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Letter to the Editor

Variant selection and transformation texture in zirconium alloy Excel

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ABSTRACT

The crystallographic texture and variant selection during phase transformations in zirconium alloy Excel (Zr–3.5% Sn–0.8% Mo–0.8% Nb) was investigated. It was shown that upon water-quenching from $\alpha_{Zr}+\beta_{Zr}$ or fully β_{Zr} regions, variant selection occurs during $\beta_{Zr} \rightarrow \alpha'_{Zr}$ martensitic transformation. Also during air-cooling from the $\alpha_{Zr}+\beta_{Zr}$ region, only a partial memory effect and some transformation texture with variant selection was observed which is contrary to previous reports on zirconium alloys heat treated in the $\alpha_{Zr}+\beta_{Zr}$ region.

1. Introduction

Zirconium alloy Excel (Zr–3.5% Sn–0.8% Mo–0.8% Nb) is a promising material for CANDU reactors pressure tube due to its high strength and superior creep resistance [1]. It is a dual phase α_{Zr}-hcp and β_{Zr}-bcc alloy with the approximate α_{Zr} and β_{Zr} volume fractions of 87% and 13% respectively in the pseudo-equilibrium condition at room temperature [2]. The crystallographic texture of the pressure tube has a strong effect on its in-reactor behaviour such as irradiation growth and creep. In the present study, the crystallographic texture and variant selection upon phase transformation in Excel with different microstructures were investigated using neutron diffraction texture measurements.

2. Experimental procedure

Details about the material's processing history and microstructure can be found in an earlier work [2].

Four different heat treatments were developed to be investigated: (1) Solution treated at 980 °C (fully β_{Zr}) and water-quenched which results in a fully martensitic microstructure (α'_{Zr}-hcp with almost identical lattice parameters to α_{Zr}-hcp), (2) Solution treated at 890 °C (about 30% α_{Zr} and 70% β_{Zr}) and water-quenched upon which the 70% β_{Zr} transforms into α'_{Zr}-hcp martensite and the 30% primary α_{Zr} remains untransformed, (3) Solution treated at 890 °C followed by air-cooling to room temperature, resulting in a final microstructure of about 42% primary α_{Zr} and 58% transformed β_{Zr} in the form of fine Widmanstätten α_{Zr}-hcp grains with a continuous network of β_{Zr}-bcc along the grain boundaries, (4) Solution treated and water-quenched from 860 °C (about 60% α_{Zr} and 40% β_{Zr}) which results in a microstructure consisting of about 60% α_{Zr}-hcp and 40% retained β_{Zr}-bcc with ω-phase precipitates inside the β_{Zr} grains [2].

The textures of the as-heat treated samples mentioned above and of the as-received cold-worked and annealed material were measured by neutron diffraction.

3. Results and discussion

Fig. 1 depicts the α_{Zr} basal pole figures[1] of the samples water-quenched from 890 °C and 980 °C, and air-cooled from 890 °C. Textures of the quenched samples were measured in the quenched and aged condition. The resolved fraction of basal plane normals in the axial, radial, and transverse directions for each sample are given in Table 1.

Fig. 2 shows texture of the α_{Zr} and β_{Zr} phases for the as-received sample as well as the sample water-quenched from 860 °C.

The strong axial component in the α_{Zr} basal pole figure of the heat treated samples (Fig. 1a–c) is a result of texture inheritance from the high temperature β_{Zr} texture through the Burgers relationship. In zirconium and titanium alloys the Burgers orientation relationship, a crystallographic orientation relationship between α and β phases when the alloy undergoes a phase transformation, is expressed as $\{0002\}_\alpha \| \{110\}_\beta$ and $\langle 1\,1\,\bar{2}\,0\rangle_\alpha \| \langle 1\,1\,1\rangle_\beta$ [3]. As a result of the Burgers orientation relationship there are six equivalent orientation variants during the $\alpha \rightarrow \beta$ phase transformation and twelve variants during the $\beta \rightarrow \alpha$ phase transformation [4]. If all of the variants have the same probability of occurrence, then the final texture would be significantly randomized by an $\alpha \rightarrow \beta \rightarrow \alpha$ phase transformation process [3]. However this is not the case and many researchers have reported either retention/

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[1] All the pole figures in this study are stereographic projection.

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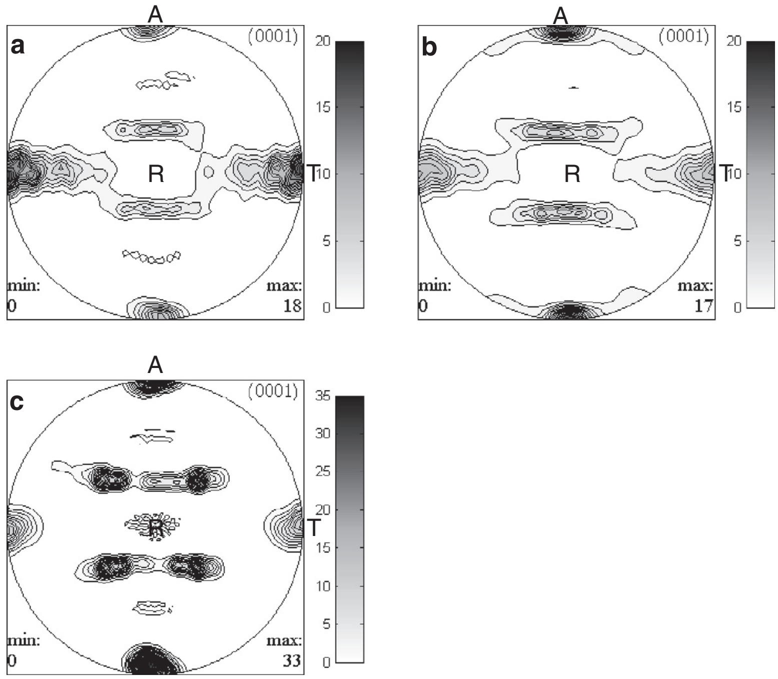

Fig. 1. α_{Zr} (0002) pole figure of (a) 890 °C air-cooled (b) 890 °C water-quenched (c) 980 °C water-quenched samples. (All the samples were aged at 450 °C for 1 h).

strengthening of the existing texture, i.e., a memory effect, or a strong texture after phase transformation, i.e., variant selection.

Wenk et al. [5] studied the phase transformation behaviour of hot rolled Zircaloy-4 and found that there is variant selection during the $\alpha_{Zr} \rightarrow \beta_{Zr}$ phase transformation and memory effect/texture strengthening during the $\beta_{Zr} \rightarrow \alpha_{Zr}$ phase transformation. The memory effect was attributed to growth of remnant untransformed α_{Zr}, which is more likely the case, or variant selection due to internal stresses induced by constraint imposed by neighbouring grains.

Romero et al. [3] observed that if cold-rolled Zircaloy-2 was only heated into the $\alpha_{Zr} + \beta_{Zr}$ phase field, an almost perfect memory effect was seen upon cooling to α_{Zr}. Further they found no variant selection upon heating fully into the β_{Zr} regime, but did observe variant selection during subsequent cooling, where the α_{Zr} inherited the high temperature β_{Zr} texture selectively during the $\beta_{Zr} \rightarrow \alpha_{Zr}$ phase transformation. Similar to Romero et al., Daymond et al. [6] also found no change in texture of Zr-2.5Nb pressure tube material if heated into the $\alpha_{Zr} + \beta_{Zr}$ region (but staying below the β_{Zr} transus temperature) and then returning to ambient conditions. However Daymond et al. [6] did report significant variant selection during the $\alpha_{Zr} \rightarrow \beta_{Zr}$ phase transformation when heating above the β_{Zr} transus temperature, as well as during the subsequent $\beta_{Zr} \rightarrow \alpha_{Zr}$ phase transformation. This variant selection led to the removal of the initial transverse (0002) intensity, which was replaced by strong axial (0002) intensity, in locations similar to that seen in Fig. 1(a)–(c). The strong 'cube' like poles of the (0002) that are shown in Fig. 1c) were associated in Daymond et al.'s study [6] with β_{Zr} grain growth in the fully β_{Zr} phase field.

Table 1
Resolved fraction of basal plane normals in the axial, f_a, transverse, f_t and radial, f_r, directions.

	As-received	890AC	890WQ	980WQ
f_a	0.05	0.12	0.27	0.33
f_t	0.67	0.55	0.41	0.35
f_r	0.27	0.32	0.32	0.32

Fig. 1b and c show the α_{Zr} basal pole figures of the samples water-quenched from 890 °C (about 70% β_{Zr} and 30% α_{Zr}) and 980 °C (100% β_{Zr}), respectively. These pole figures resemble the α_{Zr} basal pole figures of Zr–2.5Nb in [6] after $\alpha_{Zr} \rightarrow$ fully $\beta_{Zr} \rightarrow \alpha_{Zr}$ using slow heating/cooling rate, hence associated with a diffusional phase transformation. Starting with a predominant transverse component in the α_{Zr} basal pole figure which is typical of pressure tubes (Fig. 2), and assuming no variant selection, i.e. equal probability of all variants, the α_{Zr} basal pole figure in the final texture after $\alpha_{Zr} \rightarrow \beta_{Zr} \rightarrow \alpha_{Zr}$ phase transformation is expected to resemble the theoretical (110) pole figure of the high temperature β_{Zr} as shown in the predicted pole figures of Excel in Fig. 3. This is similar to the predicted pole figures of Zr–2.5Nb in Ref. [6] and the theoretical pole figures of α_{Zr} shown by Cheadle and Ells [7]. A similar β_{Zr} texture to this no-variant selection high temperature texture was observed at room temperature for the as-received Excel pressure tube and for the sample water-quenched from 860 °C (which has about 40% β_{Zr} at room temperature [2]), see Fig. 2. This suggests epitaxial growth of the pre-existing β_{Zr} grains during heating as opposed to nucleation and growth of new grains, a behaviour contrary to the observation of Daymond et al. [6] in the case of Zr–2.5Nb pressure tube material, where the initial texture of β_{Zr} is very weak and random but it developed to a strong texture very similar to the β_{Zr} texture of the sample water-quenched from 860 °C (Fig. 2); this suggests that in Zr–2.5Nb pressure tube material the β_{Zr} texture arose either due to growth of only a subset of the original β_{Zr} grains, or nucleation of new ones.

Comparing Fig. 1b and c with Fig. 3 shows that the two maxima at about 30° from the axial direction on the periphery are missing, which indicates that variant selection has occurred. Assuming that the β_{Zr} texture at 890 °C and 980 °C is the same as that at 860 °C, it is likely that this variant selection happens during quenching, i.e. the $\beta_{Zr} \rightarrow \alpha'_{Zr}$ phase transformation. This assumption is based on the observation of Daymond et al. [6] in Zr–2.5Nb, in which there was no significant change in the texture of β_{Zr} during heating in the $\alpha_{Zr} + \beta_{Zr}$ until the fully β_{Zr} region is reached.

The variant selection observed in this study is contrary to the texture reported by Ibrahim and Holt [8] for a Zr–2.5Nb pressure