Westinghouse Atomic Power Division

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WCAP-3677-6

MASTER

FRACTURE MECHANICS EVALUATION OF REACTOR VESSEL STEELS QUARTERLY PROGRESS REPORT FOR THE PERIOD ENDING DECEMBER 31, 1967

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PRELIMINARY REPORT — U. S. EURATOM EXCHANGE

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PROGRAM DESCRIPTION

An experimental program is being performed directed towards further development and evaluation of a fracture mechanics approach to the problem of brittle fracture of reactor vessel materials, based upon the use of modified Wedge Opening Loading (WOL) specimens. Experimental testing of a group of reactor vessel steels is being performed to investigate the application of the fracture mechanics technique to these materials in both the unirradiated and irradiated conditions. Because of test reactor dimensional constraints, scaled-up specimens can only be used to obtain pre-irradiation data; therefore, irradiation effects will be determined only on small specimens.

Testing in the unirradiated and irradiated conditions will be conducted to determine the variability in fracture toughness of various materials. Materials being investigated include base metal samples from two different heats of a nickel modified, manganese-molybdenum steel and a European forging grade material; and weld and heat affected zone samples from one heat of a nickel modified, manganese-molybdenum steel. Tensile, Charpy V-notch and drop weight specimens from those materials are included in the program in order to provide correlation data.

EUFM-100 - Program Management (Summary of Progress)

L. F. Cochrun - Project Engineer

This is the sixth technical progress report on a USAEC-Euratom joint program on fracture mechanics. The previous technical progress reports were:

EURAEC-1924 WCAP-3677-5	"Fracture Mechanics Evaluation of Reactor Vessel Steels Quarterly Progress Report for the Period Ending September 30, 1967
EURAEC-1879 WCAP-3677-4	"Fracture Mechanics Evaluation of Reactor Vessel Steels Quarterly Progress Report for the Period Ending June 30, 1967"
EURAEC-1829 WCAP-3677-3	"Fracture Mechanics Evaluation of Reactor Vessel Steels Technical Progress Report for the Period March 31, 1967"
EURAEC-1780 WCAP-3677-2	"Fracture Mechanics Evaluation of Reactor Vessel Steels Technical Progress Report for the Period Ending December 31, 1966"
EURAEC-1720 WCAP-3677-1	"Fracture Mechanics Evaluation of Reactor Vessel Steels Technical Progress Report for the Period Ending September 30, 1966"

Progress during the period October 1, 1967 through December 31, 1967 is summarized as follows:

1. The first series of irradiation capsules, containing all material except the 12 inch plate material is still being irradiated in the Babcock and Wilcox test reactor. Failure of heaters in one capsule was compensated by changing capsule locations.
2. The 12 inch plate has been received and is being sectioned in preparation for specimen machining.
3. Pre-irradiation testing of all material except the 12 inch plate has been completed.

EUFM-200 IRRADIATION AND ANALYSIS

T. R. Mager W. S. Hazelton F. O. Thomas

This task provides for the planning of the irradiation experiment including the design, manufacture and assembly of the irradiation capsules. Technical direction shall be provided during the capsule irradiation, capsule disassembly, and post-irradiation examination of specimens. Analysis and evaluation of the experimental results will be performed under this task.

The irradiation of the first three test capsules in the Babcock & Wilcox Test Reactor (BAWTR) is continuing. The capsules were rotated 180 degrees during BAWTR outing after the first irradiation cycle. The purpose of rotating the capsules is to minimize the attenuation of the neutron flux. The capsules will be rotated again after the third and fourth cycles of this experiment.

During the last week of October, #2 capsule lost its heaters and four of its six thermocouples. It was operating at 400°F by means of gamma heating. It was proposed that the temperature could be increased by introducing nitrogen gas into the capsule. No change in temperature occurred when the gas was purged through the capsule, indicating that the system was already operating with a pure nitrogen atmosphere. The only possible method of increasing the temperature was to increase the amount of gamma heating. This was possible by interchanging capsule #2 with capsule #1 which was closer to the center of the core. Interchanging the capsules increased the temperature in capsule #2 to a peak of about 535°F. The temperature fluctuates with the reactor power and coolant temperature, but is generally >510°F at reactor powers of > 5.5 MW. The temperature in capsules #1 and #3 is maintained at about 540°F with the electrical heat. A typical temperature reading is given in Table 200.1.

Table 200.1

Typical Temperature for Irradiation Capsules

Thermocouple Number	Capsule #1
1	535°F
2	555°F
3	545°F (Control)
4	515°F
5	535°F
6	510°F
13	545°F (Control)
14	510°F
15	525°F
16	529°F
17	Open
18	544°F

EUFM-300 - Pre-Irradiation Testing

T. R. Mager W. S. Hazelton F. O. Thomas

Under this task, the material required for the test specimens will be procured and the pre- and post-irradiation specimens will be manufactured. The testing of the pre-irradiation specimens will be carried out and the results developed for analysis and evaluation under Task EUFM-200.

Procurement of Materials

The procurement of the 12-inch thick plate of SA533 Grade B Class I (MnMo with Ni) steel was completed during this quarter. The material is currently being sectioned into specimen blanks. The machining of the required test specimens will be initiated early in the next report period.

Mechanical Testing

Fracture toughness testing of three of the four AEC approved materials (SA533 Grade B Class I steel from the 8-inch thick plate, the European Forging Grade steel, and a weldment from a heat of SA533 Grade B Class I steel) was completed this quarter. As discussed in previous quarterly reports pertaining to fracture mechanics, the requirements of the type of fracture toughness testing employed are unusual in that it is necessary to compare post-test data to specimen pre-test dimensions to determine if the fracture toughness measured (K_Q) is the critical value (K_{IC}) for the material. In other words, validity of the test can be determined only after testing. Two criteria for validity have been proposed:

1. Reference 1 proposes use of the secant off-set method to determine that the majority of strain is due to crack elongation.

2. Reference 2 proposes (specifically for bend specimens, of which WOL specimens are a modification) that both the crack length and specimen thickness exceed 2.5x (Fracture Toughness/Yield Strength).[2]

Fracture toughness measured for specimens meeting these criteria is considered to be the critical value (K_{IC}) for the material. If the criteria are not met, the measured fracture toughness (K_Q) is considered to have been biased by specimen size. The stress intensity factors (fracture toughness) for AEC approved materials are presented in Tables 300.1, 300.2, 300.3 and 300.4.

Metallography

Samples from the weldment of SA533 Grade B steel were submitted to the Metallography Laboratory. The samples were polished and etched in 2% nital to reveal the microstructures shown in Figures 300.1 through 300.3. The samples were then separated from their mount and hardness readings were taken of each grain size area. The hardness values are summarized in Table 300.5.

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(1) J. E. Srawley, Notes Pertaining to Sect. 7.3.2 of Draft Recommended Practice, "Interpretation of Test Record and Calculation of K_{IC}," January 2, 1967.

(2) ASTM, E24 Sub T Task Group, "Recommended Practice for Plane Strain Fracture Toughness Testing of High Strength Metallic Materials Using a Fatigue-Cracked Bend Specimen," draft of proposal practice, December 14, 1966.

TABLE 300.1

Results of WOL Fracture Toughness Tests
SA533 Grade B Class I (From 8" Plate)

Specimen Number	Size	Temp. (°F)	Y.S. (ksi)	a (in.)	a/W	Plastic Zone Size r(in.)	Stress Intensity Factor (K_{IC},K_Q) See Text (ksi $\sqrt{in.}$)	Validity (See Note)
8"-5	1-X	-320	110.0	0.617	0.548	0.004	31.6	1
1T4	1-T	-320	110.0	0.939	0.368	0.005	32.5	1
Luk-3	1-X	-250	94.6	0.453	0.400	0.010	40.9	1
8"-4	1-X	-250	94.6	0.562	0.500	0.008	37.1	1
8"-3	1-X	-250	94.6	0.625	0.556	0.011	44.0	1
1T6	1-T	-250	94.6	0.951	0.372	0.010	40.8	1
1T1	1-T	-250	94.6	1.035	0.406	0.006	31.2	1
Luk-2	1-X	-200	82.5	0.501	0.431	0.007	30.6	1
8"-1	1-X	-200	82.5	0.539	0.479	0.015	43.2	2
Luk-4	1-X	-200	82.5	0.459	0.408	0.006	29.0	1
1T11	1-T	-200	82.5	0.944	0.370	0.010	35.6	1
1T8	1-T	-200	82.5	1.042	0.408	0.014	42.8	1
1T10	1-T	-175	78.3	0.916	0.359	0.025	55.5	2
8"-6	1-X	-150	75.3	0.531	0.472	0.041	67.9	2
1T7	1-T	-150	75.3	1.056	0.414	0.025	51.7	2
1T9	1-T	-150	75.3	1.083	0.424	0.027	53.4	2
3	2-T	-150	75.3	1.830	0.358	0.020	46.9	1
Luk-1	2-T	-150	75.3	2.085	0.407	0.043	66.9	1
Luk-2	2-T	-100	69.0	2.025	0.395	0.049	68.3	2
4	2-T	- 50	67.5	1.820	0.355	0.052	69.2	2

Note: 1 Meets both criteria: a and B greater than 2.5 $(K_{IC}/y.s.)^2$ and secant offset.

2 Fails a and B greater than 2.5 $(K_{IC}/y.s.)^2$, meets secant offset.

TABLE 300.2

Results of WOL Fracture Toughness Tests
European Forging Grade Steel

Specimen Number	Size	Temp. (°F)	Y.S. (ksi)	a (in.)	a/W	Plastic Zone Size r(in.)	Stress Intensity Factor (K_{IC},K_Q) See Text (ksi $\sqrt{in.}$)	Validity (See Note)
17	1-X	-320	115.0	0.589	0.524	0.006	39.6	1
24	1-X	-320	115.0	0.468	0.468	0.003	27.5	1
T4	1-T	-320	115.0	0.936	0.367	0.008	47.5	1
NOK27	1-X	-250	99.6	0.469	0.417	0.010	43.2	1
19	1-X	-250	99.6	0.616	0.547	0.011	47.9	1
NOK11	1-X	-250	99.6	0.460	0.408	0.009	41.6	1
B5	1-T	-250	99.6	0.917	0.360	0.014	51.3	1
T2	1-T	-250	99.6	0.943	0.370	0.015	53.9	3
NOK25	1-X	-200	90.0	0.415	0.369	0.021	56.3	2
NOK23	1-X	-200	90.0	0.438	0.389	0.023	59.9	2
26	1-X	-200	90.0	0.465	0.413	0.011	41.2	2
B3	1-T	-200	90.0	1.056	0.414	0.028	68.2	2
T6	1-T	-200	90.0	0.905	0.355	0.019	55.0	1
B6	1-T	-200	90.0	0.919	0.364	0.023	60.8	2
T4	2-T	-200	90.0	1.831	0.359	0.012	43.3	1
T1	1-T	-150	83.9	0.939	0.368	0.025	57.7	2
B2	1-T	-150	83.9	0.936	0.367	0.039	73.2	4
T3	1-T	-150	83.9	1.048	0.412	0.059	97.8	4
NOKB4	2-T	-150	83.9	1.835	0.360	0.025	57.2	1
NOK-T2	2-T	-125	82.0	2.065	0.403	0.025	56.2	1
T6	2-T	-100	79.5	1.835	0.339	0.026	56.0	1
B3	2-T	-100	79.5	1.819	0.357	0.053	79.2	4
NOKB1	2-T	- 75	80.0	2.116	0.415	0.046	74.6	2
T1	2-T	0	74.0	1.998	0.390	0.078	92.7	4

Note: 1 Meets both criteria: a and B greater than 2.5 $(K_{IC}/y.s.)^2$ and secant offset

2 Fails a and B greater than 2.5 $(K_{IC}/y.s.)^2$, meets secant offset

3 Meets a and B greater than 2.5 $(K_{IC}/y.s.)^2$, fails secant offset

4 Fails both criteria

TABLE 300.3

Results of WOL Fracture Toughness Tests
SA533 Grade B Class I (Weld)

Specimen Number	Size	Temp. (°F)	Y.S. (ksi)	a (in.)	a/W	Plastic Zone Size r(in.)	Stress Intensity Factor (K_{IC},K_Q) See Text (ksi $\sqrt{in.}$)	Validity (See Note)
PW4X	1-X	-320	115.0	0.518	0.460	0.004	29.7	1
PW5X	1-X	-320	115.0	0.505	0.451	0.003	27.2	1
PW6X	1-X	-250	97.0	0.475	0.424	0.008	37.6	1
PW13X	1-X	-250	97.0	0.503	0.447	0.007	37.8	1
PW2X	1-X	-250	97.0	0.519	0.463	0.020	65.7	2
PW7Y	1-T	-250	97.0	0.958	0.376	0.010	43.6	1
PW6Y	1-T	-250	97.0	0.935	0.367	0.025	67.7	2
PW6Z	2-T	-250	97.0	1.999	0.392	0.033	55.6	1
PW18X	1-X	-225	93.5	0.506	0.452	0.021	62.3	2
PW16X	1-X	-225	93.5	0.500	0.446	0.014	57.7	2
PW3X	1-X	-225	93.5	0.485	0.433	0.013	47.8	2
PW9Y	1-T	-225	93.5	0.973	0.381	0.003	40.1	1
PW3Y	1-T	-225	93.5	0.921	0.361	0.016	52.8	1
PW1Z	2-T	-225	93.5	2.073	0.405	0.027	66.2	1
PW4Y	1-T	-200	90.5	0.959	0.376	0.037	76.0	2
PW8Y	1-T	-200	90.5	0.933	0.366	0.027	64.3	2
PW2Z	2-T	-200	90.5	2.015	0.393	0.032	70.7	1
PW4Z	2-T	-200	90.5	2.033	0.399	0.048	86.9	2
PW3Z	2-T	-125	85.0	2.245	0.440	0.063	92.9	2

Note: 1 Meets both criteria: a and B greater than 2.5 $(K_{IC}/y.s.)^2$ and secant offset

2 Fails a and B greater than 2.5 $(K_{IC}/y.s.)^2$, meets secant offset

TABLE 300.4

Results of WOL Fracture Toughness Tests
SA533 Grade B Class I (Heat Affected Zone)

Specimen Number	Size	Temp. (^{o}F)	Y.S. (ksi)	a (in.)	a/W	Plastic Zone Size r (in.)	Stress Intensity Factor (K_{IC},K_Q) See Text (ksi $\sqrt{in.}$)	Validity See Note
PH6X	1-X	-320	110.0	0.511	0.456	0.004	30.3	1
PH2X	1-X	-250	94.6	0.502	0.446	0.007	35.2	1
PH7X	1-X	-250	94.6	0.500	0.447	0.009	40.4	1
PH2Y	1-T	-250	94.6	0.998	0.391	0.005	30.5	1
PH4Y	1-T	-250	94.6	0.925	0.362	0.011	44.2	1
PH3Y	1-T	-225	89.0	0.909	0.356	0.034	75.0	2
PH3X	1-X	-200	82.5	0.515	0.460	0.021	56.5	2
PH1Y	1-T	-200	82.5	0.908	0.356	0.057	90.5	2
PH2Z	2-T	-200	82.0	2.051	0.402	0.040	71.2	1
PH1Z	2-T	-150	74.0	2.150	0.413	0.084	97.9	3

Note:
1. Meets both criteria: a and B greater than 2.5 $(K_{IC}/y.s.)^2$ and secant offset
2. Fails a and B greater than 2.5 $(K_{IC}/y.s.)^2$, meets secant offset
3. Fails both criteria: a and B greater than 2.5 $(K_{IC}/y.s.)^2$ and secant offset

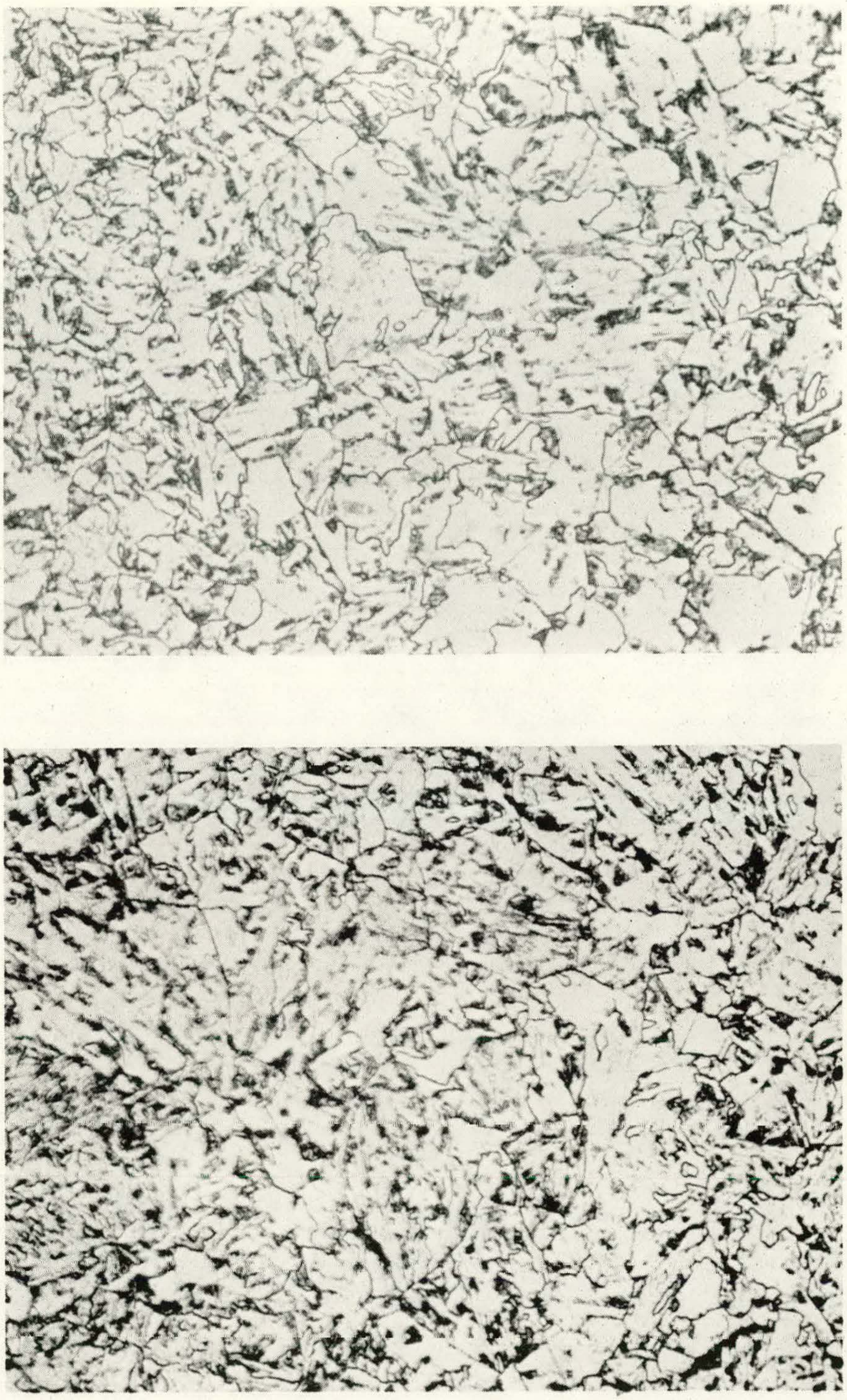

Figure 300.1 Two Representative Views - Base Metal - SA 533 Grade B Class I - 500X

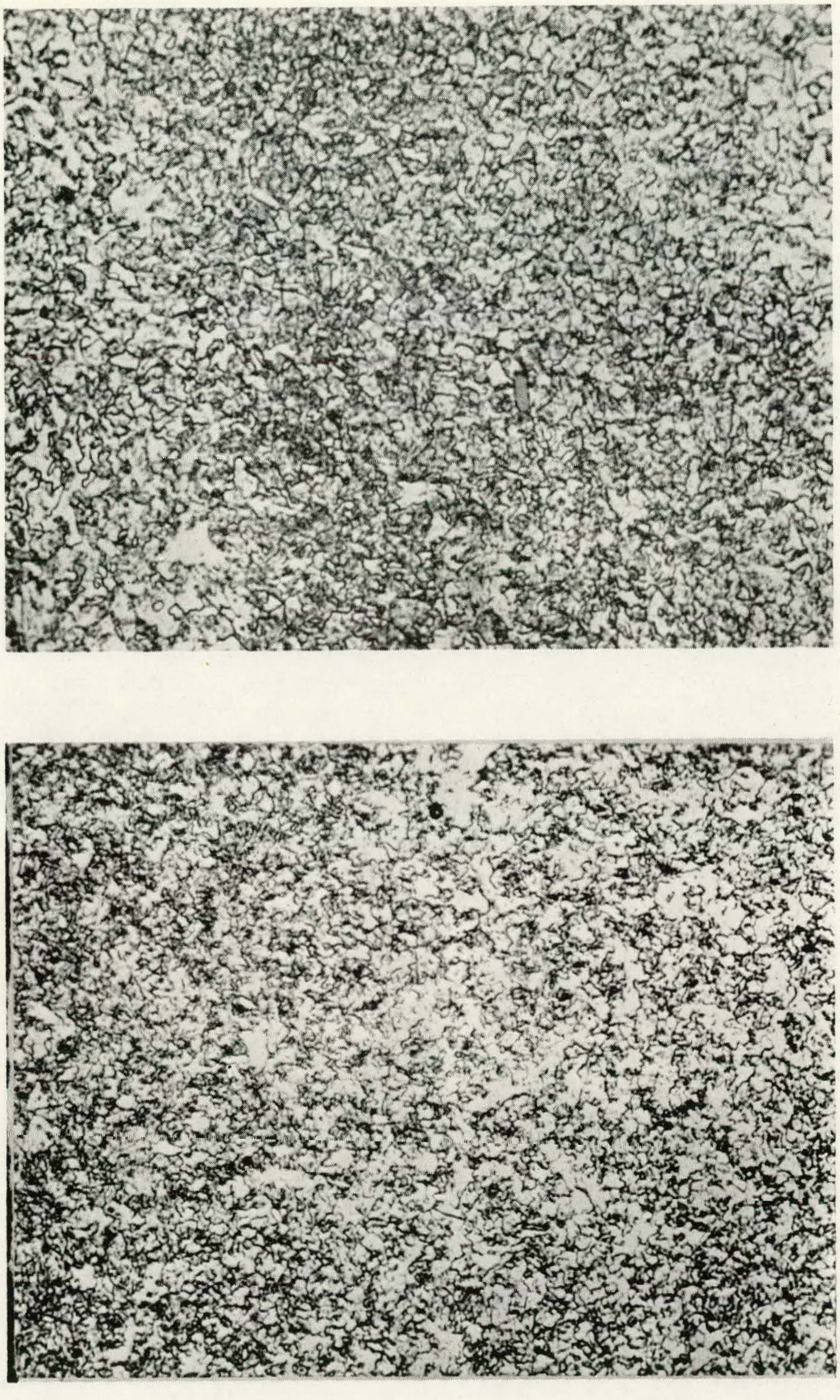

Figure 300.2 Two Representative Views - Heat Affected Zone - SA 533 Grade B Class I - 500X

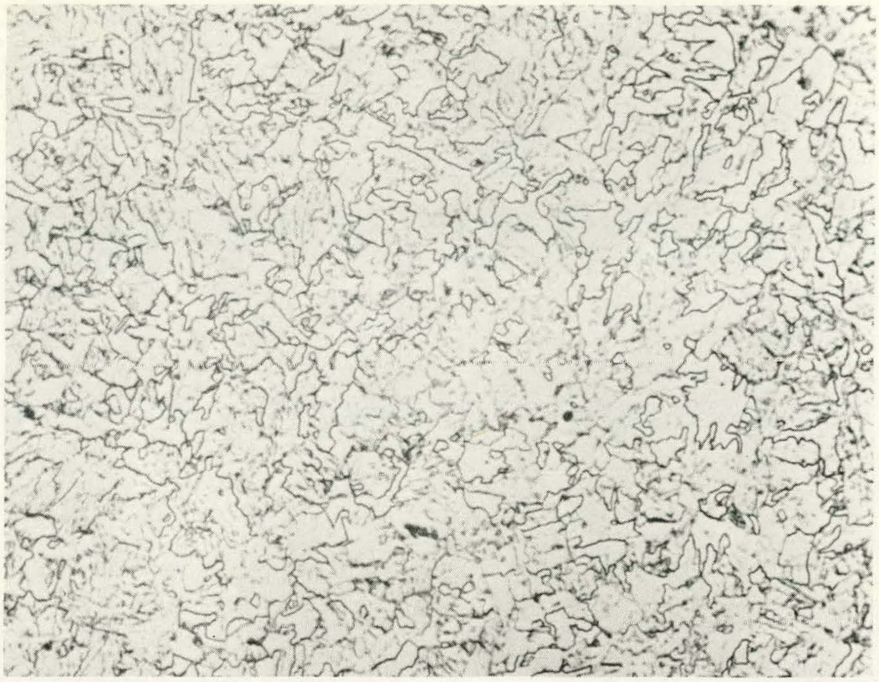

Figure 300.3 Two Representative Views - Weld Metal - SA 533 Grade B Class I - 500X

Table 300.5

Hardness Values of Weldment (SA533 Grade B Class I Steel)

Material	Hardness (R_B) (AVE)
Base	91
Heat Affected Zone	98
Weld	92