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Charpy Toughness and Tensile Properties of a Neutron-Irradiated Stainless Steel Submerged Arc Weld Cladding Overlay

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METALS AND CERAMICS DIVISION

CHARPY TOUGHNESS AND TENSILE PROPERTIES OF A NEUTRON-IRRADIATED STAINLESS STEEL SUBMERGED ARC WELD CLADDING OVERLAY

W. R. Corwin, R. G. Berggren, and R. K. Nanstad

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CONTENTS

FOREWORD

The work reported here was performed at Oak Ridge National Laboratory (ORNL) under the Heavy-Section Steel Technology Program, C. E. Pugh, Program Manager. The program is sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission (NRC). The technical monitor for the NRC is Milton Vagins.

This report is designated Heavy-Section Steel Technology Program Technical Report 74. Prior reports in this series are listed below.

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CHARPY TOUGHNESS AND TENSILE PROPERTIES OF A NEUTRON-IRRADIATED STAINLESS STEEL SUBMERGED ARC WELD CLADDING OVERLAY

W. R. Corwin, R. G. Berggren, and R. K. Nanstad

ABSTRACT

The ability of stainless steel cladding to increase the resistance of an operating nuclear reactor pressure vessel to extension of surface flaws depends greatly on the properties of the irradiated cladding. Therefore, weld overlay cladding irradiated at temperatures and fluences relevant to power reactor operation was examined. The cladding was applied to a pressure vessel steel plate by the submerged arc, single-wire, oscillating-electrode method. Three layers of cladding provided a thickness adequate for fabrication of test specimens. The first layer was type 309, and the upper two layers were type 308 stainless steel. The type 309 was diluted considerably by excessive melting of the base plate. Specimens were taken from near the base plate—cladding interface and also from the upper layers. Charpy V-notch and tensile specimens were irradiated at 288°C to a fluence of 2×10^{23} neutrons/m^2 (>1 MeV).

When irradiated, both types 308 and 309 cladding increased 5 to 40% in yield strength and slightly increased in ductility in the temperature range from 25 to 288°C. All cladding exhibited ductile-to-brittle transition behavior during impact testing. The type 308 cladding, microstructurally typical of that in reactor pressure vessels, showed very little degradation in either upper-shelf energy or transition temperature due to irradiation. Conversely, the impact properties of the specimens containing the highly diluted type 309 cladding, microstructurally similar to that produced during some off-normal welding conditions in existing reactors, experienced significant increases in transition temperature and drops of up to 50% in upper-shelf energy. The impact energies of the Charpy specimens containing the type 309 layer strongly reflected the amount of the type 309 actually in the specimen, falling into two distinct high- and low-energy populations with the low-energy population corresponding to a higher fraction of type 309 in the specimen.

INTRODUCTION

It has been proposed that the existence of a tough surface layer of weld-deposited stainless steel cladding on the interior of a reactor pressure vessel (RPV) can keep a short surface flaw from becoming long, either by impeding the initiation of extension of a static flaw and/or by arresting a running flaw. To obtain preliminary material properties typical of those needed to make such an evaluation for light-water reactors

(LWRs), a program has been established to obtain data on the degradation (or lack thereof) of the fracture properties of stainless steel weld overlay cladding. A recent review of the literature[1] has indicated that fracture properties of stainless steel weld metal can degrade significantly under irradiation conditions relevant to LWRs. To evaluate this potential degradation, tensile, Charpy V-notch, and precracked Charpy specimens of stainless steel weld overlay cladding were irradiated to about 2×10^{23} neutrons/m^2 (>1 MeV) at 288°C. The results of tensile and Charpy V-notch tests are reported here and compared with the properties of unirradiated cladding.

MATERIALS

The specimens were all taken from a single laboratory weldment fabricated by the automated single-wire oscillating submerged arc procedure for a companion program investigating structural effects of stainless steel cladding on composite four-point bend specimens.[2,3] The weldment consisted of a lower layer of type 309 stainless steel deposited on A 533 grade B class 1 plate, followed by two upper layers of type 308 stainless steel cladding.

The welding wires for both the types 308 and 309 stainless steel were 4 mm in diameter and chosen to be representative of cladding formerly applied in industry. The cladding was deposited on plates that were 114 mm thick by 406 mm wide by 914 mm long to minimize distortion and provide an adequate heat sink. The clad plates were then postweld heat treated (PWHT) at 621°C for 40 h to represent commercial practice.

The single-wire oscillating submerged arc welding process used involved a preheat temperature of 121°C and an interpass temperature below 288°C. The welding parameters were as follows:

1. wire extension, 27.0 mm;
2. oscillation width, 19.0 mm;
3. frequency, 0.3 Hz;
4. dc, 500 A;
5. dc straight polarity voltage, 36 V; and
6. forward travel speed, 2.1 mm/s.

The three layers of cladding were applied to provide adequate cladding thickness (~20 mm) to obtain test specimens. The material compositions of each layer of weld metal are given in Table 1. This contrasts with typical commercial practice, in which a single layer of overlay approximately 5 mm thick is applied by either multiple wire or strip-cladding submerged arc procedures. Subsequent metallographic examination showed that the upper layer appeared typical of LWR stainless steel overlay, whereas the lower layer had incurred excessive dilution as a result of base metal melting during welding. Photomicrographs of the three passes illustrate the radically different microstructures in the

Table 1. Chemical composition of overlay weldments

Layer	Content[a] (wt %)												
	C	Cr	Ni	Mo	Mn	Si	Co	Cu	V	Al	Ti	P	S
Lower	0.145	13.46	6.90	0.47	1.47	0.56	0.066	0.14	0.02	0.014	<0.005	0.018	0.01
Middle	0.081	18.52	8.81	0.27	1.47	0.70	0.092	0.10	0.04	0.010	<0.005	0.021	0.01
Upper	0.065	20.01	9.36	0.21	1.49	0.76	0.100	0.09	0.04	0.16	0.006	0.022	0.01

[a] Balance Fe, with Nb, <0.01; Ta, <0.01; As, <0.03; and B, <0.001 for all layers.

finished weldment. The upper pass (Fig. 1) shows a distribution of δ-ferrite in an austenite matrix quite typical of microstructures seen in good practice commercial weld overlay cladding in reactor pressure vessels.[4] The effect of the 40-h PWHT on these materials is to partially transform the δ-ferrite to sigma phase. Although this is difficult to resolve in the optical micrographs, magnetic etching with ferrofluid, the use of a colloidal suspension of magnetic particles in the presence of a local magnetic field,[5] and color staining techniques verified that the partial transformation had occurred.

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Fig. 1. The microstructure of the top layer of type 308 stainless steel weld overlay is typical of reactor pressure vessel cladding with δ-ferrite in an austenite matrix.

The lower and middle layers of cladding, on the other hand, formed atypical microstructures as a result of the excessive dilution (approximately 50%) by the base metal and lower pass weldment, respectively. Amounts of dilution in good practice cladding are typically in the range of 10 to 25%. The middle layer (Fig. 2) contains δ-ferrite dispersed in austenite but in addition contains limited regions in which martensite is also present. The bottom layer had sufficient dilution to move it

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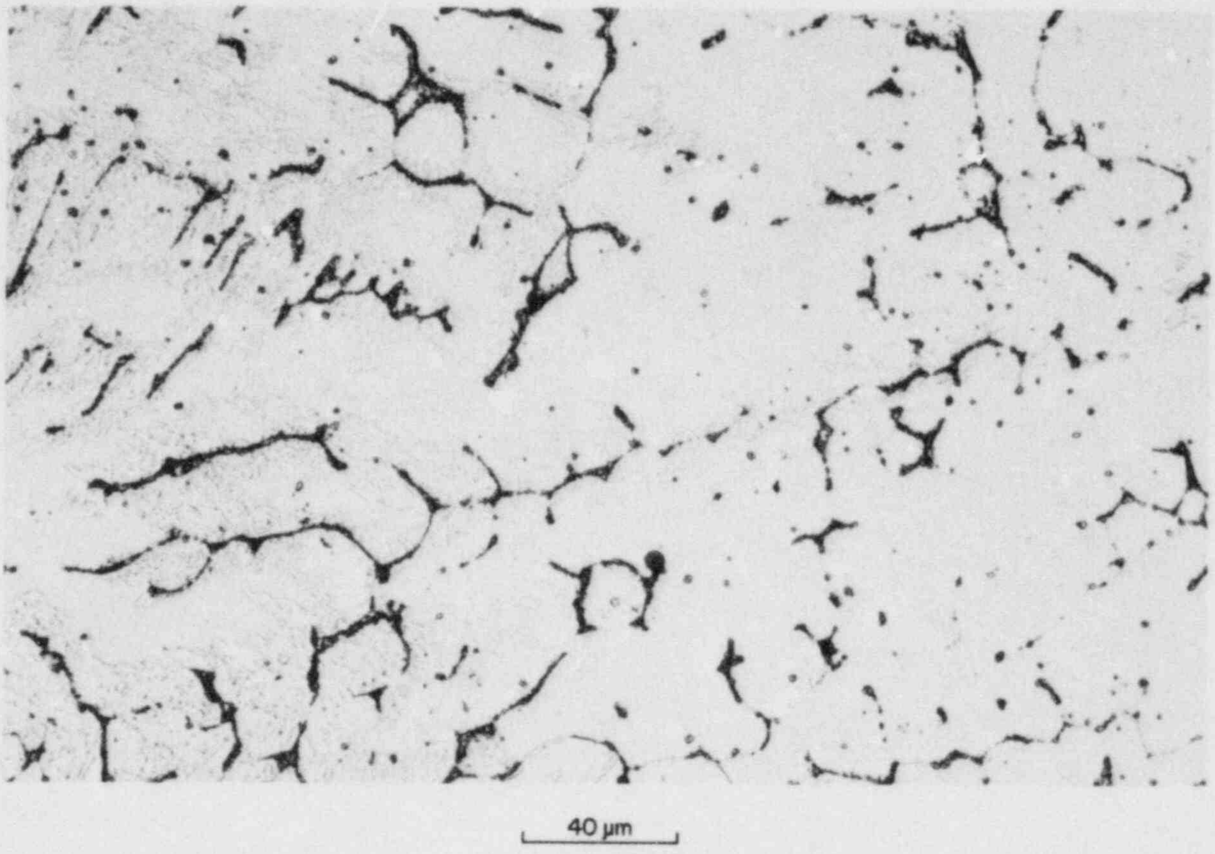

Fig. 2. The middle layer of the overlay (type 308 stainless steel) includes patches of martensite (light gray) in addition to the δ-ferrite in an austenite matrix.

entirely from the δ-ferrite-forming region of the Schaeffler diagram[6] and into the austenite-plus-martensite region (these are the dominant phases). Examination of its microstructure (Fig. 3), however, shows three distinct regions. The use of the ferrofluid magnetic etching technique and studies in the transmission electron microscope verified the lightest regions to be austenite, the light gray regions tempered martensite, and the dark regions δ-ferrite decorated with $M_{23}C_6$.

Although the investigation of high-dilution cladding was not the initial aim of the cladding studies, it may well be highly germane to the question of the effects of cladding on RPV integrity. High base metal dilution of cladding, caused by inadequate control of welding procedures, and the resulting microstructures have been documented[7,8] in commercial RPVs. Typically, the resulting material has poorer mechanical and/or corrosion properties in the unirradiated condition; no information is available on the irradiation damage of such material. The inclusion of such material may provide insight into the behavior of substandard weld overlay cladding representative of irradiated material actually in the field.

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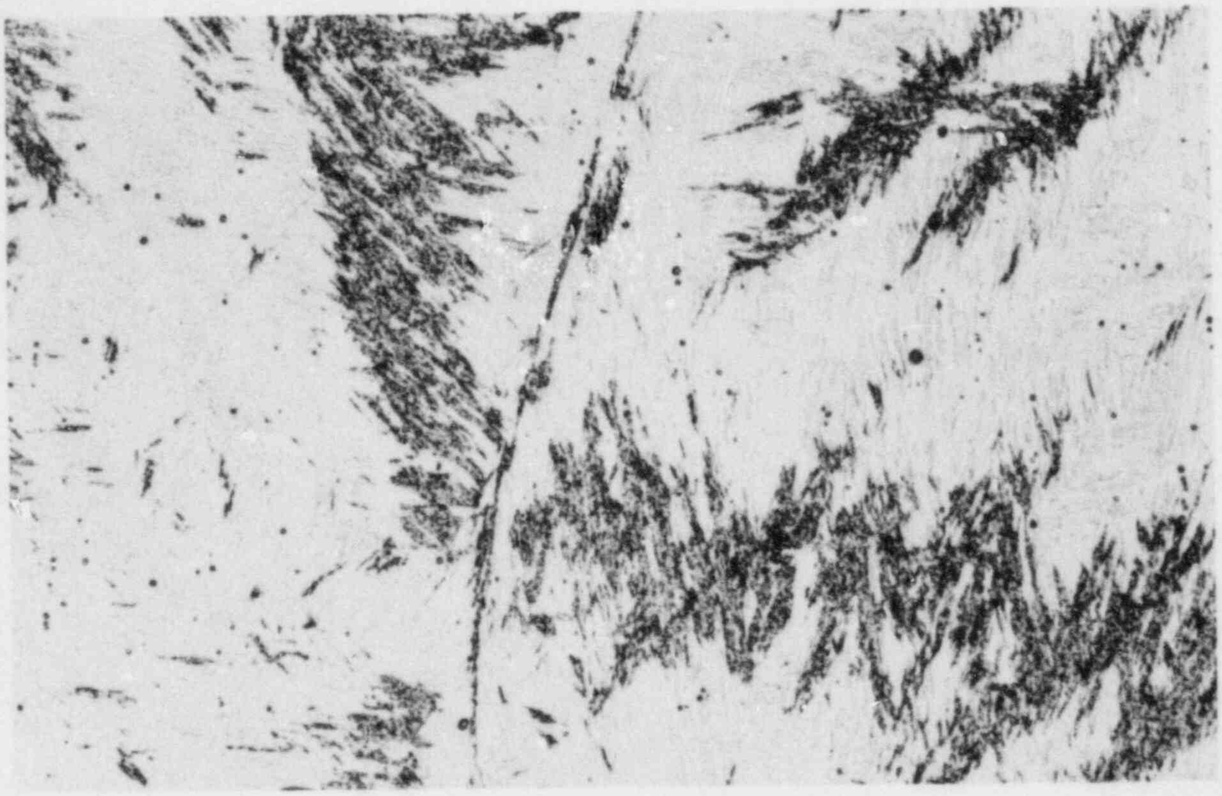

Fig. 3. The high base metal dilution of the lowest layer of cladding, type 309 stainless steel, resulted in a three-phase microstructure of austenite (lightest region), martensite (light gray), and δ-ferrite decorated with additional carbides (black).

To examine the effects of the varying microstructures, two sets of tensile and Charpy V-notch specimens were carefully fabricated to be contained as fully as possible within either the upper two layers (nominally type 308 specimens) or the lower layer (nominally type 309 specimens). All specimens were fabricated with the specimen axis parallel to the welding direction. The Charpy specimens were notched on the surface parallel to and nearer the base metal in all cases.

Ferrite numbers were measured on the finished Charpy specimens with a Ferrite Scope, which locally measures the percentage of ferromagnetic material in the sample. The nominally type 308 specimens consistently had ferrite numbers of 2 to 6 (corresponding roughly to percentages of ferrite), as did the portion of nominally type 309 specimens composed of upper weld pass layers. The notched side of the nominally type 309 specimens closest to the base metal interface exhibited a wide range of ferrite numbers from 2 to greater than 30 (off scale). This wide range was presumably due to the volume of material over which the Ferrite Scope takes a measurement and to the inclusion, in some cases where the amount of type 309 weldment was thin, of some of the type 308 upper layer cladding. Optical examination of the microstructure of the type 309 layer indicates the amounts of martensite and ferrite to be 30 to 45% and 10 to 15%, respectively.

IRRADIATION HISTORY

The specimens were irradiated by Materials Engineering Associates in the core of the 2-MW pool reactor (UBR) at the Nuclear Science and Technology Facility, Buffalo, New York. Two separate capsules were used, one each for the types 308 and 309 stainless steel specimens. The capsules were instrumented with thermocouples and dosimeters and were rotated 180° once during the irradiation for fluence balancing. The capsule containing the type 308 specimens reached an average fluence of 2.09×10^{23} neutrons/m^2 (>1 MeV) ± 10% during 679 h of irradiation. The capsule containing the type 309 specimens reached an average fluence of 2.02×10^{23} neutrons/m^2 (>1 MeV) ± 5% in 508 h. The fluences are for a calculated spectrum based on Fe, Ni, and Co dosimetry wires. Temperatures were maintained at 288 ± 14°C except for the initial week of irradiation. During that time, temperatures as low as 263°C were recorded for the type 308 specimens.

RESULTS AND DISCUSSION

Tensile testing was conducted at room temperature, 149°C, and 288°C. Irradiation increased the yield strength of the type 309 specimens by 30 to 40%, whereas the increase of the type 308 specimens was only 5 to 25% (Fig. 4). Surprisingly, the total elongation and reduction of area of both materials increased during irradiation (Fig. 5). Tensile properties are detailed in Table 2.

The effect of irradiation on the Charpy impact properties of the type 308 weld metal representative of typical weld overlay cladding was relatively small (Fig. 6). Only a very slight upward shift in transition temperature (~15°C) and drop in upper shelf (<10%) were observed. It should be noted for both the control and irradiated specimens that Charpy curves more typical of ferritic materials than of austenitic stainless steel were observed with respect to the abrupt transition from high- to low-energy fracture. Fracture surfaces of selected specimens were examined in the lower transition and upper-shelf regions. Macrographs of the irradiated type 308 specimens tested at temperatures low in the transition show flat fracture with clear definition of some of the large grains produced during welding (Fig. 7). By comparison, specimens at upper-shelf temperatures produced fracture surfaces more typical of wrought stainless steel with deep shear lips and a dull appearance. Scanning electron microscopy (SEM) of unirradiated specimens tested in the lower transition and upper-shelf regions clearly show the transition from

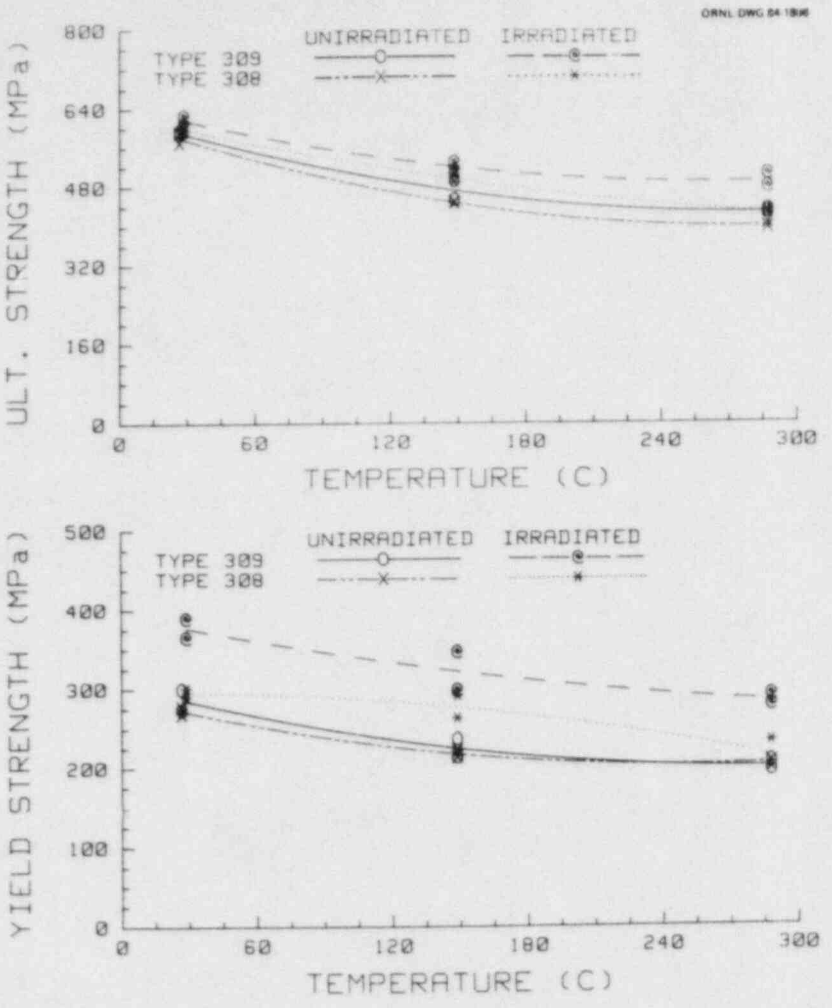

Fig. 4. Effect of irradiation at 288°C to a fluence of 2 × 10^{23} neutrons/m^2 (>1 MeV) on the tensile strength of the nominally types 308 and 309 stainless steel weld metal.

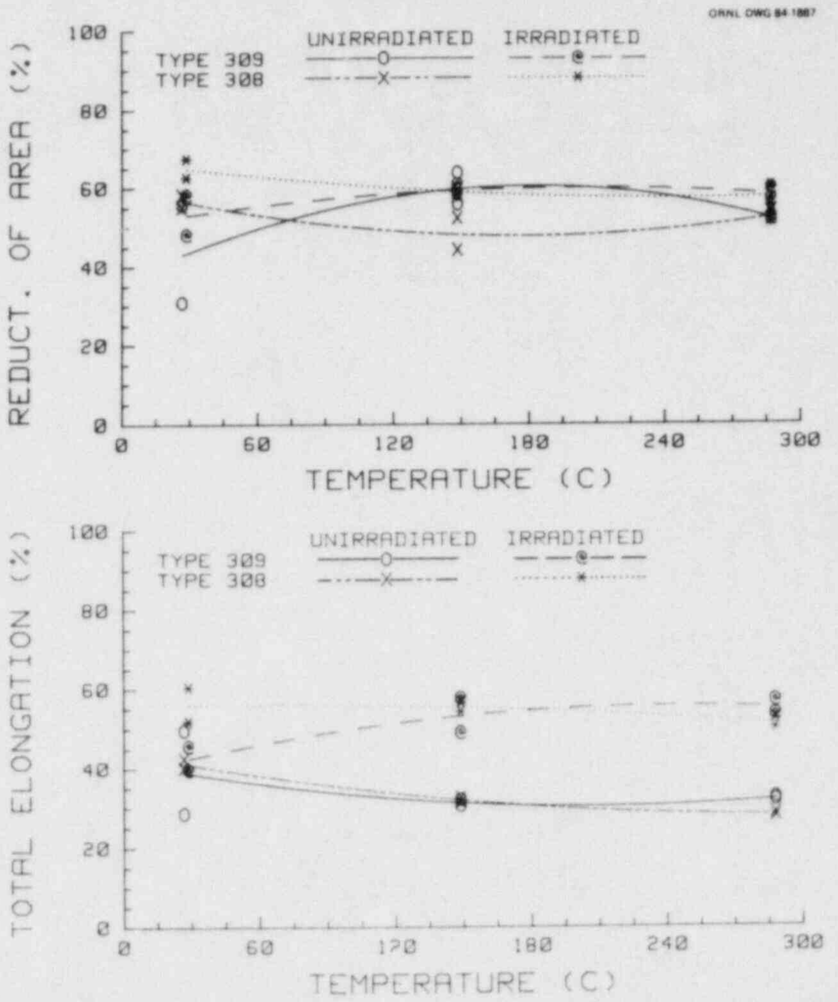

Fig. 5. Effect of irradiation at 288°C to a fluence of 2 × 10^{23} neutrons/m^2 (>1 MeV) on the tensile ductility of the nominally types 308 and 309 stainless steel weld metal.

Table 2. Tensile properties of stainless steel cladding before and after irradiation at 288 ± 14°C

Specimen	Material type[a]	Fluence, >1 MeV (neutrons/m^2)	Test temperature (°C)	Strength (MPa) Yield	Strength (MPa) Ultimate	Total elongation[b] (%)	Reduction of area (%)
CPL-80	309	0	27	299	593	28.4	30.6
CPL-83	309	0	27	273	586	49.5	55.5
CPC-72	308	0	27	268	589	40.0	55.0
CPC-73	308	0	27	276	568	42.4	58.0
CPL-81	309	2.0×10^{23}	29	388	606	39.4	48.0
CPL-85	309	2.0	29	364	624	45.4	58.0
CPC-70	308	2.1	29	289	605	51.5	62.3
CPC-75	308	2.1	29	300	589	60.1	67.1
CPL-86	309	0	149	213	448	31.9	55.5
CPL-89	309	0	149	236	450	30.4	63.4
CPC-77	308	0	149	221	445	31.3	44.0
CPC-78	308	0	149	213	444	32.4	52.0
CPL-82	309	2.0	149	297	508	57.2	57.9
CPL-87	309	2.0	149	345	526	48.6	60.4
CPC-71	308	2.1	149	290	501	56.3	59.3
CPC-76	308	2.1	149	262	485	53.8	58.1
CPL-90	309	0	288	195	429	31.7	51.5
CPL-91	309	0	288	207	423	32.4	52.2
CPC-79	308	0	288	205	393	28.5	51.4
CPC-80	308	0	288	205	402	27.6	53.3
CPL-84	309	2.0	288	277	475	52.9	56.6
CPL-88	309	2.0	288	290	501	56.3	59.3
CPC-74	308	2.1	288	198	422	51.9	55.0
CPC-81	308	2.1	288	232	427	49.5	59.8

[a] Type 309 consists primarily of the first metal pass, type 308 primarily the third (last pass).

[b] Gage length/diameter = 7.

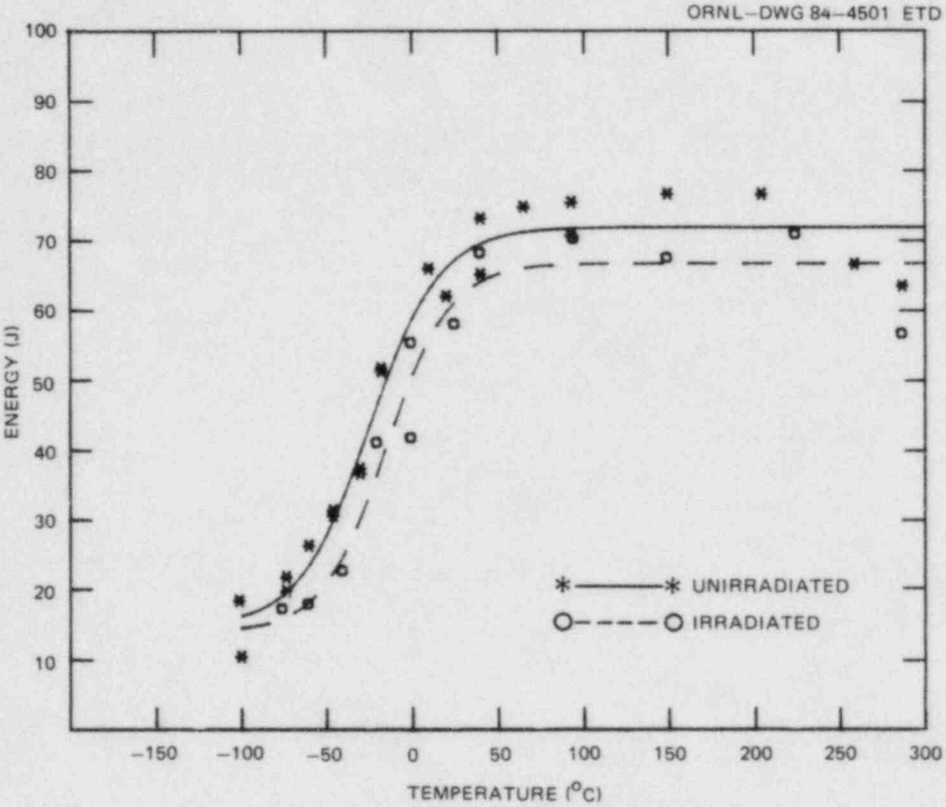

Fig. 6. Effect of irradiation on the Charpy impact energy of type 308 stainless steel cladding.

a cleavage or quasi cleavage to a fibrous fracture mode (Fig. 8). This behavior compares well with the work of other researchers,[9,10] who have shown that fully ductile fracture occurs in as-welded austenitic weld metal as low as 4 K but that quasi cleavage can occur in weld metal that has received a PWHT in the temperature range in which carbide precipitation and sigma formation occur. Studies on weld metal examined here indicate that the fracture path preferentially follows the ferritic phases. At low temperatures the fracture appears typically to follow the δ-ferrite in both the type 308 and 309 weld metals, going through the austenite or martensite only where necessary to reach the next δ-ferrite island. On the upper shelf this does not occur because the fracture is no longer dominated by the ferrite but passes through austenitic and ferritic phases with equal ease. Therefore, the failure of ferrite at low temperature, resulting from its inherent ductile-to-brittle behavior, appears to govern the macroscopic transition-type failure behavior of the austenitic weld metal.

The interpretation of the impact results of the nominally type 309 specimens is more complicated. Since the type 309 weld pass was not thick enough to obtain specimens composed entirely of type 309 weld metal, a portion of all the specimens nominally called type 309 is indeed type 308. Macrographs of the irradiated specimen fracture surfaces show that over the range of the full Charpy curve, the portion composed of type 309 weldment remains bright and faceted (Fig. 9). The remainder

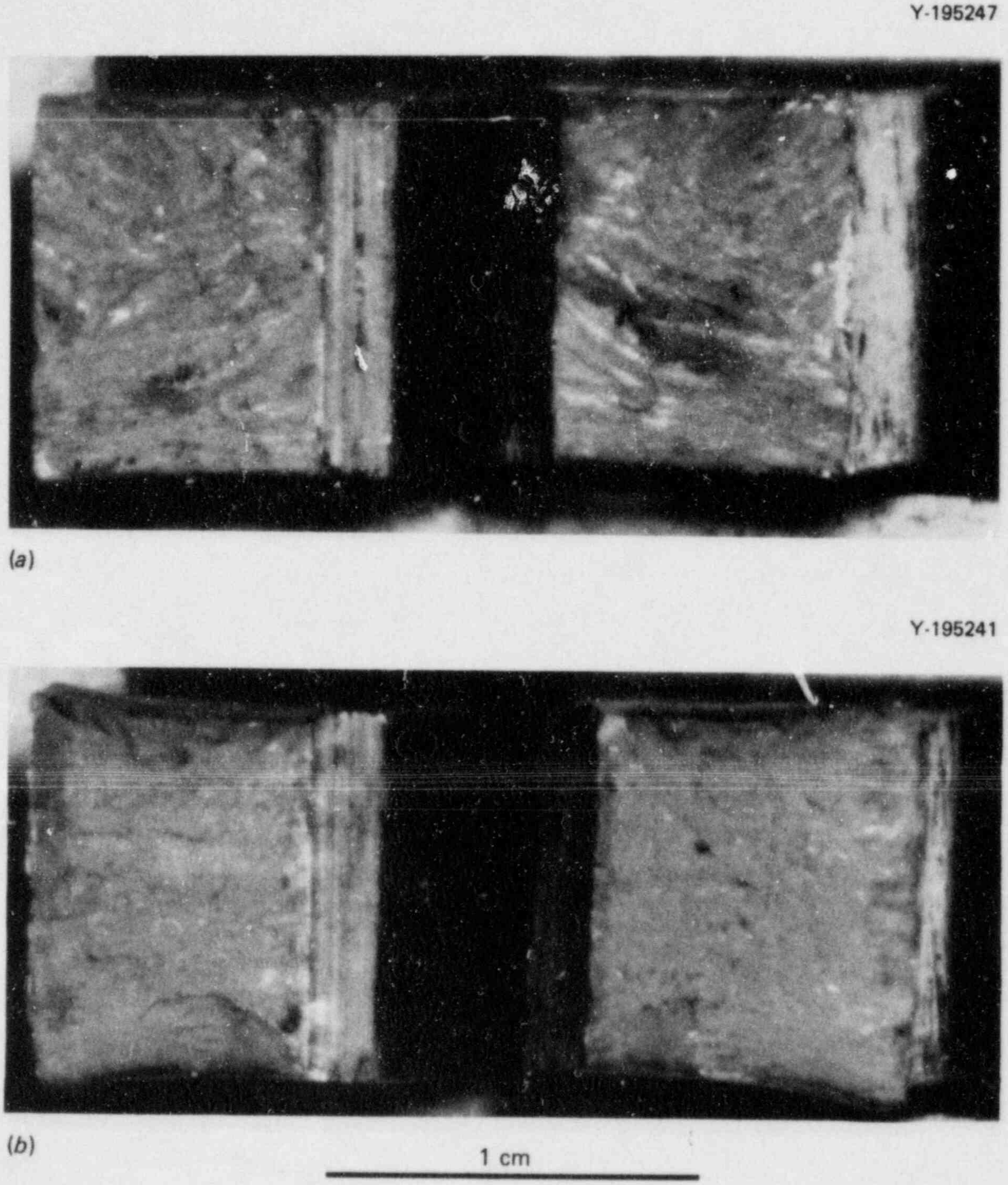

Fig. 7. Fracture surfaces of irradiated type 308 stainless steel cladding Charpy impact specimens. (*a*) Specimen CPC-304 tested at −60°C very low in the transition range. (*b*) Specimen CPC-290 tested at 150°C on the upper shelf.

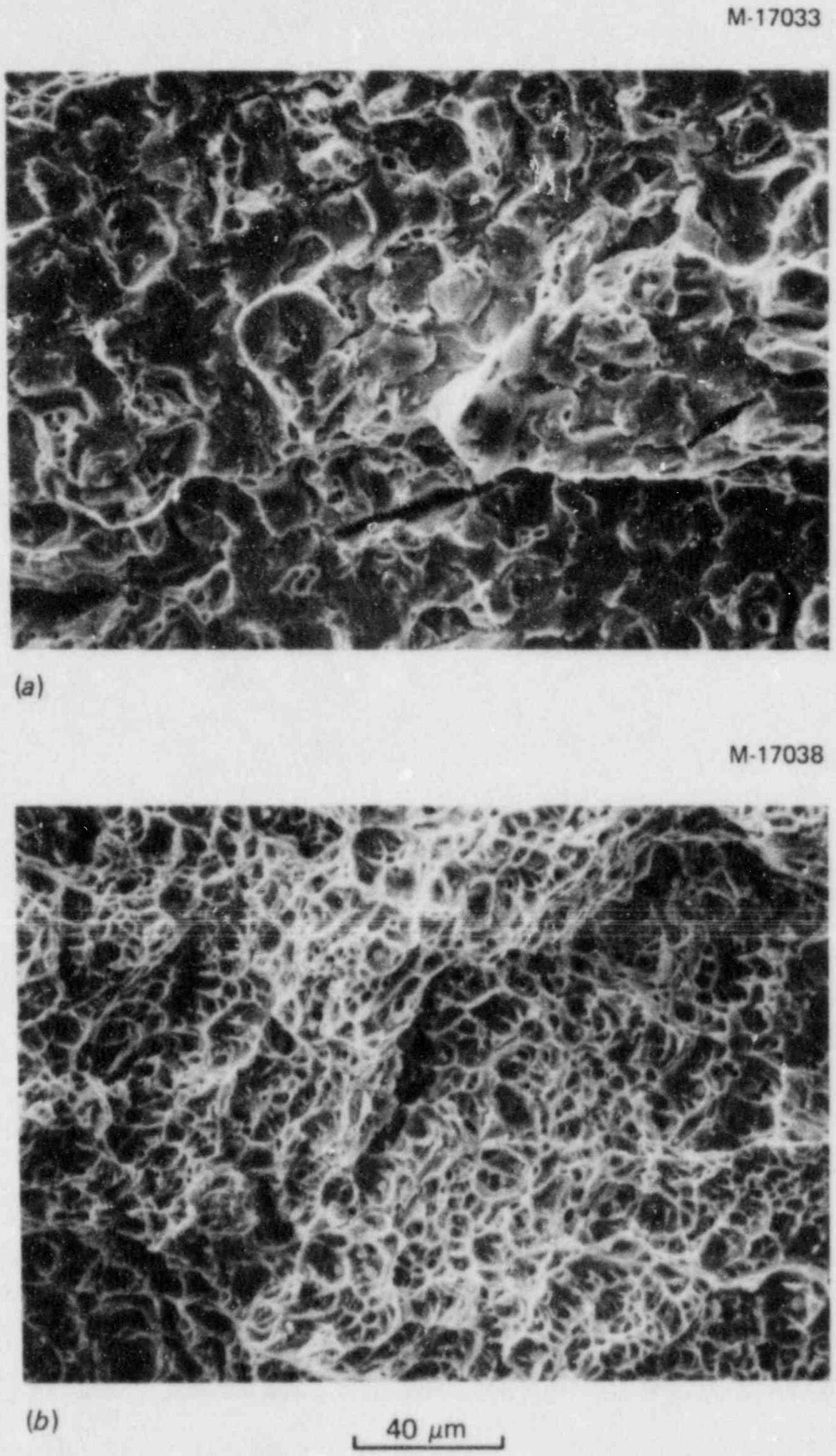

Fig. 8. Scanning electron micrographs of the fracture surfaces of unirradiated type 308 stainless steel cladding Charpy impact specimens. (*a*) Specimen CPC-283 tested at −100°C on the lower shelf, showing predominantly brittle fracture. (*b*) Specimen CPC-298 tested at 150°C on the upper shelf, showing fibrous fracture.

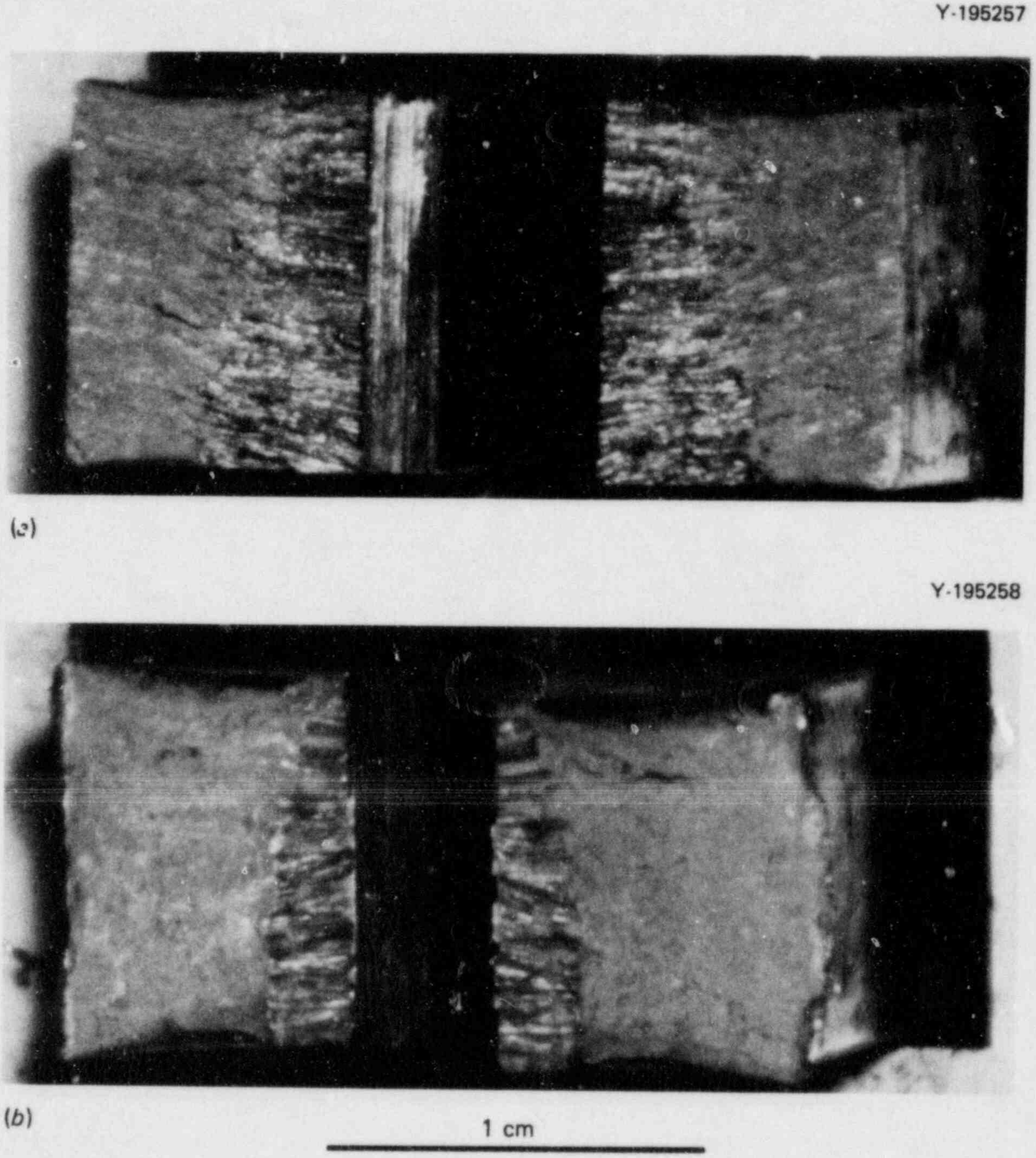

Fig. 9. Fracture surfaces of irradiated stainless steel cladding Charpy impact specimens (nominally type 309) clearly showing the bright faceted type 309 weld metal directly below the notch and the duller type 308 weld metal composing the rest of the specimen. (*a*) Specimen CPL-515 tested at 0°C in the very low transition region. (*b*) Specimen CPL-518 tested at 250°C on the upper shelf.

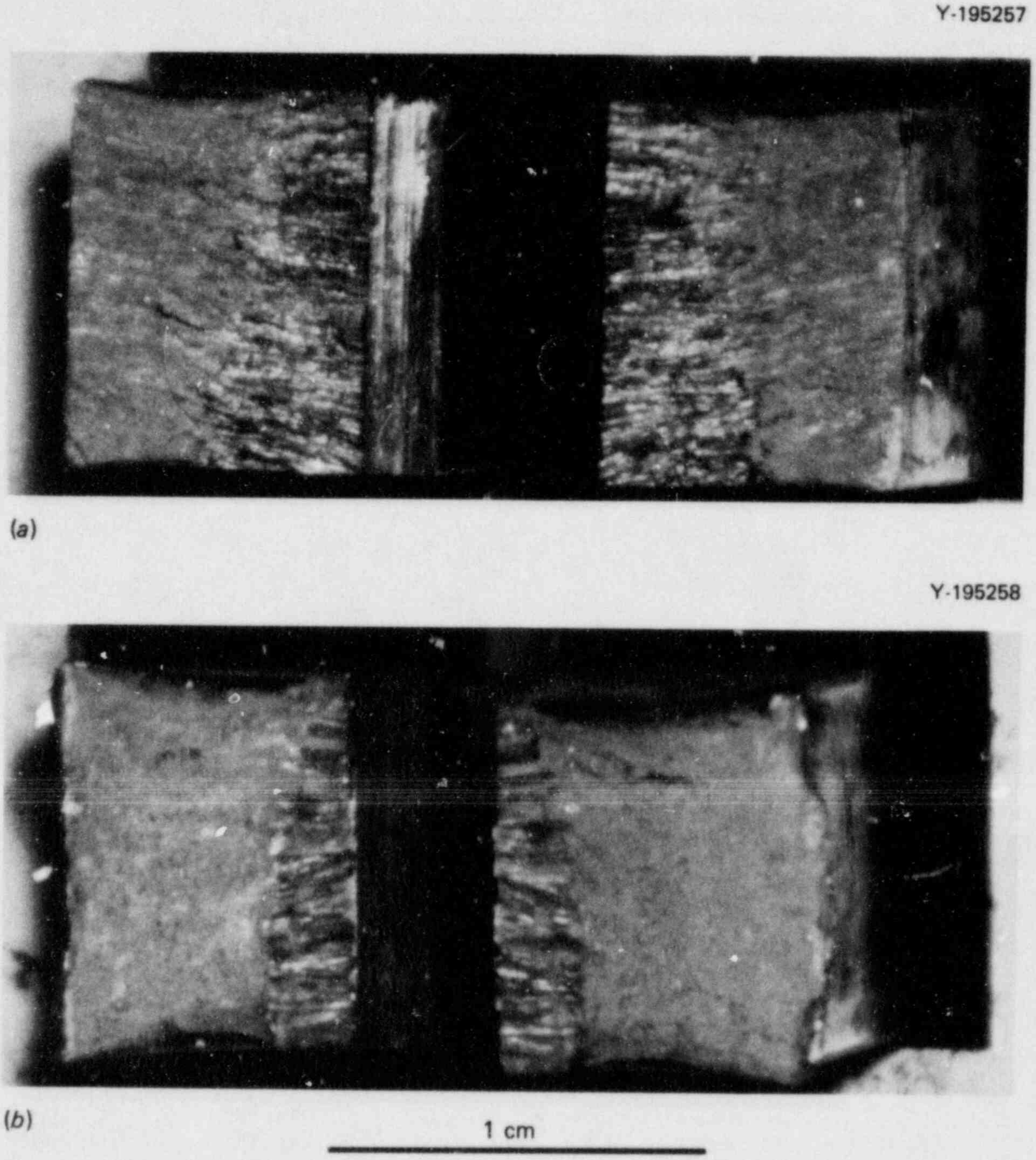

Fig. 9. Fracture surfaces of irradiated stainless steel cladding Charpy impact specimens (nominally type 309) clearly showing the bright faceted type 309 weld metal directly below the notch and the duller type 308 weld metal composing the rest of the specimen. (*a*) Specimen CPL-515 tested at 0°C in the very low transition region. (*b*) Specimen CPL-518 tested at 250°C on the upper shelf.

of the fracture surface, composed of upper cladding layers of type 308 weld metal, exhibits the same behavior seen in the fully type 308 specimens.

Scanning electron microscopy of an unirradiated specimen from the lower transition range (Fig. 10) illustrates the very different fracture morphology of the type 309 weld metal just below the notch and the rest of the the fracture surface composed of type 308 weld metal. The type 309 is very flat and formed predominately by cleavage (Fig. 11) at a temperature (−32°C) at which the type 308 weld metal is still mixed mode (Fig. 12). At upper-shelf temperatures, although the type 309 and 308 weld metals can still be distinguished in the SEM, both fail in a fibrous manner (Fig. 13).

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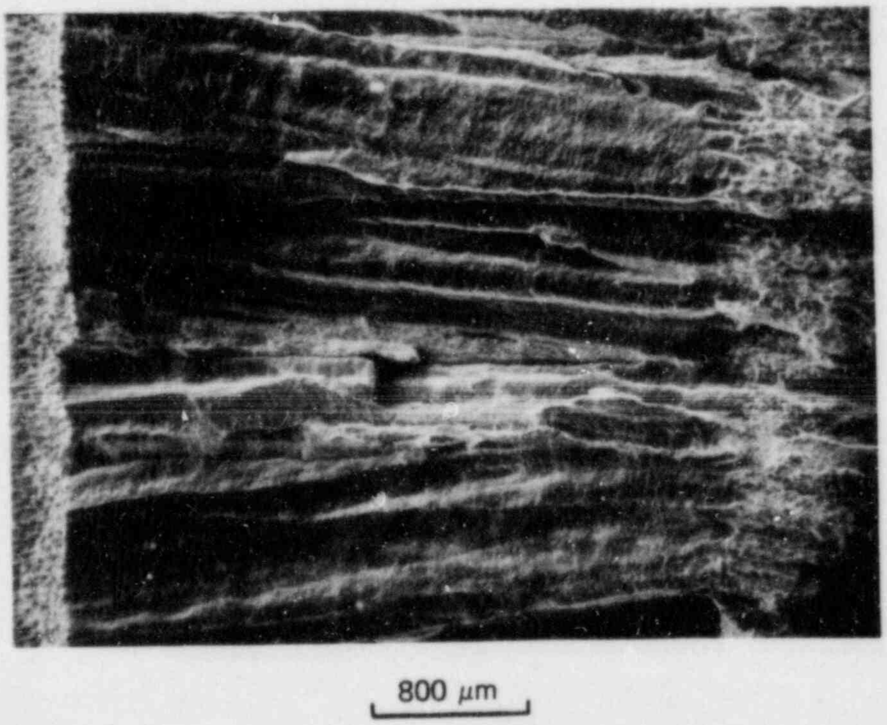

Fig. 10. Scanning electron micrograph of fracture face of unirradiated Charpy specimen CPL-516 (nominally type 309 stainless steel) tested at −32°C in the transition region. The dimpled area at the left is the specimen notch, the central flat portion is the type 309 weld metal, and the rough portion at the right is the first type 308 weld pass.

In the nominally type 309 specimens, interpreting the Charpy impact curves demands that the dual fracture properties of the type 308 and 309 portions of the material be taken into consideration. Examination of the fracture surfaces shows clearly that the type 308 weld metal has a lower

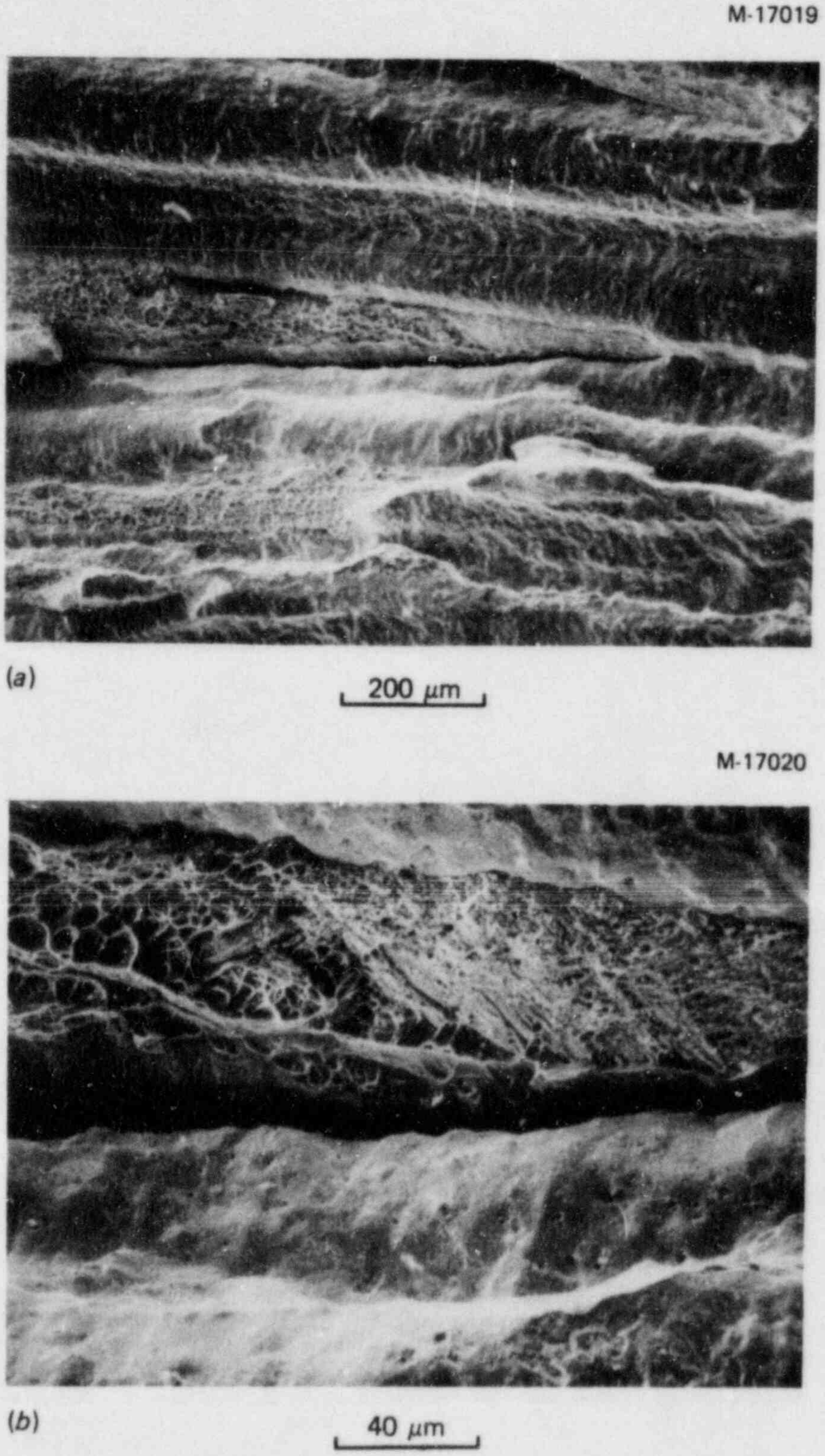

Fig. 11. Detailed views of the type 309 stainless steel weld metal fracture surface of specimen CPL-516 (tested at −32°C) showing predominantly flat fracture with islands of fibrous tearing.

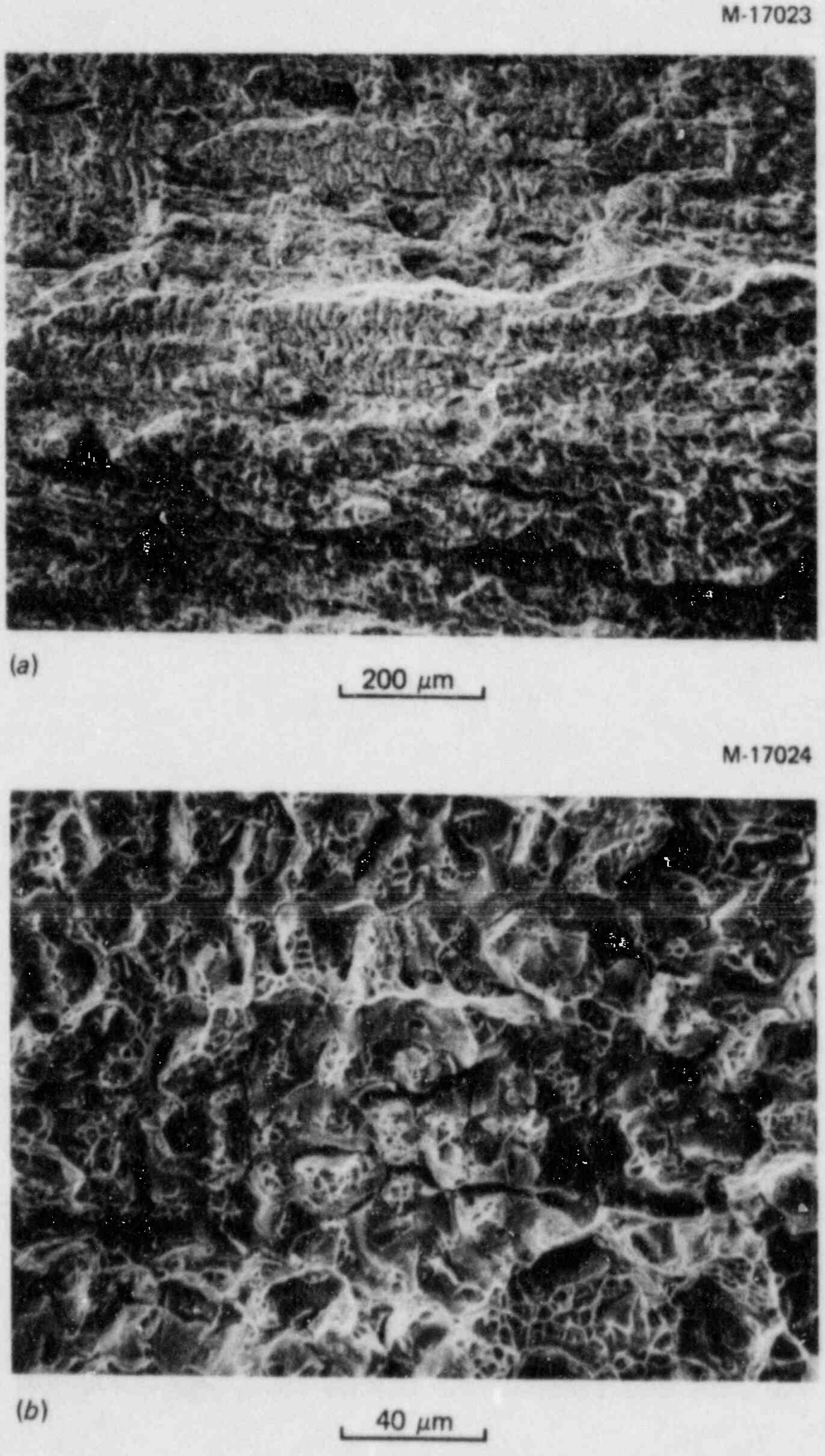

Fig. 12. Detailed views of the type 308 stainless steel weld metal fracture surface of specimen CPL-516 (tested at −32°C) showing mixed-mode fracture.

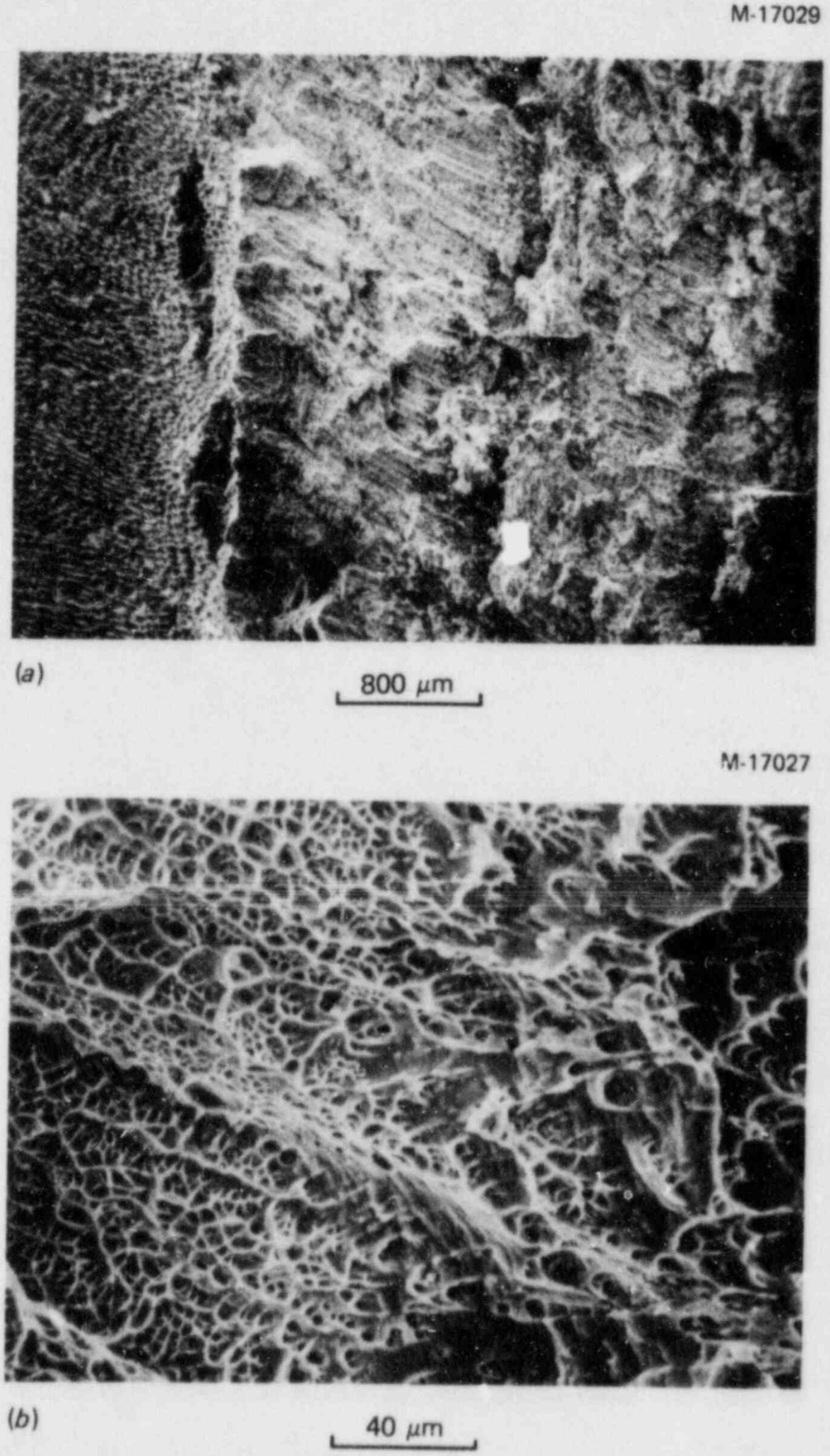

Fig. 13. Scanning electron micrograph of the fracture surface of unirradiated nominally type 309 stainless steel Charpy specimen CPL-524 tested at 177°C on the upper shelf. (*a*) Low-magnification view of the notch, the type 309 weld layer, and the type 308 weld layer, each constituting roughly one-third of the micrograph from left to right. (*b*) Detail of the type 309 weld layer showing fibrous fracture.

transition temperature than does the type 309. Examining the impact data reveals a bimodal population related to the amount of the tougher type 308 weld metal present in the sample. The more type 308 in the specimen, the lower the apparent transition temperature of the specimen. The compilation of the unirradiated and irradiated impact data in Tables 3 and 4, respectively, includes the percentage of type 308 weld metal measured visually on each fracture surface. By using this percentage as a criterion, the impact data were divided into low- and high-energy populations. The most appropriate criteria for separating the low-energy populations were arbitrarily chosen to be less than 70 and 80% type 308 weld metal for the unirradiated and irradiated data sets, respectively (Figs. 14 and 15), because these produced the most distinct difference between the data sets.

Table 3. Charpy impact energy of unirradiated nominally type 309 stainless steel cladding

Specimen	Test temperature (°C)	Impact energy (J)	Amount of type 308 weld metal[a] (%)
Low-energy population[b]			
CPL-516	−32	9.5	65
CPL-530	−30	12.7	65
CPL-534	10	33.4	60
CPL-514	20	28.5	65
CPL-545	50	36.2	60
CPL-542	66	34.6	55
CPL-517	93	67.1	60
CPL-524	177	80.3	60
CPL-522	260	72.3	40
High-energy population[c]			
CPL-519	−100	5.4	85
CPL-539	−73	6.9	75
CPL-520	−40	12.9	75
CPL-540	−30	11.5	75
CPL-529	−4	44.7	95
CPL-532	−4	54.2	95
CPL-547	−4	30.5	70
CPL-544	10	65.1	100
CPL-527	20	63.0	80
CPL-535	50	83.9	80
CPL-525	66	69.2	80
CPL-537	150	93.3	70
CPL-549	150	94.9	70

[a] As measured on the fracture surface.

[b] Less than 70% type 308 weld metal.

[c] At least 70% type 308 weld metal.

Table 4. Charpy impact energy of nominally type 309 stainless steel cladding irradiated to 2 × 10^{23} neutrons/m^2 (>1 MeV) at 288°C

Specimen	Test temperature (°C)	Impact energy (J)	Amount of type 308 weld metal[a] (%)
Low-energy population[b]			
CPL-515	0	10.8	60
CPL-543	40	17.0	75
CPL-541	65	25.1	65
CPL-548	85	15.6	40
CPL-521	100	25.1	60
CPL-523	150	40.7	65
CPL-518	250	42.7	70
CPL-528	288	36.6	75
High-energy population[c]			
CPL-533	−20	12.0	80
CPL-538	0	21.7	90
CPL-526	28	40.7	100
CPL-531	80	54.2	95
CPL-546	120	51.5	80
CPL-536	130	56.9	85

[a] As measured on the fracture surface.

[b] Less than 80% type 308 weld metal.

[c] At least 80% type 308 weld metal.

Once these populations within the type 309 data were established, the effect of irradiation was seen to be quite appreciable (Fig. 16). Both populations experienced large drops in upper-shelf energy of up to 50% and shifts in transition temperature of up to 100°C.

The extensive toughness degradation seen in the type 309 material as compared with very little in the type 308 is probably due to the higher fraction of ferritic phases in the type 309 resulting from the excessive base metal dilution and their intrinsically higher radiation sensitivity.

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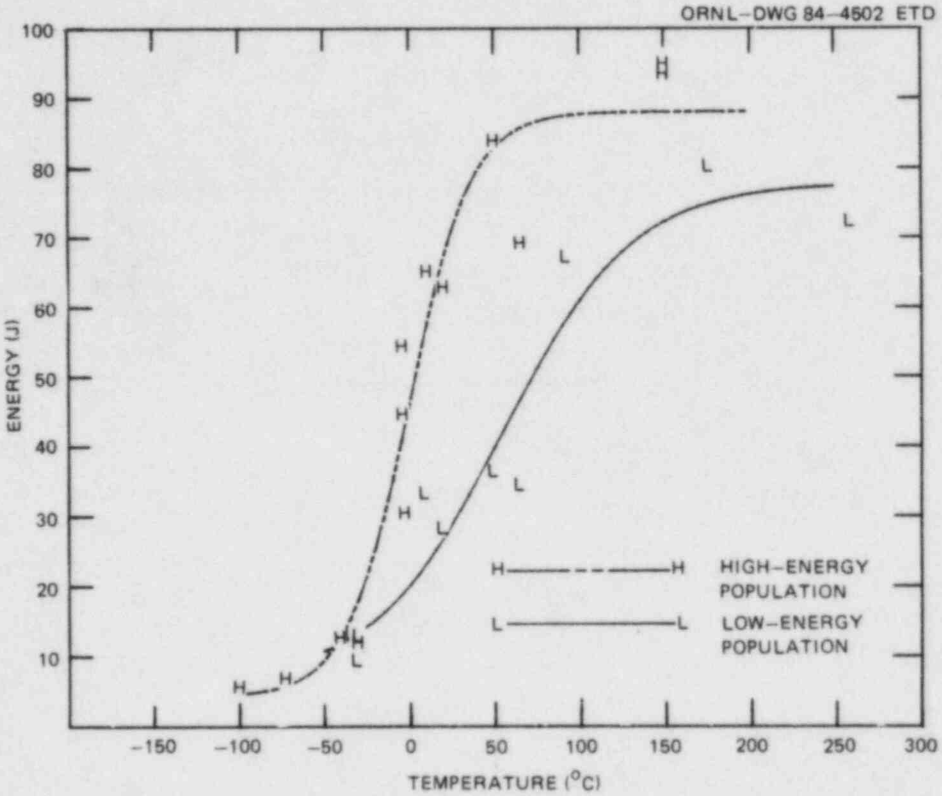

Fig. 14. Charpy impact energy of the unirradiated nominally type 309 stainless steel cladding divided into low- and high-energy populations based on the fraction of type 308 weld metal in the specimen ligament.

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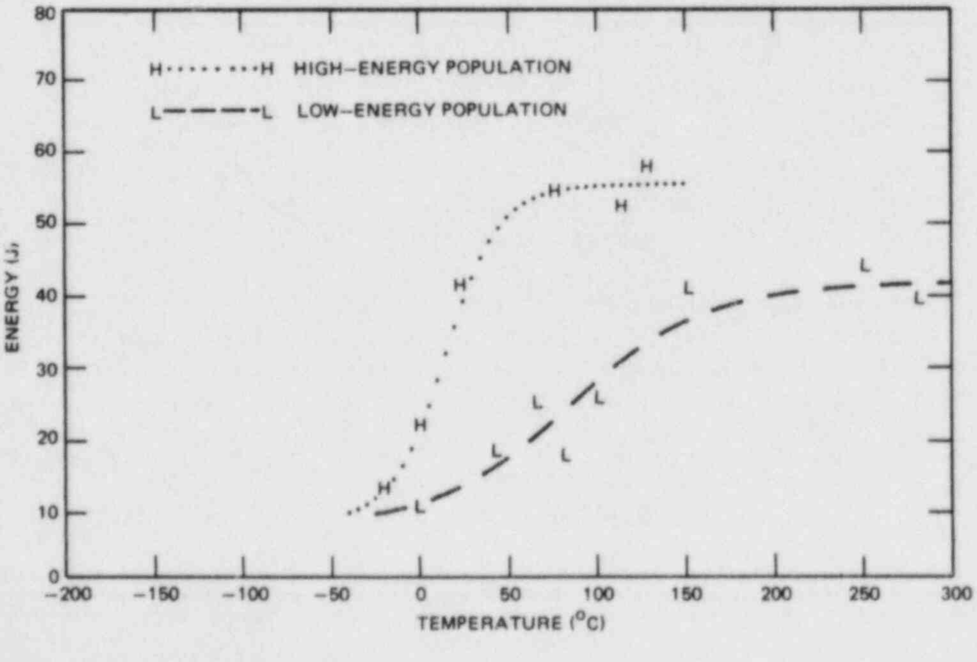

Fig. 15. Charpy impact energy of the irradiated nominally type 309 stainless steel cladding divided into low- and high-energy populations based on the fraction of type 308 weld metal in the specimen ligament.

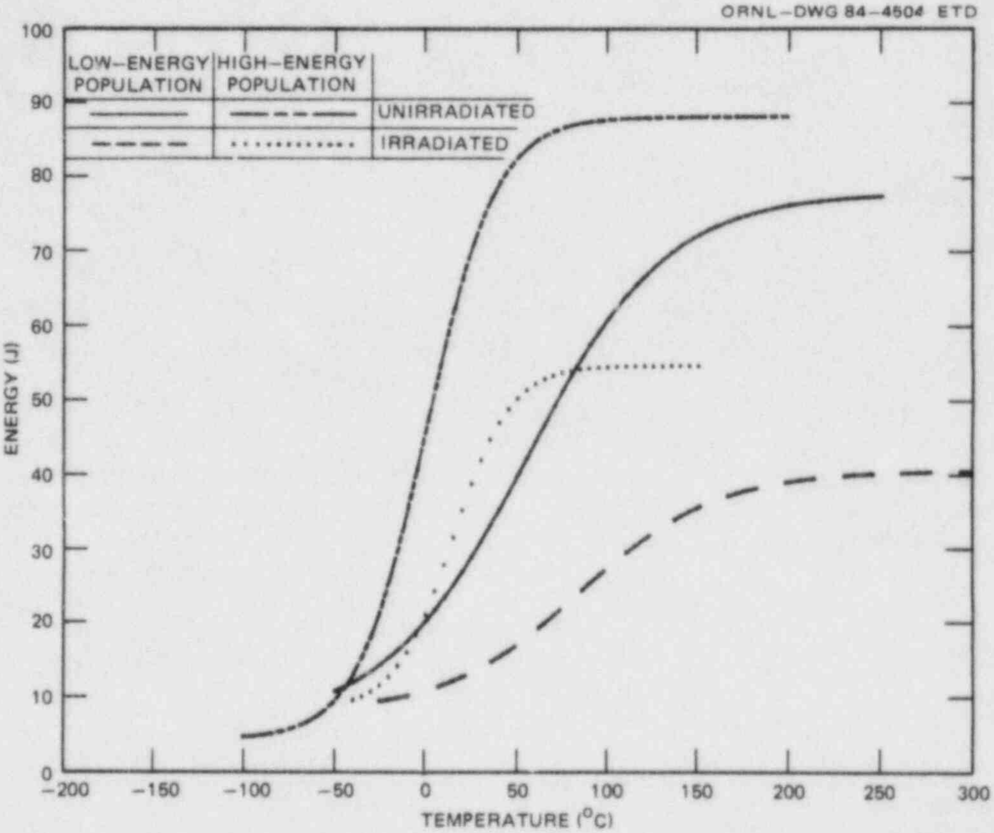

Fig. 16. Effect of irradiation on the Charpy impact energy of high- and low-energy populations of the specimens of nominal type 309 cladding.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

On the basis of irradiation of one weldment of stainless steel overlay at a temperature and fluence similar to those at end of life for an LWR, very little degradation of the notch-impact toughness displayed by good quality cladding would be expected. In fact, both the tensile strength and the fracture ductility were improved slightly by irradiation. It must be stressed, however, that this is only a single case and that no conclusions, positive or negative, can be drawn regarding welding procedures or compositions leading to material appreciably different from that studied here.

It would be very valuable to repeat this type of experiment on cladding overlays produced by other methods similar to those used for existing cladding in LWR reactor pressure vessels (e.g., multiple wire or strip cladding).

Results from the highly diluted type 309 weld metal do show appreciable radiation-induced degradation of notch-impact toughness, even though both the tensile strength and the tensile fracture ductility were improved slightly by irradiation. In the few known cases where welding has produced abnormal cladding with excessive dilution in operating reactors, the radiation effects on notch-impact toughness may be cause for concern.

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16. ABSTRACT (200 words or less)

The ability of stainless steel cladding to increase the resistance of an operating nuclear reactor pressure vessel to extension of surface flaws depends greatly on the properties of the irradiated cladding. Therefore, weld overlay cladding irradiated at temperatures and fluences relevant to power reactor operation was examined. The cladding was applied to a pressure vessel steel plate by the submerged arc, single-wire, oscillating-electrode method. Three layers of cladding provided a thickness adequate for fabrication of test specimens. The first layer was type 309, and the upper two layers were type 308 stainless steel. The type 309 was diluted considerably by excessive melting of the base plate. Specimens were taken from near the base plate–cladding interface and also from the upper layers. Charpy V-notch and tensile specimens were irradiated at 288°C to a fluence of 2×10^{23} neutrons/m^2 (>1 MeV).

When irradiated, both types 308 and 309 cladding increased 5 to 40% in yield strength and slightly increased in ductility in the temperature range from 25 to 288°C. All cladding exhibited ductile-to-brittle transition behavior during impact testing. The type 308 cladding, microstructurally typical of that in reactor pressure vessels, showed very little degradation in either upper-shelf energy or transition temperature due to irradiation. Conversely, the impact properties of the specimens containing the highly diluted type 309 cladding, microstructurally similar to that produced during some off-normal welding conditions in existing reactors, experienced significant increases in transition temperature and drops of up to 50% in upper-shelf energy. The impact energies of the Charpy specimens containing the type 309 layer strongly reflected the amount of the type 309 actually in the specimen, falling into two distinct high- and low-energy populations with the low-energy population corresponding to a higher fraction of type 309 in the specimen.

17. KEY WORDS AND DOCUMENT ANALYSIS

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