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Interaction between SS-302 and Zircaloy during fuel pin welding

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The interaction between Zircaloy and stainless steel has been investigated in the past and the results have been reported in the literature [1–4]. Earlier studies were made on Zircaloy-2–stainless steel diffusion bonds produced by different methods. In this letter, an attempt has been made to study the interaction which occurs between SS-302 spring and Zircaloy-4 during tungsten inert gas (TIG) welding of small-diameter experimental nuclear fuel pins. The fuel pin consisted of uranium dioxide pellets with SS-302 spring at one end, encased in a Zircaloy-4 clad tube and sealed at both ends by TIG welding of Zircaloy-4 end plugs. During radiographic examination of these welded fuel pins, a dark indication was observed on the radiographs at the point of contact of the plug with the spring in some cases (Fig. 1a). Analysis of the interface was carried out using optical microscopy, micro-hardness testing and energy dispersive spectroscopy (EDAX) and the results are reported.

The experimental fuel pins which showed fusion of the spring with the end plug on the radiograph were isolated and cut open. The springs were cut near the tip leaving a portion inside the plugs.

The specimens were sectioned perpendicular to the cross-section and metallographically prepared. The samples were etched initially by standard Zircaloy etchant [3] and viewed under an optical microscope at 250X. The samples revealed a beta-transformed Zircaloy structure of the plug material and SS-spring (unaffected by the above etchant). The samples were then etched with Glisergia [5]. Beta-transformed Zircaloy structure, diffused zone, crater and step structure of SS-spring are shown in Fig. 1b. Fig. 2a shows a eutectoid type of structure along with micro-cracks in the diffused zone and Fig. 2b shows a bright white intermetallic structure with eutectoid background.

Several micro-hardness indentations were taken on three regions, namely the Zircaloy plug, diffusion zone and SS-spring. The mean value of microhardness was highest on the diffusion zone (54.6 mN/

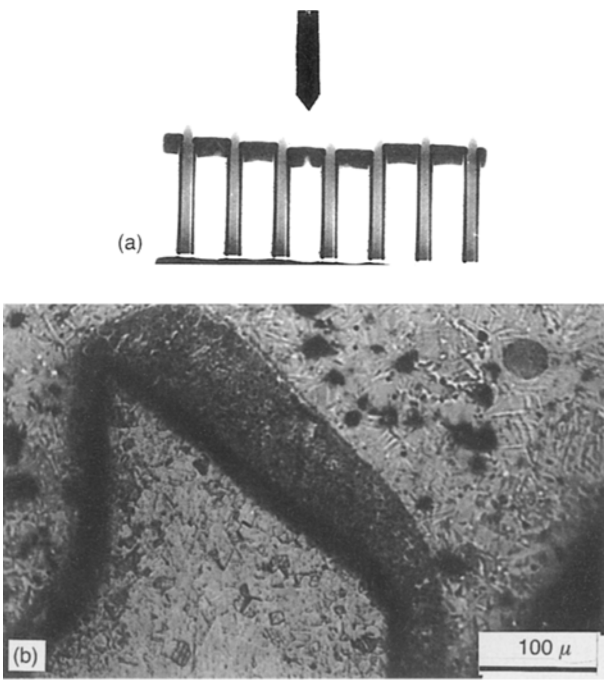

Figure 1 Fusion of SS-spring with Zircaloy endplug: (a) X-radiograph (pin indicated by arrow); (b) photomicrograph.

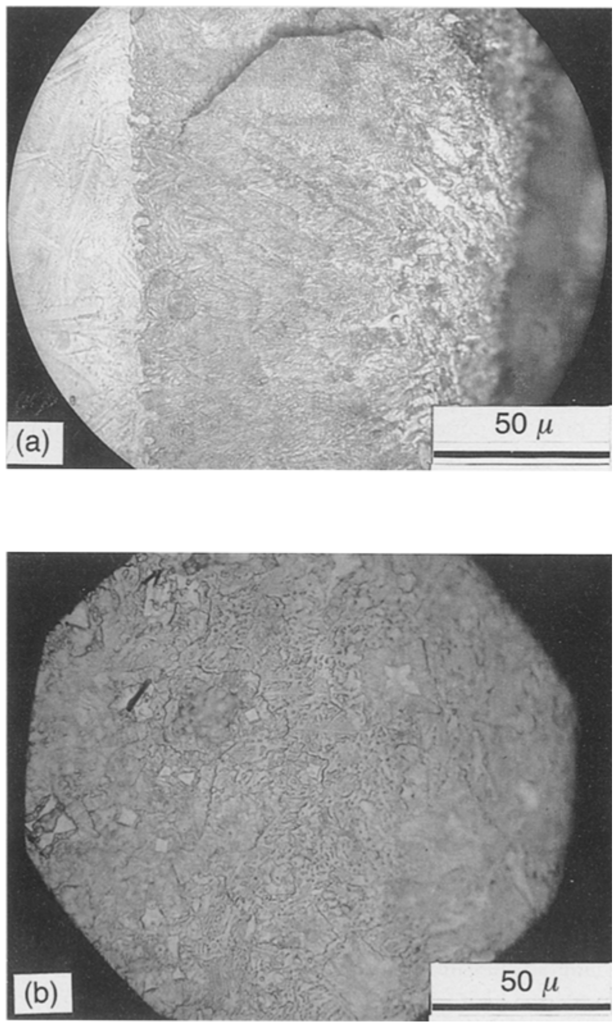

Figure 2 Photomicrograph of the interface showing (a) eutectoid structure and (b) intermetallics.

μm^2, $\sigma = 0.98$) in comparison to the SS-spring (28.6 mN/μm^2, $\sigma = 1.1$) and Zircaloy-4 plug material (22.7 mN/μm^2, $\sigma = 0.93$).

The sample was analysed using scanning electron microscopy(SEM)/EDAX. Spot scanning of the sample at 10 different locations across the SS-spring, diffusion zone and Zircaloy plug was performed. The first point was selected on the SS-spring. Consecutive spots were selected at a regular interval of 20 μm from the previous location except the third and fourth locations. The third and the fourth locations were taken on either side of the boundary formed by the crater between the SS-spring and the diffusion zone. The results of the scan obtained are represented graphically in Fig. 3.

Analysis has shown that the maximum concentration of iron which has diffused into the Zircaloy plug region was 16%. The diffusion of chromium and nickel, however, was less than that of iron.

An iron–Zirconium phase diagram (partly shown in Fig. 4) shows that Zirconium forms a eutectic with 15% iron at 948 ± 5 °C [6]. The micro-structure adjacent to the diffusion zone (Fig. 1b) shows a beta-transformed structure of Zircaloy-4 suggesting that the temperature at the point of contact exceeded 872 °C during welding. At temperatures below 800 °C, the probable phases are intermetallics $FeZr_2$, $FeZr_4$ and saturated alpha-Zirconium. The intermetallic θ($FeZr_4$) along with alpha-Zirconium probably forms the eutectoid. The high value of microhardness (54.59 mN/μm^2) in the diffusion zone suggests the formation of intermetallics. X-ray diffraction studies could not be carried out because the region affected was very small. The extent of the diffusion zone towards the plug side was only 60 μm. This may be due to the short time during which the entire welding cycle is completed (30 s). Formation of micro-cracks and micro-fissures due to thermal stress on cooling after the weld cycle indicates the brittle characteristics of the intermetallic. The crater formed between the diffusion zone and the SS-spring is probably due to differential thermal stress during cooling.

The temperature at the point of contact of the welds, which had shown fusion of the spring with the end plug, probably had exceeded 948 °C leading to a considerable amount of diffusion of iron into the Zircaloy plug and formation of the eutectic. This eutectic, on cooling, gives rise to the formation of eutectoid ($\theta + \alpha$) with traces of bright cuboid precipitates which may be $FeZr_2$ or zirconium carbide [1]. To identify the phases formed correctly, a large number of samples have to be generated under simulated conditions and the atomic ratio of the constituent phases have to be determined from accurate EDAX analysis or electron microprobe analysis.

A judicious choice of welding cycle has to be made so that the temperature at the interface does not exceed 872 °C so as to avoid fusion of the spring with the end plug during fuel pin welding. When the radiographs of the end plug welds are evaluated, one should carefully examine the radiograph for any indication of melting of the Zircaloy plug at the point of contact with the spring.

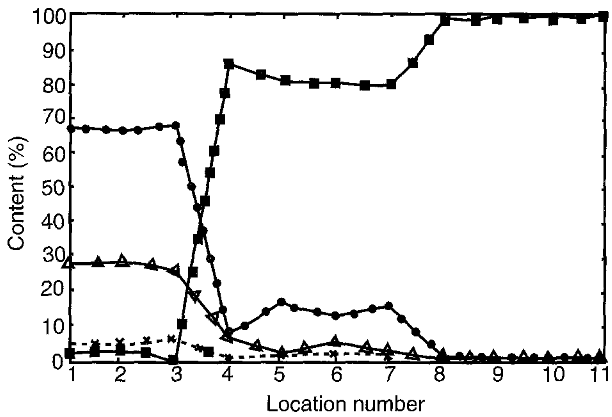

Figure 3 Diffusion profile of different elements at the interface (—•—•— Fe, —△—△— Cr, ···×···×··· Ni, —■—■— Zr).

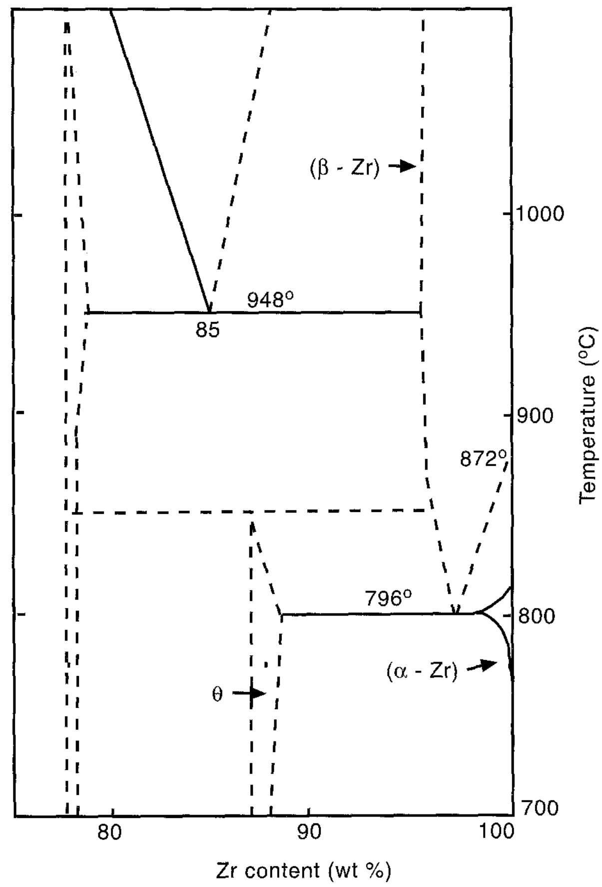

Figure 4 Partial phase diagram of Zr–Fe system.

This study shows that brittle intermetallics are formed during fusion of a stainless spring tip at the point of contact with a Zircaloy plug.

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References

1. G. PERONA, R. SESINI, W. NICODEMI and R. ZOJA. *J. Nucl. Mater.* **18** (1966) 278.
2. B. M. PANDE, R. P. AGARWALA and M. C. NAIK. *ibid.* **28** (1968) 324.
3. R. E. BEAL and J. P. SAPARSTEIN. *Weld. J.* **50** (1971) 2753.
4. S. MISHRA. M. Tech. Thesis submitted to I. I. T. Kharagpur (1992).
5. G. L. KEHL in "The principles of metallographic laboratory practice" (McGraw-Hill, New York, 1949).
6. "Metals Handbook" Vol. 8, 8th Edn (ASM, OHIO, 1973).

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