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Fabrication of simulated plate fuel elements: Defining role of stress relief annealing

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ABSTRACT

This study involved fabrication of simulated plate fuel elements. Uranium silicide of actual fuel elements was replaced with yttria. The fabrication stages were otherwise identical. The final cold rolled and/or straightened plates, without stress relief, showed an inverse relationship between bond strength and out of plane residual shear stress (τ_{13}). Stress relief of τ_{13} was conducted over a range of temperatures/times (200–500 °C and 15–240 min) and led to corresponding improvements in bond strength. Fastest τ_{13} relief was obtained through 300 °C annealing. Elimination of microscopic shear bands, through recovery and partial recrystallization, was clearly the most effective mechanism of relieving τ_{13}.

1. Introduction

Plate fuel elements are widely used in high flux research reactors involved in the production of radioisotopes, irradiation studies, etc. [1–7]. Roll bonding is the usual fabrication route [1,3–8]. The final cold rolled plate is expected to have high stress gradients. This has been shown through simulations [9–11], as well as with experimental observations on plate fuels [12,13] and also in accumulative roll bonding [14,15]. A preceding study [13] has shown that such stress gradients are mainly in terms of out of plane residual shear stress (τ_{13}). A direct correlation between τ_{13} and bond strength between, aluminum cladding and simulated fuel meat (of aluminum and yttria particles), was also indicated. The stress relief process, typically given at the end of fabrication, is a topic of considerable academic/applied interests [9,16–18]. Because of its apparent correlation with bond strength [12,13], stress relief is naturally of concern to the fabrication of plate fuel elements. However, comprehensive studies relating stress relief with property (such as bond strength) changes and microstructural developments are virtually non-existent. It was hence decided to initiate the present study: role of stress relief on bond strength and microstructural developments.

An earlier study [13], as well as the present one, explored fabrication of simulated plate fuel elements. Yttria (Y_2O_3) replaced uranium silicide as surrogate fuel in a typical (Fig. 1a) picture-frame assembly. The fabrication stages (Fig. 1b) were otherwise identical. The preceding study [13], by the same team, had documented aspects of microstructural developments at all (except stress relief) fabrication stages. This study, on the other hand, tries to rationalize careful observations on residual stresses with developments in microstructures and bond strength.

2. Experimental details

Fig. 1a shows the schematic of a picture-frame assembly. Composition of AA6061 cladding plates is given in Table 1. Surrogate fuel meat consisted of a compact: aluminum and yttria (Y_2O_3) particles (60:40 by volume) of 20–100 μm size. This was cold compacted at 900 MPa stress and a density of ⩾95%. Y_2O_3 is selected as surrogate fuel instead of actual uranium silicide (U_3Si_2). The two materials have similar elastic modulus and coefficient of thermal expansions. It may also be noted that a preceding study [13], in the same journal, used this surrogate fuel and made observations on plastic deformation. The present manuscript, on the other hand, focuses on the stress relief annealing: the final stage of plate fuel fabrication. Fig. 1b shows the process flow sheet used. Readers may find further description in Ref. [13]. The final cold rolling was often followed by industrial straightening operation [18]. The straightening consisted of 10 set of rolls placed on a rolling table. This provided cyclic, albeit alternating, bending but did not impose reductions in thickness. The final plates were subjected to stress relief (followed by furnace cooling with similar cooling rates

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Abbreviations: AA, Aluminum Association; ASTM, American Society for Testing and Materials; EBSD, Electron Backscattered Diffraction; RD, Rolling Direction; ND, Normal Direction; TD, Transverse Direction; GIXRD, Grazing Incidence X-Ray Diffraction; XEC, X-ray Elastic Constant; FEG, Field Emission Gun; SEM, Scanning Electron Microscope; OIM, Orientation Imaging Microscopy.

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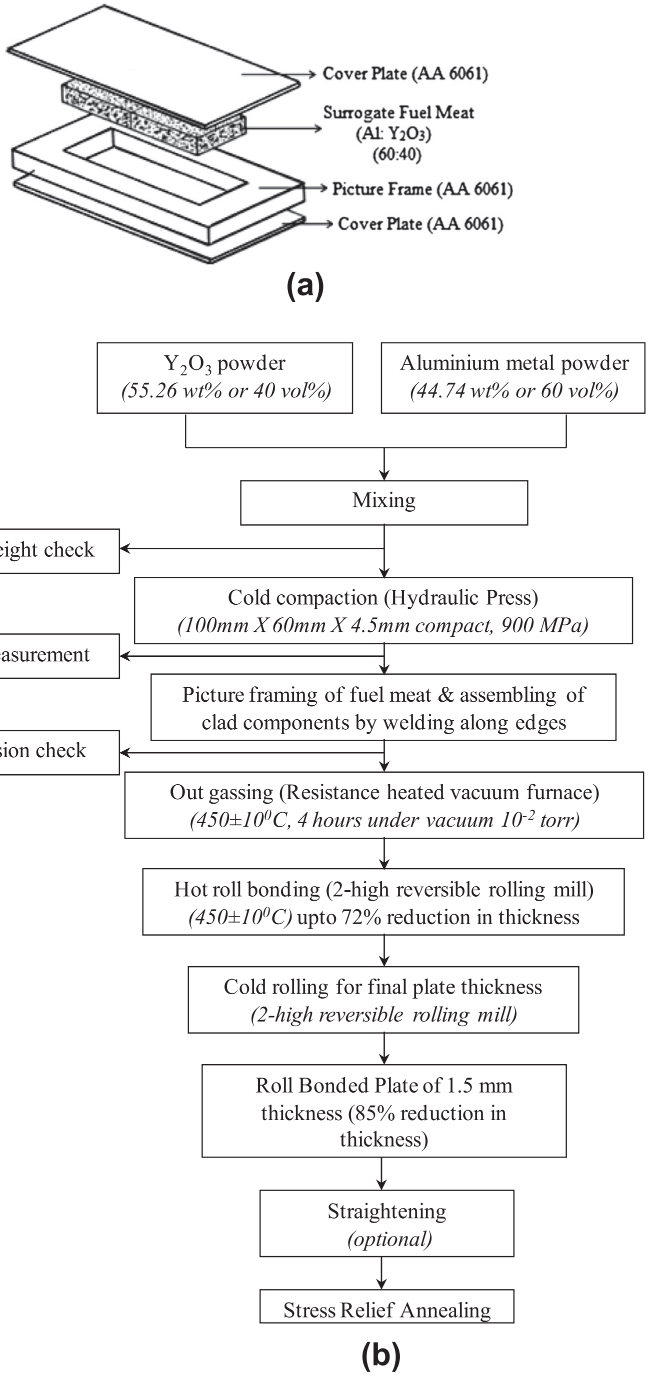

Fig. 1. (a) Schematic showing typical picture-frame assembly. This included aluminum (AA6061) cladding (cover plate and picture frame) and surrogate fuel meat. The latter consisted of 60:40 (by volume) aluminum and yttria (Y_2O_3) cold compacted powder. (b) Process flow sheet for simulated plate fuel fabrication. In the actual plate fuel fabrication, Y_2O_3 is replaced with uranium silicide (U_3Si_2). Process flow sheet is otherwise identical.

Table 1
Composition of AA6061 in wt.% alloying elements.

Mg	Si	Mn	Fe	Cu	Cr	Zn	Ti	Al
1	0.67	0.19	0.20	0.30	0.024	0.015	0.022	97.57

of 0.7 °C/min) at various temperatures (200 °C, 300 °C, 400 °C and 500 °C) and times (0, 15, 30, 60 and 240 min).

Mid-width sections of the rolled plates, with and without stress relief, were taken for peel tests. This was carried out with ASTM D1876-01 standard [19], after proportionately scaling down one quarter in all the dimensions. At least three samples were measured. Limited numbers of samples were also subjected to pull test [20]. This established, also shown in Ref. [13], a similar trend between peel and pull test data.

Characterization involved residual stress and EBSD measurements. Stress measurements were made with appropriate depths of X-ray penetration (to be discussed latter) of the rolling plane (plane containing RD and TD). On the other hand, EBSD scans were taken on the long-transverse section (containing RD and ND). EBSD samples were prepared by standard metallography followed by electropolishing. Electropolishing involved an electrolyte of