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Fracture of Zr-alloy pressure tubes due to hydride blister formation

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1. Introduction

Hydrogen migration under thermal stress gradient in zirconium alloys results in formation of hydride blisters [1]. An array of blisters makes Zirconium alloy components of nuclear reactors susceptible to fracture [2]. The whole process of hydride blister formation and fracture of these components is very complex and involves hydrogen migration under thermal gradient, hydride precipitation, straining of the matrix, setting up of hydrostatic stress gradient, enhanced hydrogen migration under the combined influence of thermal and stress gradient, stress-reorientation of hydrides [3], cracking of hydrides, crack growth by delayed hydride cracking mechanism [4], interlinking of blisters and spontaneous fracture of the component.

In this work we estimate the stress components in hydride blisters and the surrounding matrix for certain assumed blister depths. The estimated stress predicts the hydride orientation in the matrix surrounding the blisters and will be subsequently used to model the hydrogen diffusion under hydrostatic stress and temperature gradients.

2. Computation

The matrix of dimension in the ratio 1:5 was considered. The matrix material was Zr having hexagonal crystal structure with orthotropic elastic constants [5] and zirconium hydride has faced centered cubic with isotropic elastic constants [6]. Computations were made for axisymmetric case with symmetry axis along direction 2 (Fig. 1) and with hydride/matrix yield strength ratio of 0.2 [7] and 1.0. Transformation of zirconium hydrogen solid solution into hydride is associated with about 17 percent positive change in volume [8]. The body was partitioned into several small layers with each layer transformed sequentially (Fig. 1). Phase transformation was achieved by imposing small temperature rise and using thermal expansion command [9].

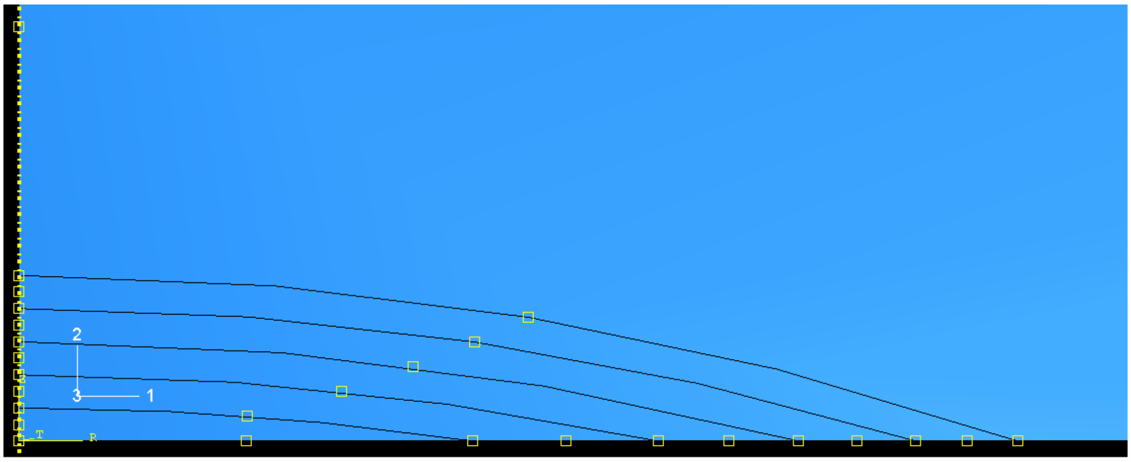

Fig. 1 Part of the body used for computation. Blister aspect ratio of 5 was considered.

3. Results & Discussion

Fig. 2 shows the contour plot of equivalent stress in the blister and matrix around it for the hydride/matrix yield strength ratio of 0.2 [7]. Phase transformation was achieved by raising the temperature. As is evident from this figure most of the regions inside blister and matrix are under negligible stress with a small strip at the boundary between blister and hydride under very high stresses. Since the hydride is having much lower yield strength as compared to matrix, most of the volume change is accommodated inside the blister by hydride plastic flow.

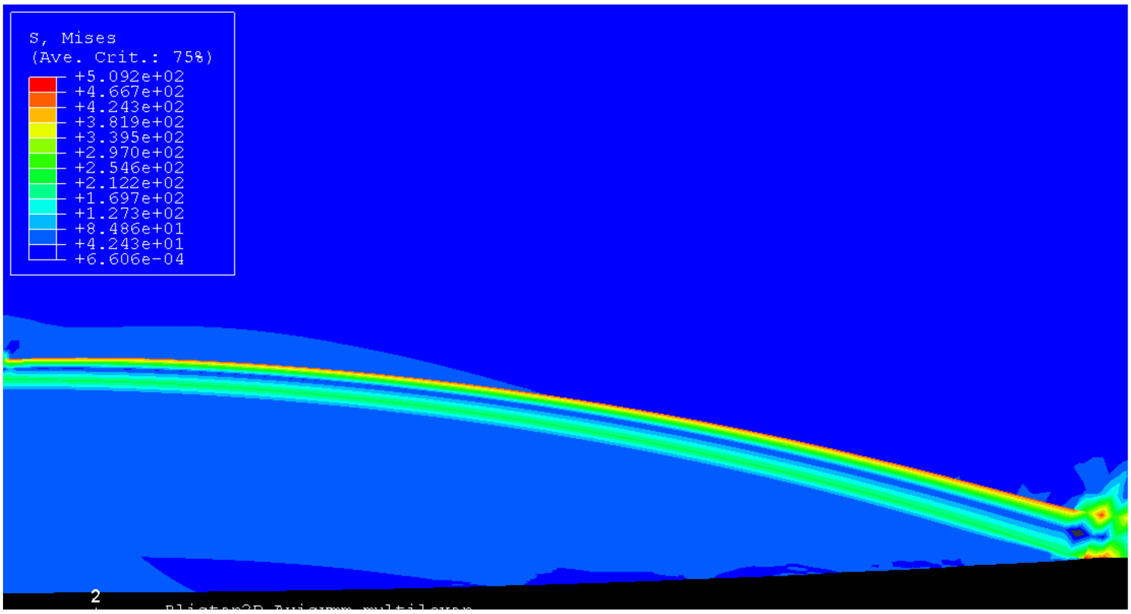

Fig. 2 Contour plot of equivalent stress in the soft blister and matrix around it. Phase transformation achieved in multiple steps.

Fig.3 shows the contour plot of the equivalent stress inside blister and matrix around it with both hydride and matrix having identical yield strength. Phase transformation was achieved by raising the temperature. The maximum value of equivalent stress was observed at the interface between blister and matrix. The stress decays as one move away from the blister matrix interface. All earlier investigations [9-10] on hydride blisters have achieved the phase transformation by raising temperature and allowing the phase transformation of the whole region transforming to hydride in one step. For comparison the contour plot of equivalent stress inside blister and in the matrix around it are shown in Fig. 4. As is evident equivalent stresses in the blister and matrix are higher for single step transformation than that for multistep transformation. Since hydride blister grow sequentially single step phase transformation results in overestimation of stress. For single step transformation elastic, plastic dissipation and total energy are 91, 1369 is 1460 MJ for the whole body (Fig. 1) as compared to 50.9, 1442.6 and 1493.5 MJ, respectively, for multiple step expansion.

Fig.5(a) shows the a section of hydride blister [11]. It is evident from this figure that a section of hydride blister has three regions. Far away from the center of blister lies region I, comprising of matrix and circumferential hydrides (horizontal dark lines). As one approaches the center of blister, region II comprising of matrix, circumferential hydrides and radial hydrides (normal to circumferential ones) can be seen. Region III is the region of single-phase hydride. The texture and microstructure of cold worked and stress relieved Zr-alloy tubes is such that under unstressed condition of hydride precipitation circumferential hydrides form. When hydride precipitation takes place under stress greater than a threshold value, radial hydride may form.

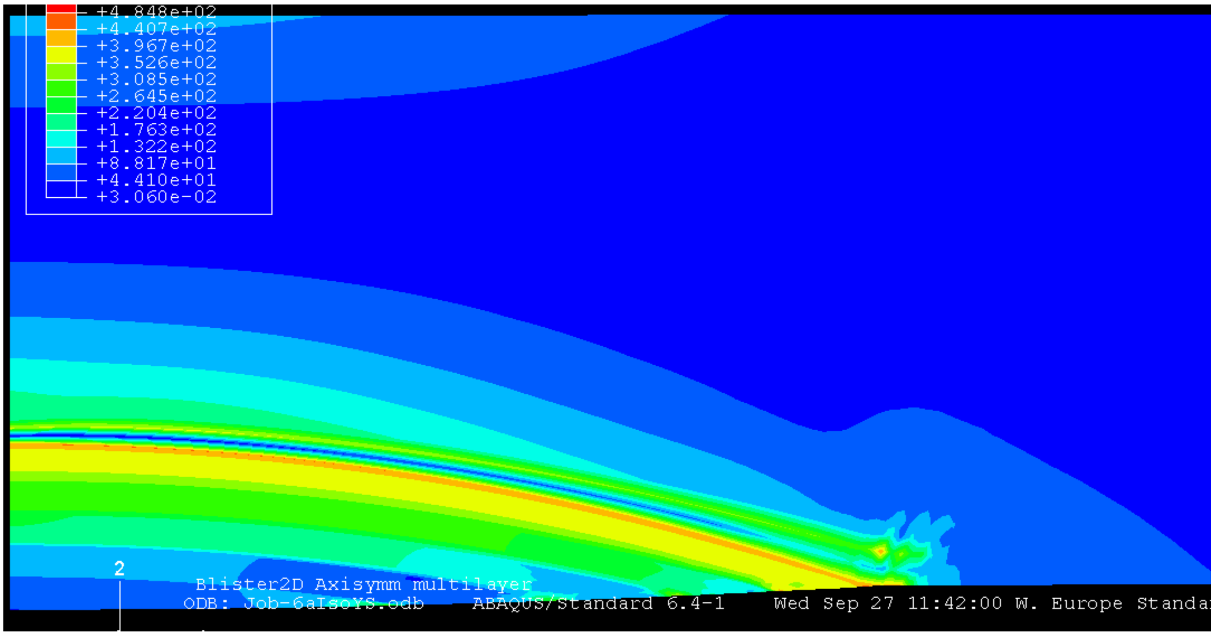

Fig. 3 Contour plot of equivalent stress in the blister and matrix around it for hydride/matrix Yield stress ratio of unity. Phase transformation achieved in multiple steps.

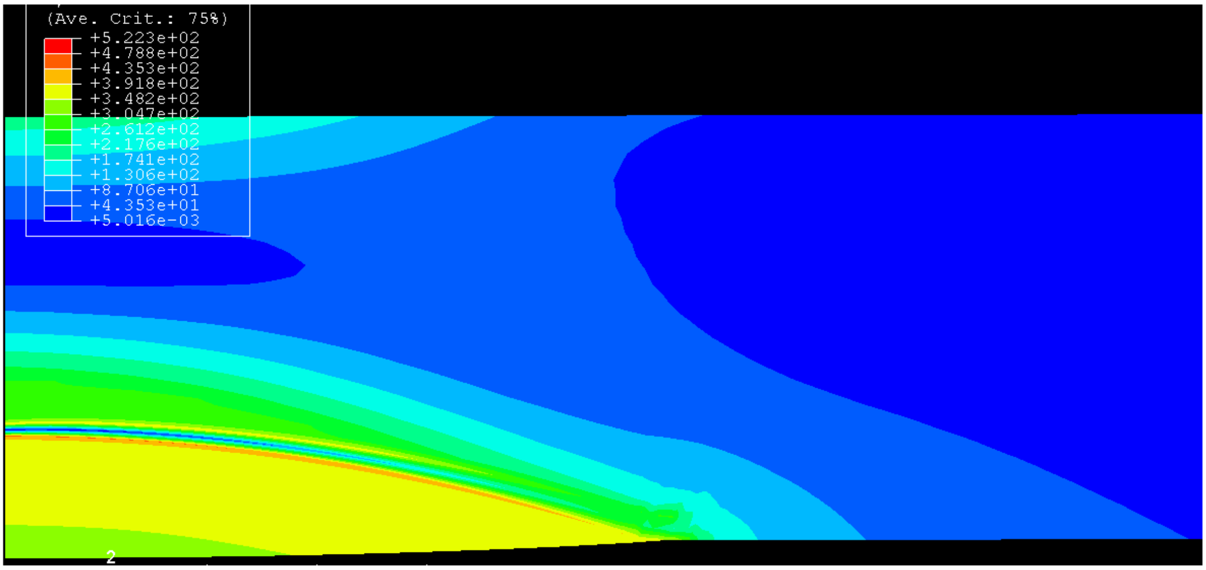

Fig. 4 Contour plot of equivalent stress in the blister and matrix around it for hydride/matrix yield stress ratio of unity. Phase transformation achieved in single step.

In Fig. 5(b), the threshold stress variation across sample thickness is superimposed on the plots of estimated stress for blister depths of 0.2, 0.5 and 1.0 mm. The hydride platelet orientation at any location in the matrix around the blister is governed by the stresses generated due to the hydride blisters. For the regions where tensile stress prevailing at any point in the matrix is greater than the threshold stress for reorientation of hydrides, radial hydride will also precipitate out.

5. Conclusions

Stress field in the hydride blister and Zr-matrix were estimated using finite element method. The estimated stress computed by carrying out the single step transformation of hydride is higher as compared to that obtained by multi-step transformation. The estimated stress field could explain the formation of radial hydride in the matrix near the interface region.

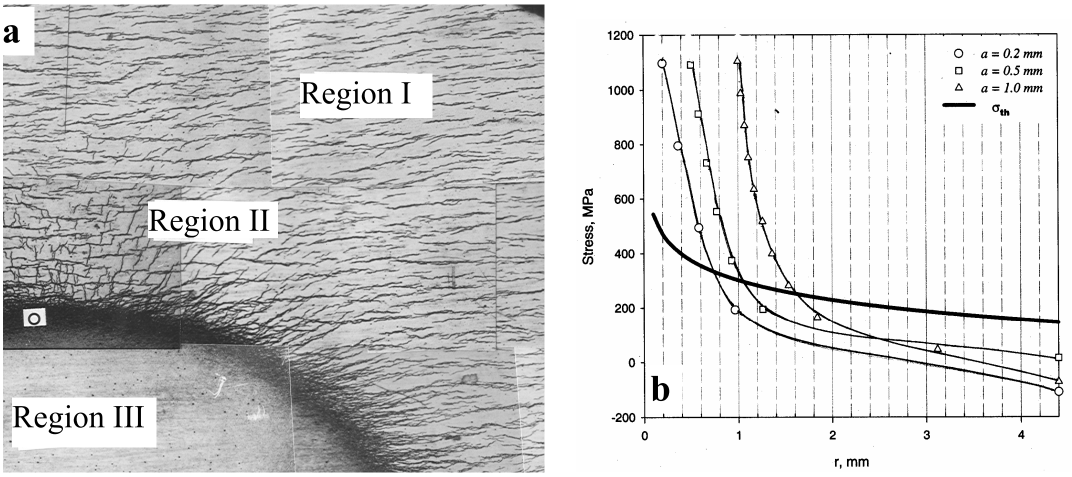

Fig. 5 shows (a) a section of blister in Zr-alloy [11] and (b) Comparison of the estimated stress and threshold stress for reorientation of hydrides across the thickness of the plate used for growing hydride blister.

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References

1. Sawatzky, A., *Can. Metall. Q.*, **24**(3) (1985) 227.
2. Puls, M. P., *Metall. Trans. A*, **19A** (1988) 2247.
3. R. N. Singh, R. Kishore, S. S. Singh, T. K. Sinha and B. P. Kashyap, *Jl. of Nucl. Mater.* **325** (2004) 26.
4. R. N. Singh, Niraj Kumar, R. Kishore, S. Roychowdhury, T. K. Sinha and B. P. Kashyap, *Jl of Nucl. Mater.* **304**, (2002) 189.
5. E. S. Fisher and C. J. Renken, *Phy. Rev. A* **135** (1964) 482.
6. S. Yamanakaa, K. Yoshiokaa, M. Unoa, M. Katsuraa, H. Anadab, T. Matsudac, S. Kobayashic, *Jl. of Alloys & Comp.* **293-295** (1999) 23.
7. M. P. Puls, S. Q-Shi, J. Rabier, *Jl. of Nucl. Mater.* **336** (2005) 73.
8. D. O. Northwood, and U. Kosasih, *Intl. Metals Rev.s*, **28(2)** (1983) 92.
9. Y. J. Kim and M. L. Vanderglas, *Proc. of ASME-PVP conf.*, New Orlearns, USA, June (1985) 161.
10. T. P. Byrne, D. R. Metzger, M. Leger, *Transactions of the 11th international conference on structural mechanics in reactor technology*. Tokyo (Japan). 18-23 Aug 1991. Shibata, Heki (ed.) Atomic Energy Society of Japan. **B** pp. 335-340. (1991).
11. R. N. Singh, R. Kishore, T. K. Sinha, S. Banerjee and B. P. Kashyap, *Mater. Sc. and Engg. A* **339** (2003) 17.