AEC
RESEARCH
and
DEVELOPMENT
REPORT

325
4-20-65

BNWL - 1

MASTER

**THE COMBINED EFFECTS OF TEMPERATURE
AND IRRADIATION ON THE MECHANICAL PROPERTIES
OF AUSTENITIC STAINLESS STEELS**

JANUARY 1965

PACIFIC NORTHWEST LABORATORY operated by BATTELLE MEMORIAL INSTITUTE

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.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

PACIFIC NORTHWEST LABORATORY

Operated By

BATTELLE MEMORIAL INSTITUTE

For The

U. S. ATOMIC ENERGY COMMISSION

Under Contract No. AT(45-1)-1830

BNWL-1

UC-25, Metals, Ceramics,
and Materials
(TID-4500, 37th Ed.)

THE COMBINED EFFECTS OF TEMPERATURE AND IRRADIATION
ON THE MECHANICAL PROPERTIES OF AUSTENITIC STAINLESS STEELS

By

FIRST UNRESTRICTED
DISTRIBUTION MADE

APR 8 '65

J. E. Irvin, A. L. Bement, and R. G. Hoagland
Metallurgy Research Section
Reactor and Materials Technology Department

January 1965

BATTELLE-NORTHWEST
RICHLAND, WASHINGTON

Work performed under Contract No. AT(45-1)-1830 between the
Atomic Energy Commission and Battelle Memorial Institute

Printed by/for the U.S. Atomic Energy Commission

Printed in USA. Price \$2.00. Available from the
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards
U.S. Department of Commerce
Springfield, Virginia

THE COMBINED EFFECTS OF TEMPERATURE AND IRRADIATION ON THE MECHANICAL PROPERTIES OF AUSTENITIC STAINLESS STEELS

INTRODUCTION

Austenitic stainless steels have been used in a variety of nuclear reactor applications because of their good corrosion resistance, intermediate strength, and ductility. Consequently, many studies have been made of the effects of neutron irradiation on the mechanical properties of these steels.⁽¹⁻⁸⁾ A review of the results of these studies indicates several areas where additional experiments are needed to resolve discrepancies in the data. The combined effects of neutron irradiation and elevated temperatures on the mechanical properties and metallurgical stability of these alloys are foremost among the uncertainties noted.

Considerable disagreement exists concerning the change in mechanical properties obtained at room temperature as a function of irradiation temperature. This is particularly true of tensile strength and ductility. When specimen geometry, material preparation, and the uncertainty in flux measuring techniques are considered, much of the apparent disagreement can be resolved for materials irradiated below about 100 C. This is not true, however, for room temperature test data obtained from elevated temperature irradiations or of elevated temperature tests of irradiated materials.

In addition to the large changes caused by neutron irradiation, austenitic stainless steels are subject to subtle changes due to metallurgical instability. Metallurgical changes are temperature dependent and are influenced by such variables as chemical composition, fabrication history, and heat treatment. For example, the temperature at which the austenite to martensite transformation occurs will vary considerably as a function of chemical composition.⁽⁹⁾ The formation of embrittling constituents in these metastable alloys is enhanced by elevated service temperatures,⁽¹⁰⁻¹³⁾ and may be further accelerated by neutron irradiation.

The data to be presented represents the results obtained to date for only two of a number of stainless steels irradiated for various exposures

to 1.5×10^{21} neutrons/cm². Irradiations have been performed at about 50 C, 290 C, and 750 C. Additional specimens are being irradiated to higher exposures ranging to 1.0×10^{22} neutron/cm^{2*} as part of a continuing program.

SUMMARY

The effects of neutron irradiation and temperature on the mechanical properties of AISI 348 and 304 stainless steels have been determined using smooth and notched tensile specimens containing different amounts of cold work. Smooth tensile specimens were irradiated at about 50 C, 290 C, and 750 C. Room temperature and 300 C tests on specimens in both the annealed and 25% cold worked conditions show a marked reduction in ductility with increasing exposure and increasing test temperature. Damage accumulation as measured by changes in mechanical properties occurs more rapidly at the intermediate irradiation temperature. Control specimens exposed in an out-of-reactor loop at 282 C for times in excess of 5000 hr underwent a significant change in mechanical properties.

Notched tensile specimens of AISI 348 stainless steel in the annealed, 10, 20, and 40% cold worked conditions were irradiated at about 290 C and tested at room temperature. The mode of fracture was ductile in nature throughout the range of cold work and neutron exposures studied. A transition from notch strengthening to a notch sensitive behavior was observed for specimens in the 20 and 40% cold work levels after an exposure of about 1.0×10^{20} neutrons/cm².

The effects of cold work, temperature, and chemical composition on the metallurgical stability of these materials were examined using magnetic measurements and X-ray diffraction. The magnetic susceptibility of both materials containing up to 70% cold work was determined before irradiation. No measurable change was noted in the magnetic susceptibility of either the annealed or 25% cold worked materials which were irradiated to exposures of 1.5×10^{21} neutrons/cm². Optical and electron microscopy

* Unless otherwise stated, neutron fluxes refer to neutrons whose energies are greater than 1 MeV.

studies on both materials revealed no changes in structure due to the combined effects of irradiation and temperature.

EXPERIMENTAL PROCEDURE

The specimens used in this investigation were fabricated from a single annealed 0.250 in. plate of composition shown in Table I. This plate was rolled to a final thickness of 0.100 in. in two conditions: annealed and 25% cold worked. Specimens milled from this material had a 2 in. gage length and nominal dimensions of 0.100 by 0.200 in. at the gage section. The fabrication history is outlined in Table II.

TABLE I
ANALYSIS OF AISI 304 AND 348 STAINLESS STEEL USED FOR TEST SPECIMENS

Alloy Designation	Chemical Analysis, wt%												
	C	Mn	P	S	Si	Cr	Ni	Cb	Ta	Co	Cu	Mo	B
	Vendor's Analysis												
AISI 304													
Heat No.	0.044	1.16	0.026	0.013	0.60	18.40	9.26	--	--	0.13	--	--	--
X-60059-2													
AISI 348													
Heat No.	0.039	1.82	0.019	0.010	0.60	18.00	11.62	0.72	0.04	0.11	--	--	
X-57618-1A													
Alloy Designation	Certified Analysis												
	C	Mn	P	S	Si	Cr	Ni	Cb	Ta	Co	Cu	Mo	B
	Certified Analysis												
AISI 304	0.049	1.21	0.029	0.017	0.60	18.81	9.63	--	--	--	0.17	0.18	0.0008
Heat No.	0.049	1.20	0.028	0.018	0.59	18.51	9.57	--	--	--	0.17	0.21	0.0009
X-60059-2	0.049	1.21	0.029	0.018	0.60	18.37	9.57	--	--	--	0.17	0.21	0.0008
AISI 348	0.045	1.66	0.019	0.019	0.48	18.26	11.94	0.80	0.09	0.09	0.11	0.18	0.0008
Heat No.	0.048	1.66	0.018	0.019	0.49	18.70	12.00	0.82	0.12	0.09	0.11	0.21	0.0008
X-57618-1A	0.044	1.70	0.018	0.017	0.47	18.66	11.92	0.81	0.11	0.09	0.11	0.18	0.0008

TABLE II
FABRICATION HISTORY OF AISI 304 AND 348 STAINLESS STEEL

1. Starting condition, annealed 1/4 in. plate.
2. Cold roll to 0.133 in.
3. Anneal at 1800 F, air cool
4. Cold roll to 0.100 in.
 - a. One-half plate; machine 25% cold worked specimens
 - b. One-half plate; anneal at 1800 F, air cool; machine annealed specimen

Notched tensile specimens were fabricated in a similar manner with 0, 10, 20, and 40% cold work. The 0.050 in. thick specimens were prepared with 60° side notches extending one-quarter of the width inward from each side. The root radius of all notches was less than 0.001 in. Typical specimens are shown in Figure 1.

Irradiations at 50 and 290 C were performed in core positions of the Engineering Test Reactor (ETR) designated G-7 and G-6. The G-7 position contains a recirculating pressurized hot water loop operated at 282 C and 2000 psi. The specimen hanger and containers used in this loop are shown in Figure 1. Detailed information on the operation of this facility is given elsewhere.⁽¹⁴⁾ Flow-through capsules were used for the 50 C irradiations⁽¹⁵⁾ in ambient temperature reactor water. The 750 C irradiations were performed in a gaseous environment in another reactor.

Flux monitors were included with all experiments. Dosimeter wires of iron, nickel, titanium, and an aluminum-cobalt alloy were used in each monitor assembly.

Neg. 0640127

FIGURE 1

Irradiation Assembly and Specimens
for G-7 Loop

All of the specimens were tested with an Instron testing machine. The smooth tensile specimens were tested at a crosshead speed of 0.005 in./min, and the notched tensile tests were performed at speeds of 0.05 and 2.0 in./min. An extensometer was used on the smooth tensile specimens to a point beyond the 0.2% yield point in both the room temperature and 300 C tests. The 300 C tests were performed in air. At least two tests were performed for every data point reported.

Control specimens were exposed in an out-of-reactor loop for times and temperatures similar to those received in the G-7 Hot Water Loop. Water quality and flow rate in this loop were comparable to that in the G-7 loop.

Magnetic measurements were made with an Aminco-Brenner Magna-Gage on both alloys containing various levels of cold work in the as-prepared condition, after exposure in the out-of-reactor control loop, and after irradiation in the G-7 Hot Water Loop. X-ray diffraction studies were performed on unirradiated specimens to determine the relative amount of martensite transformed as a function of cold work.

RESULTS AND DISCUSSION

Tensile Properties

The effects of neutron irradiation at 50 C and 290 C on the room temperature yield strength of AISI 348 and 304 are shown in Figures 2 and 3. The yield strength is greater for these materials when they are irradiated at 50 C to nominal exposures of 1.0×10^{20} neutrons/cm² than for the equivalent exposure at 290 C. Crossover occurs for exposures between 1.0×10^{20} and 7.0×10^{20} neutrons/cm², and beyond this point the yield strength of the material irradiated at 290 C is greater. The lower temperature irradiations show little further change in yield strength at exposures beyond approximately 1.0×10^{20} neutrons/cm². While definite signs of saturation are indicated at 50 C, the yield strength of the material irradiated at 290 C continues to increase with increasing exposure. In both the AISI 348 and 304 stainless steel irradiated at 290 C, the rate of property change is greater for the annealed than for the 25% cold worked

material. An exposure of about 1.0×10^{21} neutrons/cm² causes a 100% increase in the yield strength for the annealed material irradiated at 50 C and a 400% increase for the 290 C irradiation.

FIGURE 2

Effects of Irradiation on the Room Temperature Yield Strength of AISI 348 Stainless Steel

FIGURE 3

Effects of Irradiation on the Room Temperature Yield Strength of AISI 304 Stainless Steel

The effects of irradiation at these temperatures on the total elongation of AISI 348 and 304 are shown in Figures 4 and 5. Initially, the decrease in elongation is greater for irradiations at 50 C than at 290 C for the AISI 348 stainless steel and about the same for the AISI 304 stainless steel. For higher exposures, however, irradiation at 290 C results in a greater decrease in ductility than does irradiation at 50 C. The decrease in total elongation for the annealed material for exposures of 1.0×10^{21} neutrons/cm² was between 40 and 50% for irradiations at 50 C and between 80 and 90% for irradiations at 290 C. There was no obvious difference in the decrease in ductility as a function of irradiation temperature for the 25% cold worked material. These same observations also apply to uniform elongation. This indicates that the ductility decrease is primarily a decrease in the uniform elongation and not the necking strain at these temperatures.

FIGURE 4

Effects of Irradiation on Room Temperature Ductility
of AISI 348 Stainless Steel

In general, transverse specimens showed a greater increase in strength and decrease in ductility than did the longitudinal specimens.

FIGURE 5

**Effects of Irradiation on Room Temperature Ductility
of AISI 304 Stainless Steel**

However, the existence of a strong anisotropy effect was not indicated. Directional effects were more pronounced in the notched tensile properties.

Room temperature tests were performed on tensile specimens of AISI 348 stainless steel irradiated to an exposure of about 1.0×10^{20} neutrons/cm² at 750 C in a gaseous environment. The effects of prior cold work were completely erased by irradiation at this temperature. Both the annealed and 25% cold worked material exhibited 0.2% yield strengths and ultimate tensile strengths equal to those of the annealed material in the unirradiated condition. The decrease in ductility due to irradiation at 750 C was much less than that observed for irradiations at 50 C or 290 C. For the 25% cold worked material, the 0.2% yield strength decreased from 133,000 psi to 36,000 psi, and the total elongation increased from about 8 to 52%.

Results of tests performed at both room temperature and 300 C on AISI 348 and 304 stainless steel irradiated at 290 C are listed in Table III.

The yield strengths of both alloys at 300 C in the unirradiated condition is 10,000 to 15,000 psi below that of the room temperature values. Nominal exposures increase this difference to 40,000 psi, indicating the temperature dependence of yield strength as a function of neutron exposure.

TABLE III
TENSILE PROPERTIES OF AUSTENITIC STAINLESS STEELS

AISI Material	Working Direction	Cold Work, %	Exposure, nvt (> 1 MeV)	Test Temp., C	Strength, 10 ³ psi		Total Elongation, %	Reduction of Area, %
					0.2% Yield Strength	Ultimate Tensile Strength		
As-Fabricated, Unirradiated								
348	Transverse	Annealed	0	20	37.8	89.5	64.3	63.6
348	Rolling	Annealed	0	20	37.0	89.4	59.7	73.1
348	Transverse	25	0	20	109.8	133.1	8.1	50.9
348	Rolling	25	0	20	112.4	129.2	11.2	57.1
304	Transverse	Annealed	0	20	32.5	91.1	85.7	72.7
304	Transverse	25	0	20	104.3	133.9	21.3	65.2
348	Transverse	Annealed	0	300	28.2	63.0	34.1	54.2
348	Rolling	Annealed	0	300	28.9	65.4	33.3	58.3
348	Transverse	25	0	300	101.2	112.9	3.8	33.1
348	Transverse	25	0	300	93.5	104.1	3.8	44.6
304	Transverse	Annealed	0	300	22.5	66.8	43.6	55.5
304	Transverse	25	0	300	94.7	108.0	4.8	34.9
Irradiated at 290 C								
348	Transverse	Annealed	5.1 x 10 ¹⁹	300	45.1	69.2	26.4	46.2
348	Rolling	Annealed	5.1 x 10 ¹⁹	300	47.2	73.1	25.3	42.8
348	Transverse	25	5.1 x 10 ¹⁹	300	117.2	125.4	3.1	23.7
348	Rolling	25	4.1 x 10 ¹⁹	300	120.8	123.9	3.9	25.6
304	Transverse	Annealed	4.1 x 10 ¹⁹	300	47.8	74.6	26.6	45.5
304	Transverse	25	4.1 x 10 ¹⁹	300	120.1	128.9	3.1	27.9
348	Transverse	Annealed	5.5 x 10 ²⁰	300	75.8	81.8	8.2	41.5
348	Rolling	Annealed	5.5 x 10 ²⁰	300	78.0	83.0	7.7	37.6
304	Transverse	Annealed	1.5 x 10 ²¹	300	109.5	109.5	3.3	35.5
304	Transverse	25	1.5 x 10 ²¹	300	147.2	151.1	2.5	22.9

Materials tested at 300 C in the unirradiated condition had about one-half the ductility found at room temperature. The decrease in ductility with exposure was less at 300 C than at room temperature. The minimum ductility for all the tests conducted was observed for 25% cold worked material irradiated to beyond 1.0×10^{21} neutrons/cm² and tested at 300 C. This minimum ductility (amounting to about 3% total elongation) is sufficiently low to cause concern in the design of reactor components. Other investigators have noted ductility minimums for different combinations of irradiation and test temperatures. (16)

A comparison of the properties of materials in the as-prepared condition, exposed in the out-of-reactor loop, and irradiated in the G-7 loop is shown in Figure 6. Prolonged exposures at 282 C are sufficient to

cause an increase in yield strength of 10,000 psi and a significant decrease in elongation. If the property changes due to temperature effects alone are added to those caused by irradiations at 50 C, the total change is less than that observed for irradiations at 290 C. A cooperative process probably exists that causes an additional property change under the combined influence of temperature and neutron irradiation.

FIGURE 6

Effects of Irradiation and Environment
on the Room Temperature Yield Strength and Ductility
of AISI 348 and 304 Stainless Steel
(Irradiation temperature, ~290 C)

Magnetic and X-ray diffraction measurements indicate the degree to which the AISI 348 and 304 stainless steels are susceptible to the formation of martensite and ferrite with cold work. Because of variations in composition, primarily due to the difference in nickel content, the AISI 304 is less stable metallurgically. A relationship between the chemical composition and temperature at which the martensite transformation will occur has been established by other investigators.⁽⁹⁾ Measurements with

a Magna-Gage of unirradiated AISI 348 and 304 stainless steels cold-rolled to various levels were used to establish the relationship between cold work and martensite formation illustrated in Figure 7. The assumption is made that the magnetic force will vary linearly with martensite content. The amount of martensite present was estimated from the relationship, $\text{Martensite (\%)} = \frac{\Delta M}{\Delta M_T} \times 100$, where ΔM is the change in magnetic force at a given true strain, and ΔM_T is the change in magnetic force for complete transformation to martensite. Qualitative verification

FIGURE 7
Martensite Formation
in Stainless Steel
as a Function
of Plastic Deformation

of the presence of martensite was obtained from X-ray diffraction studies.

From Figure 7, cold worked specimens of AISI 304 stainless steel exposed for various times at 300 C exhibited a substantial increase in magnetic response. If this increase is interpreted as an increase in martensite, the structural hardening resulting could account for the property changes observed in Figure 6 for out-of-reactor exposures. Magnetic measurements on irradiated specimens show an increase in susceptibility over that observed in the unirradiated and unexposed specimens. However, this increase was equal to the difference noted between specimens in the as-fabricated condition and the specimens exposed in the out-of-reactor loop. Therefore, no increase due

to neutron irradiation alone could be detected with the instrument used. Neutron irradiation produces additional structural defects that act as nuclei for the austenite to martensite transformation. However, since this transformation is more temperature and strain dependent, little additional change is expected. These very small changes can be detected⁽¹⁰⁾ with instruments more sensitive than the Magna-Gage.

Notch Tensile Properties

The principal parameters of interest in these tests were the maximum load attained and the amount of plastic extension that had occurred at fracture. The notch strength is calculated by dividing the maximum load by the cross-sectional area at the plane of the notch. The insert in Figure 8 shows a typical load extension curve and the manner in which the plastic extension is measured. The amount of plastic extension increases with plastic deformation and slow crack growth prior to fracture. Therefore, plastic extension can be used to infer relative measurements of the ability of the material to resist rapid crack propagation. This ability is commonly referred to as crack toughness. The plastic extension measured does not have any direct relationship to the tensile ductility shown in Figures 4 and 5.

FIGURE 8

Effects of Neutron Irradiation
on the Room Temperature Notch Tensile Plastic Extension
at Fracture Properties of AISI 348 Stainless Steel

The results of these tests as a function of irradiation and cold work are shown in Figures 8, 9, and 10. Data for material tested in the as-prepared condition is also presented in Figures 8 and 9. It was found that thermal environment comparable to the G-7 loop environment had no effect on the notch properties.

FIGURE 9

Room Temperature Notch Tensile Strength
of AISI 348 Stainless Steel
as Influenced by Neutron Irradiation at 290 C

FIGURE 10

Effect of Increasing Loading Rate
in AISI 348 Stainless Steel Irradiated to 1×10^{20} nvt
(Data points were obtained by interpolation.)

The notch strength increases with increasing exposure for the annealed and 10% cold worked conditions as shown in Figure 9. In contrast to this, the material containing 40% cold work undergoes a loss in notch strength with increasing neutron exposure.

Examination of Figure 8 reveals that for the annealed and 10% cold worked conditions the increase in notch strength with increasing exposure is obtained at a sacrifice in plastic extension, or crack toughness. Furthermore, the neutron damage causes more reduction in crack toughness for crack propagation in the transverse direction than in the rolling direction. The zero plastic extension values for the 40% cold worked condition, together with the decreasing notch strength over the range of exposures studied, indicates a tendency towards notch sensitivity.

The transition from a notch insensitive to a notch sensitive state with increasing cold work and neutron exposure is further substantiated by the results obtained from testing at different crosshead speeds. Figure 10 shows that from the annealed up to the 20% cold worked condition, the notch strength is increased with increasing crosshead speed. Between 20 and 40% cold work the change in notch strength becomes negative. This point where notch strength changes from a positive to a negative value can be expected to shift with different ratios of crosshead speed.

Since increasing the amount of cold work, loading rate, and neutron exposure are all means of increasing the yield strength of this steel, the above data indicate that at some particular yield strength level the notch properties are optimum, i.e., the material has a high notch strength with some degree of resistance to rapid crack propagation. The yield strength at optimum notch strength may vary somewhat depending on the manner in which it is attained. However, the magnitude of this variation with respect to cold work, loading rate, and neutron exposure is not expected to be large.

Metallographic examination of both unirradiated and irradiated specimens revealed numerous inclusions of the type shown in Figure 11. These particles cleave in a brittle manner when the matrix is stressed. If the

Neg. C420

FIGURE 11

250X

As-Polished Microstructure of AISI 348 Stainless Steel
Showing Brittle Particles Present in the Matrix
(The micrograph is of a 20% cold worked sample
irradiated to 9×10^{19} nvt.)

particles are bonded to the matrix, the cleavage cracks will cause high stress concentrations at the interface. In a ductile matrix, severe deformation and tearing will accompany the slow extension of cracks initiated in this manner. Even though a considerable amount of deformation may occur in the localized region at the crack tips, the apparent overall ductility of the structure may be seriously impaired if the cracks begin to extend at low nominal stresses. An example of microcrack formation from these particles can be seen in Figures 12a and 12b. The cracks grew in a ductile manner in this example and for the other levels of cold work studied.

Neg. C384

(a)

1000X Neg. C334

(b)

1000X

FIGURE 12

Polished and Etched Microstructure of AISI 343 Stainless Steel in the Annealed Condition Showing Microcracks Associated with Brittle Particles Near the Fracture Surface of the Specimen
 [(a) Remnant of a brittle particle associated with the microcrack can be seen at the blunted end.
 (b) Microcrack extending from a brittle particle at the fracture surface. This material has been irradiated to 9×10^{19} nvt. Etchant: aqua regia ($3\text{HCl}:1\text{HNO}_3$) diluted 1:1 with H_2O , immersed 15 to 20 sec.]

The length that a crack can progress at a given stress before propagating rapidly is a direct measure of the crack toughness of a material. If, in a stressed notched specimen, a number of cracks exist in addition to the main crack at the notch tip, then the slow progression of the main crack is accompanied by extension of the microcracks. If the stress is suddenly released, such as by fracture of the specimen, then the shape and length of the microcracks are retained. By comparing the average microcrack length in different specimens, one can make a qualitative estimate of the crack toughness of the material.

Figure 13 shows a relationship between the average microcrack length and the percent cold work for broken transverse notched tensile specimens. The decrease in microcrack length with increasing cold work indicates a corresponding decrease in crack toughness. This is in accord with Figure 8 where at a given exposure level the decreasing plastic extension infers a decreasing crack toughness. With higher exposure levels, the curve in Figure 13 would be shifted to the left.

FIGURE 13

Average Microcrack Length vs. Percent Cold Work
in AISI 348 Stainless Steel

[Transverse notch tensile specimens irradiated to 9×10^{19} nvt (fast)]

In general, the formation of microcracks from brittle particles adversely affects the notch properties of structural materials. Therefore,

considerable difference in mechanical property behavior may result from heat to heat variations in the amount and distribution of particles similar to those observed.

CONCLUSIONS

From the results of the tests conducted on AISI 348 and 304 stainless steels, the following conclusions were drawn.

- Irradiations at 290 C result in a greater accumulation of damage for both materials than irradiations performed at both 50 and 750 C.
- Irradiation damage at 290 C continually increases with exposures to 1.5×10^{21} neutrons/cm².
- In both the AISI 348 and 304 stainless steels, the rate of damage accumulation is greater for the annealed state than for the 25% cold worked condition.
- Changes in yield strength saturate at exposures less than 1.0×10^{21} neutrons/cm² at 50 C.
- The temperature dependence of tensile properties of these alloys increases with exposure for irradiations at 290 C.
- Complete recovery of prior cold work results from irradiations at 750 C. A small decrease in room temperature ductility is noted in annealed materials irradiated at this temperature.
- Prolonged exposures at 282 C in an out-of-reactor loop resulted in changes in the strength and ductility of both materials. The greatest change occurred in materials which had received 25% cold work prior to exposure.
- Metallurgical stability of these materials is highly dependent upon chemical composition and prior cold work.
- AISI 348 stainless steel becomes notch sensitive with certain combinations of irradiation and prior cold work.
- Brittle inclusions cause microcracks in the material when the matrix is stressed.
- Crack toughness for a given exposure decreases with increasing cold work.

ACKNOWLEDGMENT

The authors gratefully acknowledge the services provided by Phillips Petroleum Company at the National Reactor Testing Station in counting the flux dosimeters under the direction of C. H. Hogg and testing part of the smooth tensile specimens under the direction of J. H. Ronsick. The assistance of R. W. Barker and P. K. McDaniel in conducting the elevated temperature tests on both unirradiated and irradiated materials, and personnel of Battelle-Northwest Radiometallurgy Operation in conducting the room temperature tests on irradiated smooth and notched tensile specimens is greatly appreciated. The authors are also appreciative of the assistance of personnel from the Physical Metallurgy Group under the direction of H. E. Kissinger for performing the X-ray diffraction studies.

REFERENCES

1. S. H. Bush and J. C. Tobin. "The Effects of Neutron Flux and Reactor Environments on Stainless Steels," paper given at ASTM Symposium held concurrently with the Annual Meeting in Atlantic City, June 23-28, 1963. April 1963.
2. W. E. Murr, F. R. Shober, R. Lieberman, and R. F. Dickerson. Effects of Large Neutron Doses and Elevated Temperature on Type 347 Stainless, BMI-1609. Battelle Memorial Institute, January 21, 1963.
3. F. R. Shober. The Effects of Nuclear Radiation on Structural Metals, REIC Report No. 20. September 15, 1961.
4. R. E. Schreiber. Mechanical Properties of Irradiated Stainless Steels, A Compilation of the Data in the Literature, DP-579. E. I. du Pont de Nemours & Co., Inc., Aiken, S.C., September 1961.
5. F. R. Shober. The Effect of Nuclear Radiation on Structural Materials, DMIC. September, 1961.
6. A. N. Hughes and J. R. Caley. "The Effects of Neutron Irradiation at Elevated Temperatures on the Tensile Properties of Some Austenitic Stainless Steels," J. Nucl. Mater., vol. 10, no. 1, pp. 60-62. 1963.
7. A. C. Roberts and D. R. Harries. "Elevated Temperature Embrittlement Induced in 20% Chromium: 25% Nickel: Niobium Stabilized Austenitic Steel by Irradiation with Thermal Neutron," Nature, vol. 200. 1963.
8. W. E. Murr and F. R. Shober. Annealing Studies on Irradiated Type 347 Stainless, BMI-1621. Battelle Memorial Institute, March 1963.
9. T. Angel. "Formation of Martensite in Austenitic Stainless Steels," J. Iron and Steel Inst. May 1954.
10. M. B. Reynolds, J. R. Low, Jr., and L. O. Sullivan. "Study of the Radiation Stability of Austenitic Type 347 Stainless Steel," J. Metals, pp. 555-559. April 1955.
11. J. Dash and H. M. Ott. "The Martensite Transformation in Stainless Steel," Acta Met., vol. II. October 1963.
12. A. J. Goldman, W. D. Robertson, and D. A. Koss. "The Association of HCP and BCC Structures in the Martensite Transformation," Trans. Met. Soc. AIME, vol. 230. February 1964.
13. M. Farrow. Some Causes of Brittleness in Chromium-Nickel Austenitic Stainless Steels, A Literature Survey, TRGR-564-C. September 1963.

14. J. E. Irvin and A. L. Bement. Unpublished Data, Battelle-Northwest, Richland, Washington.
15. J. J. Cadwell. Quarterly Progress Report, Metallurgy Research Operation, April, May, June, 1963, HW-77954. July 15, 1963.
16. W. R. Martin. Unpublished Data, Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee. (Personal Communication).

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

INTERNAL DISTRIBUTIONCopy Number

1	F. W. Albaugh
2	R. C. Aungst
3	J. A. Ayres
4	R. W. Barker
5-19	A. L. Bement
20	W. A. Burns
21	S. H. Bush
22	J. J. Cadwell
23	T. T. Claudson
24	L. J. Defferding
25	R. F. Dickerson
26	R. L. Dillon
27	E. A. Evans
28	S. L. Fawcett
29	R. G. Hoagland
30-49	J. E. Irvin
50-52	J. H. Johnson
53	R. S. Kemper
54	H. E. Kissinger
55	J. J. Laidler
56	G. A. Last
57	R. D. Leggett
58	P. K. McDaniel
59	J. E. Minor
60	D. N. Nyman
61	D. P. O'Keefe
62	R. E. Olson
63	H. M. Parker
64	F. A. Smidt, Jr.
65	R. Teats
66-71	J. C. Tobin
72	F. W. Van Wormer
73	K. R. Wheeler
74	R. G. Wheeler
75	O. J. Wick
76	R. D. Widrig
77	J. A. Williams
78	Technical Publications
79-84	Technical Information Files
85	W. A. Briggs, Jr.

EXTERNAL DISTRIBUTION (Special)Number of Copies

1	Atomic Energy Commission, Washington Military Liaison Committee Attn: Captain D. E. McCoy, Staff Assistant to the Chairman
6	Argonne National Laboratory Attn: R. J. Armani T. H. Blewitt J. H. Kittel F. D. McGinnis - EBR-I, Idaho Falls, Idaho A. D. Rossin D. K. Youngdahl
1	Battelle Memorial Institute Attn: F. R. Shober
3	Brookhaven National Laboratory Attn: J. G. Y. Chow D. H. Gurinsky S. B. McRickard
2	General Atomic Division Attn: T. A. Trozera W. P. Wallace
4	General Electric Company, Richland Attn: D. H. Curtiss M. C. Leverett M. Lewis J. W. Richcs
4	Naval Research Laboratory Attn: J. W. Hawthorne J. M. Krafft L. E. Steele A. M. Sullivan
7	Nuclear Materials and Propulsion Operation Attn: C. L. Brassfield F. E. Kingsbury J. McGurty J. Moteff R. C. Rau F. C. Robertshaw J. R. Smith
10	Oak Ridge National Laboratory Attn: R. G. Berggren W. E. Brundage N. E. Hinkle E. C. Miller S. M. Ohr

EXTERNAL DISTRIBUTION (Special) (contd.)Number of Copies

	J. T. Stanley
	M. S. Wechsler
	J. R. Weir
	J. M. Williams
	F. W. Young
3	Phillips Petroleum Company
	Attn: J. M. Beeston
	W. C. Francis
	C. H. Hogg
4	Richland Operations Office
	Attn: P. G. Holsted
	J. M. Musser
	Technical Information Library
	R. K. Sharp
1	Southwest Research Institute
	Attn: W. J. McGonnagle
1	USAEC - Chicago Operations Office
	Attn: Claude Pursell
1	USAEC - Idaho Operations Office
	Attn: J. F. Kaufmann
1	USAEC - Oak Ridge Operations Office
	Attn: D. F. Cope
4	USAEC - Washington, D.C.
	Division of Licensing and Regulation
	Attn: M. Bolotsky
	E. G. Case
	J. J. DiNunno
	A. B. Holt
7	Division of Reactor Development
	Attn: I. H. Mandil
	J. L. Mershon
	W. L. R. Rice
	J. M. Simmons
	R. H. Steele
	S. A. Szawlewics
	N. J. Triner
1	Division of Research
	Attn: D. K. Stevens
<u>Others</u>	
1	NASA Lewis Research Center
	Attn: M. L. Ault
1	General Electric Company, Pleasanton
	Attn: L. P. Bupp

EXTERNAL DISTRIBUTION (Special)(contd.)Number of Copies

1	J. A. Erlewine Senior AEC Representative, Brussels Office U. S. Mission to the European Communities 23 Avenue des Artes Brussels, Belgium
1	R. H. Fillnow Bettis Power Laboratory P. O. Box 1468 Pittsburgh, Pennsylvania
1	A. E. Focke University of Cincinnati Dept. of Chemical Engineering and Metallurgical Engineering Cincinnati 21, Ohio
15	R. F. Fraley Executive Secretary Advisory Committee on Reactor Safeguards U. S. Atomic Energy Commission Washington, D. C. 20545
1	J. F. Haines Nuclear Power Department, Washington Atomic Energy Division Allis-Chalmers Manufacturing Company 508 Kennedy Street, N. W. Washington 11, D. C.
1	E. T. Hayes Special Assistant for Materials DDR&E The Pentagon Washington 25, D. C.
1	M. Krasner Nuclear Reactor Division Lewis Research Center 21000 Brookpark Road Cleveland 35, Ohio
1	E. Landerman Westinghouse Electric Corporation Atomic Power Division P. O. Box 355 Pittsburgh 30, Pennsylvania
1	J. R. Lane Materials Advisory Board National Academy of Sciences 2101 Constitution Avenue, N. W. Washington 25, D. C.

EXTERNAL DISTRIBUTION (Special) (contd.)Number of Copies

1	S. G. Nordlinger AEC Scientific Representative USAEC London Office U. S. Embassy London, England
20	J. W. Norris Chief, Cataloging Branch U. S. Atomic Energy Commission Division of Technical Information Extension P. O. Box 62 Oak Ridge, Tennessee 37831
1	L. M. Raring Pratt & Whitney Aircraft Division CANEL Operation P. O. Box 611 Middletown, Connecticut
1	Headquarters Directorate of Materials and Processes Aeronautical Systems Division Air Force Systems Command U. S. Air Force Attn: Col. L. J. Standifer Wright-Patterson Air Force Base, Ohio
1	J. Van Ullen Knolls Atomic Power Laboratory P. O. Box 1072 Schenectady, New York
1	C. Washburn Reactor Division U. S. Atomic Energy Commission San Francisco Operations Office 2111 Bancroft Way Berkeley, California 94704
1	George Knighten Nuclear Power Field Office Engineer Research and Development Center Fort Belvoir, Virginia 22060
1	A. T. Lovell Nuclear Materials and Propulsion Operation National Reactor Test Station P. O. Box 2147 Idaho Falls, Idaho

Ptd.	Standard Distribution	Ptd.	Standard Distribution
3	ABERDEEN PROVING GROUND	1	BUREAU OF SHIPS (CODE 1500)
2	AEROJET-GENERAL CORPORATION	1	CARBORUNDUM COMPANY
1	AEROJET-GENERAL NUCLEONICS	1	CHICAGO PATENT GROUP
2	AERONAUTICAL SYSTEMS DIVISION	1	COMBUSTION ENGINEERING, INC.
1	AEROPROJECTS INCORPORATED	1	COMBUSTION ENGINEERING, INC. (NRD)
		1	DEFENCE RESEARCH MEMBER
		1	*DEL ELECTRONICS CORPORATION
1	AIR FORCE INSTITUTE OF TECHNOLOGY	1	DENVER RESEARCH INSTITUTE
		1	DOW CHEMICAL COMPANY, ROCKY FLATS
1	AIR FORCE RESEARCH AND TECHNOLOGY DIVISION	4	DU PONT COMPANY, AIKEN
1	ALLIS-CHALMERS MANUFACTURING COMPANY	1	DU PONT COMPANY, WILMINGTON
1	ALLIS-CHALMERS MANUFACTURING COMPANY, BETHESDA	1	FRANKFORD ARSENAL
		1	FRANKLIN INSTITUTE OF PENNSYLVANIA
1	ALLISON DIVISION-GMC	1	FUNDAMENTAL METHODS ASSOCIATION
10	ARGONNE NATIONAL LABORATORY	2	GENERAL ATOMIC DIVISION
1	ARMY ENGINEER RESEARCH AND DEVELOP- MENT LABORATORIES	2	GENERAL DYNAMICS/FORT WORTH
1	ARMY MATERIALS RESEARCH AGENCY	2	GENERAL ELECTRIC COMPANY, CINCINNATI
1	ARMY MISSILE COMMAND	1	GENERAL ELECTRIC COMPANY, PLEASANTON
1	ARMY RESEARCH OFFICE, DURHAM	6	GENERAL ELECTRIC COMPANY, RICHLAND
1	ARMY TANK-AUTOMOTIVE CENTER	1	GENERAL ELECTRIC COMPANY, SAN JOSE
1	ATOMIC ENERGY COMMISSION, BETHESDA	1	GENERAL NUCLEAR ENGINEERING CORPORATION
1	AEC SCIENTIFIC REPRESENTATIVE, BELGIUM	1	GOODYEAR ATOMIC CORPORATION
1	AEC SCIENTIFIC REPRESENTATIVE, FRANCE	1	IIT RESEARCH INSTITUTE
1	AEC SCIENTIFIC REPRESENTATIVE, JAPAN	1	INTERNATIONAL BUSINESS MACHINES CORPORATION
3	ATOMIC ENERGY COMMISSION, WASHINGTON		
4	ATOMIC ENERGY OF CANADA LIMITED	2	IOWA STATE UNIVERSITY
		2	JET PROPULSION LABORATORY
2	ATOMIC ENERGY OF CANADA LIMITED, WHITESHELL	1	JOHNS HOPKINS UNIVERSITY
4	ATOMICS INTERNATIONAL	3	KNOLLS ATOMIC POWER LABORATORY
1	AYCO CORPORATION	1	LING TEMCO VOUGHT, INC.
4	BABCOCK AND WILCOX COMPANY	1	LOCKHEED-GEORGIA COMPANY
2	BATTELLE MEMORIAL INSTITUTE	1	LOCKHEED MISSILES AND SPACE COMPANY (NASA)
2	BEERS (ROLAND F.), INC.	3	LOS ALAMOS SCIENTIFIC LABORATORY
1	BERYLLIUM CORPORATION	1	M & C NUCLEAR, INC.
1	BLUME (JOHN A.) AND ASSOCIATES	1	MALLINCKRODT CHEMICAL WORKS
2	BROOKHAVEN NATIONAL LABORATORY	1	MARE ISLAND NAVAL SHIPYARD
1	BUREAU OF MINES, ALBANY	1	MARITIME ADMINISTRATION
1	BUREAU OF NAVAL WEAPONS	1	MARTIN-MARIETTA CORPORATION

Ptd.	Standard Distribution	Ptd.	Standard Distribution
1	*MINNESOTA MINING AND MANUFACTURING COMPANY (BRANDT)	1	REACTIVE METALS, INC.
1	MOUND LABORATORY	1	REACTIVE METALS, INC., ASHTABULA
		1	RENSELAER POLYTECHNIC INSTITUTE
1	NASA LEWIS RESEARCH CENTER	1	SAN FRANCISCO OPERATIONS OFFICE
		2	SANDIA CORPORATION, ALBUQUERQUE
1	NASA MANNED SPACECRAFT CENTER	1	SANDIA CORPORATION, LIVERMORE
2	NASA SCIENTIFIC AND TECHNICAL INFORMATION FACILITY	1	SOUTHWEST RESEARCH INSTITUTE
		1	STANFORD UNIVERSITY (SLAC)
2	NATIONAL BUREAU OF STANDARDS	1	SYLVANIA ELECTRIC PRODUCTS, INC.
1	NATIONAL BUREAU OF STANDARDS (LIBRARY)	1	TENNESSEE VALLEY AUTHORITY
2	NATIONAL LEAD COMPANY OF OHIO	1	TRW SPACE TECHNOLOGY LABORATORIES (NASA)
1	NAVAL POSTGRADUATE SCHOOL	1	UNION CARBIDE CORPORATION, CLEVELAND
3	NAVAL RESEARCH LABORATORY	2	UNION CARBIDE CORPORATION (ORGDP)
		5	UNION CARBIDE CORPORATION (ORNL)
1	NRA, INC.		
1	NUCLEAR MATERIALS AND EQUIPMENT CORPORATION	1	UNION CARBIDE CORPORATION (PADUCAH PLANT)
1	NUCLEAR METALS, INC.	2	UNITED NUCLEAR CORPORATION (NDA)
1	NUCLEAR UTILITY SERVICES, INC.	1	U. S. GEOLOGICAL SURVEY, DENVER
1	OFFICE OF ASSISTANT GENERAL COUNSEL FOR PATENTS (AEC)	1	U. S. GEOLOGICAL SURVEY, MENLO PARK
2	OFFICE OF NAVAL RESEARCH	1	U. S. GEOLOGICAL SURVEY, WASHINGTON
1	OFFICE OF NAVAL RESEARCH (CODE 422)	1	U. S. PATENT OFFICE
1	OHIO STATE UNIVERSITY	2	UNIVERSITY OF CALIFORNIA, BERKELEY
1	PETROLEUM CONSULTANTS	2	UNIVERSITY OF CALIFORNIA, LIVERMORE
4	PHILLIPS PETROLEUM COMPANY (NRTS)	1	UNIVERSITY OF PUERTO RICO
1	PHYSICS INTERNATIONAL, INC.	1	WESTERN RESERVE UNIVERSITY (MAJOR)
1	PICATINNY ARSENAL	4	WESTINGHOUSE BETTIS ATOMIC POWER LABORATORY
1	POWER REACTOR DEVELOPMENT COMPANY	1	WESTINGHOUSE ELECTRIC CORPORATION
3	PRATT AND WHITNEY AIRCRAFT DIVISION	1	WESTINGHOUSE ELECTRIC CORPORATION (NASA)
1	PURDUE UNIVERSITY	325	DIVISION OF TECHNICAL INFORMATION EXTENSION
1	RADIOPTICS, INC.		
1	RAND CORPORATION	75	CLEARINGHOUSE FOR FEDERAL SCIENTIFIC AND TECHNICAL INFORMATION