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MECHANICAL PROPERTIES OF HIGHLY IRRADIATED 20 PERCENT COLD-WORKED TYPE 316 STAINLESS STEEL

M. L. Hamilton, N. S. Cannon and G. D. Johnson

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M. L. Hamilton,[1] N. S. Cannon[2] and G. D. Johnson[3]

MECHANICAL PROPERTIES OF HIGHLY IRRADIATED 20 PERCENT COLD WORKED TYPE 316 STAINLESS STEEL

REFERENCE: Hamilton, M. L., Cannon, N. S. and Johnson, G. D., "Mechanical Properties of Highly Irradiated 20 Percent Cold Worked Type 316 Stainless Steel," Effects of Radiation on Materials: Eleventh Conference, ASTM STP 782, H. R. Brager and J. S. Perrin, Eds., American Society for Testing and Materials, 1982

ABSTRACT: Recent experiments have extended the mechanical properties data base of 20 percent cold worked 316 stainless steel to a fluence of 1.3×10^{23} n/cm^2 (E >0.1 MeV), the goal exposure of the Fast Flux Test Facility. Both uniaxial and biaxial tests were conducted on specimens of developmental cladding which were irradiated in the Experimental Breeder Reactor-II at temperatures ranging from 370°C to 650°C. Uniaxial tensile tests were conducted at strain rates ranging from 10^{-5}/s to 10^{-3}/s. Controlled Biaxial Strain Rate (CBSR) tests, recently developed at the Hanford Engineering Development Laboratory, were conducted only at a strain rate of 10^{-5}/s. CBSR specimens are gas-loaded to produce a constant diametral strain rate. These tests are otherwise analogous to uniaxial tensile tests. The tensile strength and ductility of the cladding were generally in good agreement with the predicted values. These predictions were based on data obtained at lower fluences and at test temperatures ranging from 232°C to a maximum of 110°C above each of the irradiation temperatures. The temperature and fluence dependence of the yield strength was found to be consistent with the predictions of microstructurally-based models of irradiation effects at irradiation temperatures above approximately 500°C. The strengths obtained from CBSR testing were in good agreement with the correlations developed from uniaxial data only, although the ductility of the biaxial tests was generally somewhat lower. Both types of tests have shown that the cladding possesses the requisite strength and ductility for FFTF operation to goal exposure.

KEY WORDS: mechanical properties, 316 stainless steel, high fluence, irradiation effects, ductility, microstructure

Liquid Metal Fast Breeder Reactors (LMFBRs) will use stainless steels in numerous core component applications. In particular, the initial core loadings in the Fast Flux Test Facility (FFTF) contain 20 percent cold worked AISI 316 cladding and ducts. Reliable operation of fast reactors requires a complete characterization of the effects of the LMFBR environment on the mechanical properties of this material.

[1]Engineer, Westinghouse Hanford Company, Richland, WA 99352
[2]Senior Engineer, Westinghouse Hanford Company, Richland, WA 99352
[3]Manager, Mechanical Properties, Westinghouse Hanford Company, Richland, WA 99352

Until recently, tensile data on irradiated 20 percent cold worked 316 stainless steel was available only up to a fluence of 8.4 x 10^{22} n/cm^2 (E >0.1 MeV) [1]. The present work describes the effects of fast reactor irradiation to fluences as high as 1.3 x 10^{23} n/cm^2 (E >0.1 MeV) at irradiation temperatures ranging from 370°C to 650°C. Uniaxial tensile tests were conducted at temperatures ranging from room temperature to 110°C above the irradiation temperature and at initial strain rates ranging from approximately 10^{-5} to 10^{-3} s^{-1}.

Anticipated and hypothetical reactor transients will produce circumferential cladding loads due to the differential in the rates of thermal expansion between the mixed oxide fuel and the stainless steel cladding. Since a biaxial stress state is more representative of the imposed transient loading conditions than is the uniaxial stress state of a standard tensile test, a biaxial test was developed which tested cladding specimens at a constant temperature and a constant diametral strain rate, but which was otherwise analogous to a tensile test [2]. Controlled Biaxial Strain Rate (CBSR) tests were performed at test temperatures at or above the irradiation temperature and at a constant strain rate of 10^{-5} s^{-1}.

EXPERIMENTAL TECHNIQUE

Specimens 44.5 mm long were sectioned from 5.8 mm outside diameter by 0.38 mm wall tubing. The tubing material was 20 percent cold worked AISI 316 (Heat Number 87210, Lot T). Specimens to be irradiated at high temperatures were placed in subcapsules filled with sodium to minimize temperature gradients during irradiation in the Experimental Breeder Reactor-II. The subcapsules were positioned in larger capsules to provide a predetermined helium gas gap. The temperature gradient across the helium due to gamma heating provided the desired irradiation temperatures. Low irradiation temperatures were obtained in a "weeper" pin which allowed free ingress of ambient reactor sodium coolant. Nominal irradiation temperatures ranged from 370°C to 650°C. Peak neutron fluence levels of 1.3 x 10^{23} n/cm^2 (E >0.1 MeV) were attained.

The tensile tests were performed on a hard-beam testing machine with an Instron load-extension recorder and with compression fittings gripping the specimens. Tests were performed at room temperature and the irradiation temperature as well as at temperatures which simulated refueling and controlled transients. A vacuum furnace was used to obtain the desired test temperatures with about 15 to 20 minutes for specimen heatup and thermal stabilization. Initial strain rates ranged from approximately 4×10^{-5} to 4×10^{-3} s^{-1}.

The CBSR tests were performed by argon gas-loading the specimens in an induction coil to produce a constant diametral strain rate, which was maintained through continuous measurement of the specimen diameter during the test. The specimen pressure and temperature were controlled by the computer through digital-to-analog converters. Specimens were heated to the test temperature in two to three minutes, with one minute for stabilization, followed by pressurization to failure.

RESULTS

Figures 1 through 6 show the 0.2 percent offset yield strengths obtained in the tensile tests for specimens irradiated at six temperatures and tested at a strain rate of 4×10^{-5} s^{-1}. Figure 7 shows the total elongations obtained in these tests. The correlations shown in each of these figures will be discussed in the next section.

A CBSR test generates pressure-strain traces, like those in Figures 8a and 8b, which are comparable to the load-extension records produced in tensile tests. The types of traces obtained in tests performed at different temperatures are shown in Figure 8a, while Figure 8b shows the effect of strain rate at a high test temperature. While

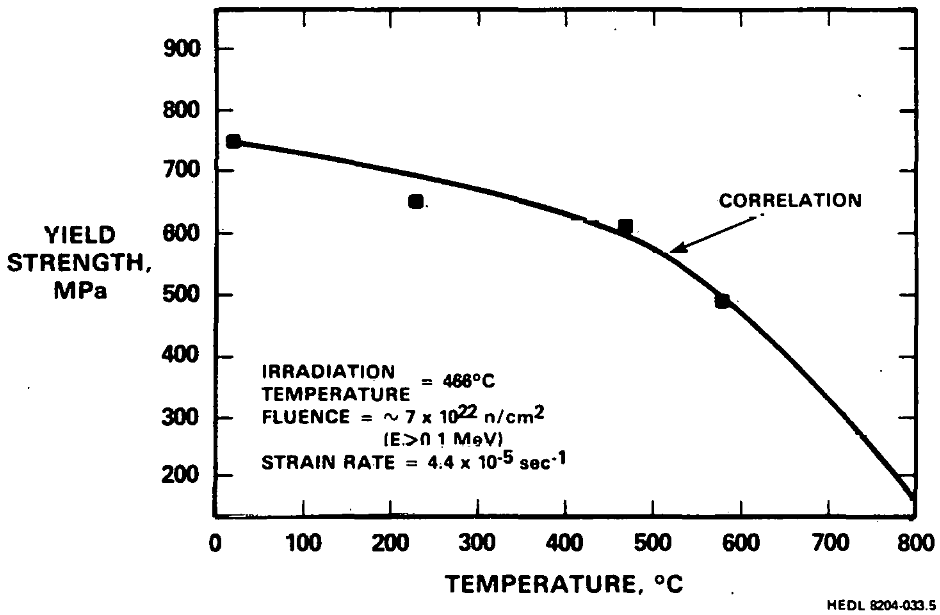

Fig. 1-Yield strength of type 316 stainless steel (T-lot) irradiated at 466°C.

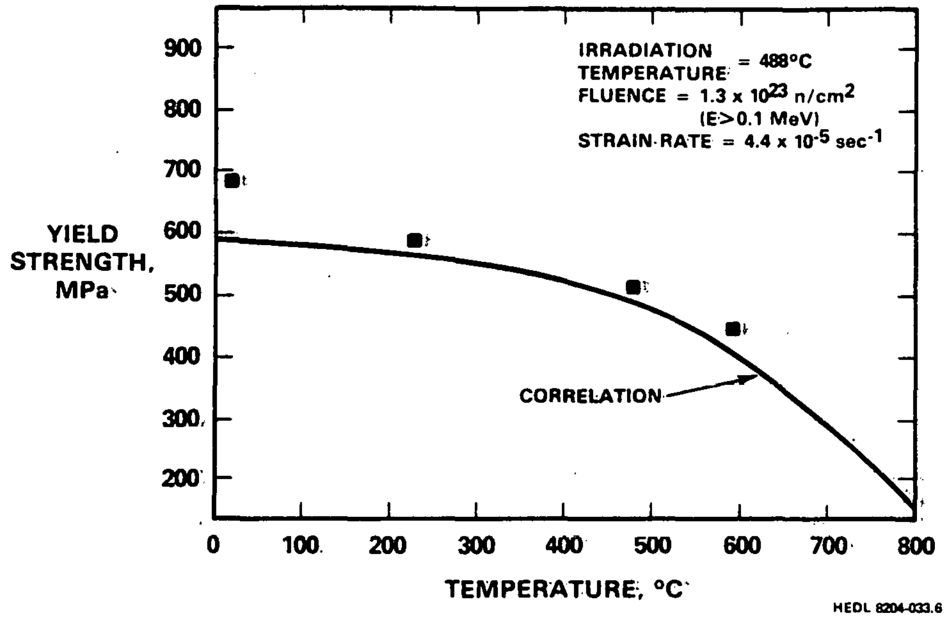

Fig. 2-Yield strength of type 316 stainless steel (T-lot) irradiated at 488°C.

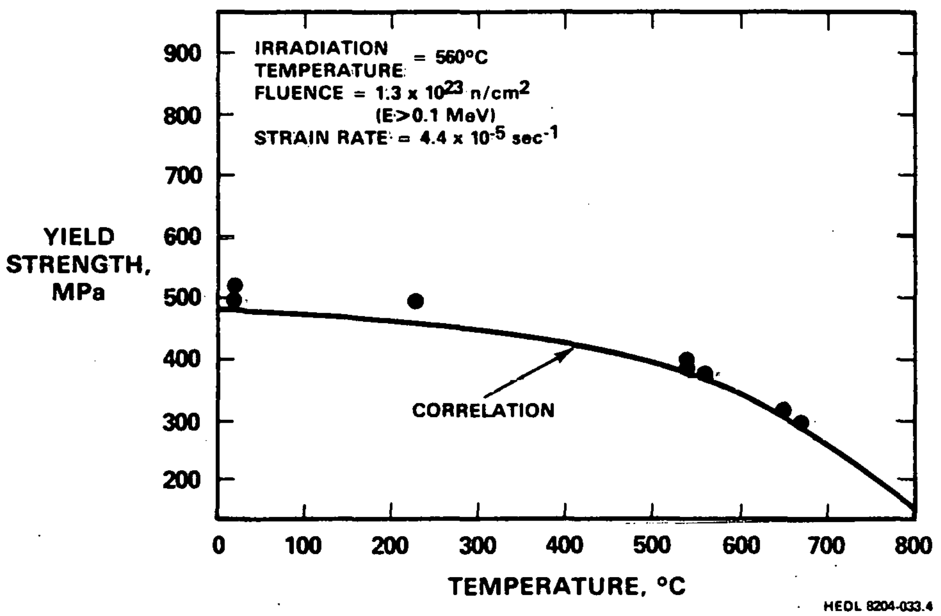

Fig. 3-Yield strength of type 316 stainless steel (T-lot) irradiated at 560°C.

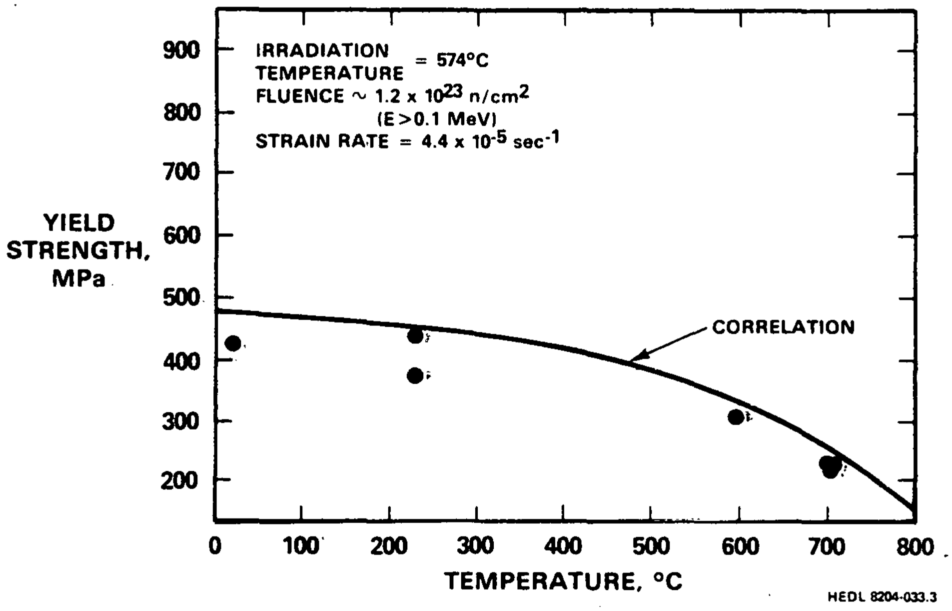

Fig. 4-Yield strength of type 316 stainless steel (T-lot) irradiated at 574°C.

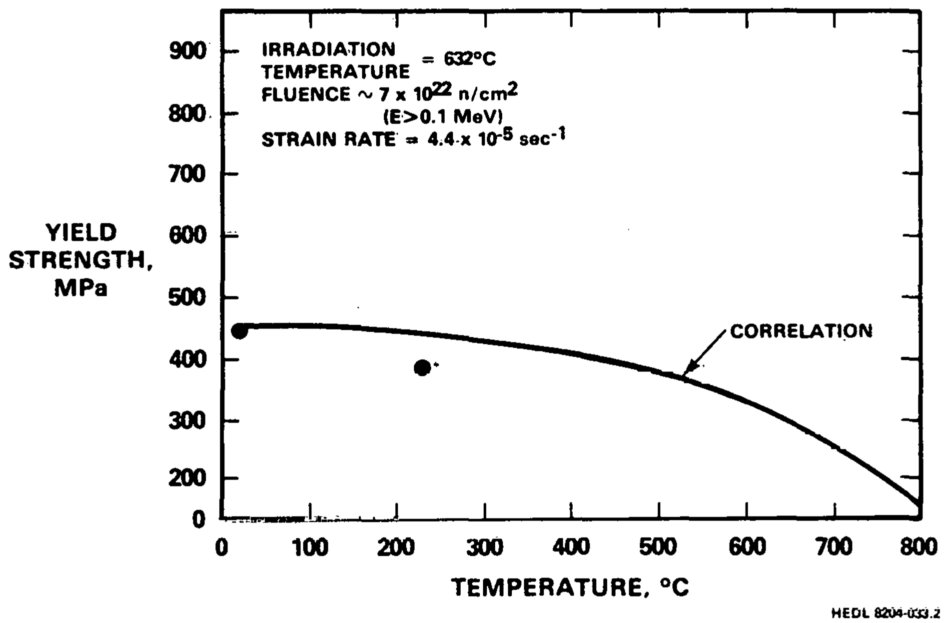

Fig. 5-Yield strength of type 316 stainless steel (T-lot) irradiated at 632°C.

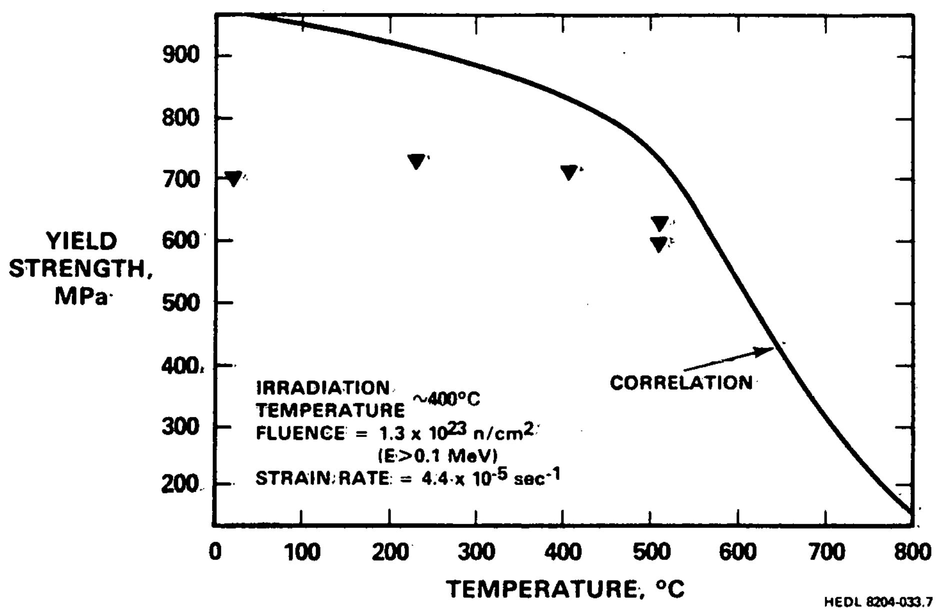

Fig. 6-Yield strength of type 316 stainless steel (T-lot) irradiated at approximately 400°C.

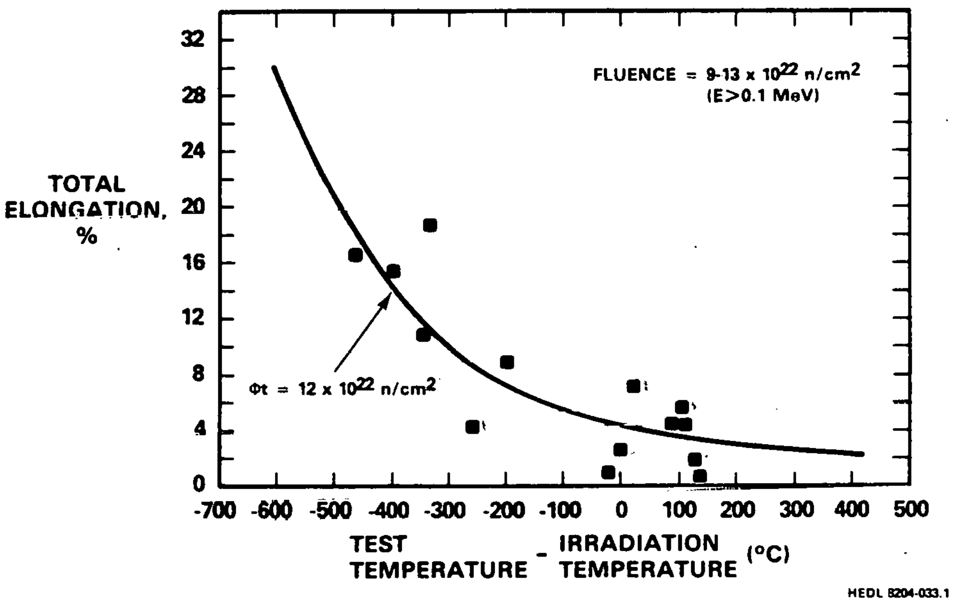

Fig. 7-Total elongation of irradiated 20 percent cold worked 316 stainless steel.

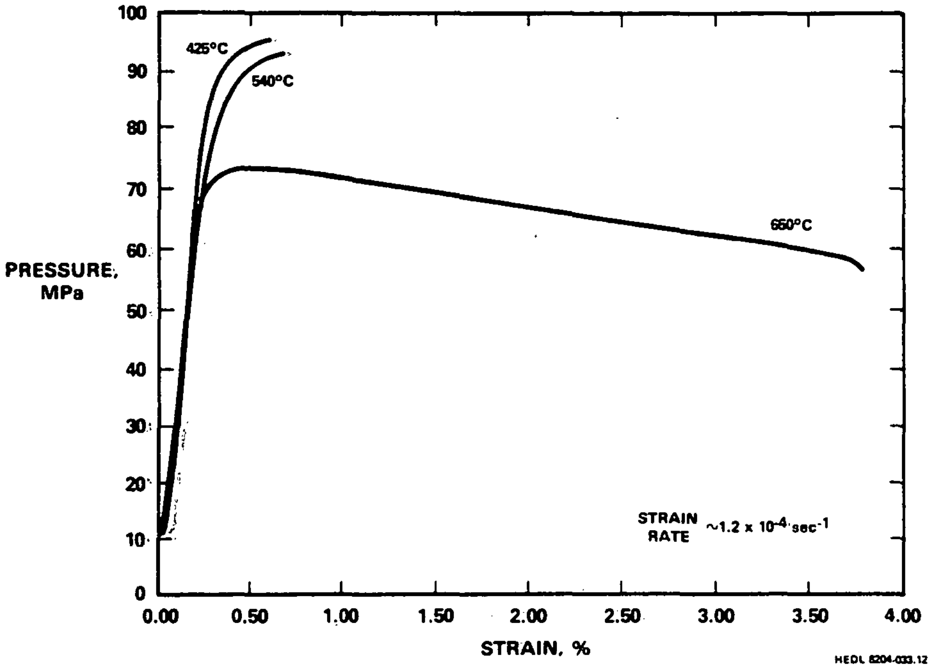

Fig. 8a–Pressure-strain curves at a strain rate of 1.2×10^{-4} sec^{-1} for 425, 540 and 650°C.

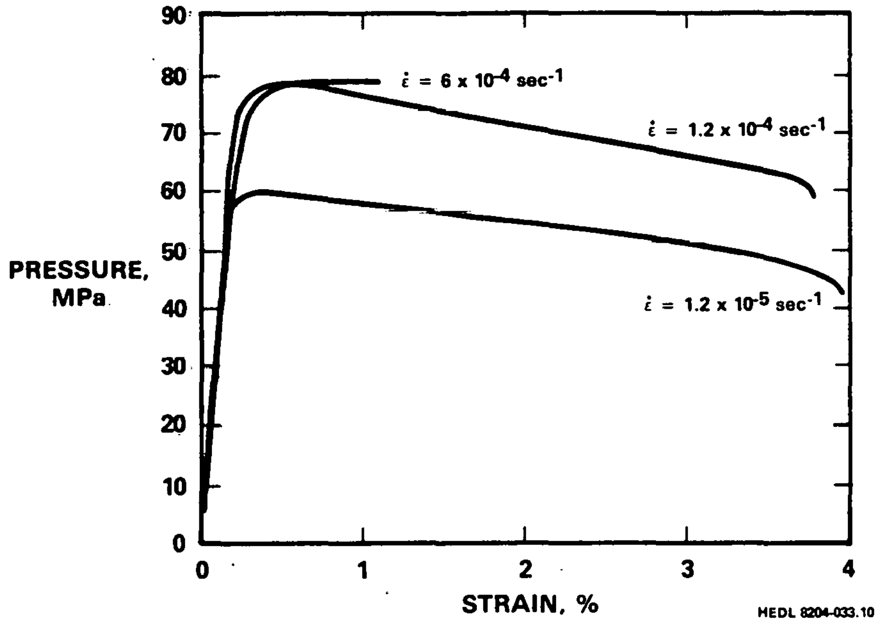

Fig. 8b–Pressure-strain curves at 650°C for strain rates of 1.2×10^{-5}, 1.2×10^{-4} and 6×10^{-4} sec^{-1}.

significant strain-hardening is shown to occur at low test temperatures, this is prevented at higher test temperatures by the recovery of the microstructure. At high temperatures and high strain rates, however, both strain-hardening and recovery are precluded due to the short duration of the test.

From the CBSR traces can be obtained pressures analogous to the proportional elastic limit (PEL), yield and ultimate strengths, as well as ductilities corresponding to the uniform elongation. The PEL was determined graphically as the pressure at which the initial portion of the pressure-strain trace first deviates from linearity. The yield pressures were determined using a 0.17 percent offset hoop strain at the specimen outer diameter. This strain value was calculated using the thin wall approximation to correspond to a 0.2 percent effective strain at the specimen midwall [2]. The relationships between uniaxial and biaxial strengths and ductilities will be discussed in the following section.

DISCUSSION

Strength

Correlations based on an equation of state approach were developed previously by Fish, et. al. [1] describing the effects of irradiation on the tensile properties of 20 percent cold worked 316 stainless steel. The basic premise of these correlations was that the deformation state of the material can be characterized by a structure parameter describing the material's hardness. The data on which these correlations were based were obtained from specimens irradiated to a maximum fluence of 8.4×10^{22} n/cm^2 (E >0.1 MeV). These data established that the increase in strength observed after irradiation at low temperatures saturated by a fluence of about 5×10^{22} n/cm^2, whereas the decrease in strength with irradiation at high temperatures was equivalent to that exhibited by thermally aged material. As shown in Figures 1 through 5, the strengths obtained verify the correlation predictions at high fluences for irradiation temperatures above approximately 460°C. At temperatures above approximately 500°C, the data are also in good agreement with microstructurally-based predictions [3,4] which correlate the yield strength with radiation-induced changes in both the number densities and sizes of various microstructural components, e.g., precipitates, Frank loops, voids and dislocations (Figure 9).

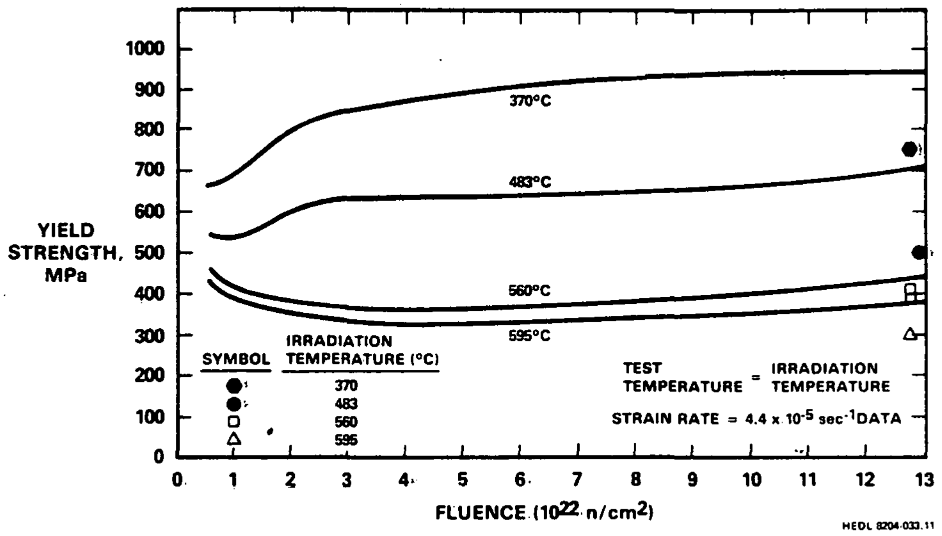

Fig. 9-Comparison of high fluence tensile strengths with microstructural correlation predictions.

High fluence exposure below 500°C, however, induces a concurrent softening and increase in ductility for which no microstructural explanation is yet available. The decrease in strength observed for an irradiation temperature of approximately 400°C is shown in Figure 6. Investigation into the nature of this softening effect are ongoing.

Comparison factors developed by Cannon, [2] relating the biaxial PEL, yield and ultimate strengths to equivalent tensile quantities, have been found to be relatively independent of specimen test and irradiation histories. The comparison factors are defined as the ratio of the relevant tensile stress to the appropriate CBSR pressure, and tests on unirradiated material show that they are equal to 7.14, 5.74 and 6.91 for the PEL, yield and ultimate strengths, respectively. A more detailed description of the comparison factors may be found in Reference 2.

When coupled with the existing tensile correlations, the comparison factors provide an excellent prediction of the strengths obtained in CBSR tests on irradiated material having a wide range of exposure. This is shown in Figure 10 for both the yield and ultimate strengths at high fluences. Similar results are observed for the PEL, although the scatter is slightly larger due to the subjective nature of the PEL measurements.

Ductility

Simple correlations were developed from the tensile data base to describe the uniform and total elongations. The total elongation was fit to

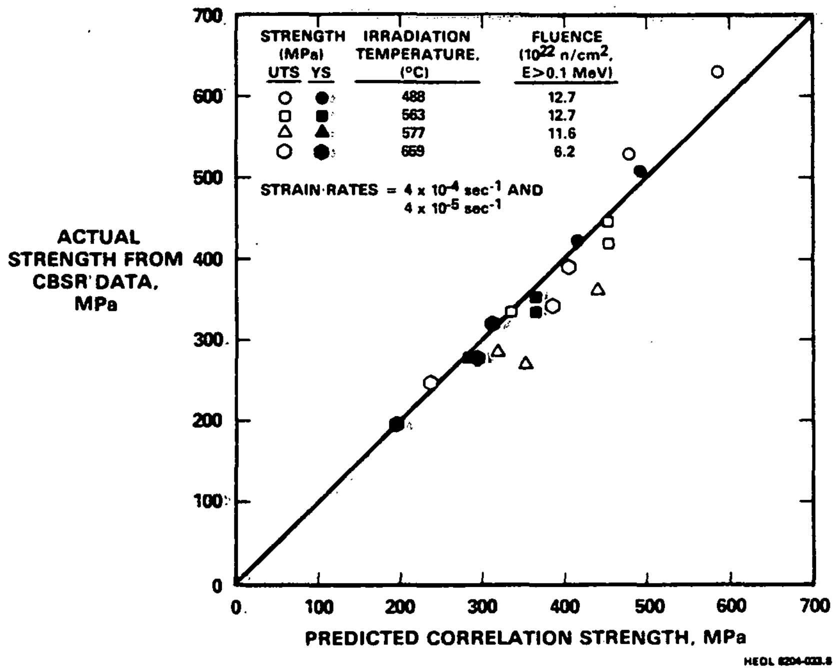

Fig. 10-Comparison of strengths predicted by correlation and CBSR strengths calculated with the appropriate comparison factors.

$$\varepsilon_T = 2 + 28 \exp[-4.17 \times 10^{-3}(T - T_i + 600)] + 3.5[1 - \tanh(\phi t - 1.5)]$$

while the uniform elongation was fit to

$$\log \varepsilon_U = 0.524 + 0.32 \exp(-.0577\ \phi t) - 1.315 \times 10^{-3}(T - T_i)$$

where ε is in percent, ϕt is in 10^{22} n/cm^2 (E $\geq$0.1 MeV), and T and T_i are the test and irradiation temperatures in °C, respectively. The high fluence tensile ductilities were generally in good agreement with these predictions, as is shown in Figure 7.

While biaxial cladding strength can be predicted relatively accurately from existing tensile correlations, biaxial ductility cannot. Biaxial ductilities are consistently lower than corresponding uniaxial strains, which results from the inherent differences in the instability and failure configurations of the two stress states. Instability and failure occur at smaller strains under this biaxial loading condition than under uniaxial tension since a through-wall crack represents failure in a gas-loaded tube while complete decohesion is required for uniaxial failure. It has been shown by Lankford and Saibel [5] that, for the case of power law strain-hardening, the hoop strain at the maximum pressure in a gas-loaded tube should be equal to one-half of the uniform strain of a similar uniaxial test. Figure 11 shows that, for cladding irradiated at low

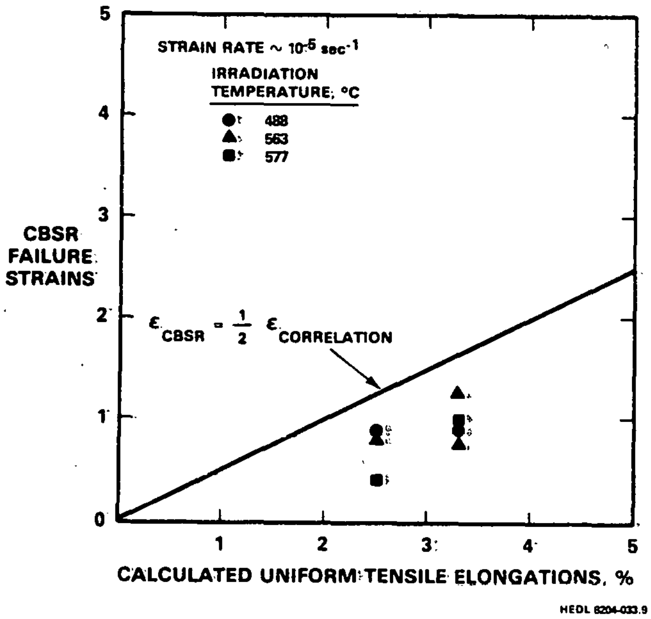

Fig. 11–Comparison between CBSR ductility and ductility predicted by tensile correlations for cladding irradiated at low temperatures.

temperatures, the failure strains obtained in the CBSR tests are consistently below the elongations which were predicted on the basis of the existing tensile correlations and the analysis described above.

CONCLUSION

The mechanical properties have been determined for AISI 316 stainless steel cladding irradiated to high fluences. Tensile strength and ductility are in good agreement with both equation of state and microstructral correlations above irradiation temperatures of 500°C. While biaxial strength can be predicted from tensile correlations, biaxial ductility is somewhat lower than corresponding tensile ductility. Both types of data indicate that 20 percent cold worked AISI 316 possesses adequate strength and ductility for FFTF operation to goal exposure.

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