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TENSILE PROPERTIES OF UNIRRADIATED PCA FROM ROOM TEMPERATURE TO 700°C*

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The tensile properties of Prime Candidate Alloy (PCA) austenitic stainless steel after three different thermomechanical treatments were determined from room temperature to 700°C. The solution-annealed PCA had the lowest strength and highest ductility, while the reverse was true for the 25%-cold-worked material. The PCA containing titanium-rich MC particles fell between the other two heats. The cold-worked PCA had nearly the same tensile properties as cold-worked type 316 stainless steel. Both alloys showed ductility minima at 300°C.

1. INTRODUCTION

The Prime Candidate Alloy (PCA) is an austenitic stainless steel that is being evaluated for possible application in a fusion reactor. Although the composition of PCA is close to that of type 316 stainless steel, numerous small, but important, changes have improved the radiation resistance of the alloy. Further optimization of PCA has been investigated through the use of various thermomechanical treatments. Seven different treatments were originally developed for PCA,[1] and of these, three were selected for further testing because of their superior resistance to swelling. Specimens of PCA given these three treatments are now being studied with regard to their resistance to helium embrittlement. The purpose of this paper is to provide data on the tensile properties of unirradiated PCA in the three different conditions that will serve as a basis of comparison for the embrittlement tests.

Table 1. Alloy Composition (wt %)

PCA				316 SS			
Fe	Bal	Mo	2.3	Fe	Bal	Mo	2.2
Ni	16.2	Mn	1.8	Ni	12.4	Mn	1.7
Cr	14	C	0.05	Cr	17.3	C	0.05
Ti	0.24	Si	0.4	Ti	—	Si	0.7
		P	0.01			P	0.03

Table 2. Alloy Thermomechanical Treatments

Designation	Microstructure	Treatment
PCA-A1	Solution annealed	25% cold-worked, 30 min at 1100°C
PCA-A3	Cold worked	30 min at 1100°C, 25% cold worked
PCA-B2	MC precipitation	30 min at 1100°C, 8 h at 800°C, 25% cold worked plus 2 h at 750°C
CW 316	Cold worked	20% cold worked

2. EXPERIMENTAL

The composition and thermomechanical treatments for PCA and type 316 stainless steel (MFE reference heat) are given in Tables 1 and 2, respectively. Small tensile specimens of the "SS-1" design (Fig. 1) were machined from 0.76-mm-thick sheet of both PCA and the 20% cold-worked type 316 (CW 316) stainless steel. The specimens were tested in air in an Instron tensile testing machine fitted with a wire-wound resistance furnace. The crosshead speed was 0.5 mm/min (0.02 in./min) and the strain rate was $4.2 \times 10^{-4}\ s^{-1}$. The microstructure of the alloys was examined by transmission electron microscopy (TEM) before tensile testing and selected fracture surfaces

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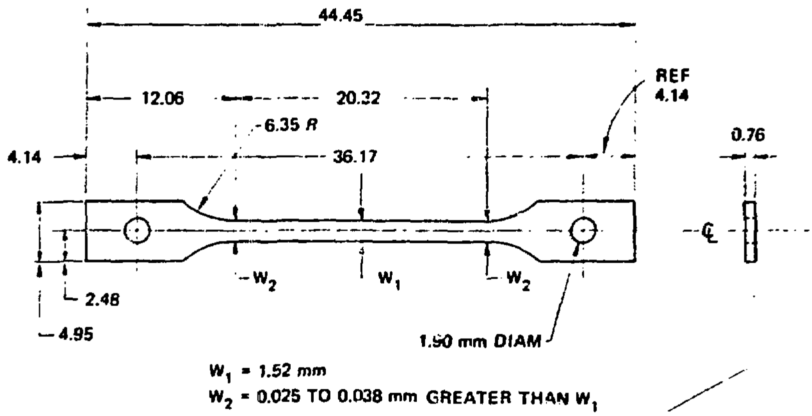

FIGURE 1
The SS-1 sheet tensile specimen. (Dimensions are in millimeters).

were observed by scanning electron microscopy (SEM) after testing.

3. RESULTS AND DISCUSSION

3.1 Microstructure

The microstructure of PCA after three different thermomechanical treatments is shown by the TEM micrographs in Fig. 2. The PCA in the solution annealed or Al condition [Fig. 2(a)] had a relatively low dislocation density and did not contain any titanium-rich MC particles. The cold-worked PCA or PCA-A3 [Fig. 2(b)] had a high dislocation density and no MC particles. The PCA-B2 had a complex microstructure with coarse titanium-rich MC particles on the grain boundaries and very fine MC on matrix dislocations as shown in Fig. 2(c). Although the microstructure of 20% CW 316 stainless steel is not shown, it closely resembles that of PCA-A3 in Fig. 2(b).

3.2 Tensile Properties

The results of the tensile tests for the three PCA alloys and CW 316 stainless steel are given in Fig. 3. The ultimate and yield strength values are plotted as a function of test temperature in the upper portion of each figure, while the uniform and total elongation values are shown below. The PCA-Al demonstrated

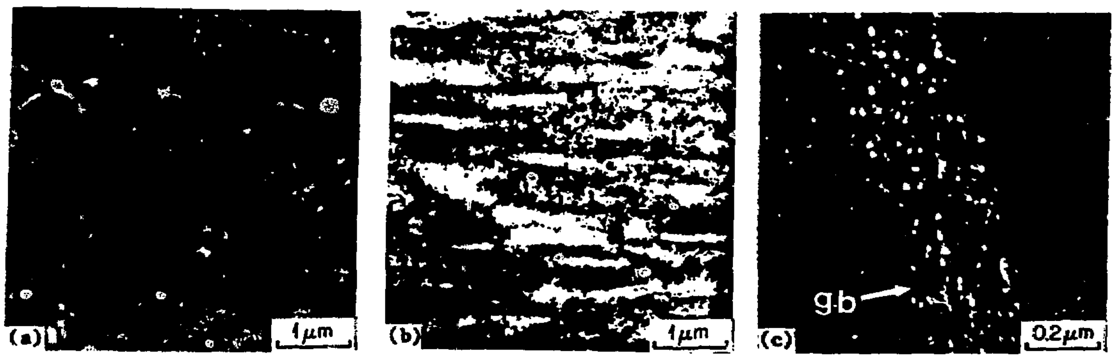

FIGURE 2
Microstructure of PCA after three different treatments: (a) solution annealed (Al), (b) 25% cold worked (A3), and (c) 25% cold worked and aged 15 min at 750°C (B2) (precipitate dark field imaging — MC appears white).

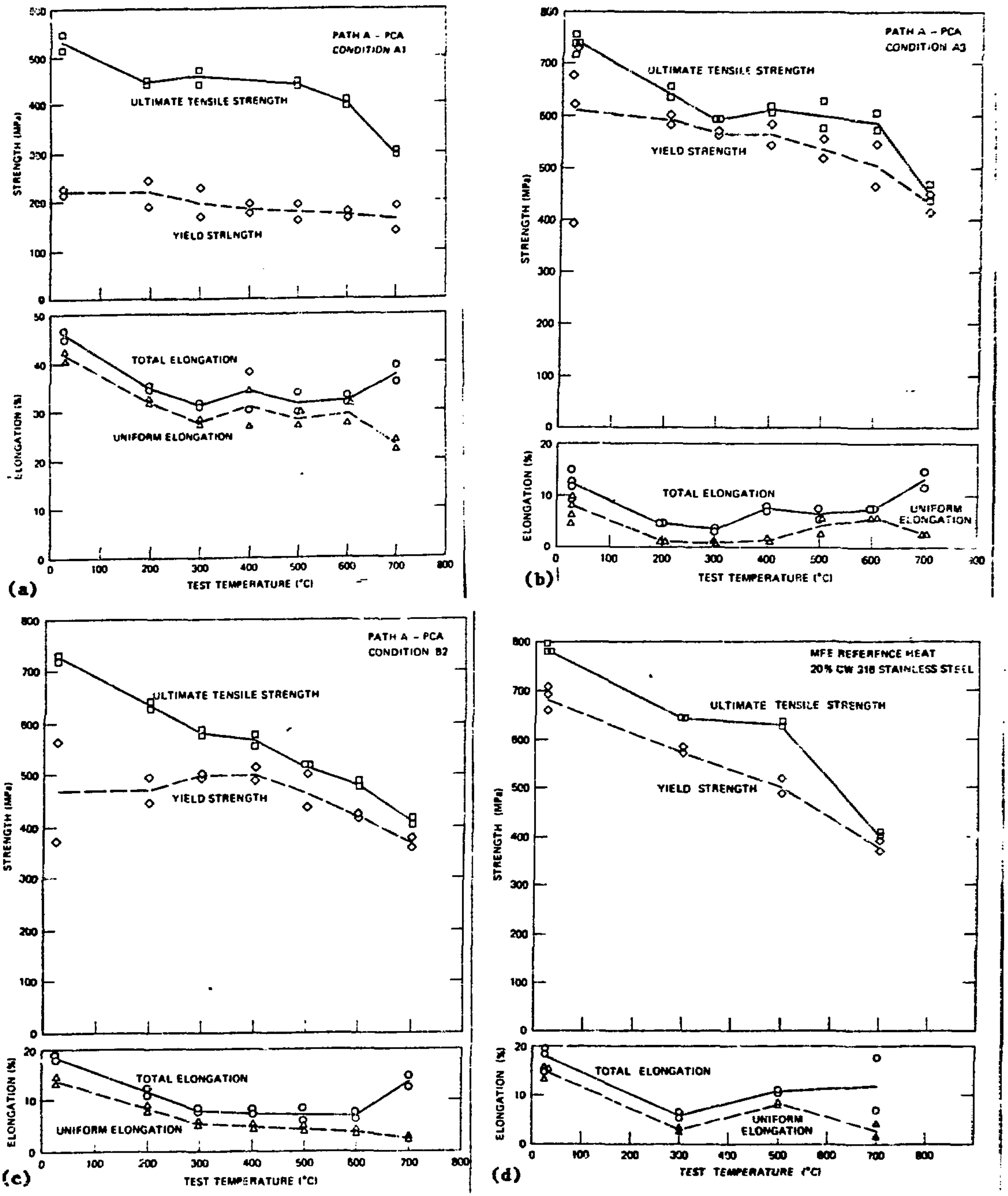

FIGURE 3

Tensile properties as a function of test temperature for (a) PCA-A1 (solution annealed), (b) PCA-A3 (25%-cold worked), (c) PCA-B2 (25%-cold worked for 15 min at 750°C), and (d) 20%-cold-worked 316 stainless steel.

yield strengths that were about one-half of the ultimate strengths and rather high values of ductility [Fig. 3(a)]. The respective values are nearly the same as those reported for a titanium-modified type 316 stainless steel.[2] Cold working the PCA increased the yield and ultimate tensile strengths and decreased the ductility at all temperatures [Fig. 3(b)]. However, the PCA-A3 was somewhat weaker (and more ductile) than the 20%-cold-worked titanium-modified type 316 stainless steel at 35 and 300°C (ref. 2). Relatively low ductilities were measured for PCA-A3 around 300°C. Possible causes for these low ductilities are discussed in a later section dealing with fracture. The PCA-B2 [Fig. 3(c)] showed modest increases in strength due to the precipitation of fine MC on its dislocation-laden structure, but the material was not as strong as the cold-worked PCA-A3. The results for the CW 316 stainless steel, in Fig. 3(d), were nearly the same as those for the cold-worked PCA [Fig. 3(b)], including a ductility minimum at 300°C. Apparently, the effects of cold work obscured any effects caused by the relatively small differences in composition. Of course, the response of these two alloys to subsequent thermal aging or neutron irradiation is expected to be very different and, in this sense, the small differences in composition are extremely important.

Higher strengths and good ductility can be achieved in the PCA alloy using rapid solidification techniques and powder metallurgy consolidation.[3] Those fabrication techniques produce a very fine grain size and a uniform distribution of MC particles throughout the grain matrices.

3.3 Fracture

The ductility minimum observed in CW 316 and PCA-A3 was investigated further by examining the fracture surfaces of the PCA-A3 by SEM and conventional metallography. Figure 4 shows comparisons of the fracture surface of specimens

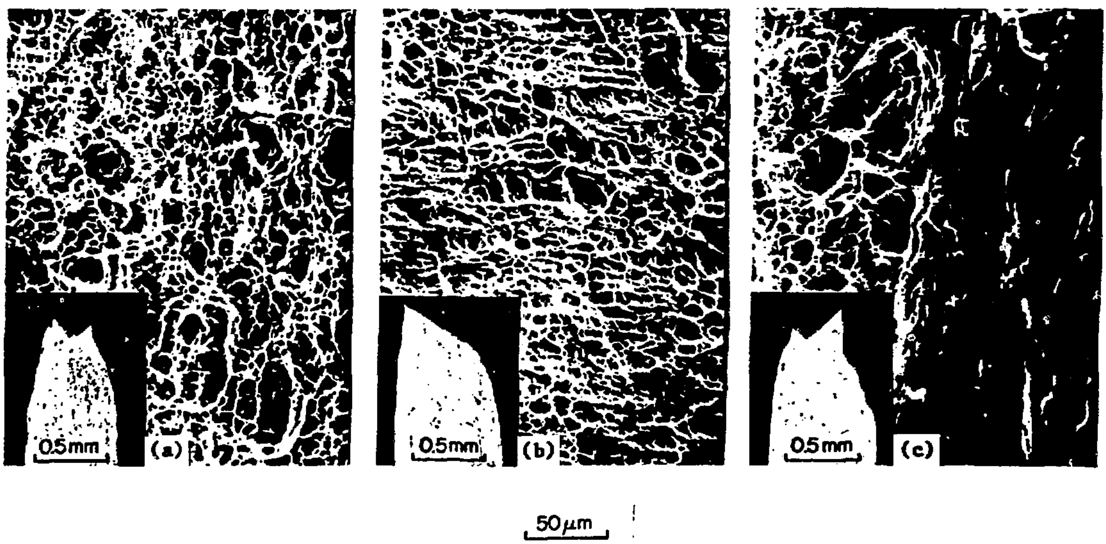

FIGURE 4
Fracture surfaces and profiles (insets) for PCA-A3 (25% cold worked) tested at (a) room temperature, (b) 300°C, and (c) 600°C.

tested at room temperature, 300, and 600°C. At room temperature, the PCA-A3 specimens failed in a ductile fashion as evidenced by the "cup and cone" fracture of which the cone portion is shown in the inset in Fig. 4(a). The dimpled appearance of the fractograph is also typical of ductile fracture in which a mechanism of void coalescence is operating. At 300°C, where ductility was a minimum, the fracture mode was still ductile as shown by the dimples. However, the dimples were elongated, which usually indicates ductile tearing.[4] The specimen profile near the fracture showed less necking than observed at room temperature, and fracture occurred at ~35° to the load axis [Fig. 4(b) inset]. This suggests that there might have been a stronger shear component involved in the fracture. The reason for this behavior is not understood at this time. The specimens tested at 600°C showed cup and cone fractures with moderate necking as shown in the inset in Fig. 4(c). At this elevated temperature, the shear lip was more pronounced. The fractograph in Fig. 4(c) was taken at the root of the cup, so the surfaces to the right, where shear was prominent, were relatively smooth, while areas to the left were dimpled.

4. CONCLUSIONS

1. The tensile properties of PCA depended on the thermomechanical treatment given the alloy. Higher strength and lower ductility were measured after cold working, while intermediate strengths and ductility were achieved for a microstructure containing titanium-rich MC particles. Lower strengths and higher ductilities were characteristic of the solution-annealed material.

2. The PCA-A3 had nearly the same tensile properties as CW type 316 stainless steel.

3. The PCA-A3 and CW 316 exhibited ductility minima at 300°C.

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