AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

Conf-920673--24

**DEGRADATION OF MECHANICAL PROPERTIES OF STAINLESS
STEEL CLADDING DUE TO NEUTRON IRRADIATION AND THERMAL AGING***

Fahmy M. Haggag

**Metals and Ceramics Division
OAK RIDGE NATIONAL LABORATORY
P.O. BOX 2008
Oak Ridge, TN 37831-6151**

*Research sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, under Interagency Agreement DOE 1886-8011-9B with the U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-84OR21400. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED 875 ✓

Fahmy M. Haggag¹

**DEGRADATION OF MECHANICAL PROPERTIES OF STAINLESS STEEL
CLADDING DUE TO NEUTRON IRRADIATION AND THERMAL AGING**

REFERENCE: F. M. Haggag, "Degradation of Mechanical Properties of Stainless Steel Cladding Due to Neutron Irradiation and Thermal Aging," *Effects of Radiation on Materials: 16th International Symposium, ASTM STP 1175*, Arvind S. Kumar, David S. Gelles, Randy K. Nanstad, and Edward A. Little, Eds., American Society for Testing and Materials, Philadelphia, 1993.

ABSTRACT: Thermal aging of three-wire series-arc stainless steel weld overlay cladding at 288°C for 1605 h resulted in an appreciable decrease (16%) in the Charpy V-notch (CVN) upper-shelf energy (USE), but the effect on the 41-J transition temperature shift was very small (3°C). The combined effect following neutron irradiation at 288°C to a fluence of 5×10^{19} neutrons/cm² (>1 MeV) was a 22% reduction in the USE and a 29°C shift in the 41-J transition temperature. The effect of thermal aging on tensile properties was very small. However, the combined effect of irradiation and aging was an increase in the yield strength (6 to 34% at test temperatures from 288 to -125°C) and no apparent change in ultimate tensile strength or total elongation. Neutron irradiation reduced the initiation fracture toughness (J_{Ic}) much more than did thermal aging alone. However, irradiation slightly decreased the tearing modulus but no reduction was caused by thermal aging alone. The effects of long-term thermal exposure times (20,000 and 50,000 h) will be investigated when the specimens become available. Also, long-term thermal exposure of the three-wire cladding as well as type 308 stainless steel weld materials at 343°C is in progress.

KEYWORDS: neutron irradiation, thermal aging, stainless steel cladding, three-wire cladding, tensile properties, Charpy impact, fracture toughness

INTRODUCTION

Thermal aging at relatively low temperatures (343°C) has been shown to significantly degrade the Charpy impact toughness of type 308 stainless steel welds [1]. The stainless steel cladding applied to the inner surface of some reactor pressure vessels is very similar to this material. Hence, an experimental program was initiated at Oak Ridge National Laboratory (ORNL) to evaluate the effects of thermal aging on stainless steel cladding as well as its contribution to toughness degradation during irradiation experiments. Neutron irradiation effects on three-wire stainless steel cladding were studied and detailed results are given elsewhere [2-4] and briefly summarized here. The effects of neutron irradiation on single-wire stainless steel cladding are briefly

¹Development Staff Member, Metals and Ceramics Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge TN 37831-6151.

described in Ref. 4. The goals of the thermal aging studies are to quantify and separate the damage contributions of thermal aging and neutron irradiation for short-term exposures, and to evaluate the effects of aging for long-term exposures. Since the irradiation to the highest fluence of 5×10^{19} neutrons/cm² (>1 MeV) was conducted at 288°C for 1605 h, tensile, CVN, and compact fracture toughness specimens were thermally aged as discussed in the thermal aging plan described below. This paper summarizes the experimental plan and presents the results of short-term thermal aging at 288°C (550°F) together with comparisons to neutron irradiation effects. The three-wire cladding material was produced by Combustion Engineering, Inc., Chattanooga, Tennessee. Various combinations of type 304, 308, and 309 stainless steel wires were used to produce three layers of cladding (approximately 20 mm thick). Details of the three-wire series-arc cladding procedure, postweld heat treatment, etc., are given in Ref. 4.

EXPERIMENTAL PROCEDURES

Stainless steel weld overlay cladding was fabricated using the three-wire series-arc method. Three layers of cladding were applied to a pressure vessel plate to provide adequate thickness (~20 mm) for fabrication of test specimens. The chemical composition of the cladding is given in Table 1. The cladding material was thermally aged at 288°C for 1605 h. Testing of tensile, CVN, and 12.7-mm-thick compact [0.5T C(T)] fracture toughness specimens was conducted according to ASTM Standards E 8-89, E 23-88, and E 813-89, respectively. Precracked CVN specimens were also thermally aged; the dynamic fracture toughness (K_{IC}) test results will be presented later. The thermal aging plan that describes other thermal aging temperatures and times is given below. Irradiation conditions are given in Ref. 4.

TABLE 1--Chemical composition of the three-wire stainless steel weld clad overlay.

Layer	Content ^a (wt %)										
	C	Cr	Ni	Mo	Mn	Si	Co	Cu	V	P	S
Lower	0.052	19.75	9.75	0.18	1.59	0.63	0.03	0.07	0.03	0.016	0.014
Middle	0.049	19.38	9.18	0.23	1.28	0.78	0.07	0.36	0.06	0.023	0.017
Upper	0.049	19.34	9.04	0.23	1.34	0.82	0.08	0.39	0.06	0.023	0.017

^aBalance Fe, with Nb < 0.01%, Ti < 0.01%, and N < 0.057% for all layers.

Thermal Aging Plan

Pieces and specimens from three-wire series-arc stainless steel cladding are being thermally aged in air in two separate furnaces as given below. Several thermocouples were spot welded to the specimens and aging temperatures were recorded daily.

1. Aging temperature of 288°C (550°F) for times of 1,605, 20,000, and 50,000 h. The aging time of 1,605 h is equal to the irradiation time of the high-fluence [5×10^{19} neutrons/cm² (>1 MeV)] specimens; this will enable us to separate the effects of thermal aging from those of neutron embrittlement. Also, the three aging times will provide data on effects of thermal aging versus time. The 1605-h aging is completed and test results are presented in this paper while the others are still in progress.

2. Aging temperature of 343°C (650°F) for 20,000 h to compare with specimens from type 308 stainless steel welds thermally aged and tested earlier [1] (additional pieces from this material are currently being aged for up to 50,000 h). These agings are still in progress.

Both thermal aging series above include several round tensile (RT), CVN impact, precracked Charpy V-notch (PCVN), and 12.7-mm-thick compact [0.5T C(T)] fracture toughness specimens. All specimens have an L-S orientation (L is the welding direction).

RESULTS AND DISCUSSION

The effects of neutron irradiation and thermal aging alone at 288°C for 1605 h on impact, tensile, and fracture toughness properties are described and discussed below.

Effects of Neutron Irradiation and Thermal Aging on Charpy Impact Properties

All cladding exhibited ductile-to-brittle transition behavior during Charpy impact testing due to the dominance of delta-ferrite failures at low temperatures. Comparisons of the CVN impact energy and lateral expansion of the three material conditions (as-received, thermally aged, and irradiated) are shown in Figs. 1 and 2, respectively. The drop in the upper-shelf energy for the irradiated specimens [fluence of 5×10^{19} neutrons/cm² (>1 MeV), irradiation temperature of 288°C] was 22% due to the combined effect of neutron irradiation and thermal aging. The upper-shelf energy was reduced by 16% due to thermal aging exposure. Hence, it appears that the contribution of thermal aging to the CVN upper-shelf drop is large compared to the irradiation damage (16 vs 6%, assuming that the effects of irradiation and thermal aging can simply be added together). Additionally, thermal aging resulted in a 3°C shift of the Charpy impact transition temperature at the 41-J level. The effect of thermal aging on the 41-J transition temperature shift was very small compared to the combined effect during neutron irradiation (3 vs 29°C). Also, the lateral expansion upper and lower shelves were lowered (compared to the as-received material) due to thermal aging by 4 and 48%, respectively. The drops in the lateral expansion upper and lower shelves after irradiation were 42 and 93%, respectively.

Effects of Neutron Irradiation and Thermal Aging on Tensile Properties

The effect of thermal aging at 288°C for 1605 h on the tensile properties (yield strength, ultimate tensile strength, and total elongation) was very small or negligible. The uniaxial tensile data (yield strength, ultimate tensile strength, and total elongation) for unirradiated, thermally aged (at 288°C for 1605 h), and irradiated specimens [at 288°C to a fluence of 5×10^{19} neutrons/cm² (>1 MeV)] are shown in Figs. 3 through 5. These figures show that the increase (6 to 34%) in yield strength of the three-wire stainless steel cladding can be attributed solely to neutron irradiation-induced embrittlement with no appreciable contribution due to short-term thermal aging. The ultimate strength and the total elongation were not affected by irradiation and/or thermal aging.

Effects of Neutron Irradiation and Thermal Aging on Fracture Toughness

The test results of the 12.7-mm-thick compact [0.5T C(T)] fracture toughness specimens (all specimens were side-grooved 10% on each side and tested using a computerized single-specimen unloading-compliance

FIG. 1--Effect of thermal aging at 288°C and neutron irradiation on the Charpy impact energy of three-wire series-arc stainless steel cladding, L-S orientation.

FIG. 2--Effect of thermal aging at 288°C and neutron irradiation on the Charpy impact lateral expansion of three-wire series-arc stainless steel cladding, L-S orientation.

FIG. 3--Effect of thermal aging at 288°C and neutron irradiation on the yield strength of three-wire series-arc stainless steel cladding.

FIG. 4--Effect of thermal aging at 288°C and neutron irradiation on the ultimate strength of three-wire series-arc stainless steel cladding.

FIG. 5--Effect of thermal aging at 288°C and neutron irradiation on the total elongation of three-wire series-arc stainless steel cladding.

FIG. 6--Effects of neutron irradiation and thermal aging at 288°C on the initiation fracture toughness, J_{IC} , of three-wire stainless steel cladding at various test temperatures.

FIG. 7--Effects of neutron irradiation and thermal aging at 288°C on the deformation J-integral tearing modulus of three-wire stainless steel cladding at various test temperatures.

technique) are shown in Figs. 6 and 7 for the unirradiated, thermally aged (1605 h at 288°C) and irradiated [637 h at 288°C to a fluence of 2.4×10^{19} neutrons/cm² (>1 MeV)] material conditions. The deformation J-integral values of J_k and tearing modulus at various test temperatures are shown in Figs. 6 and 7, respectively. These results indicate that thermal aging reduced the initiation fracture toughness (J_k) at room temperature and at 120°C; however, there was no apparent effect at 288°C. The effect of thermal aging on the tearing modulus was insignificant (no reduction) for all test temperatures (room temperature, 120, and 288°C). The effect of thermal aging at 288°C on the J_k at the test temperature of 288°C will be further clarified from J_k tests following the 20,000-h aging. The low values of J_k and tearing modulus for irradiated cladding [comparable to low upper shelf ferritic steels sensitive to irradiation [4]] raise concern about the potential adverse impact of stainless steel cladding on the integrity of a pressure vessel during an overcooling transient (e.g., pressurized thermal shock) in which the growth of small surface flaws can have a significant effect on the probability of vessel failure. This is particularly important since cladding failures have occurred in several pressure vessels [5].

The effect of thermal aging on the dynamic fracture toughness (K_{Ic}) will be reported following the testing of precracked Charpy V-notch (PCVN) specimens that were thermally aged with the other specimens.

CONCLUSIONS

Thermal aging of three-wire stainless steel weld overlay cladding at 288°C for 1605 h resulted in an appreciable decrease (16%) in the USE, but the effect on the 41-J transition temperature shift was very small (3°C). The combined effect following neutron irradiation at 288°C

to a fluence of 5×10^{19} neutrons/cm² (>1 MeV) was a 22% reduction in the USE and a 29°C shift at the 41-J level. The effect of thermal aging on tensile properties was very small or negligible. However, the combined effect after neutron irradiation was an increase (6 to 34% at test temperatures from 288°C to -125°C) in the yield strength and no apparent change in ultimate tensile strength or total elongation. Neutron irradiation reduced the initiation fracture toughness (J_{Ic}) much more than did thermal aging. Furthermore, irradiation slightly reduced the tearing modulus but no reduction was caused by thermal aging alone.

FUTURE WORK

The effects of short-term thermal aging on dynamic fracture toughness values will be reported later. The effects of long-term thermal exposure times (20,000 and 50,000 h) will be investigated later when the specimens become available. Thermal exposure at 343°C of the three-wire cladding as well as type 308 stainless steel weld materials is in progress. Results of CVN, tensile, and fracture toughness (static and dynamic) specimens aged at 343°C will be reported later.

Stainless steel cladding from the decommissioned German boiling-water reactor at Gundremmingen will be examined using subsize and miniature specimen techniques to compare to our test reactor data (for possible fluence rate or spectrum effects). The subsize and miniature tests will be conducted on specimens and materials from the recently acquired four trepans cut from the decommissioned reactor (two from the core belt region and two from near the closure head; for maximum and minimum neutron fluence effects).

ACKNOWLEDGMENTS

This research was sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, under Interagency Agreement DOE 1886-8011-9B with the U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

REFERENCES

- [1] D. J. Alexander, K. B. Alexander, and R. K. Nanstad, "The Effect of Aging at 343°C on Type 308 Stainless Steel Welds," pp. 217-21 in *Recent Trends in Welding Science and Technology*, Proceedings of the 2nd International Conference on Trends in Welding Research, Gatlinburg, Tenn., May 14-18, 1989, S. A. David and J. M. Vitek, Eds., ASM International, Materials Park, Ohio, 1990.
- [2] F. M. Haggag, W. R. Corwin, D. J. Alexander, and R. K. Nanstad, "Tensile and Charpy Impact Behavior of an Irradiated Three-Wire Series-Arc Stainless Steel Cladding," pp. 361-72 in *Effects of Radiation on Materials: 14th International Symposium (Volume II)*, ASTM STP 1046, N. H. Packan, R. E. Stoller, and A. S. Kumar, Eds., American Society for Testing and Materials, Philadelphia, 1990.
- [3] F. M. Haggag, W. R. Corwin, and R. K. Nanstad, *Irradiation Effects on Strength and Toughness of Three-Wire Series-Arc Stainless Steel Weld Overlay Cladding*, NUREG/CR-5511 (ORNL/TM-11439), February 1990.
- [4] F. M. Haggag, W. R. Corwin, and R. K. Nanstad, "Effects of Irradiation on the Fracture Properties of Stainless Steel Weld Overlay Cladding," *Nuclear Engineering and Design*, 124, 129-141 (1990).
- [5] E. A. Wimunc, "How Serious are Cladding Failures?" *Power Reactor Technology*, 9(3), 101-109 (1966).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DATE

FILMED

10/21/94

END