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NEUTRON DIFFRACTION MEASUREMENT OF TEXTURE VARIATIONS NEAR A WELD IN A Zr-2.5%Nb PLATE

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ABSTRACT

A welded Zr-2.5%Nb plate with a texture similar to that of a CANDU* nuclear reactor pressure tube has been studied to determine the texture variations in the fusion zone and the heat affected zone (HAZ). The texture of the HAZ is explained by preferential growth of (001)[110] grains in the high-temperature bcc phase, with subsequent variant selection on cooling to enhance the volume fraction of (0002) normals perpendicular to the line of the weld. The same texture is observed in the fusion zone along with a (001)[100] texture component arising from solidification. The textures of the fusion zone and HAZ are not expected to increase the susceptibility of the welded plate to delayed hydride cracking.

INTRODUCTION

The pressure tubes in CANDU* nuclear reactors are made of the alloy Zr-2.5%Nb which has a low neutron capture cross section and good mechanical properties. The alloy in its operating temperature range is predominantly in the hexagonal close-packed (hcp) α phase with a small percentage in the body-centred cubic (bcc) β phase which is stabilized by a high concentration of niobium. Above 610 °C the zirconium is composed of a mixture of α and β phases while above 900 °C the zirconium is found in a pure β phase[1] which melts at 1850 °C. Burgers showed that the crystallographic phases have orientational relationships on transformation such that a (0002) plane in the hcp phase becomes a (110) plane in the bcc phase and a $[11\bar{2}0]$ direction becomes a [111] direction.[2] The texture of α zirconium in a typical pressure tube is very sharp and arises from extrusion of the tube during fabrication. The dominant texture component, denoted $(11\bar{2}0)[1\bar{1}00]$, has $\{11\bar{2}0\}$ plane normals along the tube radial direction, $\{10\bar{1}0\}$ plane normals along the tube axis and (0002) basal plane normals along the tube hoop direction. This texture can be detrimental from the standpoint of delayed hydride cracking. Dissolved hydrogen precipitates as brittle zirconium hydride platelets on cooling of the pressure tube from the normal operating temperature. When there is a tensile hoop stress, many platelets become aligned parallel to the $(10\bar{1}7)$ plane of the zirconium matrix[3] which is nearly pa-

*CANDU: CANada Deuterium Uranium. Registered trademark.

rallel to the basal plane of the hcp lattice. The texture of the tube enhances the likelihood that the brittle platelets will extend through the tube wall and along its length and reduces the fracture toughness of the tube. During neutron diffraction measurements of residual stress near a circumferential electron beam weld in a Zr-2.5% Nb tube, a dramatic increase of intensity of the (0002) diffraction peak in the axial direction was observed in a small zone near the weld.[4] This suggested a sharp texture with (0002) normals parallel to the tube axis, which could reduce the fracture toughness of the tube in throughwall, circumferential cracking.

In this paper we present the textures of the α phase of a welded Zr-2.5%Nb plate in the base material, in the fusion zone and in the heat affected zone (HAZ) where the microstructure exhibits strong grain coarsening. The texture in the fusion zone is controlled by solidification from the melt into the high-temperature β phase. Solidification in cubic materials has been observed to occur as growth of large grains with {001} planes parallel to the solid-liquid interface[5]. One therefore expects a (001)[100] texture in the weld at high temperature. Here, (hkl) denotes the plane parallel to the surface of the plate and [hkl] denotes a direction parallel to the plate rolling direction. On cooling, the Burgers transformations are activated and one expects to observe hcp (0002) plane normals where there would have been bcc (110) plane normals in the (001)[100] texture. Each of the eight observable (0002) normals has associated with it three observable $(11\bar{2}0)$ normals, one of which coincides with a <111> direction in the (001)[100] texture. In the HAZ directly adjacent to the fusion zone, the temperature of the base material is raised close to the melting point so the zirconium is all transformed from the original hcp phase into the bcc phase. Many grain orientations may be created as the Burgers transformations occur on cycling from the α to $\alpha+\beta$ to β phases and back again. However, grains with a subset of the possible orientations may grow preferentially because of the stress fields and thermal gradients that occur throughout the thermal cycle. This variant selection could therefore simplify the eventual texture of the HAZ at room temperature.

Neutron diffraction is an excellent technique for the determination of texture in the neighbourhood of a weld because neutrons penetrate easily through zirconium. The pathlength for a 30% reduction of beam intensity for neutrons is 1.2 cm. By penetrating into the bulk of the material neutrons sample many more grains in a coarse grained specimen, yield directly the volume averaged texture in the specimen and permit collection of complete pole figures with a single setting of the specimen on the orienting apparatus. In this paper texture data are obtained by neutron diffraction and presented in pole figures in which χ, the angle of tilt from the plate normal, N, ranges from 0° to 90° and is <u>proportional</u> to distance from the centre

of the figure. The azimuthal angle, η, from the plate rolling direction, R, is plotted counterclockwise from the top of the figure and the transverse direction, T, is towards the left. Points of equal intensity are joined by contours. Dashed lines indicate intensity less than that of a random distribution of crystallite orientations and solid lines indicate intensity greater than that of a random distribution. The heavy line indicates the level of a random distribution. Decorated contours indicate the minimum (o) and maximum (x) levels. The contour interval is quoted in multiples of the random distribution level (mrd). CODF analysis of the texture data is carried out with software developed at Chalk River Laboratories.[6]

EXPERIMENTAL

The specimen was a plate which was hot rolled at temperatures between 700 °C and 790 °C. A single-pass, full-penetration GTA butt weld was made in the T direction, spanning the width of the plate at mid-length. The plate had a thickness of 6 mm, width of 300 mm and length in the R direction of 378 mm. A polarized light photograph of the weld cross section is shown in figure 1. The surface of the sample was etched with a solution of 9% nitric acid and 1% hydrofluoric acid in lactic acid. The observed grain boundaries are the remnant of the macrostructure of the β phase grains formed during the welding process. In the fusion zone these grains are large and columnar as expected for solidification of a bcc material from a melt. In the HAZ adjacent to the fusion zone there is a region of enlarged equiaxed grains. Clearly, coarsening of β phase grains occurred at high temperature. For texture measurements, samples were cut from the fusion zone and from the region of the HAZ which exhibited enhanced grain size. The texture samples had dimensions 4 mm x 4 mm x 30 mm with the long axis parallel to the plate T direction (along the weld axis) and the fraction of material from other zones of the weld was minimized. A base plate sample was obtained far from the weld.

Texture determinations were conducted on the E3 neutron diffractometer at Chalk River Laboratories' NRU reactor. The wavelength of the neutron beam was selected to be 1.393 Å by diffraction from the (331) plane of a silicon crystal monochromator. The incident and diffracted beams both had width 50 mm and height 50 mm, so at all orientations the sample was fully illuminated by neutrons. Soller slits confined the angular divergence in the scattering plane to be 0.3°, while the detector subtended 4° vertically. The neutron diffractometer was set to the scattering angle for one of the five hcp planes: $(10\bar{1}0)$, (0002), $(10\bar{1}1)$, $(10\bar{1}2)$ or $(11\bar{2}0)$. An Eulerian cradle stepped the sample in 5 degree steps of χ and η through a complete hemisphere of orientations. The intensity at each orientation was the number of neutrons counted per fixed count on an incident beam monitor, requiring about 5 s.

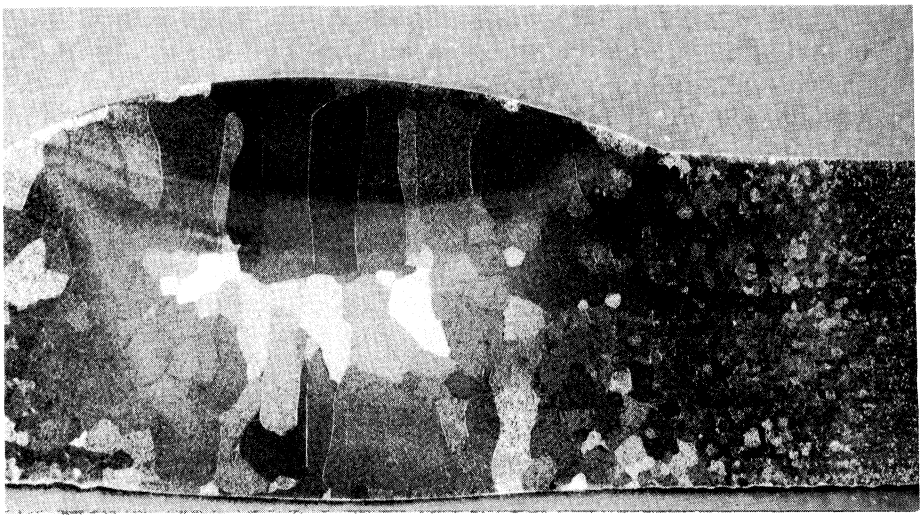

Figure 1 Polarized light photograph of a cross section of the weld in a Zr-2.5% Nb plate. The plate thickness is 6 mm.

RESULTS AND DISCUSSION

The (0002) and $(11\bar{2}0)$ pole figures for the base plate, HAZ and fusion zones are presented in figure 2. The texture in the base plate is similar to that of CANDU pressure tubes with the plate R, T and N directions corresponding to tube longitudinal, hoop and radial directions. The (0002) normals are directed 75° from the N direction in the N-T plane. There is also a strong preferred crystallographic orientation with $(10\bar{1}0)$ normals directed along the plate R direction and, correspondingly, there are $(11\bar{2}0)$ normals centred on the N-R plane at 0° and 60° from the N direction.

In the HAZ the (0002) pole figure clearly indicates there was a dominant (001)[110] texture component in the bcc phase at high temperature. This can be explained as preferential growth of the bcc grains which, through Burgers transformations, can be traced to hcp grains in the original plate with basal poles along the T direction and $(11\bar{2}0)$ plane normals in the N-R plane about 55° from the N direction. Growth of these grains evidently has occurred by consumption of grains with other orientations. For example, six-fold symmetry about the N direction is not observed in the (0002) pole figure, as would arise from bcc grains which can be traced to hcp grains in the original plate with (0002) normals along the T direction and $(11\bar{2}0)$ normals in the N direction. Also, while the pole positions in the (0002) pole figure are consistent with a high-temperature (001)[110] texture, the intensities do not exhibit four-fold symmetry. On cooling to the hcp phase, there has been additional preferential growth

of hcp grains with (0002) normals along the R direction. The thermal cycle associated with welding has therefore transferred a large volume fraction of basal plane normals from the T direction to the R direction, consistent with the observations of ref. 4.

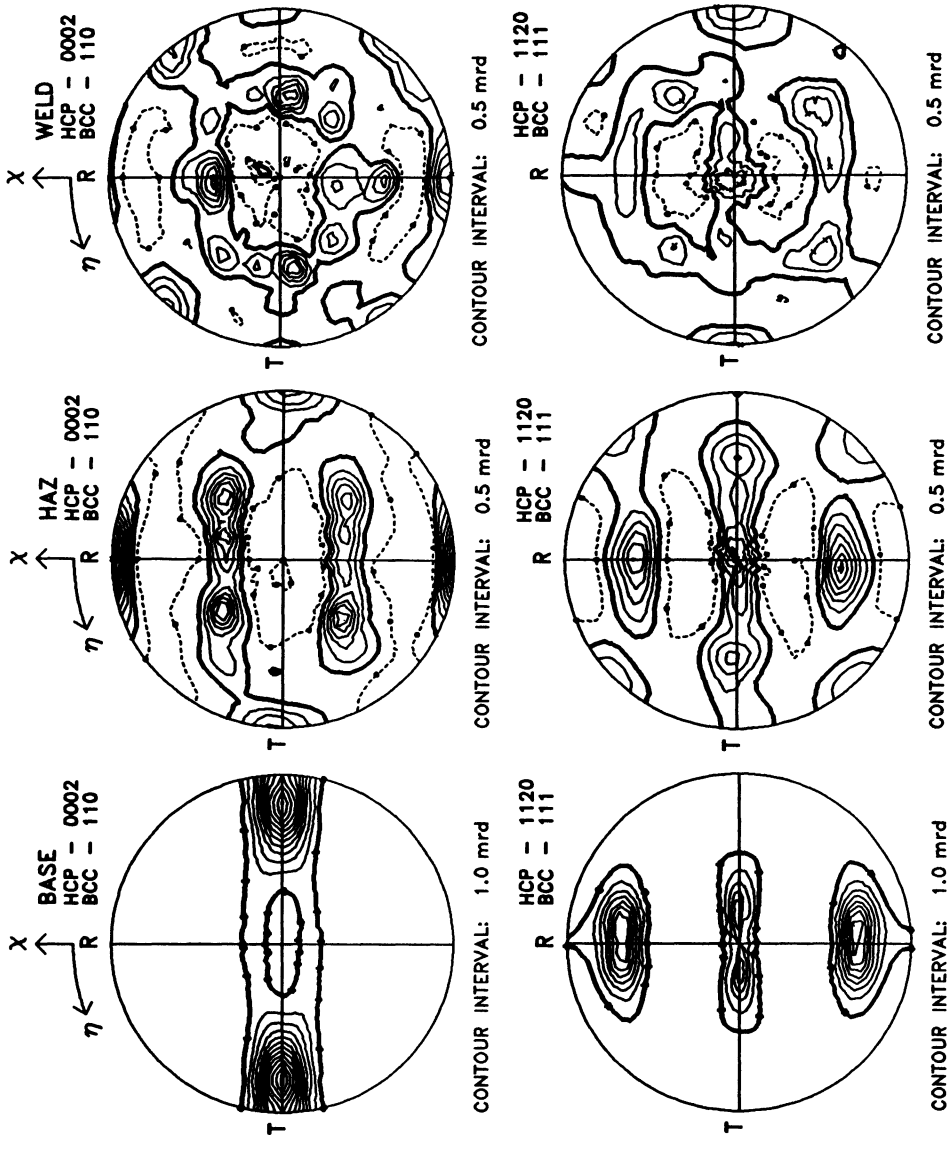

Figure 2 Pole figures for the (0002) (left) and (11$\bar{2}$0) (right) reflections for the base plate (BASE), HAZ and fusion zone (WELD). The figures are annotated with both the true hcp indices and the corresponding bcc indices which pertain to the high-temperature phase.

In the fusion zone the (0002) pole figure indicates that the high-temperature β phase was composed of two dominant texture components: (001)[100] and (001)[110]. The first component conforms to the expectation that the texture in the fusion zone arises from solidification with the easy <001> crystallographic growth direction perpendicular to the solid-liquid interfaces at the weld edges and at the weld surface. The second component is the same as that observed in the HAZ. With the current experiment one cannot decide whether the two texture components are distributed homogeneously throughout the volume or that the second component forms preferentially at the interface between the fusion zone and the HAZ, for instance.

To make a quantitative comparison of the susceptibility of each of the three weld zones to the formation of hydride platelets which might propagate in the plate normal direction we calculated the CODF for each sample. The volume fractions of crystallites with basal plane normals within 20° of the surface of the plate are 0.42, 0.35 and 0.35 for the base plate, HAZ and fusion zones respectively. From the standpoint of basal plane orientations alone, the base plate is most susceptible to throughwall hydride-enhanced cracking.

CONCLUSIONS

In a welded Zr-2.5%Nb plate the texture in the HAZ in the region of marked grain coarsening may be traced, through Burgers transformations and variant selection, to a dominant texture component, (001)[110], in the high-temperature bcc phase. There is an overall transfer of basal plane normals from the T direction in the original plate to the R direction in the HAZ, which is perpendicular to the line of the weld. The fusion zone exhibits this (001)[110] texture component as well as the remnants of a strong (001)[100] texture component in the β phase which can be explained by the growth of bcc grains with <001> directions perpendicular to the solid-liquid interface. In terms of texture alone, welding does not increase the susceptibility of the plate to hydride-enhanced throughwall fracture.

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