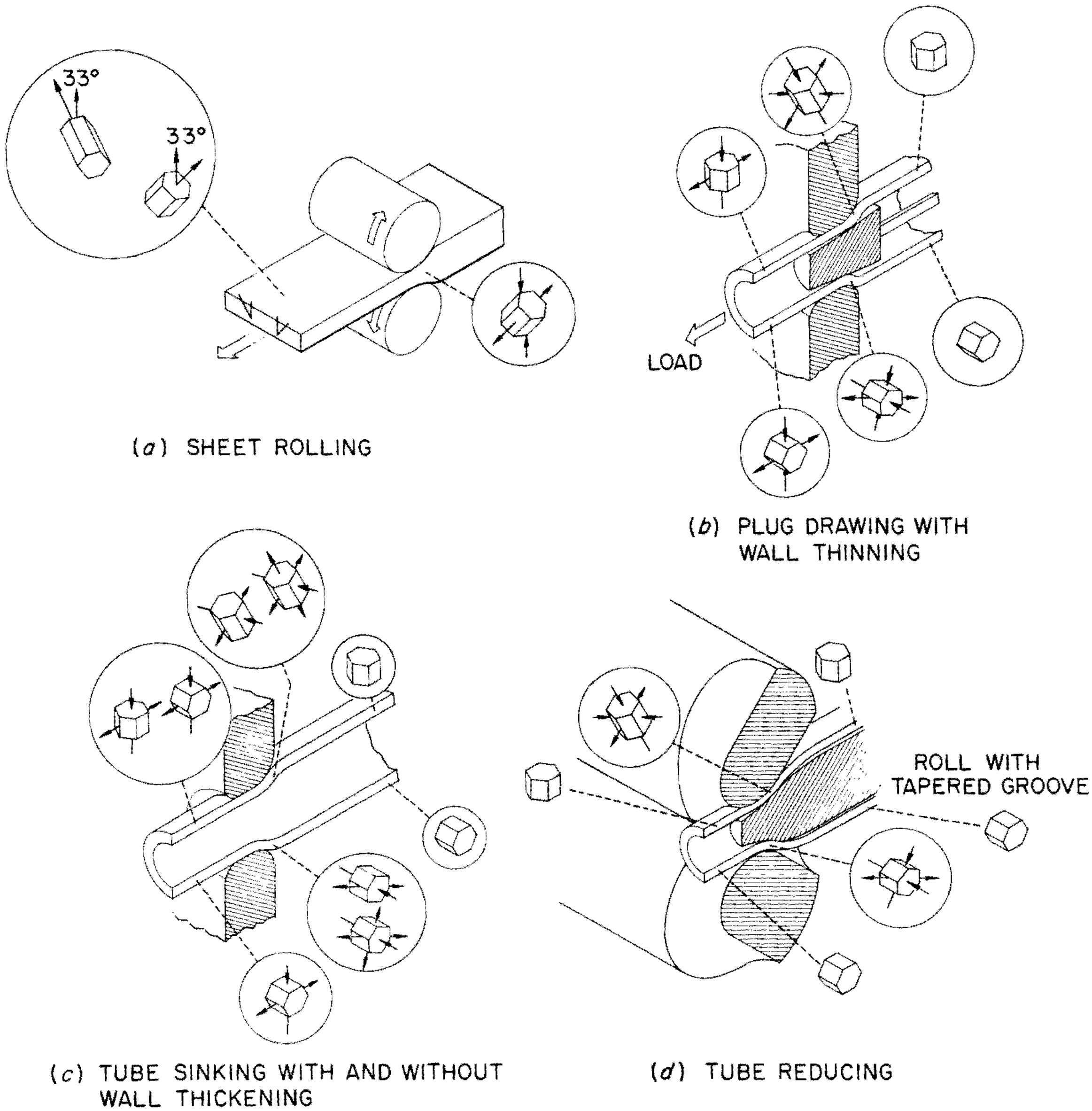

Fig. 5. Strain States During Fabrication of Zircaloy-2.

the rolling direction. This texture also requires that all of the plastic flow takes place by twinning, none by slip. Anyone who has heard annealed Zircaloy-2 cold rolled will not doubt that this is the case.

A similar situation exists in the manufacture of tubing by plug and mandrel drawing, as shown schematically in Fig. 5b. The strain conditions are shown for two textures, one having basal poles oriented in the radial direction and the other having basal poles in the tangential direction. The tubing undergoes simultaneous tensile strain in the axial direction, compressive strain in the circumferential direction, and either no change in wall thickness (plane strain) or wall thinning by compressive strain in the radial direction. The texture with basal poles in the radial direction (±30 to 40°) will be stable throughout the deformation. Any other texture will reorient to this texture, with the exception of those grains with basal poles in the tangential direction. Such grains will not reorient unless there is localized heterogeneous deformation. Thus, if the entering texture is random, the final texture will be strongly oriented with the basal poles aligned within ±30 to 40° of the radial direction. It does, however, seem possible that the texture could be caused to vary from basal poles in the radial direction to basal poles in the tangential direction by varying the reduction in circumference relative to the reduction in thickness in each drawing pass. Since specific compressive loads will vary with die angles, total reductions per pass, and frictional forces on the die, plug, and mandrel surfaces, the strain pattern actually existing in the flowing material is not known. Consequently, the prediction of the emerging texture cannot be exact.

The plastic flow occurring in the operation called tube sinking is somewhat different from that of plug and mandrel drawing if wall thickening occurs, since this will produce tensile strain in the radial direction. The conditions are shown in Fig. 5c. If the entering texture consists of basal poles oriented in the radial direction, some of the material will undergo twinning in tension and the basal poles of the twins will be oriented in the tangential direction. The remainder of the grains will maintain their orientation. The amount of material reoriented will depend on the amount of wall thickening that occurs. If, however, the texture of the entering material consists of basal poles in the tangential direction, the texture will not change, since this orientation is stable under compressive strain in the direction of the basal pole (circumferential contraction is by compression in the tangential direction).

In tube reducing, material is forced to flow (Fig. 5d) by the action of tapered grooves in an oscillating roll and a tapered mandrel which moves with the rolls. A given element in the tube is simultaneously compressed radially between the rolls and the mandrel and tangentially by the tapered grooves of the rolls. Axial elongation results, but there is no externally applied tensile load as in drawing. If the entering texture consists of basal poles oriented in either the radial or the tangential direction or both, the texture will be stable, as diagrammed in Fig. 5d. If, however, sinking is allowed before the mandrel is encountered (wall thickening), some of the basal poles in the radial direction will be moved to the tangential direction by tensile twinning, and the final texture will be a mixture, basal poles being concentrated in both the radial and tangential directions. If the entering material is randomly oriented, only those grains having basal poles oriented near the axial direction will be displaced from that direction by twinning. Thus, the emerging texture for a randomly oriented entering material should be one with an absence of basal poles in the axial direction and with the basal poles randomly distributed between the radial and the tangential directions.

A similar situation exists for tubing fabricated by swaging on a mandrel, with the exception that a sinking operation definitely occurs in the first part of the swaging die. In swaging, the emerging material will show an absence of basal poles in the axial direction if no major reduction occurs after the mandrel is contacted. If there is a major reduction in thickness after the mandrel is contacted, most of the strain will be confined to the radial direction and the texture will consist of basal poles oriented in the radial direction (±30 to 40°).

Again, it seems possible that the intensity and orientation of the emerging texture can be altered by varying the relative amounts of circumferential and radial strains in these operations.

The Influence of Texture on Forces During Fabrication

The extreme anisotropy in yield and flow strengths can cause appreciable difficulty during fabrication. On the other hand, if recognized and properly used, it can greatly reduce the working forces required in the operation.

Rolling is primarily compression (plane strain), there being compressive flow in the thickness direction, tensile flow in the rolling direction, and little if any flow in the transverse direction (for conditions where the width is many times the thickness). The texture usually produced in Zircaloy-2 consists of basal poles within $\pm 40°$ of the normal to the rolling plane. Since the compressive flow strength for this texture is high, the roll forces will be high. Reduction of roll forces can be accomplished by warm or hot rolling, tension rolling with high fore and back tension, or frequent annealing.

In plug drawing and in sinking, the drawing force is applied axially to the material that has emerged from the die. The most desirable texture, from the standpoint of working forces, in the material both entering and leaving the die consists of basal poles in the radial direction. This texture, however, is the one most likely to cause surface cracking at the point where the tubing leaves the die, a region of high tensile stress concentration. Material with this texture has maximum strength under axial tension (produced by the applied drawing load) since there is restraint in the circumferential direction and axial tensile strain can be produced only if accompanied by wall thinning by compression $\{11\bar{2}2\}$ twinning. The texture having basal poles in the tangential direction will be weakest in such axial tension because wall thinning can occur by slip. Since the forces required to strain the material in the die should be nearly the same for a given geometry of die and plug or mandrel, material having the first texture may be drawn under conditions where material with the second cannot, simply because they sustain different axial loads before failure.

The forming forces required in tube reducing should be almost independent of the entering texture, since all of the applied forces are compressive and should depend almost entirely on the reductions in wall thickness and circumference. They will, however, be relatively high since little of the flow can be by slip. The load-bearing ability of the emerging texture is unimportant here, since there is no externally applied axial load.

Applications of Texture Control in Forming Operations

One may easily demonstrate the importance of control of texture by varying the texture of the stock for various sheet metal forming operations, such as bending of sheet, drawing of cups, and stretch forming. With certain textures, the material will crack in the bend in forming of boxes, fracture in the wall of the cup or in the flange of the blank in cup drawing, or wrinkle in stretch forming while none of these happen if the material has certain other textures. Some shapes may be impossible to make unless the stock has exactly the right texture for the operation.

Consider the problem of bending of sheet stock to form sharp corners for making boxes and frames. The forces and strains involved are shown schematically in Fig. 6a. As the stock is bent, the outer surface is placed in tension and the inner surface in compression. The neutral axis is, in general, not located at the center line but is displaced toward the compression surface. Since there is restraint along the bend axis, no transverse strain may occur (except at the sides where, though undesirable, it is usually small). Thus, all of the tensile strain occurring in the outer layer (outside the neutral axis) must be accompanied by radial compressive strain. The "available ductility" of the material limits the amount of bending that can be accommodated. If it is small, the bend radius must be large or the material will crack during bending. Because of restraints (no transverse strain), the center portion will be in biaxial tension, limiting the "available ductility" even more, and cracking will start at this point and progress through the thickness and along the axis of bend.

If the basal poles are in the direction of the bend radius (see Fig. 6a), all of the tensile strain must occur by $\{11\bar{2}2\}$ twinning.

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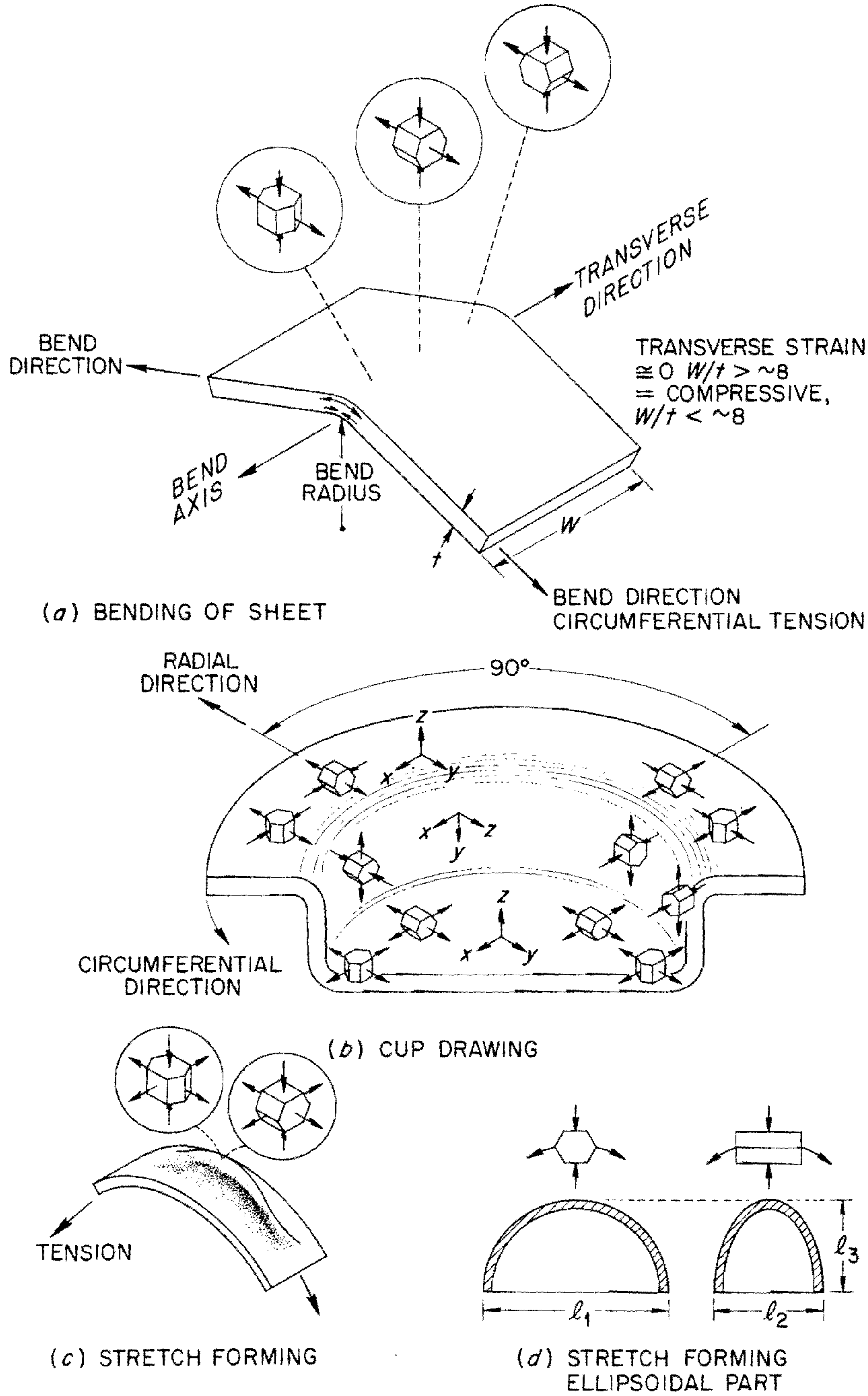

Fig. 6. Strain States in Sheet Metal Forming of Zircaloy-2.

This requires very high flow stresses and the texture is stable under this loading. The tensile stress in the surface must be high if the necessary plastic strain is to occur. At room temperature, the ductility under these conditions is limited. Therefore, the piece will crack during bending if the bend radius is small. If material of this texture must be used, the only recourse is to increase the forming temperature or the bend radius.

If the texture is such that the basal poles are parallel to the bend direction, the problem is eased to some extent and the bend radius can be reduced without encountering cracking. The initial tensile strain along the basal poles is accomplished by $\{10\bar{1}2\}$ twinning with a decrease in thickness (there being side restraint). The twinned material is now oriented to permit further thinning to occur by compressive $\{11\bar{2}2\}$ twinning (the basal pole will be in the radial direction, not the transverse, because no strain is permitted to take place in the transverse direction). The twinned material is now in the same orientation as the previous texture and will have the same strain state, but appreciable strain has already occurred by the $\{10\bar{1}2\}$ twinning. Thus, the "available ductility" of the starting texture is increased by the amount of strain produced by the $\{10\bar{1}2\}$ twinning.

If the basal poles are parallel to the bend axis, all of the strain, both tensile in the bend direction and compressive in the radial direction, can be accomplished entirely by slip. The bending forces will be low and the "available ductility" will be high. Furthermore, work-hardening will occur rapidly enough to prevent localized necking, and the bend radius can be decreased quite appreciably. The tendency for transverse strain to occur at the edges (which are not in unrestraint) will be resisted by the very high flow stress required for strain by compression along the basal pole. In this case, the strong texture can be an advantage, when compared to isotropic material, if it is important that the edges not deform during the bending operation.

A highly developed texture can be used to considerable advantage in cup drawing if the basal poles are in the normal (thickness) direction of the drawing blank.[11] The strain states in the drawing blank and the "cell" orientations for two textures during the drawing operations are shown schematically in Fig. 6b. The strain state in the flange of the cup is one of tensile strain in the radial direction, compressive strain in the circumferential direction, and tensile strain in the thickness direction if plane strain conditions are not enforced by a hold-down ring. In the wall of the cup, there is tensile strain in the direction of punch movement, compressive strain in the wall thickness direction, and restraint in the circumferential direction (the punch prevents a decrease in the circumference). In the bottom of the cup, the center is in pure biaxial tension, producing tensile strain in the radial direction and compressive strain in the thickness direction.

If the material has basal poles oriented in the thickness direction of the drawing blank, the drawing operation is eased considerably and cups can be drawn much deeper than with an isotropic material.[11] In the flange region, the strain is produced entirely by slip and thickening is resisted by the high yield stress required for $\{11\bar{2}2\}$ twinning. In the wall of the cup, tensile fracture is resisted because it requires wall thinning and compressive strains along the basal pole require quite large stresses. In the bottom of the cup, thinning is resisted for the same reason. Thus, flow is easy where it is desirable, as in the flange region, and difficult where it is undesirable, as in the wall and bottom of the cup. Further, the texture is symmetric about the punch axis, decreasing the tendency for "earing."

If the basal poles of the material are aligned in an arbitrary direction in the sheet, the texture will not be symmetric about the punch axis, giving the two different "textures" (relative to the strain axes) shown in Fig. 6b. There will be a point around the punch axis where the basal poles are aligned in the radial direction of the drawing blank. The tensile strain at this point will occur by $\{10\bar{1}2\}$ twinning. Part of the twinned material will have its basal poles

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[11] D. H. Lloyd, Sheet Metal Ind. 39, 82 (1962).

aligned in the thickness direction and will then be stable, further deformation occurring by slip. The other part of the twinned material will have its basal poles aligned in the circumferential direction and would be stable if undisturbed. However, further strain must then occur by $\{11\bar{2}2\}$ twinning and the required stresses will be high, causing heterogeneous strain, since nearby regions can flow by slip. Texture rotation will probably occur until all of the deformed material has the basal poles aligned in the thickness direction. Thus, this portion of the flange will finally have the desirable texture after a sufficient amount of strain has occurred. The surface may be rough, since $\{10\bar{1}2\}$ twinning can also produce localized thinning of the flange.

Now consider the effect of this texture at locations in the flange at 90° to that discussed above. At these locations, the basal poles will be aligned in the circumferential direction and all circumferential strain will have to occur by $\{11\bar{2}2\}$ twinning (compression along the basal pole). As a result, the forces required for such deformation in this part of the flange will be high. It is probable that thinning by slip will occur instead, leading to fracture at or near the throat of the die. In the wall of the cup, wall thinning can occur readily by slip, and the cup is again likely to fracture. In the bottom of the cup, the texture is such that wall thinning can occur by $\{10\bar{1}2\}$ twinning and by slip. Thus, the drawing operation is hampered by this texture at all points in the blank and any pronounced texture having basal poles in the plane of the sheet is quite undesirable.

A similar situation exists in stretch forming. If the material texture consists of basal poles normal to the sheet (see Fig. 6c), it will be desirably symmetric but all strain must be accomplished by $\{11\bar{2}2\}$ twinning and high forces will be required. If the texture consists of basal poles in some direction in the sheet, the forming forces will be lower but the excessive strain anisotropy may require a rejection of the part. Strain in one direction must be accomplished by $\{10\bar{1}2\}$ twinning (at relatively high stresses) and, at 90° to that direction, the strain will be accomplished by slip. Such a texture will be undesirable if the formed part is hemispherical but it may be desirable if the part is ellipsoidal and the basal pole of the texture is perpendicular to the major axis of the ellipsoid (see Fig. 6d).

Application of Texture Control in Design of Structures

Failure to consider the anisotropy of yield and flow strengths of highly textured Zircaloy-2 can cause serious problems in the design and construction of engineering structures. Alternately, it can be of considerable advantage in increasing permissible design stresses and structural loads if it is used properly. Since any yielding will be considered failure, decreased ductility (if any) is not important. For example, the principal stress operating in internally pressurized vessels is that of hoop tension. Unless the ends of the vessel are fixed, there will be a second tensile stress, orthogonal to the first, also produced by the internal pressure. Such stresses produce biaxial tensile loads in the wall of the vessel, and failure will occur by bulging and thinning of the wall. If the vessel is constructed of highly textured material having the basal poles oriented in the thickness direction, the failure stresses will be considerably higher than for any other texture, including random (which has isotropic properties). For any strain to occur in material having this texture, $\{11\bar{2}2\}$ twinning (compression) must occur. The yield stress in compression for $\{11\bar{2}2\}$ twinning is 122,000 psi. In comparison, the design value that would normally be used is that of the yield strength of a uniaxial tensile specimen of the sheet material, a value of 55,000 psi for this material (see Table 1, sched 8). Thus, a proper recognition of the role of texture in design problems will permit a design stress more than twice that permitted by conventional design criteria (which were developed for structures built of steel).

A similar situation exists for structural members made of tubing. If the basal poles are strongly oriented in the radial direction in the tubing, the axial tensile load required to cause yielding will be considerably higher than if the basal poles are oriented in the tangential direction or if the texture is random (see Fig. 5c, emerging textures). By similar reasoning, the buckling load or column stiffness should be a maximum if the basal poles are strongly oriented in the radial direction.

If a structural member is made of sheet (or can be considered to be made of sheet, such as I-beams assembled from sheet by welding), the load carrying ability should be greatest when the texture consists of basal poles strongly oriented in the direction of the normal to the plane of the sheet. In all of these uses, the part can yield only if simultaneous thinning occurs. But thinning of this texture requires $\{11\bar{2}2\}$ twinning (compression along the basal pole) and, consequently, very high flow stresses.

Future Research Work

The above analysis of the problems associated with texture and with its development and control has been the result of the previous work performed on rolled plate and sheet Zircaloy-2 and of the preliminary planning for a similar study to be conducted on Zircaloy-2 tubing. A more detailed analysis of the development of texture during fabrication, of the strain patterns present in the deforming region for different fabrication processes, and of the utilization of texture to advantage during processing and in structural design is presently under way. This analysis is also serving as a guide for setting specifications for the sequence of operations that hopefully will produce the varied textures needed for this tubing study.

The tubing study proposed will determine the effects of various fabrication variables (including intermediate beta heat treatments) on the type of texture produced and the resulting anisotropy of strain and of yield strengths. The anisotropy of flow strengths and of strain under different states of stress will be studied using a technique which is an extension of the methods developed to investigate plastic flow in torsion in rod and tubing.[12] (Unfortunately for our purposes, the authors of these earlier studies discarded the data for those

[12] G. I. Taylor and H. Quinney, Phil. Trans. Roy. Soc. London, Ser. A, 230, 323–62 (1931).

specimens which proved to be anisotropic.) The testing device is presently being designed to read photographically the distortion of a grid of squares (placed on the specimen by photoetching and then anodizing) while the specimen is being stressed by any selected combination of internal pressure, axial loading, and torsional loading. The internal volume will be continuously measured. Intermittent readings during each test will be retained for computer analysis together with the instantaneous axial and torsional strains and the appropriate loads. From the computer analysis, the stress-strain curves for the average grid square, the squares of maximum and minimum strains, and the changes in wall thickness for specific grid squares or the average change for the grid can be obtained as functions of the load variables.

As the determination of the preferred orientation in each test specimen is of prime importance in the tubing study, a new method of determining the preferred orientation (at least for the intensity and orientation of the basal pole) is being developed. This method utilizes the anisotropy of metallographically prepared specimens in polarized light. The intensity of reflected polarized light at angles of rotation relative to selected fabrication directions is measured photoelectrically on a microscope. Preliminary studies using manual rotation and visual reading of the indicating meter have been quite promising but are somewhat tedious and slow. Quantitative analysis of the curves of intensity versus angle of rotation has been unwarranted because proper standards of light intensity, alignment of the plane of polarization in the microscope, and specimen preparation have not been adequately determined. The measuring technique is being automated to plot the intensity versus angle of rotation directly on an x-y recorder and studies are being conducted to determine the standards required. If the method proves successful, and there are indications that it will, the time and effort required to determine the principal components of the texture and their intensity will be decreased considerably from that necessary for x-ray diffraction analysis. In addition, it appears quite feasible to determine textures in thin wall tubing from inner to outer surfaces without the very tedious preparation of specimens required for x-ray diffraction techniques. The rapidity and ease of the method makes practical a rather extensive study of the variation of texture from front end to back end of tubing at various stages of processing.

The proposed study of anisotropy in tubing is only a part of the research program on zirconium alloys in the Zirconium Metallurgy Group at ORNL. Studies presently under way are (1) a basic study of the optical properties of oxide films in situ on zirconium alloy specimens in an attempt to determine the defect structure and defect concentration in the oxide as functions of alloying element, oxidizing environment, film thickness, and crystallographic orientation; (2) determination of the oxidation-corrosion rates, by new and more sensitive techniques, as affected by the above variables; (3) methods of production of large single crystals of various alpha-zirconium alloys for the above studies and for basic studies of deformation mechanisms; (4) the correct phase boundaries in the zirconium-rich end of the zirconium-niobium phase diagram; and (5) determination of the transformation kinetics, mechanisms, and morphologies for a wide range of zirconium-base alloy systems.

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