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MICROSTRUCTURAL CHARACTERIZATION OF ADVANCED FERROUS ALLOYS EXPOSED TO LIQUID SODIUM

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The property requirements for breeder reactor fuel cladding materials are extremely stringent. Ideally, a fuel cladding material should have high creep strength, ductility, swelling resistance and good corrosion resistance to flowing sodium and no undesirable second phase precipitation at reactor operating temperatures. The alloy AISI 316 has shown excellent performance at low fluence levels and has fairly good properties at intermediate fluence levels. This material is the current reference alloy for fast breeder reactor fuel cladding; expected limitations to its performance at high fluence levels have prompted development of improved cladding alloys for future reactor applications.

Alloys with low sodium corrosion rates are required to avoid loss of strength from wall thinning at reactor operating temperatures. The present paper describes the data obtained on eight commercial cladding alloys including the reference alloy.

The sodium compatibility screening tests were carried out in Source Term Control Loop Number 4 and WHIRL-1 at 700°C for 2000 hours at a sodium velocity of 6m/s and and oxygen content in sodium of 1 ppm. After sodium exposure, the alloy samples have been weighed to determine the sodium-corrosion rates. The corroded surfaces have been characterized by SEM associated with energy dispersive X-ray analysis. Optical metallography and electron microprobe analysis were performed on sections of these alloys to determine the subsurface structural and compositional changes.

A summary of the sodium corrosion observations for each alloy is presented in Table 1. Based on the corrosion rates and surface morphologies, three different types of sodium-induced corrosion were observed.

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As noted, the two alloys (A-286 and Inconel 706) which show the lowest corrosion rate also exhibit similar morphological features after sodium exposure, i.e., grain-orientation dependent dissolution giving rise to lamella-type surface formations (Figure 1). For each material, surface depletion of Ti, Cr, and Ni has been observed; in addition, surface depletion of Al and Nb has been observed in Inconel 706, penetrating to a depth of 10μm.

Alloys Nimonic PE16, AISI 316, M-813 (sintered) and Inconel 718 exhibit a somewhat higher (intermediate) sodium corrosion rate. Molybdenum-rich node formations containing Fe with lesser amounts of Cr and Ni, which appear to be resistant to sodium corrosion, appear on the exposed surface (Figure 2). Analysis of the nodes extracted from the surface indicated these particles to be of Fe_2Mo Laves phase. In addition, the X-ray intensity data indicated the molybdenum enrichment of the surface to be a function of not only the molybdenum concentration of the alloy, but also the corrosion rate of the alloy. An equally important feature to note is that the alloys which contain Ti, Al, Cr, and Ni (PE16, M-813, and Inconel 718) also show evidence of grain boundary attack and hole formations after sodium exposure, suggesting the removal of a specific phase or compound. Specifically, grain boundary attack to a depth of ∿10μm has been observed for Nimonic PE16 and somewhat greater attack (to a depth of 20μm) has been observed for M-813. Severe "pocket attack" to a depth of 40μm has been observed for Inconel 718. As expected, a ferritic surface, approximately 4-5μm thick is found on the AISI 316 reference material.

Finally, alloys AISI 310 and 330 appear to corrode in sodium at the highest rate and the corroded surface is characterized by "scale-like" formations, and the micron-size holes located at grain boundaries again suggest the loss of a specific phase or compound (Figure 3). The elements Si, Cr, Ni, and possibly Mn appear to be surface depleted.

The average depth of the depleted zone calculated from the microprobe traces of these alloys is approximately 5μm. Composition profiles for one of the alloys (Nimonic PE16) are given in Figures 4 and 5. As can be seen from the figures, there is an excellent agreement between the SEM data and the microprobe data.

It can be concluded that A-286, Inconel 706, and Nimonic PE16 are highly promising commercial alloys for cladding purposes based on their corrosion resistance. Additional factors such as swelling behavior and mechanical properties must also be considered in alloy selection.

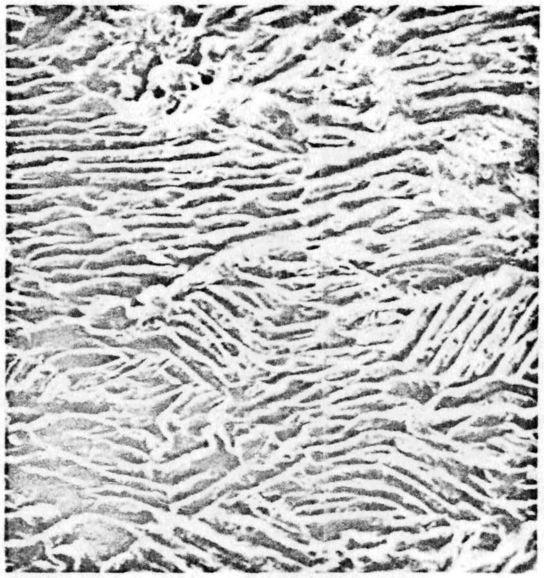
TABLE 1

SUMMARY OF SODIUM CORROSION OBSERVATIONS				
Alloy	Corrosion Features 2000 hr/700°C		Major Elements Depleted [2]	Corrosion Rate mils/year
A - 286	Lamellae Formations	Lamellae are Grain Orientation Dependent	Ti, Cr, Ni	0.18
Inconel 706		Lamellae as Above; Grain Boundary Attack to 10 μm	Al, Nb,Ti,Cr,Ni	0.27
Nimonic PE16	Mo - Rich Corrosion Resistant Formations	Grain Boundary Attack to a Depth of ~ 10 μm	Al, Ti, Cr, Ni	0.37
AISI 316		Ferritic Surface, 4-5 μm	Cr, Ni, Mn	0.45
M - 813 [1]		Micron Size Holes; Inter-granular Attack to 20 μm	Al,Ti, Cr, Ni	0.90
Inconel 718		Severe "pocket attack" to ~ 40 μm	Al, Ti, Cr, Ni	1.3
AISI 310	Scale - Like Formations	Regular Shape Micron Size Holes at Grain Boundaries; General Surface Attack	Si, Cr, Ni	1.5
Alloy 330			Si, Cr, Ni, (Mn)	1.8

(1) Sintered Alloy
(2) Iron is Also Lost During the Corrosion Process

INCONEL 706

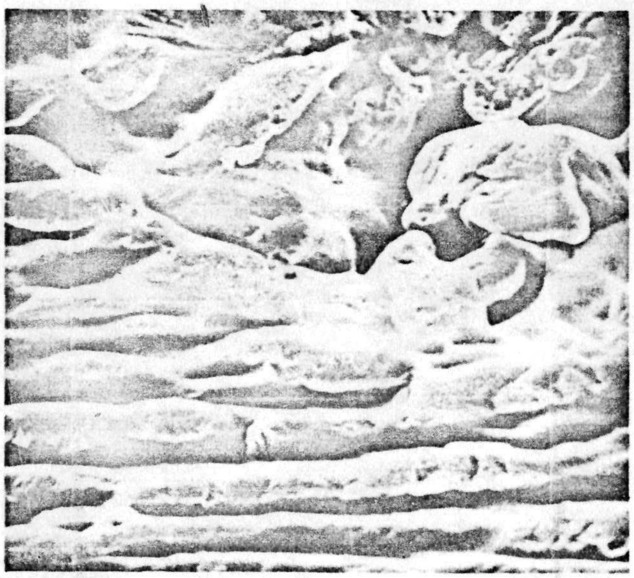
Sodium Exposed / 2000 hr / 700°C



OD Surface

20 μm

Transverse / OD



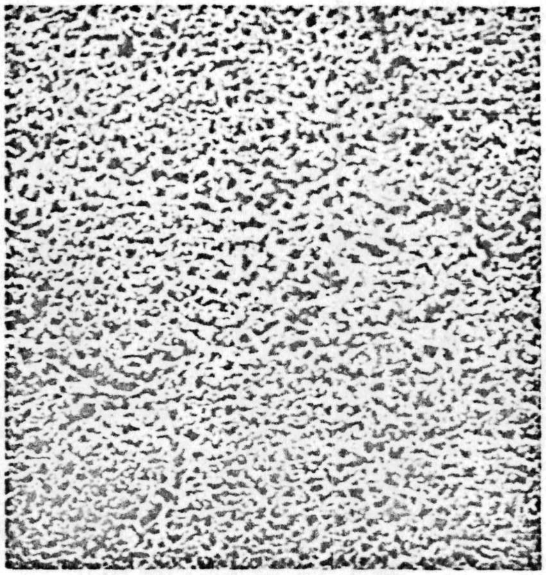
5 μm

Lamellae Formations and Localized Attack

FIGURE 1

NIMONIC PE 16

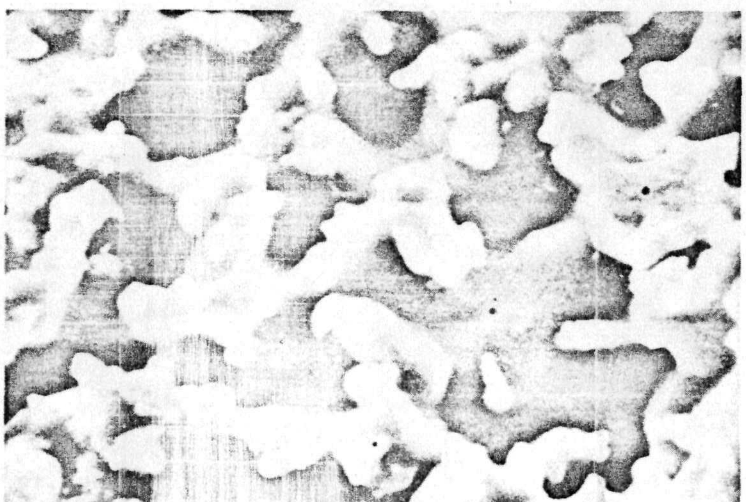
Sodium Exposed / 2000 hr / 700°C



OD Surface

Transverse/OD

20 µm



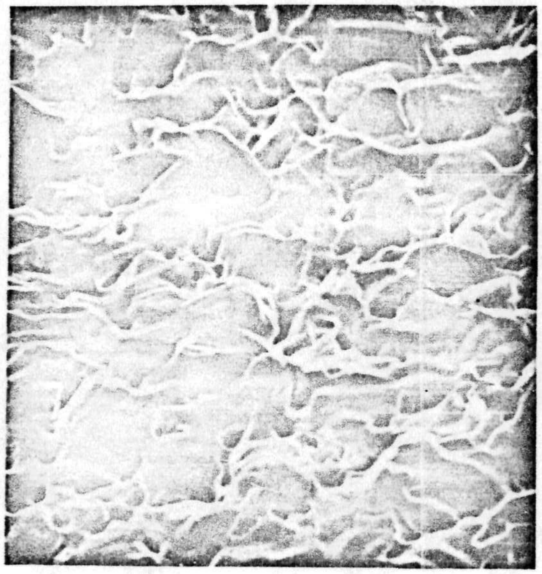
2 µm

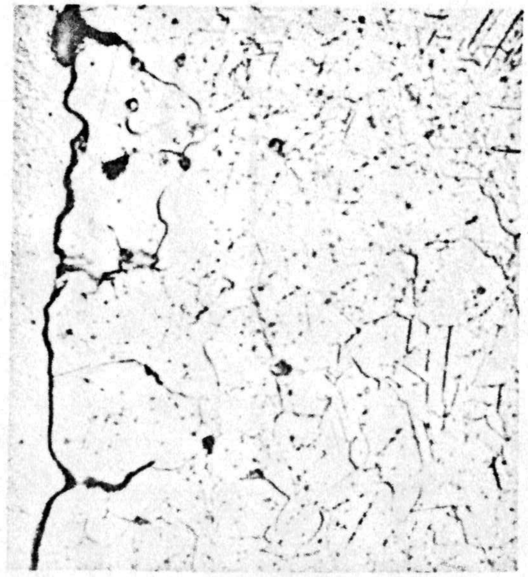
Mo-Rich Corrosion Resistant Phase

FIGURE 2

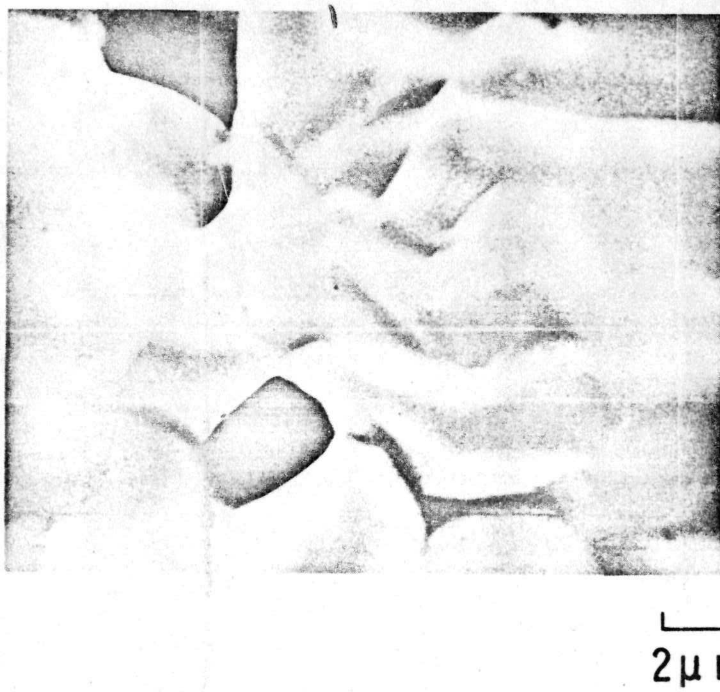
ALLOY 330

Sodium Exposed / 2000 hr / 700°C





OD Surface — 20 μm — Transverse / OD



2 μm

Deep Intergranular Holes

FIGURE 3

CONCENTRATION PROFILE OF PE16

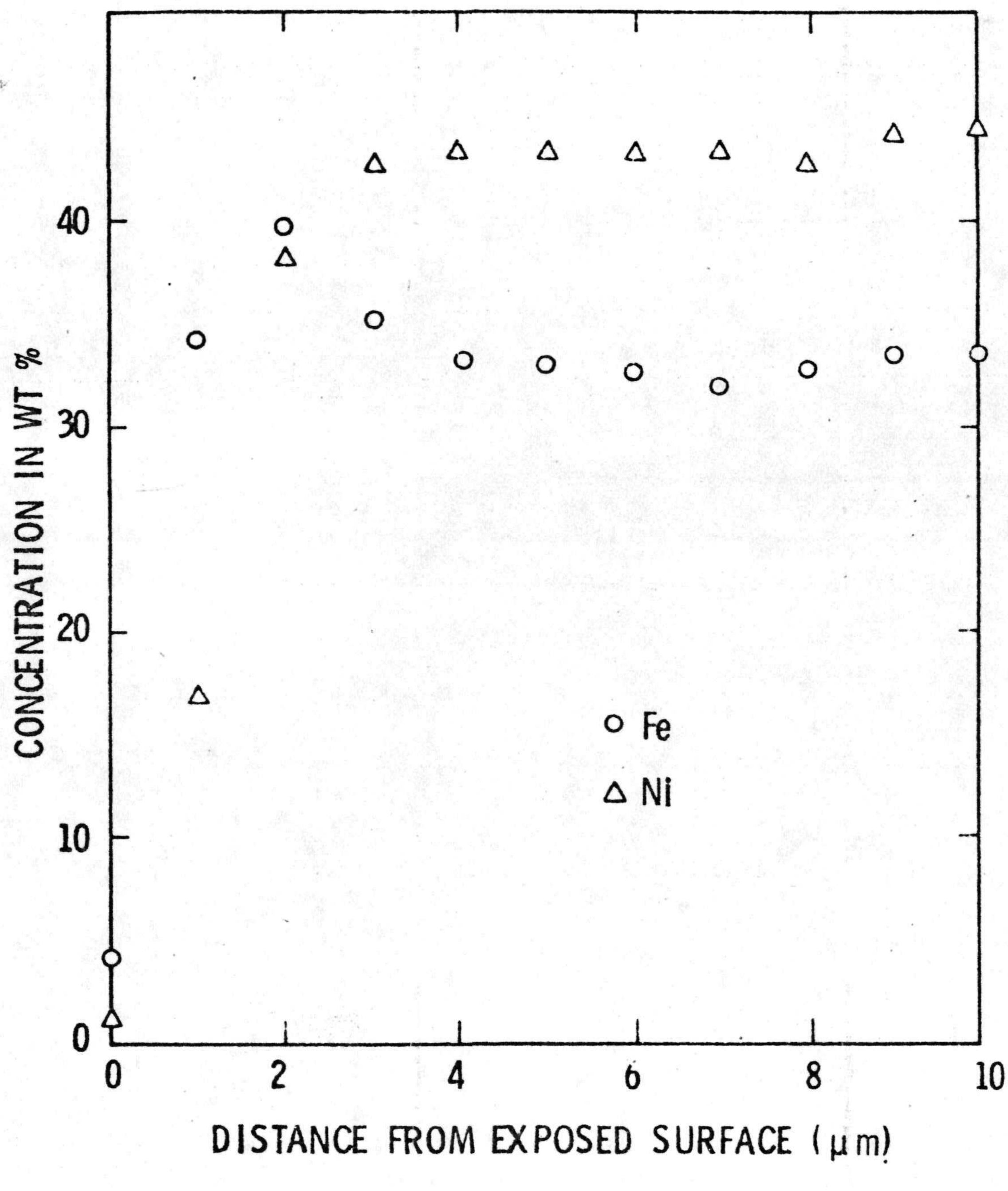


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FIGURE 4

CONCENTRATION PROFILE OF PE16

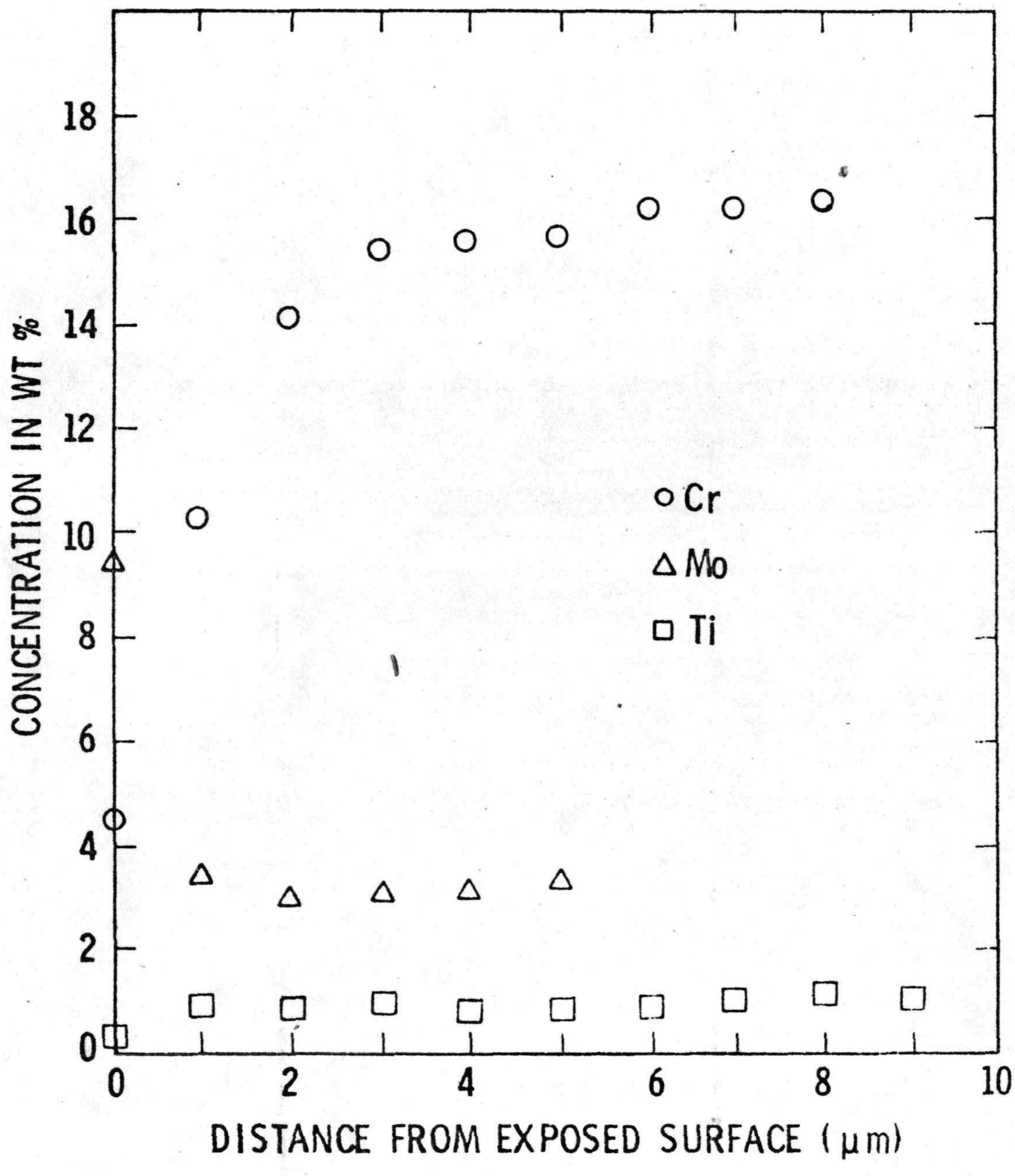

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FIGURE 5