CRACK-ARREST TESTS OF IRRADIATED HIGH-COPPER ASTM A508 SUBMERGED-ARC WELD METAL

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ABSTRACT

Experiments were conducted on SA weld-metal specimens removed from an ASTM A508 Class 2 steel pressure-vessel nozzle cutout to assess the effect of exposure to fast neutrons on strength, toughness, and crack-arrest behavior. The weldment contained about 0.3 pct. copper, which is typical for weldments employed in some of the early light-water reactors. Exposure to 0.6 to 1.0 x 10^{19} n/cm^2 (E $\geq$ 1 MeV) at 280 C caused the tensile yield strength to be raised by 25 to 30 pct., the Charpy shelf-energy to decrease by about 45 pct., and the 50 J (35 ft-lb) Charpy-energy-transition temperature to increase about 120 C. Because of the limited number of tests, no firm conclusions were drawn on the effect of irradiation on crack-arrest properties. However, the data suggest that the shifts in transition temperature for both K_{ID} and K_{Ia} were no greater than the shift in the 50 J Charpy-energy-transition temperature or than the shift in RT_{NDT} predicted on the basis of the copper content of the steel.

KEYWORDS

Crack arrest; neutron irradiation; pressure-vessel steel; AISI 4340 steel; high-copper weldment; ductile-brittle transition; tensile properties; Charpy energy.

LIST OF SYMBOLS AND ABBREVIATIONS

K_Q - Stress-intensity parameter at initiation of rapid fracture
K_{ID} - Stress-intensity parameter associated with extension of a rapidly propagating crack
K_{Ia} - Stress-intensity parameter some period of time ($\geq$ 1 ms) after arrest of a rapidly propagating crack
DCB - Double-cantilever beam
EB - Electron beam
SA - Submerged arc
LOCA - Loss-of-coolant accident
a - Crack length
b - Uncracked-ligament length

B - Thickness
B_n - Net thickness at bottom of side grooves
σ_f - Flow strength; average of yield and tensile strength
J_{Ic} - Value of J-integral at fracture initiation
NRC - Nuclear Regulatory Commission
EPRI - Electric Power Research Institute
RT_{NDT} - Reference nil-ductility transition temperature.

INTRODUCTION

It is well known that those portions of nuclear pressure vessels located in the reactor-beltline region undergo gradual property changes as they are bombarded by stray neutrons from the core. Of most concern, from the standpoint of vessel integrity during a LOCA, is the decrease in upper-shelf toughness and the increase in the ductile-brittle transition temperature that accompany irradiation. The magnitude of the property changes depends on the number of fast neutrons, the temperature, and the amount of copper and phosphorus present in the steel (Hawthorne, 1971). According to the US NRC Reg. Guide 1.99, the predicted effect of exposing a steel that contains 0.3 pct. copper and 0.012 pct. phosphorus to 10^{19} fast neutrons at 288 C is to raise the RT_{NDT} by about 135 C and to lower the upper-shelf energy by about 40 pct.

The objective of the work described here, which was part of a coordinated effort to establish a rational crack-arrest methodology for nuclear pressure vessels, was to measure the effect of fast-neutron exposure on K_{ID} and K_{Ia} of a high-copper SA weld in A508 steel. When the program was begun, virtually no data existed to show irradiation effects on these properties. At the time of preparation of this paper, a more extensive program to examine radiation effects was in progress, but results were not yet available (Mager and Marschall, 1979).

MATERIAL INVESTIGATED

Two quarter-sections of an ASTM A508 Class 2 steel pressure-vessel-nozzle cutout that contained an SA weld were used in this study. Each quarter-section had a thickness and radius of about 30 cm. The weldment was typical of those employed in some of the early light-water reactors, i.e., it contained a high percentage of copper and exhibited a relatively low Charpy upper-shelf energy, the latter resulting from the use of Linde 80 flux. After etching the surfaces to reveal the fusion zone, the material was sawed into 20 slabs ~25 mm thick, as is illustrated schematically in Fig. 1.

The composition of the SA weld is given in Table 1. Analyses for copper and phosphorus were performed in each of the 20 slabs. Individual analyses ranged from 0.24 to 0.36 pct. copper and from 0.010 to 0.020 pct. phosphorus. However, specimens that were to be irradiated were machined from slabs whose copper and phosphorus contents were close to the average values of 0.29 and 0.013 pct., respectively.

In addition to the studies on A508 SA weld metal, limited studies were conducted also to examine the effect of irradiation on the strength and toughness of the aircraft-quality AISI 4340 steel used in the crack-starter sections of duplex DCB crack-arrest specimens. Such information will have value in subsequent irradiation studies that use duplex specimens.

TABLE 1 Chemical Composition of A508 SA Weld Metal as Determined by Mass Spectrography

(Average of two measurements except where indicated)

Element	Pct by Wt.	Element	Pct by Wt.
C	0.095	Cu	0.29*
Mn	1.4	Ni	0.60
P	0.013*	Cr	0.11
S	0.014	Mo	0.39
Si	0.36	Al	0.004

*Average of 20 measurements.

EXPERIMENTAL PROCEDURES

Specimen Preparation

One group of specimens was prepared for testing in the unirradiated condition and a second group for testing after exposure to approximately 10^{19} fast neutrons ($E \geq 1$ MeV) at about 280 to 290 C, the operating temperature at the beltline region of a reactor. Specimens included standard Charpy V-notch, flat pin-loaded tensile, 0.5T compact tension, and duplex DCB. The latter was chosen in preference to compact crack-arrest specimens because of space limitations in the reactor selected for exposure of the specimens to neutron bombardment. Figure 2 shows the orientation of the specimens relative to that of the slabs cut from the weldment.

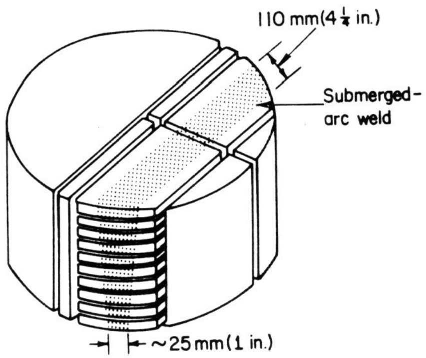

Fig. 1. Cutting pattern for weldment.

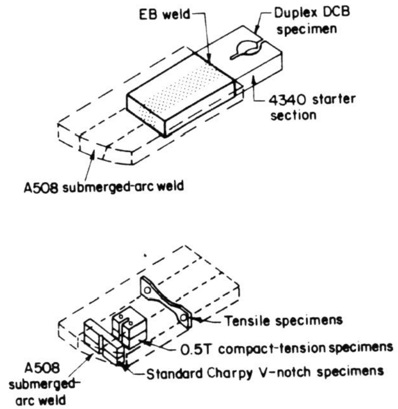

Fig. 2. Orientation of test specimens.

The duplex DCB specimen is shown in Fig. 3. It consisted of a quenched-and-tempered AISI 4340-steel crack-starter section (370 C temper, yield strength ~1380 MPa) that was EB welded to a test section of the weld material being investigated. Prior to selecting this specimen, tests were conducted to demonstrate that the fracture toughness of AISI 4340 steel is not highly sensitive to variation in temperature and that rapid fracture can be initiated from a notch at temperatures as high as 200 C.

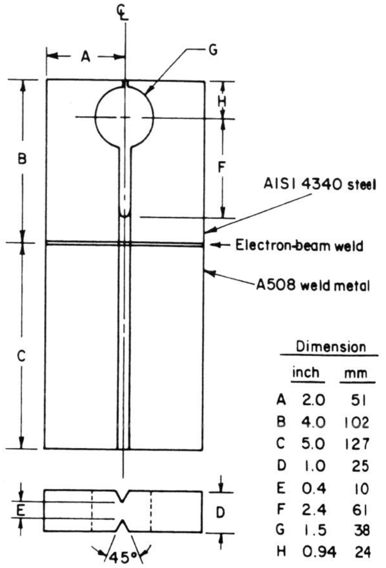

Fig. 3. Duplex DCB specimen for crack-arrest tests.

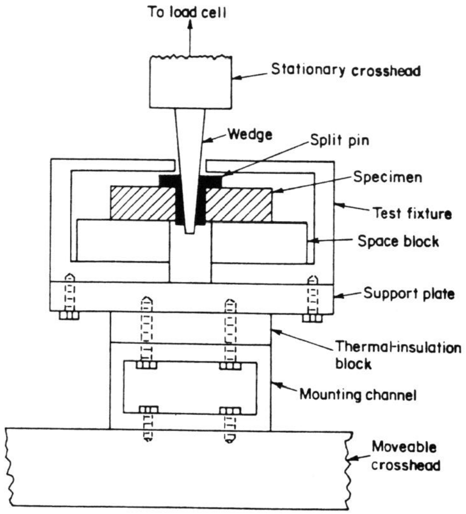

Fig. 4. Schematic front view of crack-arrest test fixture.

Special procedures were adopted to accomplish the EB welding of the duplex DCB specimens. When ordinary procedures were used, passage of the electron beam caused gas to be evolved from entrapped slag particles in the SA weld metal, resulting in excessive porosity. In addition, a plane of weakness, thought to be associated with segregation of impurities to the EB-weld centerline, was observed occasionally. To minimize these problems, the face of the SA weld material to be joined to the AISI 4340-steel starter section was first "refined" by passage of a defocused electron-beam that melted the material to a depth of 4 to 5 mm. Because this was done in a vacuum, much of the gas was released. Other impurities floated to the surface where they were removed later by a light grinding pass. The EB weld was then made in the usual manner, except that half-penetration welds were made from both sides to minimize entrapment of any gaseous impurities not removed by the first operation. Radiographic examination of the EB welds prepared in this way revealed that they were free of major defects.

Following the EB-welding step, sharp-bottom grooves were machined to a depth of 30 pct. of the thickness on each face of the DCB specimens to help maintain the rapidly propagating crack in the desired plane and to promote plane-strain conditions.

Irradiation

Specimens were exposed to fast neutrons at the Ford nuclear reactor operated by the University of Michigan in Ann Arbor, Michigan, USA. They were contained in an aluminum capsule that was designed to maintain specimen temperatures at 288 $\pm$ 15 C. Within the capsule, the specimens were arranged so as to minimize the effect of neutron-flux gradients, determined from an initial mockup experiment, that were

present near the reactor core. The actual levels of neutron exposure achieved during irradiation were estimated from iron- and copper-dosimeter wires placed in the side grooves of the DCB specimens. Details of the capsule irradiation were described by Hahn and others (1978) and Rosenfield and others (1979).

Testing

Normal procedures were followed in the testing of Charpy and tensile specimens. The 0.5T CT specimens have not been tested at this writing.

Testing of DCB specimens employed a fixture designed for use in a hot cell. As is shown schematically in Fig. 4, the fixture is a steel box, open in front and back, to contain the specimen. The bottom of the box supports the specimen; the top facilitates wedge withdrawal, because it limits the upward travel of the specimen and split pin as the wedge is withdrawn, thereby minimizing the amount of specimen handling. Not shown in Fig. 4 is a specially designed electric-heating jacket that fits around the fixture to both heat and insulate the specimen. Its 2-kW capacity was adequate to both heat the specimen and fixture to the desired temperature and heat tint the fracture surface after testing.

In conducting tests on duplex DCB specimens, the procedure is to gradually advance the wedge into the split pin so as to force the specimen arms apart. The energy stored in the specimen arms is proportional to arm displacement. At some point, a crack will initiate at the notch tip and, driven by the elastic energy released from the arms, run rapidly through the crack-starter section before encountering the test section. Eventually, the energy available in the arms is insufficient to overcome the resistance to crack growth of the test-section material, and the crack is arrested. K_{ID} can be calculated from the arm displacement at initiation and the crack-jump length, making use of a dynamic analysis (Hoagland and coworkers, 1977). K_{Ia} is calculated from arm displacement after arrest and the final crack length. The latter is measured directly from the specimen after heat tinting and separating the specimen into two halves.

RESULTS AND DISCUSSION

Analysis of the dosimeter wires contained in the irradiation capsule showed excellent agreement between the iron and the copper fast neutron fluence levels. Table 2 lists the fluences received by the different types of test specimens. As was expected, the specimens located near midheight and facing the reactor core experienced greater fluence levels than did specimens located near the ends and facing the heaters. The overall-average fluence level was slightly below the target level of 1.0 x 10^{19} n/cm^2.

Temperatures during irradiation also were slightly below the desired level of 288 $\pm$ 15 C. Thermocouples indicated that the test sections of the four DCB specimens experienced average temperatures of about 275 C and varied with time within $\pm$ 15 C of that temperature. Specimens located near midheight, i.e., in the maximum-flux region, experienced somewhat higher temperatures, near 300 C. This temperature gradient probably acted to offset, at least partially, the effect of the fluence gradient described in the preceding paragraph, because high temperatures tend to counteract some of the effects of high fluence levels.

As was pointed out earlier, the use of AISI 4340 steel in the starter section of duplex DCB specimens created some concern as to the effect of irradiation on the properties of this material and on its ability to initiate fast fracture at the desired K_Q level. The results shown in Fig. 5 suggest that the irradiation levels imposed in this study produced only modest changes in tensile properties and no discernible effect on Charpy V-notch toughness. Thus, it could be assumed that the crack-starting ability of AISI 4340 steel is not impaired by irradiation. This assumption was borne out by subsequent observations that cracking was, indeed, initiated in the 4340 starter-section of irradiated duplex-DCB specimens at desired K_Q levels.

TABLE 2 Measured Fast-Neutron Fluence

Specimen Type	Neutron Fluence (E > 1 MeV), 10^{19} n/cm^2 Maximum	Minimum	Average
Side-grooved DCB's			
Top Spec. E012	1.19	0.68	0.89*
Spec. E013	1.09	0.60	0.80*
Bottom Spec. E08A	1.14	0.42	0.65*
Spec. E06A	1.06	0.36	0.59*
Charpy V-notch			
Front specimens	1.15	1.07	1.11
Back specimens	0.89	0.78	0.84
0.5T CT			
Front specimens	1.17	1.09	1.13
Back specimens	0.90	0.78	0.84
Tensile			
Top specimens	0.97	0.72	0.85
2nd group specimens	1.13	0.82	0.98
3rd group specimens	1.00	0.76	0.88
Bottom specimens	0.71	0.53	0.62

*Calculated from average of iron- and copper-dosimeter wire segments located along the actual crack path.

In contrast to the results for AISI 4340 steel, the properties of the A508 SA weld metal were changed significantly by irradiation. As is shown in Fig. 6, the yield strength was raised by 25 to 30 pct., the Charpy shelf energy was decreased about 40 pct. and the 50-J (35-ft-lb) Charpy-energy transition temperature was raised about 120 C. The latter two observations are in close agreement with the effects predicted from US NRC Reg. Guide 1.99, based on measured copper and phosphorus contents in the steel.

In performing crack-arrest tests on irradiated duplex-DCB specimens, unexpected difficulties were encountered that clouded interpretation of the results. The results, shown in Fig. 7, require some explanation. The shaded band in Fig. 7 approximates the results anticipated on the basis of US NRC Reg. Guide 1.99 predictions for irradiation levels of 0.5 to 0.8 x 10^{19} n/cm^2. Accordingly, the first test, on Specimen E06A, was conducted at 105 C where K_{ID} and K_{Ia} were expected to be about 165 and 115 MPa $\sqrt{m}$, respectively. The results of that test suggested that the irradiated weld metal was somewhat tougher than had been expected. Although fracture was initiated at the desired K_Q level, the crack failed to penetrate the test section. Because posttest examination showed the

EB weld to be sound and free of cracks, it was assumed that the crack stopped because of the high toughness of the test section. The data points labeled A in Fig. 7 are calculated lower-bound values based on crack penetration for a distance B_n into the test section (the assumed minimum crack-jump for a valid test).

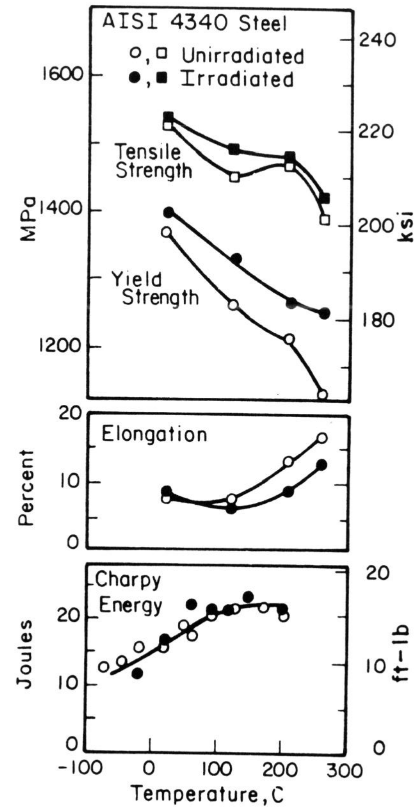

Fig. 5. Irradiation effects in AISI 4340 steel.

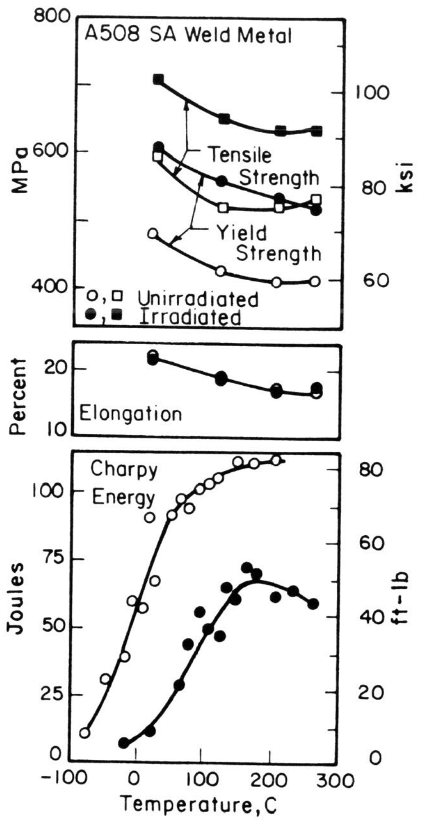

Fig. 6. Irradiation effects in A508 SA weld metal.

In an attempt to achieve penetration of the test section, the second specimen, E08A, was tested at a lower temperature of 60 C. Again, fracture was initiated at the desired K_Q level, but severe cracking occurred in the EB weld, thus preventing the fracture from penetrating the test section. On the assumption that this was simply a faulty EB weld, the third specimen, E012 was tested at the same temperature with the same result. This behavior suggested that the EB welds may have been adversely affected by irradiation and were themselves showing a transition-temperature effect. It was decided to test the one remaining specimen, E013, at 93 C, in the hope that this would be above the brittle regime of the EB weld but sufficiently low in temperature to achieve penetration of the test section. This result was, in fact, obtained. However, the crack penetration into the test section was less than B_n, the minimum penetration required for a valid test. In Fig. 7, the points labeled B represent lower-bound values based on the assumption that the crack actually extended for a distance B_n. The points labeled B_1, on the other hand, are calculated for the actual crack extension. In an attempt to obtain additional data from specimen E013, it was considered to be an ordinary DCB specimen with a deep notch and was subjected to three additional crack-arrest experiments at progressively lower temperatures (61, 43, and 24 C). The data points from those tests are labeled B_2, B_3, and B_4, respectively, in Fig. 7. The unusually high toughness value for point B_3 is believed to be due to the fact that the crack ran well out of the side grooves in that part of the experiment. Point B_4 for the room-temperature test represents an upper-bound toughness that assumes the crack arrested at the maximum distance permitted by validity considerations. Actually, the crack was not arrested at room temperature, and the specimen broke into two pieces.

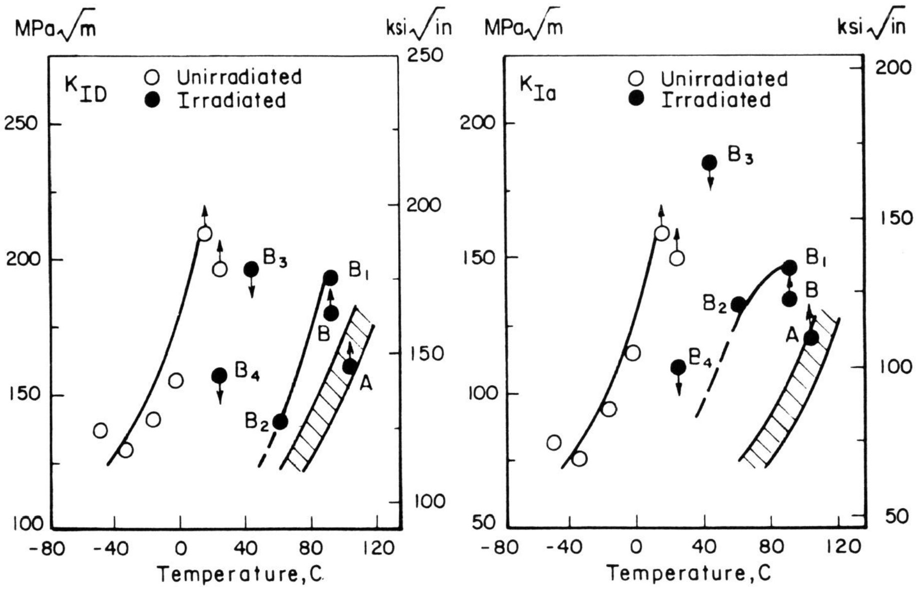

Fig. 7. Effect of irradiation at 275 C on K_{ID} and K_{Ia} of high-copper A508 SA weld metal.

Point A is Spec. E06A - 0.6 x 10^{19} n/cm^2.

Points B, B_1, etc. are Spec. E013 - 0.8 x 10^{19} n/cm^2.

Although the crack-arrest data are too limited to permit firm conclusions to be drawn, the results shown in Fig. 7 suggest that the shift in transition temperature as the result of irradiation was about + 80 C for K_{ID} and perhaps + 60 C for

K_{Ia}. Both are less than the shifts observed for the 50-J Charpy-energy transition or than the shift predicted in RT_{NDT} on the basis of the copper and phosphorus contents.

Clearly, additional data are needed to more firmly establish the effect of irradiation on crack-arrest behavior. An EPRI-funded study to meet this requirement is being carried out jointly by Battelle and Westinghouse. It will examine both baseplate and weldment material representing both past and current manufacturing practices. The EPRI program is using brittle-weld compact crack-arrest specimens of several sizes, rather than duplex specimens, in part to avoid some of the problems described earlier in connection with EB welds. At the time of preparation of this paper, no results were available from this investigation.

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