Conf-921102--4

WSRC-MS--92-181

DE92 015884

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A paper proposed for presentation at the
1992 ANS/ENS International Conference
Chicago, IL
November 15 - 20, 1992

and publication in the proceedings

This paper was prepared in connection with work done under Contract No. DE-AC09-89SR18035 with the U. S. Department of Energy.

EVALUATION OF LIQUID METAL EMBRITTLEMENT OF SS304 BY CD AND CD-AL SOLUTIONS

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Submitted to:
The 1992 ANS/ENS International Conference
15-20 November 1992
Chicago, IL

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INTRODUCTION

The susceptibility of stainless steel 304 to liquid metal embrittlement (LME) by cadmium (Cd) and cadmium-aluminum (Cd-Al) solutions was examined as part of a failure evaluation for SS304-clad cadmium reactor safety rods which had been exposed to elevated temperatures.[1,2] The active, or cadmium (Cd) bearing, portion of the safety rod consists of a 0.756" diameter aluminum alloy (Al-6061) core, a 0.05" thick Cd layer, and a 0.042" thick Type 304 stainless steel cladding. The safety rod thermal tests were conducted as part of a program to define the response of reactor core components to a hypothetical LOCA for the Savannah River Site (SRS) production reactors. LME was considered as a potential failure mechanism based on the nature of the failure and susceptibility of austenitic stainless steels to embrittlement by other liquid metals.

The term liquid metal embrittlement (LME) may be used to denote a wide range of liquid metal degradation phenomena. In the context of this evaluation, the term LME is used only to refer to the "classic" LME degradation mode; other liquid metal degradation phenomena, such as dissolution or the formation of intermetallics, were treated as separate mechanisms. Classical LME can be described as an adsorption-induced reduction in cohesive strength such that a crack nucleates and propagates faster or at lower stresses than in an inert environment, although a comprehensive mechanistic description of LME has not been developed to date.[3,4,5]

It is important to note that it is impossible to prove that a given solid-liquid metal couple is completely immune to LME, and the available literature suggests that any couple might be subject to LME given the right combination of test conditions. Therefore, the relevant issue examined in this evaluation is the likelihood of susceptibility under conditions relevant to the safety rod thermal tests and hypothetical LOCA.

RESULTS

Literature Evaluation

Only two experiments have been reported in the literature which examined the susceptibility of austenitic stainless steels to LME by liquid or solid Cd; in neither case was embrittlement observed. Old[3] discusses experiments with austenitic stainless steel (SS302) and solid Cd for temperatures between 200°C and the melting point of Cd (321°C). The composition of SS302 is similar to that of SS304, but SS302 has a slightly higher carbon concentration (0.15 vs. 0.08%); SS304 would be expected to be somewhat more resistant to embrittlement than SS302 since its yield strength is slightly lower. Dityatkovskiy et al.[6] tested the susceptibility of a normalized austenitic stainless steel (1Kh18N9T) to embrittlement by liquid Cd from 300 to 700°C at a strain rate of 2.7×10^{-3} sec^{-1}. Normalized steels, where the heat treatment utilizes a faster cooling rate than full annealing, have a higher strength than the fully annealed form and thus would be more susceptible to LME. No evidence for LME of austenitic stainless steel was found in the experiments reported by Dityatkovskiy et al. or Old. Furthermore, high strength steels were also tested as part of both experimental studies, and the susceptibility of high strength steels to embrittlement by liquid and solid Cd was clearly demonstrated; the susceptibility of high-strength steels (e.g. AISI 4130, 4140 and 4340) to embrittlement by both solid and liquid cadmium has been demonstrated in a number of other experiments.[3,4] These same steels have not exhibited embrittlement when the applied heat treatment resulted in lower yield strengths or when they are in the annealed condition. The Al-Hg system exhibits analogous behavior.[7]

Aluminum and the constituent elements of austenitic stainless steel (Fe, Ni and Cr) stainless steels form intermetallics and liquid aluminum can dissolve large amounts of these elements. It is therefore unlikely that Al would cause LME of austenitic stainless steel, and the available experimental evidence supports this conclusion.[4,8] Based on the "inert carrier" concept,[4,9] it is possible that small amounts of Al dissolved in liquid Cd might cause LME of SS despite the fact the liquid Al does not. However, small additions of Al (< 0.55%) or Ni (< 2%) have been shown to have no significant effect on the susceptibility of high strength steels to embrittlement by liquid Cd.[4]

U-Bend Tests

The U-bend tests is normally considered a screening test for LME susceptibility since the matrix is not being actively strained during the test; active straining of the matrix while in contact with the liquid metal insures that protective films are mechanically disrupted. However, the surface of the U-bend coupons were sanded just prior to immersion in the liquid cadmium to remove the protective oxide film. Two tests were conducted at 600°C, and a single test was run at 500°C. Destructive examination showed no evidence of cracking or attack of the surface by liquid cadmium.

Tensile Tests

The tensile test experimental conditions and results are summarized in Table 1. The specimens were machined from mil-annealed SS304 bar stock 0.625" in diameter. The machined gauge length and diameter were 2.00" and 0.35", respectively. The notched specimens had a notch diameter of 0.252" and a notch root radius of 0.007". The "fast" strain rate (3×10^{-3} min^{-1}) bounds the highest safety rod cladding strain rate predicted for a LOCA; susceptibility to LME generally increases with increasing strain rate. Fast strain rate tests were conducted from 325 to 600°C. The "slow" strain rate (8×10^{-5} min^{-1}) is a lower bound for the safety rod thermal tests; only one set of air and liquid metal tests at 550°C was conducted at this strain rate since it was expected to give lower LME susceptibility. A single test was conducted in Cd-Al at 550°C with a strain rate of 9×10^{-4} min^{-1} as part of the test procedure development. Notched specimen tests were included to examine the effect of triaxial loading on LME susceptibility. Only one set of air and liquid metal tests at 550°C was conducted with notched specimens; all other tests were conducted with smooth tensile specimens. The tests in air were conducted to obtain baseline tensile properties. Liquid Cd with dissolved Al-6061 was employed as the liquid metal solution since this reproduces the conditions in the safety rod thermal tests. A single test at 550°C in pure Cd was conducted for comparison to the 550°C test in Cd-Al. The tests in liquid metal were conducted by affixing a stainless steel cup to the bottom tensile grip, and loading the cup with the desired material. A stainless steel muffle or bellows was affixed over the top end of the specimen to limit Cd loss during the tests.

The tensile property data are in good agreement with those reported in the literature for these conditions.[10,11] The yield and ultimate strength data indicate that the tensile specimens had approximately 4 to 6% CW introduced by straightening operations on the bar stock;[12] the stainless steel cladding on the safety rods had 6% CW introduced by swaging during manufacture. The ratio of the total elongation, yield strength and ultimate tensile strength (UTS) data for the liquid metal tests to those conducted in air are shown in Figure 1. As can be seen, no reduction in ductility or strength was observed for the tensile tests in liquid metal solution relative to those in air for either strain rate employed or with the notched specimens. The load-displacement curves for these tests are essentially identical.

CONCLUSIONS

The experimental data demonstrate that SS304 is not susceptible to embrittlement by liquid metal Cd or Cd-Al solutions for temperatures of 325 to 600°C and strain rates 8×10^{-5} to 3×10^{-3} min^{-1}. The literature evaluation supports this conclusion. However, it is recognized that a set of experimental conditions (temperature, strain rate, and loading geometry) outside the range examined here could potentially result in LME.

ACKNOWLEDGEMENTS

The information contained in this abstract was developed during the course of work under Contract No. DE-AC09-89SR18035 with the U.S. Department of Energy.

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Table 1 Tensile Test Data.

Spec. No.	Spec. Type	Environ-ment	Strain Rate (min^{-1})	Temp. (°C)	Yield Strength (ksi) [b]	Ultimate Strength (ksi)	Uniform Elong. (%) [a]	Total Elong. (%) [a]	R.A. (%)
17	Smooth	Air	3e-03	325	41.6	79.1	33.2	39.0	69.8
19	Smooth	Air	3e-03	325	41.4	79.4	33.2	39.6	70.7
7	Smooth	Air	3e-03	400	34.7	76.5	35.3	42.2	70.1
8	Smooth	Air	3e-03	400	38.3	78.5	35.0	38.5	69.7
9	Smooth	Air	3e-03	500	33.5	74.6	35.0	41.1	67.5
10	Smooth	Air	3e-03	500	33.2	73.8	34.8	38.5	68.0
12	Smooth	Air	3e-03	550	31.3	71.3	31.0	36.3	68.8
14	Smooth	Air	3e-03	550	30.8	71.4	34.3	41.5	68.6
15	Smooth	Air	3e-03	600	32.4	63.1	25.3	38.3	66.2
16	Smooth	Air	3e-03	600	30.6	62.1	26.0	39.2	66.9
38	Smooth	Air	8e-05	550	32.2	60.8	23.6	29.8	42.2
2	Notched	Air	[c]	550	-------	91.4	-------	-------	-------
3	Notched	Air	[c]	550	-------	90.3	-------	-------	-------
20	Smooth	Cd-Al	3e-03	325	37.9	78.7	36.8	41.8	[d]
21	Smooth	Cd-Al	3e-03	400	37.9	77.5	35.1	38.8	[d]
22	Smooth	Cd-Al	3e-03	500	34.3	75.3	33.6	39.9	[d]
13	Smooth	Cd	3e-03	550	33.3	70.6	30.8	38.1	[d]
18	Smooth	Cd-Al	3e-03	550	32.2	69.7	33.[illegible]	40.7	[d]
23	Smooth	Cd-Al	3e-03	600	32.2	60.3	26.2	44.3	[d]
25	Smooth	Cd-Al	9e-04	550	33.3	68.7	31.2	37.7	[d]
26	Smooth	Cd-Al	8e-05	550	33.8	61.4	24.3	30.2	[d]
1	Notched	Cd-Al	[c]	550	-------	90.6	-------	-------	[d]

Notes:
- [a] Gauge length = 2", gauge diameter to length ratio = 5.7.
- [b] Yield corresponds to a 0.2% offset on the strain axis.
- [c] Crosshead speed as for the smooth bar tests with a strain rate of 3E-3 min^{-1}.
- [d] Reduction in Area values unavailable for the liquid metal tests.

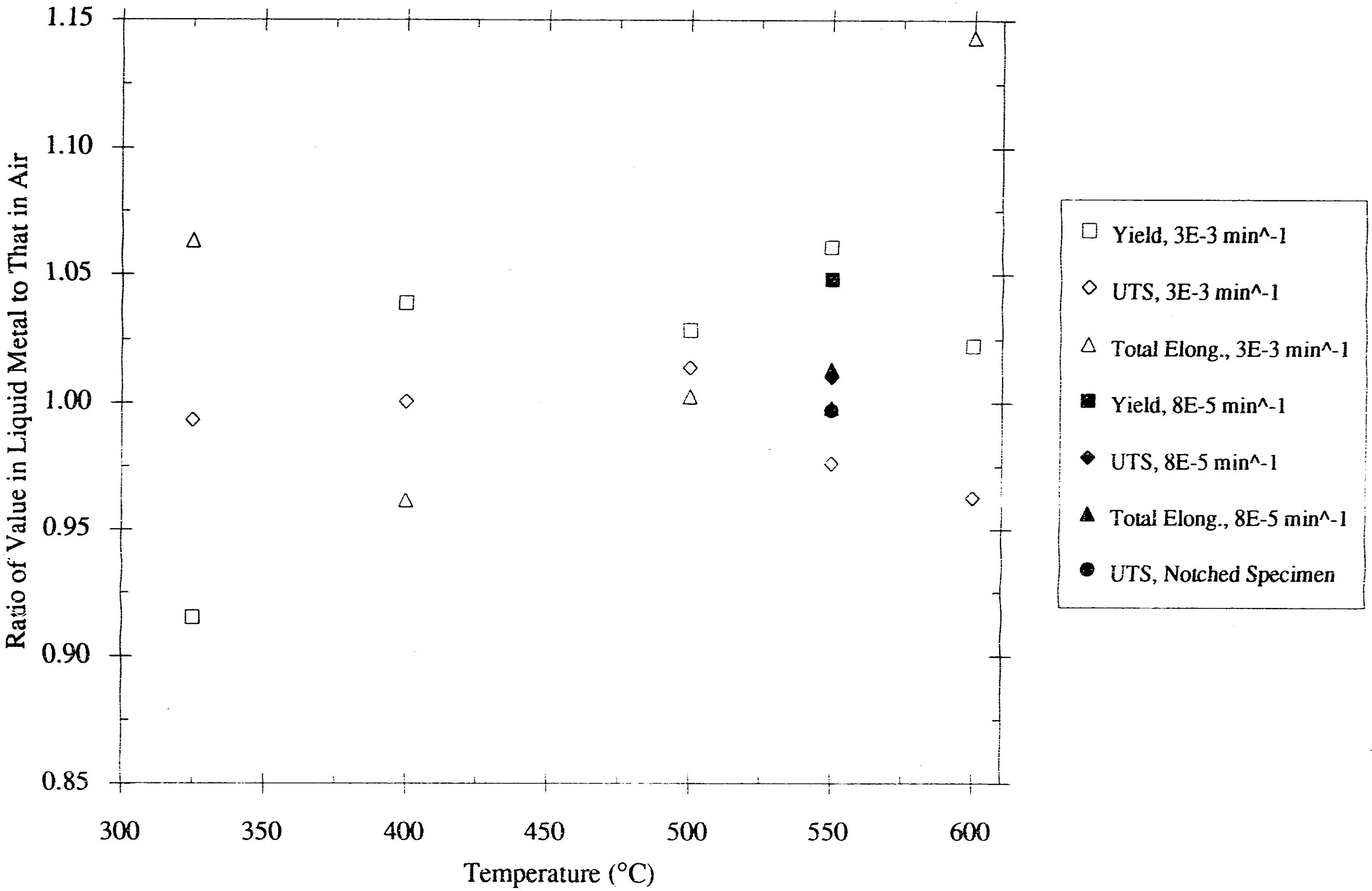

Figure 1 Comparison of Tensile Properties in Liquid Metal and in Air.

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