A COMPARISON OF THE IRRADIATED TENSILE PROPERTIES OF A HIGH-MANGANESE AUSTENITIC STEEL AND TYPE 316 STAINLESS STEEL*

R. L. KLUEH and M. L. GROSSBECK

Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830 USA

The USSR steel EP-838 is a high-manganese (13.5%), low-nickel (4.2%) steel that also has lower chromium and molybdenum than type 316 stainless steel. Tensile specimens of 20%-cold-worked EP-838 and type 316 stainless steel were irradiated in the High Flux Isotope Reactor (HFIR) at the coolant temperature (~50°C). A displacement damage level of 5.2 dpa was reached for the EP-838 and up to 9.5 dpa for the type 316 stainless steel. Tensile tests at room temperature and 300°C on the two steels indicated that the irradiation led to increased strength and decreased ductility compared to the unirradiated steels. Although the 0.2% yield stress of the type 316 stainless steel in the unirradiated condition was greater than that for the EP-838, after irradiation there was essentially no difference between the strength or ductility of the two steels. The results indicate that the replacement of the majority of the nickel by manganese and a reduction of chromium and molybdenum in an austenitic stainless steel of composition near that for type 316 stainless steel has little effect on the irradiated and unirradiated tensile properties at low temperatures.

1. INTRODUCTION

As part of a US and USSR materials collaboration, a stock of the austenitic stainless steels that are being considered as fusion reactor first wall and blanket structure candidate materials was exchanged: US type 316 stainless steel was exchanged for the USSR austenitic steel designated EP-838. The objective of this collaboration was for each country to irradiate and compare the results on the two materials.

The EP-838 steel is a high-manganese, low-nickel steel that also has lower chromium and molybdenum than type 316 stainless steel. The USSR investigators feel that because nickel has a much higher cross section for (n,p) and (n,α) reactions, it is advisable to limit the amount of nickel in the first wall structural alloy.¹ By substituting manganese for nickel, an economic advantage should also accrue.¹

Because the austenite-stabilizing power of manganese is not as great as that of nickel, the nickel was not entirely replaced by manganese.

The lower chromium and molybdenum concentration present in EP-838 relative to type 316 stainless steel also reflect manganese's lower austenite-forming capability.

In the present work we present results on the EP-838 steel in the irradiated and unirradiated condition and compare the results with similarly irradiated type 316 stainless steel. The studies were on the steels in the 20%-cold-worked condition; USSR investigators recently published results on the same steels in the solution-annealed condition.¹

2. EXPERIMENTAL PROCEDURE

The compositions of the EP-838 and type 316 stainless steel are given in Table 1; the type 316 stainless steel is from the fusion reference heat (X15893). There are several major compositional differences between the steels, most notably the Ni, Mn, Cr, Mo, and Al.

Specimens of both steels were machined from 0.76-mm-thick sheet that was in the 20%-cold-

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Table 1. Chemical Composition of Austenitic Steels

Element	Chemical Composition (wt %)	
	USSR High-Manganese Steel	Type 316 Stainless Steel
Cr	11.6	17.28
Mn	13.5	1.70
Ni	4.2	12.44
Mo	0.9	2.10
Co	0.003	0.3
Cu	0.1	0.3
Si	0.42	0.67
Nb		<0.05
V	0.01	
Ta	0.01	<0.05
Ti	<0.018	<0.05
Al	0.72	
B	0.001	0.0004
Ce	0.04	
La	0.007	
Nd	0.008	
Pr	0.001	
C	0.02	0.061
S	0.02	0.018
P	0.003	0.037
Fe ^a	68.4	63.9

^aIron is approximate, by balance.

worked condition. Before the EP-838 sheet was rolled to the final thickness, it was annealed 0.83 h at 1160°C. The type 316 stainless steel was annealed 1 h at 1050°C prior to the final deformation.

Sheet tensile specimens were used with a reduced gage section 20.3-mm long by 1.52-mm wide by 0.76-mm thick. Two specimens of EP-838 and ten of the 20%-cold-worked type 316 stainless steel (CW 316) specimens were irradiated at the HFIR coolant temperature (about 50°C). Although the maximum total fluence for the HFIR-irradiation experiment was 5×10^{26} neutrons/m² and the maximum fast fluence was 1.3×10^{26} neutrons/m² (> 0.1 MeV), the EP-838 specimens were at the ends of the capsule and received about 0.63×10^{26} neutrons/m² (> 0.1 MeV) (the minimum value). Type 316 stainless steel specimens were irradiated over the full range of fluence values.

After immersion density measurements, the specimens were tensile tested at room temperature and 300°C. Tests were conducted in a vacuum chamber on a 44-kN capacity Instron universal testing machine at a strain rate of 4.2×10^{-5} /s.

3. RESULTS AND DISCUSSION

There was no detectable change in the density of the EP-838 or the type 316 stainless steel as a result of the irradiation.

Although there were some notable differences in the unirradiated tensile properties of the EP-838 and CW 316, the irradiated properties were quite similar (Figs. 1 and 2). The 0.2% yield stress of the unirradiated CW 316 at room temperature and 300°C was ~15% greater than that of the EP-838 [Fig. 1(a)]. There was little difference in the unirradiated ultimate tensile strength [Fig. 1(b)] at room temperature, but the CW 316 was about 10% stronger at 300°C. The room temperature uniform and total elongations of EP-838 were considerably greater than those for the CW 316; however, there was little difference at 300°C (Fig. 2).

After irradiation there was very little difference in tensile properties. Both of the EP-838 specimens were irradiated to 5.2 dpa (~63 ppm He). Two CW 316 specimens irradiated to 5.2 dpa (~159 at. ppm He) and 9.5 dpa (~416 at. ppm He) were tested at room temperature. Although the specimen irradiated to 9.5 dpa was slightly stronger, the difference was less than 5%, indicating that a saturation level of hardening is probably being approached at this fluence. The yield stress and ultimate tensile strength for EP-838 were almost identical to those for the CW 316 specimen irradiated to 9.5 dpa; (the values for CW 316 shown in Figs. 1 and 2 are for the specimen irradiated to 5.2 dpa). At 300°C, there is essentially no difference in any of the properties for the EP-838 at 5.2 dpa and the CW 316 at 7.8 dpa (Figs. 1 and 2).

FIGURE 1

(a) The 0.2% yield stress and (b) the ultimate tensile strength plotted against test temperature for 20%-cold-worked EP-838 and type 316 stainless steels, unirradiated and after HFIR irradiation at about 50°C.

The similarity in behavior of the two steels and the large increase in strength and decrease in uniform and total elongation that result from irradiation are obvious when the tensile curves are examined (Fig. 3). Except for the larger unirradiated ductility of the EP-838 at room temperature, there is essentially no difference in the two steels. The low uniform elongation of these steels after irradiation seems to be characteristic of materials irradiated and tested at low temperatures. Similar large decreases were noted for ferritic steels irradiated at the HFIR coolant temperature.^{2,3}

Vortinov et al.¹ compared the effect of irradiation on the behavior of EP-838 and type 316 stainless steel in the solution-annealed condition. After irradiation to a fluence of

2.5×10^{24} neutrons/m² (>0.1 MeV), unirradiated and irradiated specimens were tensile tested over the range 20 to 750°C. The authors concluded, "The nature of the load-elongation curves and similar elongation values, in the original as well as the irradiated states, are evidence of identical deformation and fracture modes before and after irradiation."¹ This statement also summarizes our observations on the comparison of the 20%-cold-worked EP-838 and type 316 stainless steel. It should be kept in mind, however, that these conclusions follow from a very limited set of test conditions.

Recently, there has been an interest in developing alloys that only contain elements that form relatively short-lived radioactive daughter elements when irradiated in a fusion

FIGURE 2

The uniform and total elongation plotted against test temperature for 20%-cold-worked EP-838 and type 316 stainless steels unirradiated and after HFIR irradiation at about 50°C.

FIGURE 3

Engineering stress-strain curves at (a) room temperature and (b) 300°C for unirradiated and irradiated 20%-cold-worked EP-838 and type 316 stainless steel.

neutron spectrum. When the fusion reactor components made from such a material are removed from service, the type of waste-disposal and waste-management processes required would be minimal compared with alloys that contained long-lived radioactive elements. In the case of type 316 stainless steel, the elements that contribute to long-lived residual radioactivity are nickel and molybdenum. Manganese would be a favorable replacement for nickel from a radioactivity point of view.

The results of these tests indicate that the replacement of the majority of the nickel by manganese in an austenitic stainless steel has little effect on the irradiated and unirradiated tensile properties under the conditions of the present studies. Although there were slight differences in properties before irradiation, after irradiation the tensile behavior was essentially

the same. This preliminary result can be taken as a favorable indication for the development of an austenitic alloy with a reasonably rapid decay of the induced radioactivity after a component is removed from service. Such an alloy will need to contain essentially no nickel, which may produce some complications, because manganese does not have the austenite stabilizing capacity of nickel.⁴

It should be noted that for a steel to be considered a stainless steel, it must contain 12% Cr. Technically, EP-838 is not a stainless steel. If nickel is to be eliminated completely in a steel designed for rapid radioactivity decay, it will probably not be possible for it to contain 12% Cr, assuming that the carbon concentration is maintained at reasonably low levels⁴ (i.e., chromium stabilizes ferrite, which cannot be tolerated because of the possible formation of sigma phase during service at elevated temperatures). This is especially true if, as seems likely, it proves necessary to add such ferrite-stabilizing elements as titanium, silicon, and tungsten for strength, swelling resistance, and corrosion resistance.

4. SUMMARY AND CONCLUSIONS

Tensile specimens of the USSR EP-838 steel and type 316 stainless steel in the 20%-cold-worked condition were irradiated in HFIR at ~50°C. The EP-838 steel has a high manganese and low nickel concentration relative to type 316 stainless steel and also has lower chromium and molybdenum concentrations. Unirradiated and irradiated specimens were tested at room temperature and 300°C.

In the unirradiated condition the yield stress of the CW 316 was ~15% greater than that of the EP-838; there was relatively little difference in ultimate tensile strength at room temperature, and the CW 316 value was ~10% greater at 300°C. The ductility of the EP-838

was considerably greater than that of the CW 316 at room temperature, but approximately the same at 300°C. Irradiation resulted in an increase in yield stress and ultimate tensile strength and a decrease in uniform and total elongation for both materials. After the irradiation there was essentially no difference in the properties for the two steels. All indications are that the increased manganese and decreased nickel, chromium, and molybdenum in the EP-838 did not greatly affect either the unirradiated or irradiated properties.

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