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Fracture Evaluation of Surface Cracks Embedded in Reactor Vessel Cladding

Material Property Evaluations

Prepared by D.E. McCabe

Materials Engineering Associates, Inc.

Prepared for
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ABSTRACT

The materials that are present in the local region of the clad layer of RPV steel were evaluated for tensile properties and fracture toughness before and after irradiation damage. Residual stresses in the clad region were determined. The information described herein was used to understand the behavior of surface cracks embedded in the clad layer in beam tests conducted in another phase of this investigation.

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FOREWORD

The work reported here was performed at Materials Engineering Associates (MEA) under the program Structural Integrity of Water Reactor Pressure Boundary Components, F. J. Loss, Program Manager. The program is sponsored by the Office of Nuclear Regulatory Research of the U. S. Nuclear Regulatory Commission (NRC). The technical monitor for the NRC is Alfred Taboada.

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1. INTRODUCTION

Research performed to evaluate the severity of surface cracks embedded in the clad layer of reactor vessels has shown the importance of having an understanding of the mechanical properties of each material involved. In the present project, the principal objective was to simulate the surface crack embedded in cladding with four-point loaded bend specimens. This report presents the results of auxilliary tests which involved several metallurgical evaluation-like mini-studies, each of which deserved more detailed presentations than would be appropriate to a main report.

The material acquired for this project was made in simulation of a commercially clad reactor pressure vessel. A 203-mm (8-in.) thick plate of A 533-B steel with plan view dimensions of 0.3-m (12-in.) by 1.09-m (43-in.) was sliced at the mid-plane to make two 101-mm (4-in.) thick slabs. All four surfaces were clad layered using a three wire, submerged arc welding process typical of that used in older vessel construction. See Fig. 1. Two hot wires were 308 stainless steel and the surfaces were made in just one pass. The one cold wire was 304 stainless steel. A very short section (50 to 75-mm) at one end on one of the surfaces was given a second layer so that clad material could be tested as full size specimens. Hot wires of 308 and 304 stainless steel were used in the second layer. Table 1 shows the welding parameters used. The procedure included stress relief annealing. To prevent warpage during cladding, the two plates were tack welded back to back, clad layered, and then stress relief annealed at 670°C (1125°F) for 8 hours. They were then separated, turned, re-tack welded and the other two surfaces (the skin surfaces of the original plate) were then clad layered. An 8-hour stress relief anneal was applied for a second time giving the clad surfaces used in the present experiment a total of 16 hours of temper. The base metal used herein was entirely from near the midplane of the original 203-mm thick slab.

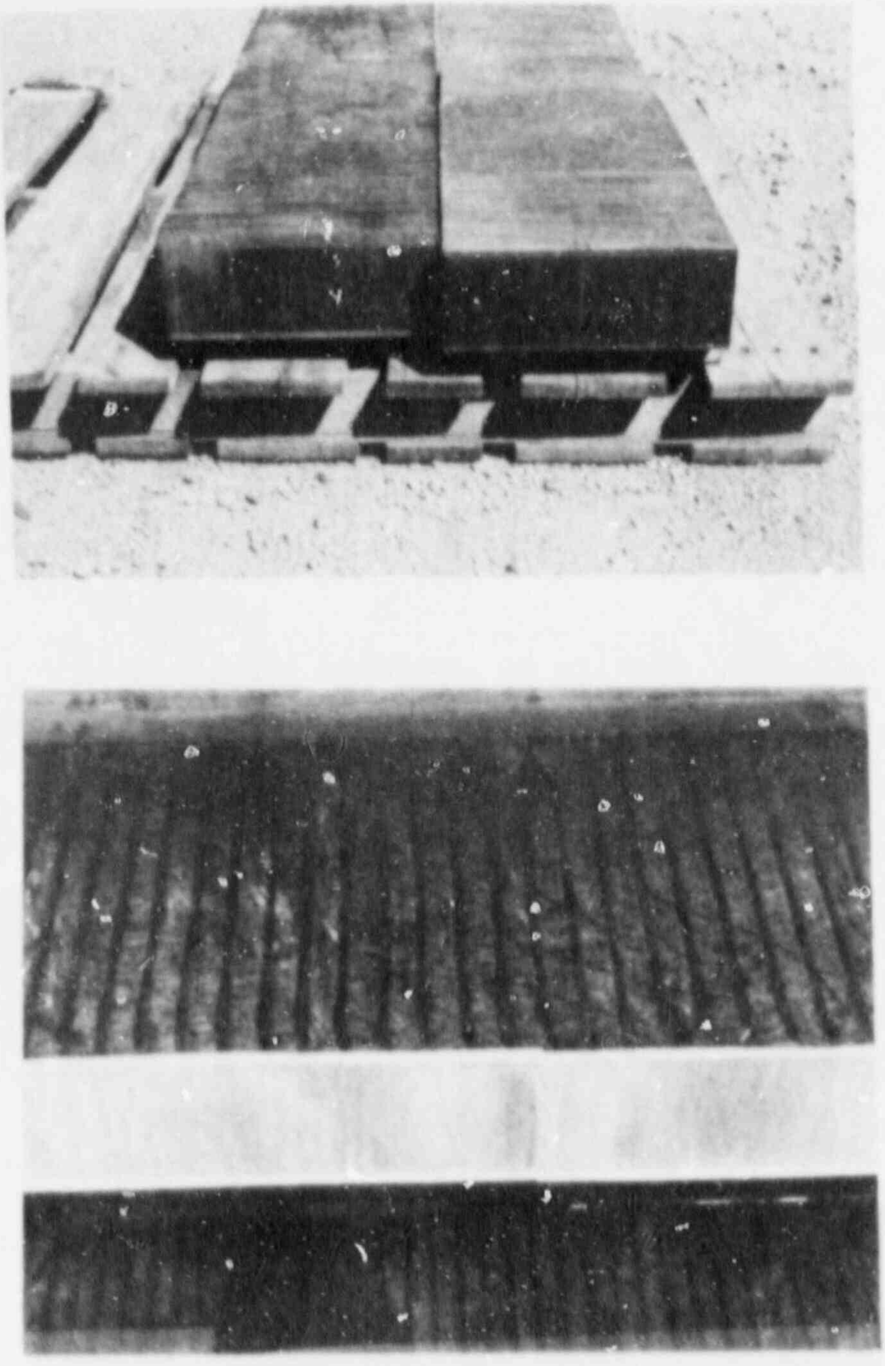


Fig. 1 Photographs of clad plates. Upper photo of as-welded surfaces. Lower photo shows scalloped appearance of weld/base metal interface.

Table 1 Welding Parameters

		First Layer	Second Layer
Amps		480	480
Volts		25-26	25-26
Travel		8 IPM	8 IPM
Flux		Arcos S-4	Arcos S-4
Hot Wire:	Size	5/32 in dia.	5/32 in dia.
No. 1	Type	308 Stainless Steel	308 Stainless Steel
	Ht. No.	9967	9967
Hot Wire:	Size	5/32 in. dia.	5/32 in. dia.
No. 2	Type	308 Stainless Steel	304 Stainless Steel
	Ht. No.	9967	646093
Cold Wire:	Size	5/32 in. dia.	5/32 in. dia.
	Type	304 Stainless Steel	304 Stainless Steel
	Ht. No.	646093	646093
Ferrite Measurement, Avg.		4.8	7.2

2. RESIDUAL STRESS MEASUREMENT

Residual stresses that develop in the clad layer are attributed to "stress relief annealing." It is generally believed that the stress build up is due to the difference in thermal contraction between stainless and ferritic steels during cool down from stress relief anneal. The effect that such secondary stresses could have on the surface crack analysis was unknown at the beginning of this program. Therefore, a task was undertaken to measure residual stresses. This study had been done by Rybicki, et al., at the University of Tulsa (Ref. 1,2), integrating experimental work and analytical predictions of residual stress. Figure 2 represents the typical residual stress measurement for replicate determinations vs. the position with respect to thickness. The data had replicated well and it was conclusively shown that the residual stress in the stainless layer was tensile and of the order of the yield strength of the stainless steel (about 310 to 380 MPa). The material in the HAZ metal (most likely to fracture by cleavage) sees some compressive stress of low magnitude. This pattern was generally confirmed by the computational model from the computer simulation.

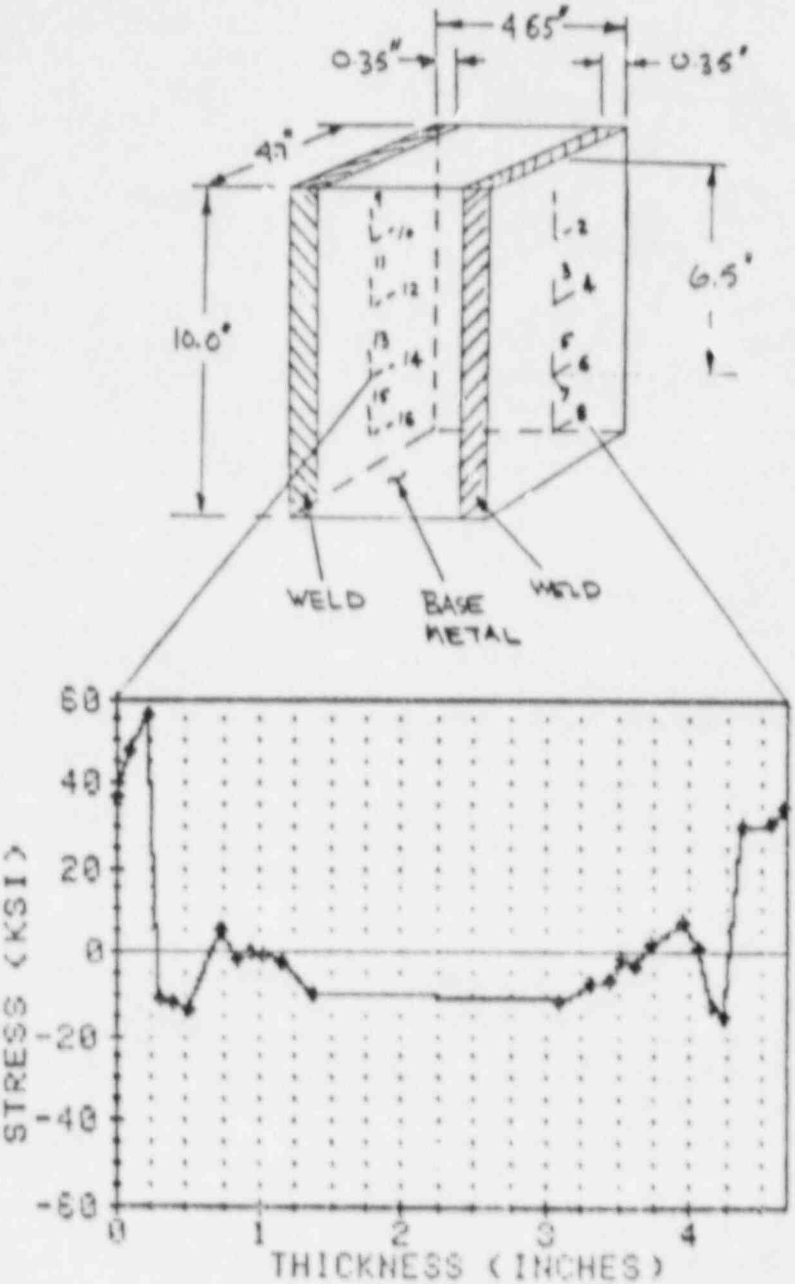


Fig. 2 Longitudinal, through-thickness residual stresses in clad plate reasured at position 140 mm (5.5 in.) from ›dge. (1 in. = 25.4 mm, 1 ksi = 6.894 MPa).

3. MATERIAL PROPERTIES

Tensile properties and chemical composition are reported in Table 2. Transition temperature curves from Charpy-V (C_v) impact tests are shown in Fig. 3. Specimens of clad metal and HAZ were less than full thickness (5-mm) because of the obvious material dimensional limitations. Base metal specimens were always full size C_v and 1T compact specimens. Therefore, a few of the following comparisons may be a bit tenuous because of a potential size-effect influence. A transition temperature index for full size C_v specimens is defined at 41 J. The comparable criterion for half-thickness C_v specimen is not specified. Therefore, we arbitarily chose 20 J. Transition temperatures so chosen are listed in Table 3. Heat affected zone metal appears to have superior transition temperature toughness compared to base metal. For upper shelf energy, base metal seems to have higher toughness. A characteristic noted here and recently by others (Ref. 3) is that austenitic stainless steel in the form of cladding displays unexpectedly low upper shelf toughness and a transition temperature behavior, even though a cleavage-like fracture mechanism is not known to develop in FCC (austenitic) crystallographic microstructures. Metallurgical studies conducted at Oak Ridge National Laboratory (Ref. 4) have identified the mechanism as temperature-dependent failure in delta (δ) ferrite. This is a relatively scarce constituent in the microstructure but it is highly effective in this case because it is dispersed in a network along austenite grain boundarys. See Fig. 4.

Transition temperature curves can also be established from compact specimens, but the characteristic temperature will almost certainly be different from that defined from C_v specimens. K_{Jc} values determined from compact specimens involve the interpretation of test records which must be varied according to fracture mode. See Fig. 5. If the test temperature is upper shelf, K_{Jc} is obtained from J_{Ic} (Ref. 5) for the onset of (significant) slow-stable crack growth. If the test temperature is in the transition regime, K_{Jc} is the elastic-plastic stress intensity factor at the onset of cleavage instability. The transition temperature is determined from the curve at 100 MPa$\sqrt{m}$, and because fracture mechanics is used, specimen size effects are diminished. See Fig. 6, and Table 3. Again, as with the C_v results, the HAZ material is indicated to have improved transition temperature over that of the virgin base metal.

R-curves were obtained at upper shelf temperature (100°C) for the three aforementioned clad zone materials. See Fig. 7. Clad metal has the lowest R-curve. These R-curves are also temperature sensitive as can be seen in Fig. 8. The loss in ductile tearing resistance had been seen earlier in C_v results in the form of an apparent transition temperature behavior due to cleavage in delta ferrite. Cleavage does not occur in clad, weld metal on a gross scale in any case.

Table 2 Mechanical Properties (Room Temp.)

Material	Condition	Yield Strength MPa	Tensile Strength MPa	% El	Upper Shelf CVN J
Base Metal[a]	As received	409	582	29	155
Heat Affected Zone[b]	As received	396	584	35.9	
Heat Affected Zone[b]	Irradiated 4.5×10^{19} n/cm^2	586	738	----	
Clad Metal[a]	As welded	281	632		54

Chemical Composition (Wt. %)

	C	Mn	P	S	Si	Ni	Cr	Mo	V	Co	Cu
Base Plate	0.21	1.38	0.017	0.006	0.17	0.61	-	0.55	-	-	0.17
Cladding	0.05	1.46	0.023	0.015	0.76	8.73	18.9	0.22	0.04	0.04	0.16

[a] 6.35 mm dia. tensile specimen
[b] 5.08 mm dia. tensile specimen

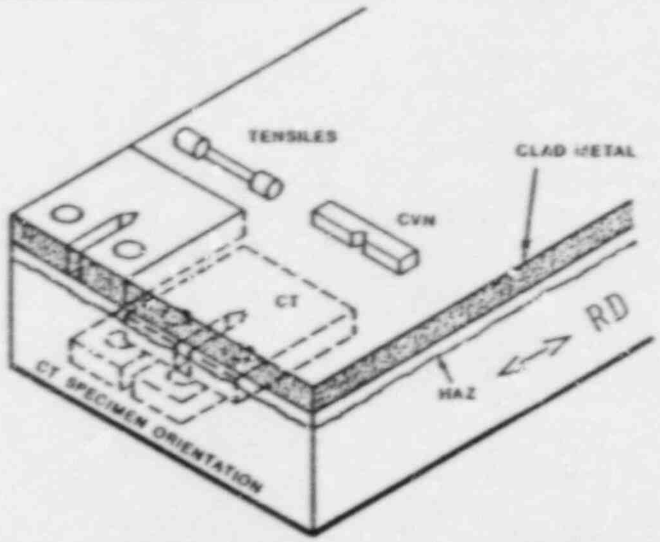


Table 3 Transition Temperatures and C_v Energy for Materials in the Region of the Clad Layer

	C_v Index	C_v Upper Shelf J	K_{Jc} @ 100 MPa$\sqrt{m}$
Base Metal[a]	-7°C[c]	157	-50°C
Heat Affected Zone	-50°C[d]	66	-90°C
Clad Metal	0°C[d]	27	-b-

a Full sized C_v specimen

b K_{Jc} > 100 MPa$\sqrt{m}$ at all test temperatures

c @ 41 J

d @ 20 J

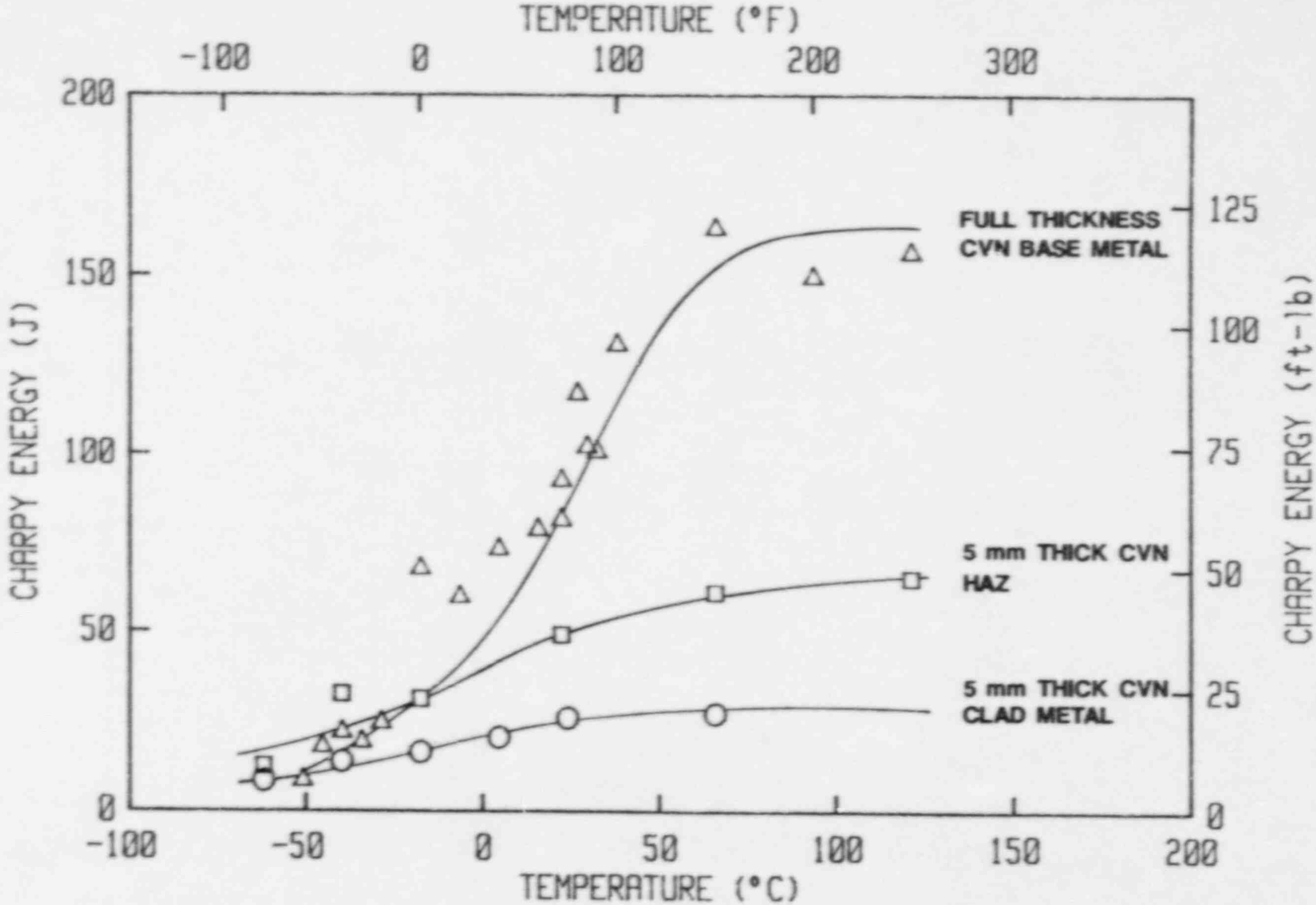


Fig. 3 Charpy-V transition curves for clad metal, base metal, and HAZ material.

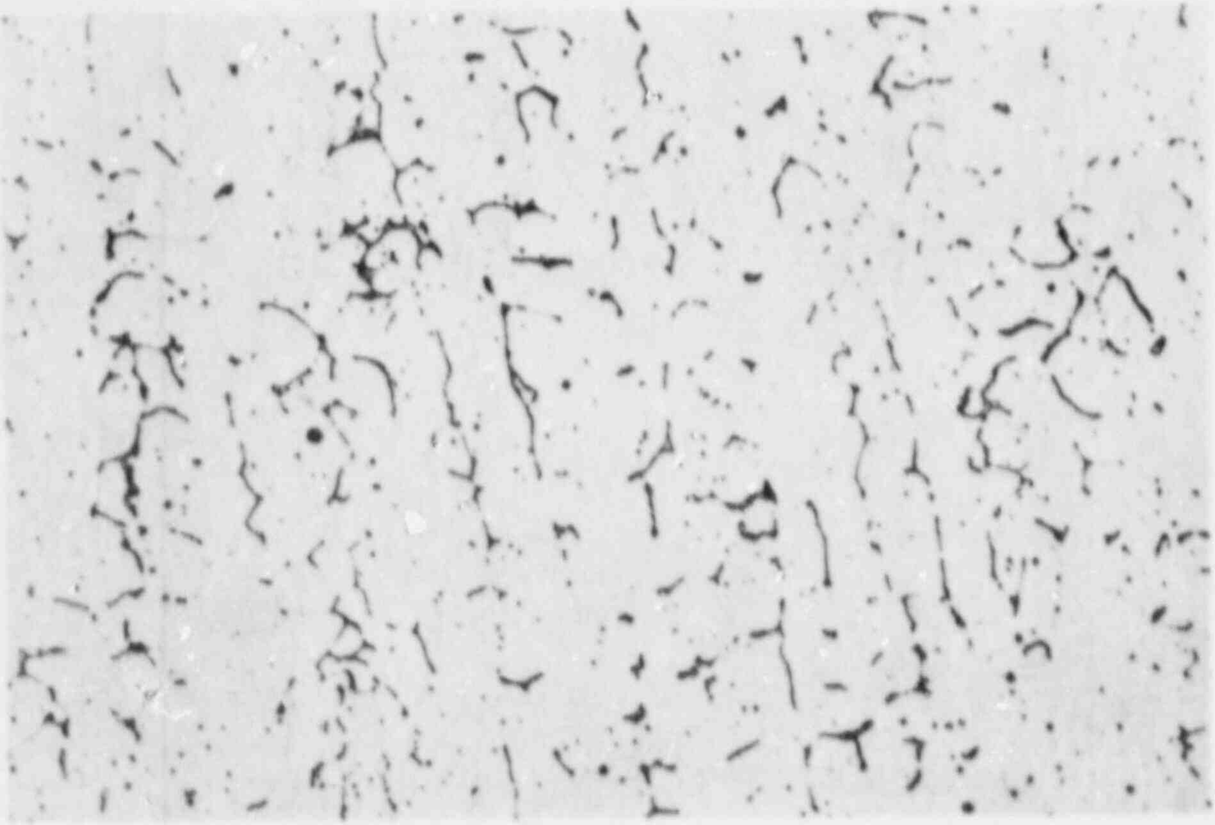


Fig. 4 Microstructure of cladding at 500X. Austenite with delta ferrite in grain boundaries. Etchant (30% HCl, 10% HNO_3, H_2O).

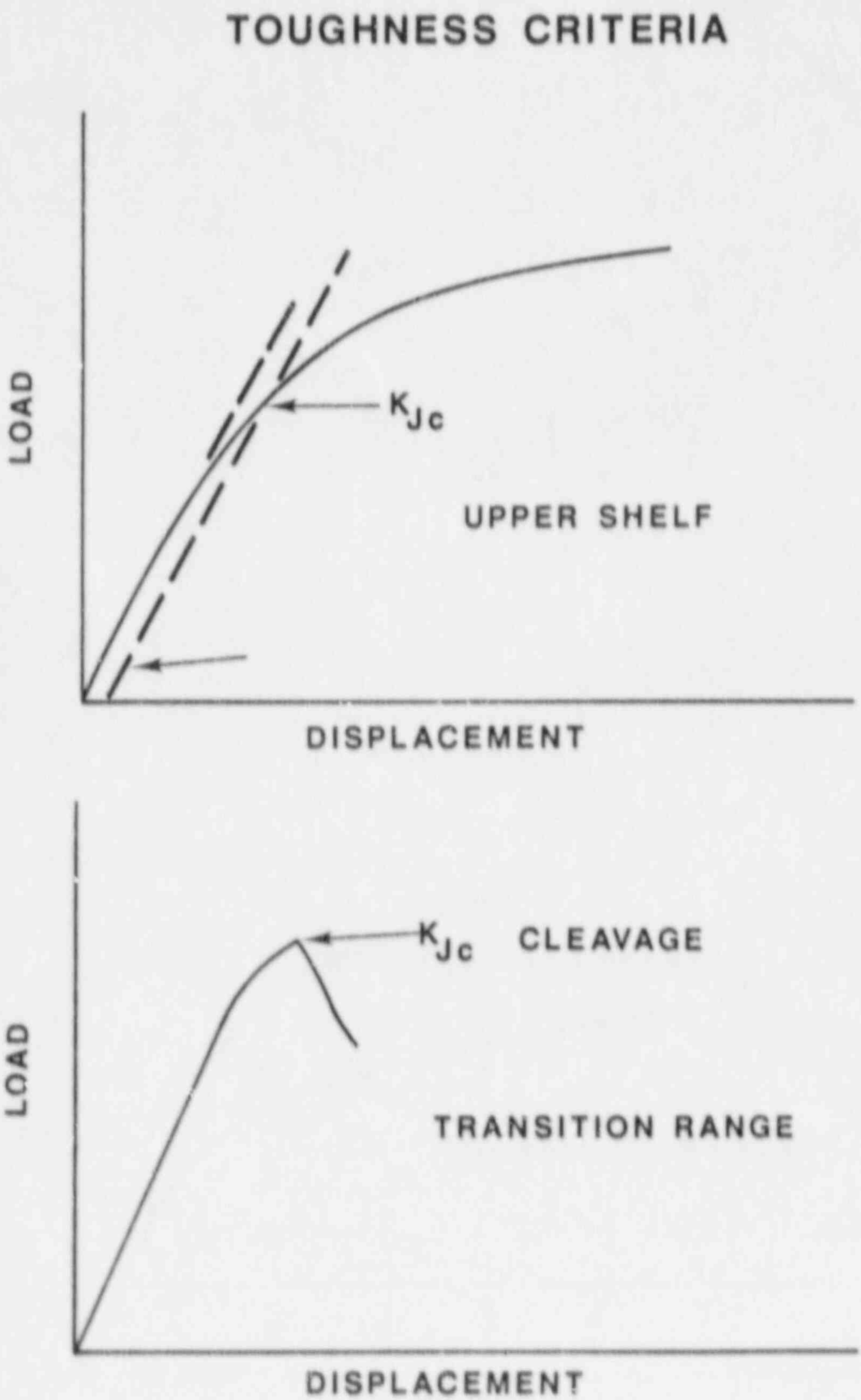


Fig. 5 Definition of K_{Jc} for two different fracture modes.

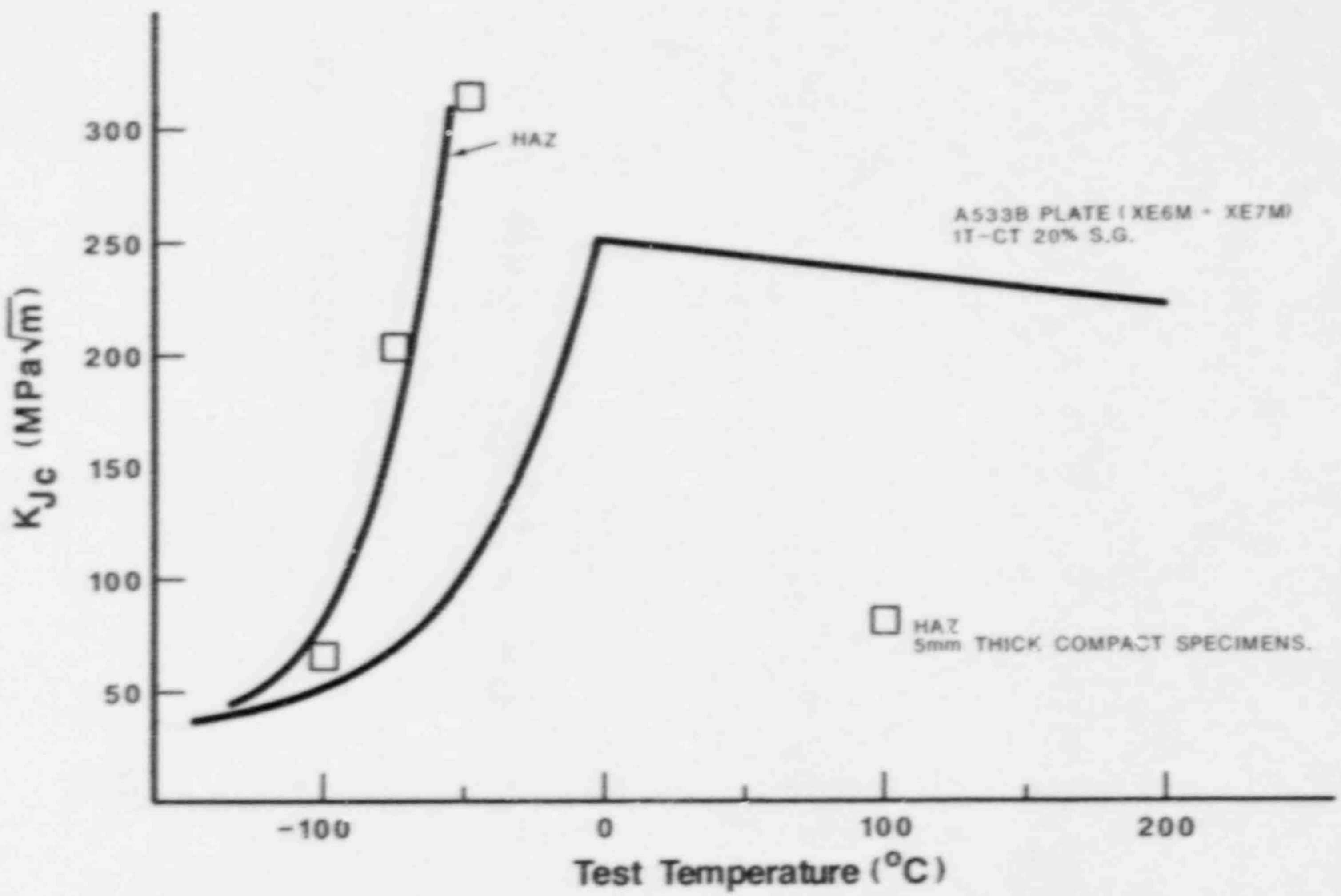


Fig. 6 Base metal and HAZ transition

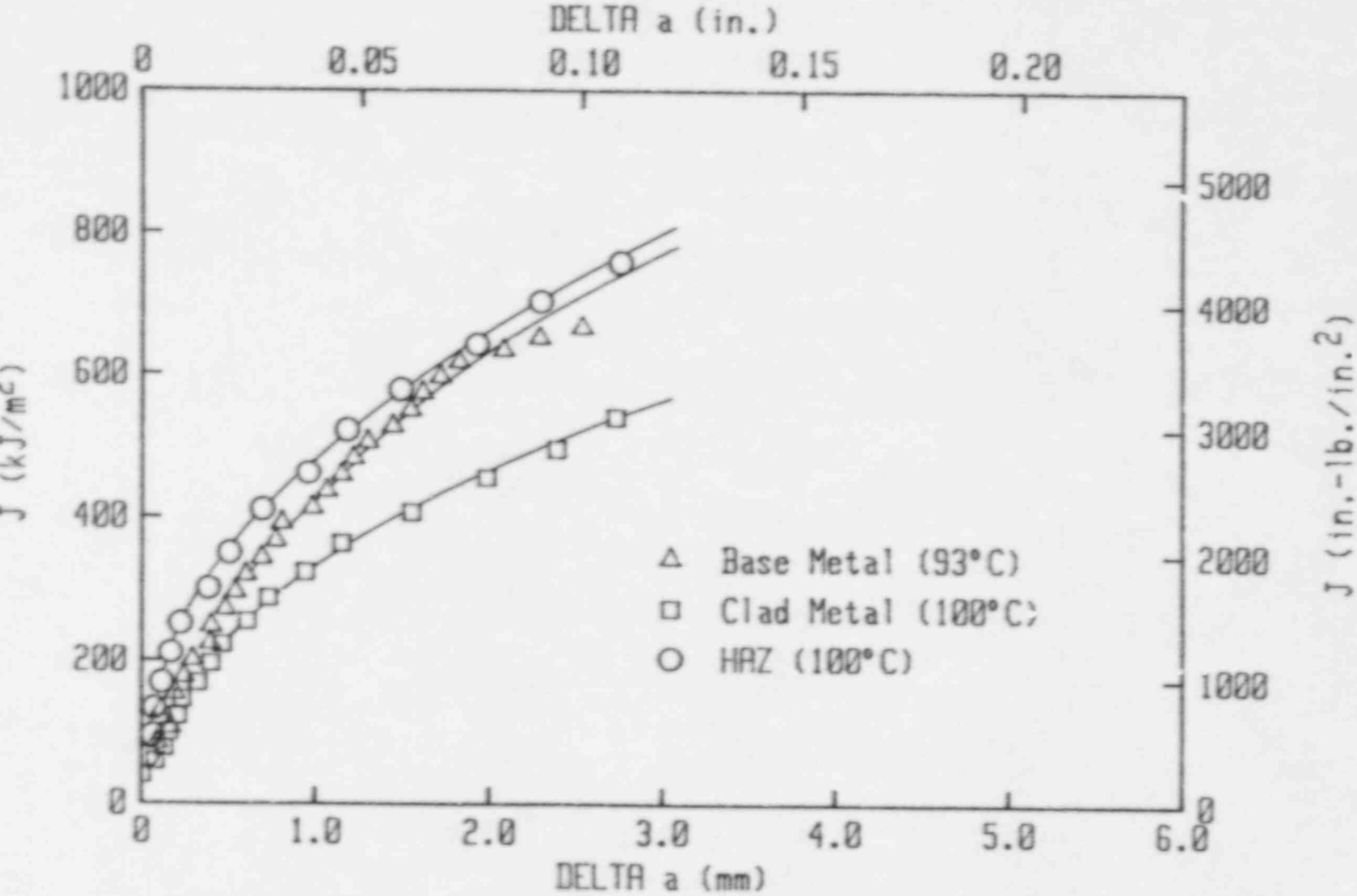


Fig. 7 J_R Curves on upper shelf for clad weld metal, base metal, and HAZ material.

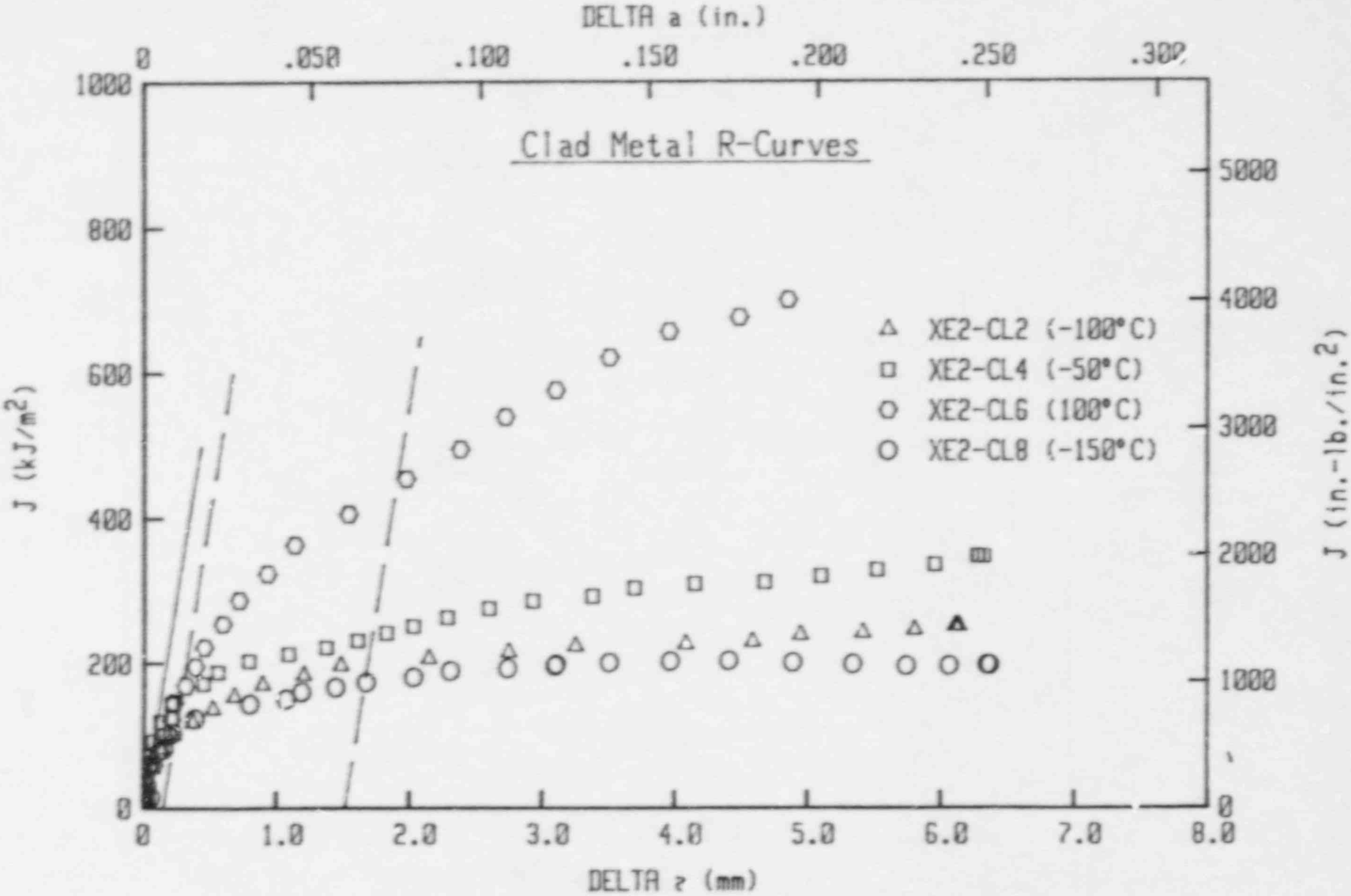


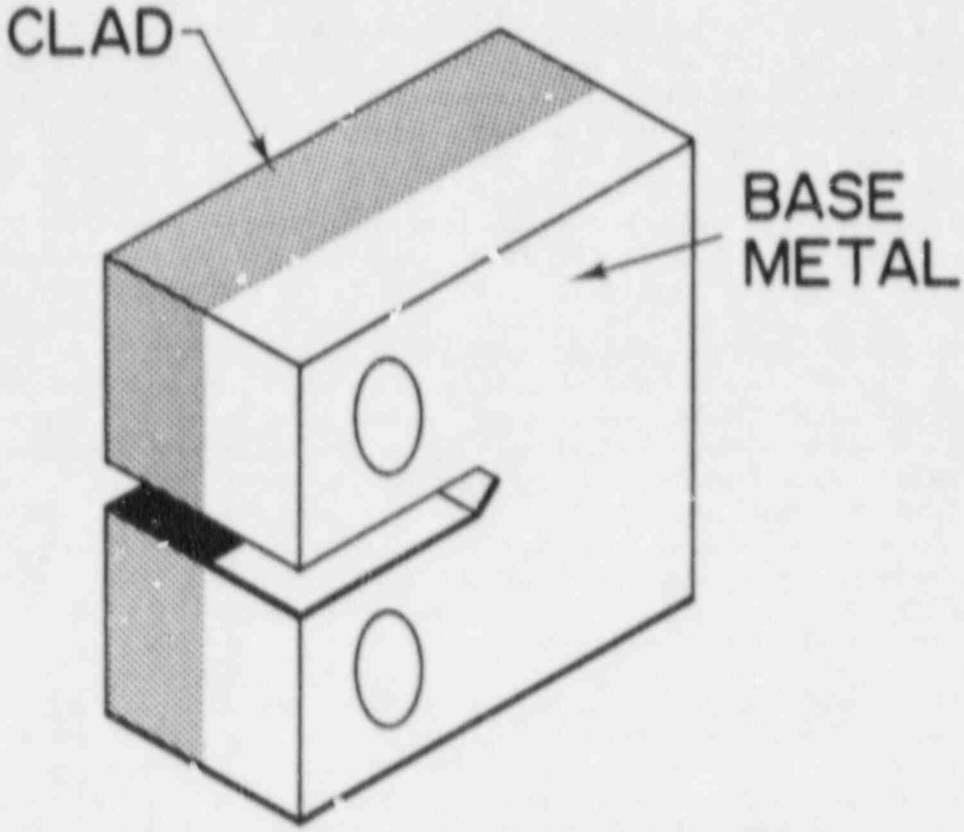
Fig. 8 J_R-curves for clad metal at various test temperatures (1/2T-CT specimens).

4. CRACK ARREST WITH CLAD METAL

The presence of a layer of austenitic stainless steel on the interior surface of a reactor wall has been viewed in the past as protection against uncontrolled running under-clad cracks. Clad metal, because it was believed to have high toughness, was expected to influence retardation of crack speed and hence promote crack arrest. In the belief that the net effect of the presence of clad metal can never be negative, safety assessments were made ignoring the existence of the cladding, and because of this, the analysis was considered conservative. Only the margin of safety was subject to question.

To verify the hypothesis, two 1/2T compact specimens were made to test the crack retardation capability of the present cladding material. These were "duplex specimens" of the type used by Framatome (Ref. 6) in their cladding evaluations. The specimens were sampled so that the weld fusion line was on the midplane as shown in Fig. 9. The temperature for test was -100°C, chosen so that the HAZ toughness would be lower than that of clad metal. Figure 10 represents a comparison of cladding toughness for onset of stable crack growth, (extracted from Fig. 4), vs. K_{Jc} of HAZ material. Clad metal toughness was about 2 times that of HAZ material.

There was cleavage fracture in HAZ at the expected K_{Jc} levels (Fig. 10). The cracks arrested almost at the point of ligament separation in HAZ. Figure 9 shows a photo of one of the heat tinted fracture surfaces, and it is clear from this that the crack in the HAZ had dominance over the ductile tear resistance of the clad metal. It therefore appears from this demonstration that clad metal has very little ability to retard and arrest running cracks in ferritic vessel material.



Weld Fusion Line Specimen

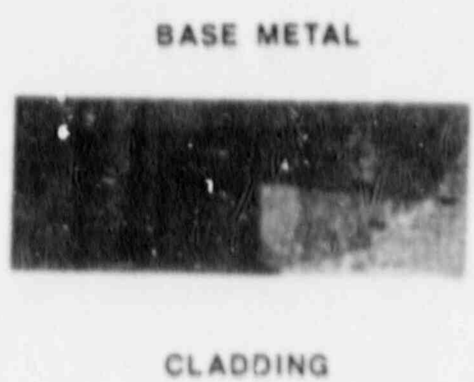


Fig. 9 Duplex specimen. Heat tinted to show arrested crack.

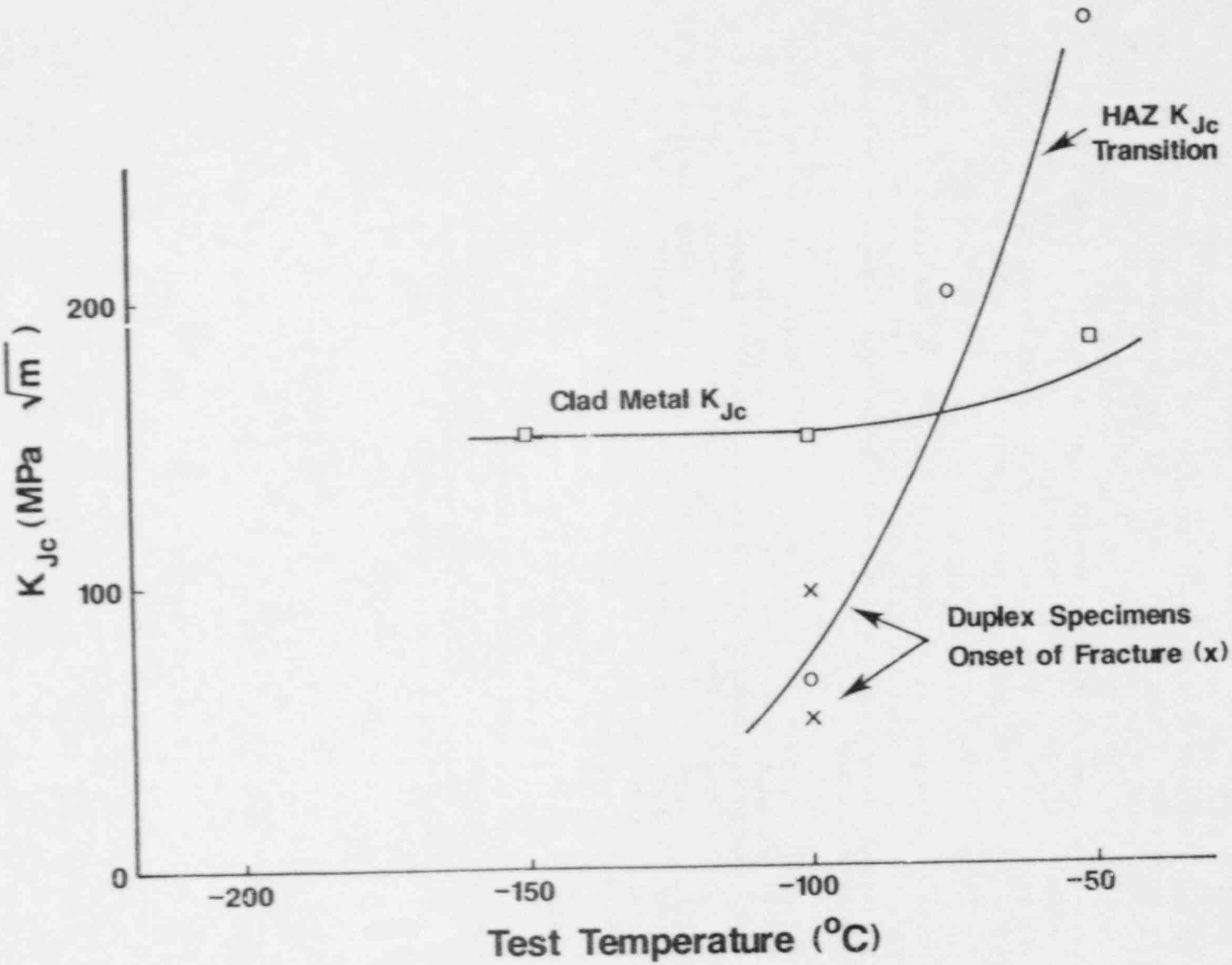


Fig. 10 K_{Jc} transition curves for clad metal and HAZ material. K_{Jc} facture levels (X) for two specimens tested at -100°C.

5. IRRADIATION EFFECTS ON FRACTURE TOUGHNESS

A few selected specimens of clad metal and HAZ material were exposed in the UBR test reactor to a fluence of 4.5×10^{19} n/cm^2 ($E > 1$ MeV) at 288°C. The specimens were four 1/2T compacts and four C_v of each material. Again, all specimens were 5-mm thick.

Table 2 shows the increase in strength of the HAZ from irradiation. The magnitude of transition temperature shift was of greater interest to this study, and the result is given in Fig. 11. The temperature elevation of the C_v index is 105°C, based on the adopted 20 J criterion. The 100 $MPa\sqrt{m}$ criterion used on K_{Jc} from compact specimens indicated the same 105°C transition shift. Note that one compact specimen shows a significantly greater toughness than the other three. This is to be expected because of inhomogeneity of HAZ material.

Using the base metal chemistry along with Regulatory Guide 1.99 (Rev. 2), a transition temperature shift of 97°C to 115°C is predicted; depending upon the choice between base metal or weld metal chemistry factor.

Irradiation damage to clad metal on the other hand was relatively minor as can be seen from Fig. 12. C_v upper shelf was reduced but there was no apparent change in the relationship between toughness vs. test temperature. The plot of K_{Jc} from compact specimens is derived entirely from fracture toughness at onset of slow stable crack growth. This characterization of fracture toughness was improved by irradiation damage, presumably accompanied with a slight increase in clad metal strength. Irradiated clad metal tensile tests were not made in the present experiment. However, experiments by W. J. Mills (Ref. 7) on austenitic stainless steels used on structurals in liquid-metal fast-breeder reactors had shown significant material strengthening from irradiation damage. Crack initiation resistance was improved but evidence of toughness loss was developed in the form of tearing modulus, T, which quantifies the resistance against slow stable crack growth. T is defined as:

$$T = \frac{E}{\sigma_o^2} \frac{dJ}{da} \quad (1)$$

where

- E = elastic modulus
- σ_o = material flow strength
- dJ/da = J_R-curve slope

Table 4 shows that the R-curve slope is reduced by irradiation damage. This fracture pattern is once again consistent with C_v indications as had been shown earlier with the transition temperature behavior of the as-received clad metal.

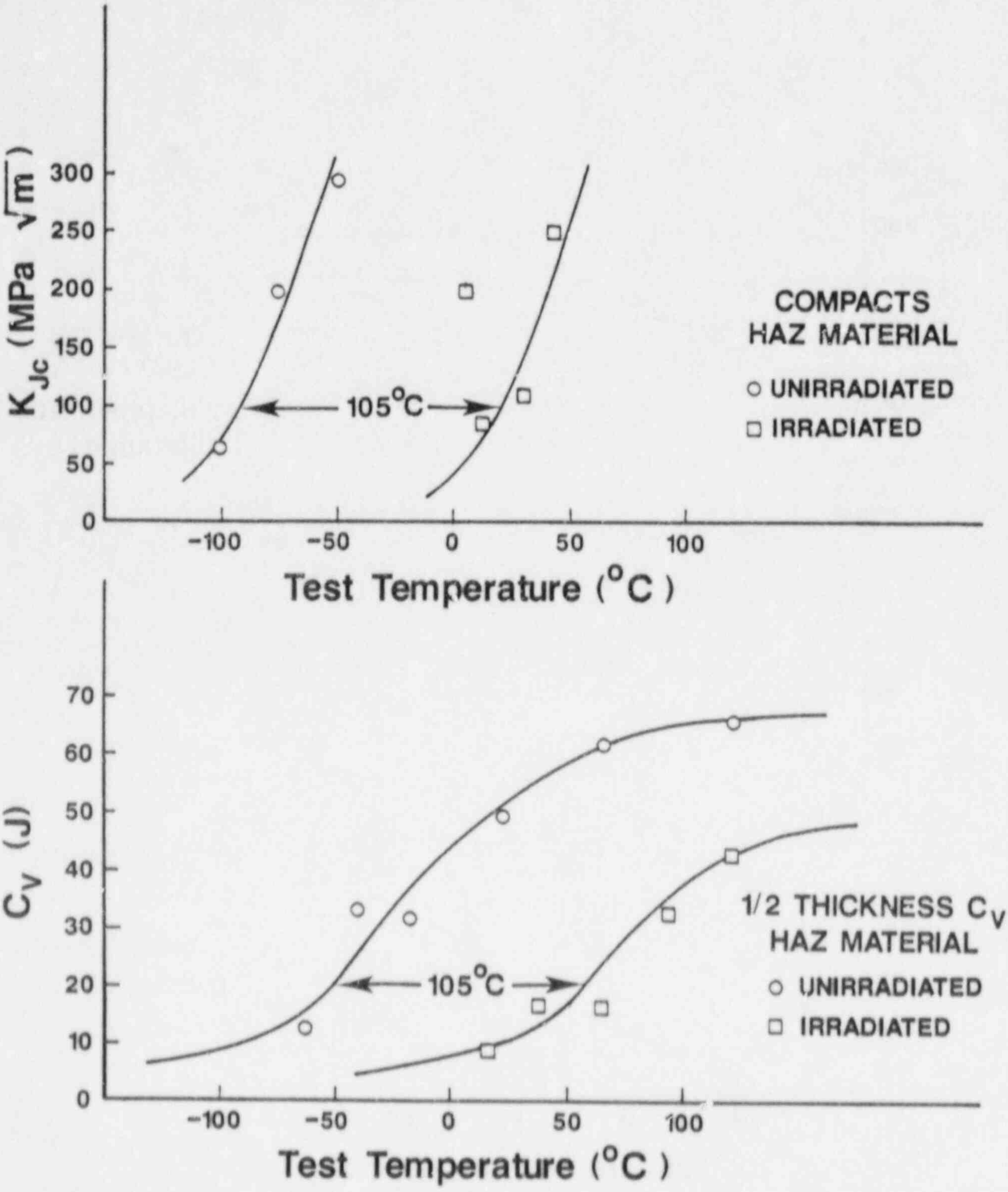


Fig. 11 Transition temperature curves for HAZ material before and after irradiation, characterized by K_{Jc} and Charpy-V tests.

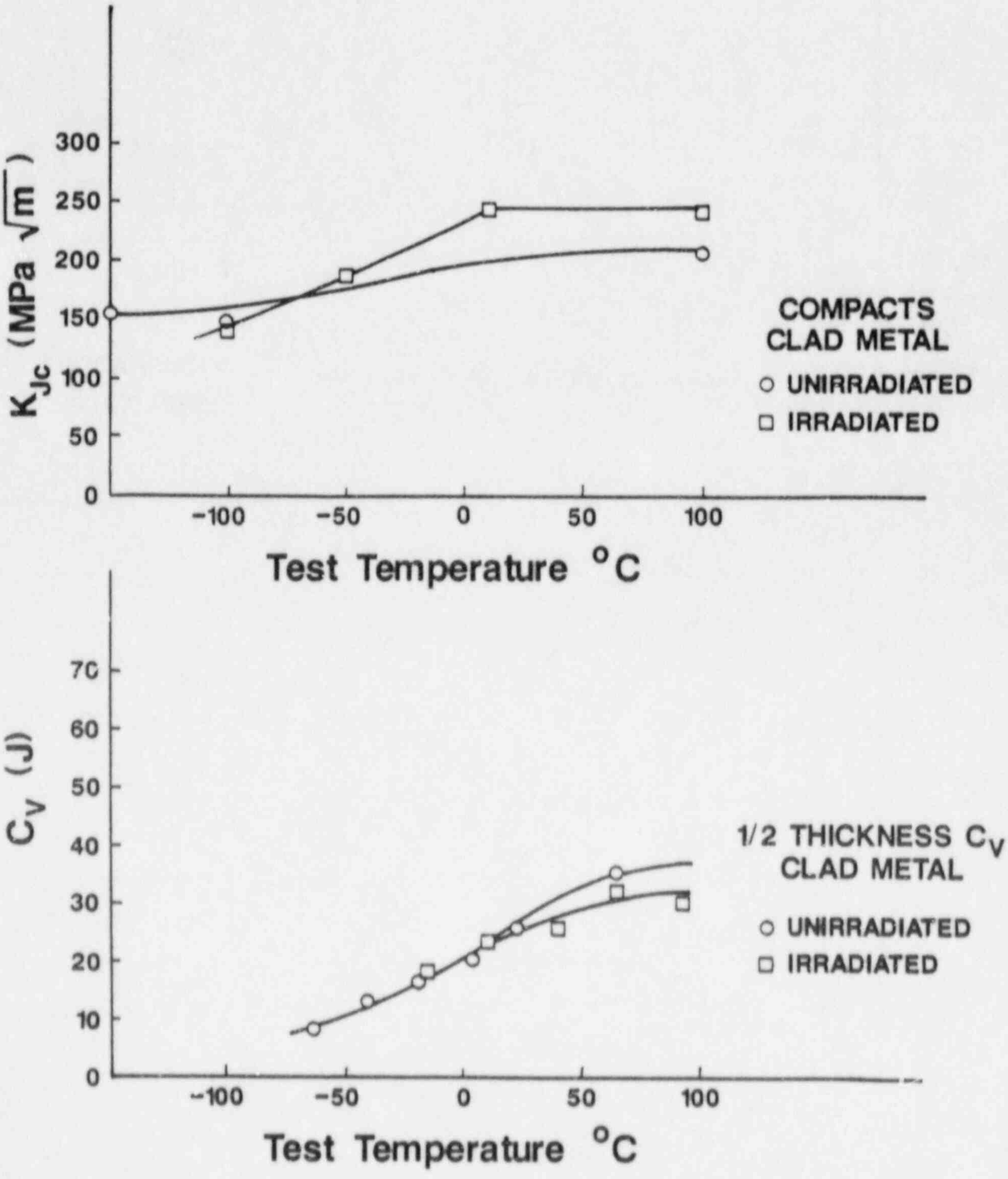


Fig. 12 Transition temperature curves for clad metal before and after irradiation, characterized by K_{Jc} and, Charpy tests.

Table 4 R-Curve Slope (T) of Clad Metal Specimens, Before and After 4.5×10^{19} n/cm^2 Irradiation, 5-mm Thick Specimens.

Test Temp.	T Before	T After
100°C (212°F)	247	139
50°C	212[a]	67
-50°C	47	37
-100°C (-148°F)	46	62
-150°C (-238°F)	25	(Not Available)

a An approximate value because T came from a 12-mm thick 1/2T specimen out of the double layered cladding. In addition, its actual test temperature was +25°C.

6. CONCLUSIONS

This report presents the background information needed to understand the material properties and conditions that could impact the performance of an embedded surface crack in welded cladding material. The following observations were made:

- Residual stresses measured within the clad layer were tensile and of the order of the yield strength of the clad metal.

- The HAZ material had improved toughness over that of base metal only in the form of lower transition temperature.

- Clad metal has very poor fracture toughness in comparison to ordinary commercial grades of ferritic pressure vessel steels.

- The crack initiation toughness of clad metal was moderately improved by irradiation exposure. J_{Ic} (K_J) crack initiation toughness was improved but there was slightly reduced toughness against continued slow-stable crack growth.

- The cladding material appears to have negligible capacity to retard running cracks in the underlying ferritic substrate material.

- The transition temperature shift in HAZ material was $\Delta T = 105^{\circ}C$. Charpy tests and compact specimen tests indicated an identical index temperature ΔT shift. However, the indexed transition temperatures themselves are test-method dependent, as might have been anticipated.

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The materials that are present in the local region of the clad layer of RPV steel were evaluated for tensile properties and fracture toughness before and after irradiation damage. Residual stresses in the clad region were determined. The information described herein was used to understand the behavior of surface cracks embedded in the clad layer in beam tests conducted in another phase of this investigation.

17. KEY WORDS AND DOCUMENT ANALYSIS

Cladding, Irradiation, J_{IC} Toughness, Charpy V, Tensile Properties, R-Curves

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