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TESTING THE SIX-INCH-THICK FLAWED TENSILE
SPECIMENS

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Sponsoring Program or Organization

HEAVY SECTION STEEL TECHNOLOGY PROGRAM

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

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Oak Ridge, Tennessee

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I. INTRODUCTION

The 15 million pound tensile test facility at Southwest Research Institute has been used to test a series of large tensile specimens for the Heavy Section Steel Technology (HSST) program. These specimens are A533 Grade B, Class 1, and are six inches thick, eighteen inches wide, four feet long and contain flaws. (The procedures used to create the flaws are discussed and pertinent data for ten tests at temperatures from 50°F to 220°F and requiring loads up to 7.5 million pounds for failure are presented.) Seven longitudinal specimens were tested at temperatures of 50°F, 75°F, 100°F (three each) and 220°F (two each). Three transverse specimens have been tested at 100°F, 130°F and 220°F.

This paper also discusses briefly the mechanics of testing the large notched tensile specimens.

II. THE TENSILE TEST FACILITY

The 15 million pound tensile test facility was designed primarily for testing 10' x 10' steel plate in brittle fracture. It has been modified to handle the HSST tensile specimen for loads up to 11 million pounds. A photograph of the test machine without attachments for the tensile specimen is presented as Figure 1. The levers are loaded with hydraulic cylinders having a 30-inch stroke and a 250,000 pound load capacity. The mechanical advantage of the levers is 7-1/2 to 1 giving the cross-head the 15 million pound capacity and a 4-inch movement. The tensile specimen grips are limited to 11 million pounds.

The fixtures used to adapt the facility to the tensile specimen are shown in Figure 2. One photograph shows the specimen being lowered into the "grip" plates and the second photograph shows the complete assembly. One may note that the specimen fits in the notched section of the grip plates and that the load is transmitted to the specimen in shear.

The test facility was calibrated using an unnotched tensile specimen. Fifteen strain gages were placed on the test section and the load was calculated using an area of 108 square inches and an elastic modulus of 30.5×10^6 psi. The elastic modulus was determined using a smaller specimen cut from the same plate as the large specimen, similarly instrumented and loaded in a Baldwin test machine. The area of both large and small specimens was carefully determined. The calibration of the large facility also proved that no bending moment is induced by the test machine.

FIGURE 1. THE SwRI 15 MILLION POUND TENSILE TEST FACILITY

FIGURE 2. ADAPTERS TO THE TENSILE TEST FACILITY
TO ACCOMMODATE THE HSST TENSILE SPECIMEN

III. DESIGN OF THE LARGE NOTCHED TENSILE SPECIMEN

A. Specimen Design

The 6" x 18" cross section of the test section and the notch configuration have been dictated by theoretical considerations while the "dog bone" shape of the tensile specimen was devised to deliver the load to the test section over the shortest possible length. The detailed dimensions of the specimen are shown in Figure 3.

B. Notch Design and Notch Sharpening

1. Criteria

A flaw from which fast fracture would initiate in a reactor pressure vessel would most likely be a propagating fatigue crack. An investigation was made to find an economical way to generate a fatigue crack or equivalent in the large tensile specimens which could also be used for the pressure vessels to be tested in the simulated service test phase of the HSST program. The basic shape of the experimental flaw was to be produced by machining and the flaw was to be sharpened with the procedure developed.

The first two specimens tested contained semielliptical notches machined using the EDM (electrical discharge machining) process with the notch in the second specimen slightly smaller than the notch in the first specimen. The remaining four specimens contained semi-circular flaws also machined using the EDM process. Notch dimensions are given in Figure 3.

MACHINED NOTCH DIMENSIONS

SPECIMEN	a	b	r	NOTCH SHAPE
1	2.375	6.598	—	SEMIELLIPTICAL
2	2.160	6.000	—	"
3-5, 7-10	2.000	8.000	5.000	SEMICIRCULAR
6	3.000	9.160	5.000	"

SECTION A-A

FIGURE 3. DIMENSIONS OF THE HSST 6-INCH-THICK FLAWED TENSILE SPECIMEN

2. Stress Corrosion

An attempt was made to develop a stress corrosion procedure to initiate sharp cracks at the root of each notch. A procedure involving maintaining a specimen at 250°F under a static tensile load and pouring $\text{NH}_4 \text{NO}_3$ into the notch was investigated; however, tests of compact K_{IC} specimens sharpened by the same procedure indicated that the static load required to generate the crack was too great, i. e., residual stresses at the tip of the crack at the temperature at which the crack was generated affected the load required to fail the specimen in the transition temperature range and lower.

3. Electron Beam Weld

It was found at Oak Ridge National Laboratory (ORNL) that cracks could be created in a small specimen by embrittling the notch root with an electron beam weld and then applying a static tensile load for a short period of time. The resulting crack would pop out of the brittle region and arrest in the base metal at a sufficiently low load. This procedure was abandoned only because a large electron beam welder was not conveniently available to ORNL for use on the large tensile specimens and intermediate test vessels. Present plans are to use this procedure on a series of one-sixth scale models.

4. Fatigue

In order to expedite the tensile tests the first two large specimens were tested at 220°F without sharpened notches as notch sharpness was not considered to be significant at this temperature.

(This proved to be the case.) The third and fourth specimens were sharpened by applying a three-point loading to the specimen for lack of a better method. The ends of the specimens rested on round bars set at a span of 42 inches while a load of 187.5 kips was applied at the center of the specimen, evenly distributed across the width on the unnotched surface. (A tensile stress was created on the notched surface.) Cracks initiated in the notch root after 15,000 cycles of loading and required a total of 35,000 cycles for the third specimen and 46,000 cycles for the fourth specimen to propagate the fatigue cracks to a sufficient depth.

The criterion that the notch sharpening procedure be applicable to the test vessels is not satisfied by the three-point loading method. Notches in the vessels could be sharpened by cycling internal pressure in the vessel but this would be very time consuming. Therefore, a method of sharpening the notch cavity with very high pressure (about 20,000 cycles of 15,000 psig were required) was developed at ORNL and notches in Specimens 5 through 10 were sharpened in this manner.

The fatigue cracks produced by pressurizing the notch cavity have proved to be more uniform in depth around the periphery of the notch than the cracks produced by bending the specimen. Also, fewer cycles are required to produce a deep fatigue crack using the pressure method. The fatigue cracks produced in specimens Number 4 and Number 5 are shown in Figure 4. The depth of the fatigue

Specimen No. 4 - Fatigue crack at the root of the notch was produced by bending the specimen

Specimen No. 5 - Fatigue crack at the root of the notch was produced by pressurizing the notch cavity

FIGURE 4. RESULTS OF TWO METHODS OF NOTCH SHARPENING USED ON THE LARGE TENSILE SPECIMEN

crack in specimen Number 5 is about 0.5 inches. The dimensions of the notches after sharpening with a fatigue crack are given in Table 1. One will note that the length, b , of the notch did not change significantly by either method.

TABLE 1. NOTCH DIMENSIONS BEFORE AND AFTER NOTCH SHARPENING

Specimen No.	Machined Notch Dimensions			Dimensions After Sharpening		Dimensions at Ultimate Load ¹	
	a	b	r	a	b	a	b
1	2.375	6.598	--	unsharpened		--	--
2	2.160	6.000	--	unsharpened		2.86	5.92 ²
3	2.000	8.000	5.000	2.05	8.37	2.05	8.37
4	2.000	8.000	5.000	2.05	8.20	3.45	8.02 ²
5	2.000	8.000	5.000	2.53	8.26	2.53	8.26
6	3.000	9.160	5.000	3.37	9.53	4.33	10.25
7	2.000	8.000	5.000	2.43	8.13	2.79	8.74
8	2.000	8.000	5.000	2.42	8.30	2.88	8.30
9	2.000	8.000	5.000	2.41	8.29	3.06	8.29
10	2.000	8.000	5.000	2.38	8.33	2.66	8.33

NOTES:

1. Measurements made after fracture
2. Lateral contraction from necking in the net section masked small amount of crack growth that occurred at the surface. Dimensions estimated by paint marking which was applied at ultimate load.

IV. TESTING THE LARGE NOTCHED TENSILE SPECIMENS

A. Instrumentation and Test Procedure

The first two specimens tested were instrumented with over 100 strain gages and the number of gages was reduced to about 50 on specimens 3 through 10. Six displacement gages were used on all but the first specimen. Acoustic emissions monitoring was performed on specimens 1, 2, 7, 8, 9 and 10. The results of these efforts are discussed in another paper. The acoustic emissions monitoring of the first two specimens was performed by Battelle Memorial Institute, Pacific Northwest Labs and the last four were monitored by Southwest Research Institute.

Strain gage and displacement data were recorded on a B&F Model 156, 100 channel data logger. This instrument will record on paper tape the channel number and strain, to the nearest microinch per inch, at a rate of 5 channels per second or to the nearest ten microinches per inch at a rate of 20 channels per second. Therefore, the actual recording of data required very little time and the greatest time spent was pressurizing the hydraulic jacks and examining data from key gages. Data was obtained in 100 kip increments above five million pounds and in 50 kip increments when the approximate failure load was approached.

The average test required two hours and thirty minutes once the test was started. Much time was consumed obtaining the required temperature or waiting for the temperature to drop when the specimen was overheated several degrees. One may see from Figure 5 that a con-

FIGURE 5. A SIDE-VIEW OF THE TENSILE SPECIMEN IN PLACE FOR TESTING

siderable amount of metal used to contain the specimen had to be heated or cooled in addition to the specimen.

Three thermocouples were used to monitor the temperature of the specimen. Two were located on the notched surface and one on the unnotched surface. All three thermocouples were on the longitudinal axis of the specimen, two inches from the plane of the notch.

B. Test Results

The discussion of test results will be limited to the nature of the fracture face, the total load and the total strain. A considerable amount of strain gage data were gathered during each test that one cannot dwell upon in a paper of this nature.

1. Longitudinal Specimens

Seven longitudinal specimens were tested at temperatures from 50°F to 220°F. Some of the pertinent data obtained from these tests is presented in Table 2 along with the results of small specimen tests which were performed in support of this program to provide answers to questions on size effect and the shape of the large tensile specimen. The elongation data presented in Table 2 were obtained from displacement gages attached to the full-size specimen with a 42-inch gage length. However, the grip, or thick section, of the specimen sees an insignificant amount of strain and the gage length was considered to be 24 inches. The same method was used on the model specimens as well.

TABLE 2. TENSILE TEST DATA FOR 6-INCH-THICK SPECIMENS AND MODEL TESTS

Specimen Number	Test Temp.	HSST Plate No.	Gage Length Inches	Width Inches	Thickness Inches	Gross Area in ²	Net Area	Elastic Limit Load Kips	Elastic Limit Stress - Ksi		Ultimate Load Kips	Ultimate Stress Ksi		Ave. Strain at Ultimate %	Ave. Strain at Fracture %
									Gross Section	Net Section		Gross Section	Net Section		
Longitudinal Specimens															
1	215°F	03	24	18	6	108	95.69	5720	54.0	59.8	7300	67.5	76.3	--	8.50
2	220°F	03	24	18	6	108	97.82	6000	55.5	61.2	7550	69.9	77.2	3.83	9.60
3	50°F	01	24	18	6	108	95.79	4400	40.7	46.0	5300	49.1	55.4	0.24	0.24
4	100°F	01	24	18	6	108	95.50	6000	55.5	62.8	7500	69.4	78.5	4.10	7.90
5	75°F	01	24	18	6	108	92.33	5500	50.9	59.7	5900	54.6	63.9	0.35	0.35
6	100°F	01	24	18	6	108	81.97	4000	37.0	48.8	4700	43.5	57.4	0.48	0.48
7	100°F	03	24	18	6	108	92.43	6500	60.2	70.4	7050	65.2	76.2	0.88	0.88
1/6 Model 2	210°F	03	4	3	1	3	2.66	175	58.4	65.7	230.6	78.6	88.9	5.61	10.5
1/6 Model 3	50°F	03	4	3	1	3	2.42	176	58.6	72.7	223.0	74.3	92.2	5.75	10.9
1/12 Model 03ED -2003	75°F	03	2	1.5	.5	0.75	0.68	45	60.0	66.3	65.0	86.6	95.7	7.5	--
1/12 Model	75°F	03	2	1.5	.5	0.75	Unnotched	49.0	65.4	--	64.8	86.4	--	10.2	38.9
1/12 Model	200°F	03	2	1.5	.5	0.75	Unnotched	47.5	63.0	--	63.4	84.0	--	10.0	32.4
Standard .505	75°F	03	2	0.505	--	0.20	--	13.5	67.5	--	17.3	86.6	--	11.5	31.5
Standard .505	200°F	03	2	0.505	--	0.20	--	12.6	63.0	--	16.5	82.8	--	10.2	26.0
1/48 Model 03ED -2005	75°F	03	1	0.370	--	0.0451	0.0408	2.900	64.3	71.2	4.140	91.8	101.5	--	13.5
1/96 Model 03ED -2004	75°F	03	1	0.176	--	0.0118	0.0107	0.700	58.2	65.4	0.992	84.1	92.6	--	13.5
Transverse Specimens															
8	100°F	03	24	18	6	108	92.55	6400	59.4	69.4	6800	63.0	73.5	0.74	0.74
9	220°F	03	24	18	6	108	93.30	5000	46.4	54.1	6675	61.8	71.6	2.00	3.60
10	130°F	03	24	18	6	108	93.15	6200	57.4	66.5	6650	61.6	71.4	1.19	2.69

The net section at ultimate load was determined in a crude but fairly effective manner. If the specimen failed in a brittle manner or failed while the load-strain curve was positive, then crack growth, if any, was easily noted by the appearance of the fracture and the size of the crack at fracture could be measured. If the load-strain curve began to flatten or a considerable drop in load occurred when pumping was stopped, then the project engineer would spray the notch with paint. A paint of a different color would be applied if additional loading proved that ultimate load had not been reached. After failure, the size of the notch was determined by the paint marking. The paint markings on Specimen 4 may be easily seen in Figure 4.

Stress-strain curves for the various tests are presented in Figure 6. Stress was computed by the conventional method of load divided by the gross section area. Strain was computed by dividing the displacement by the length of the test section as just described.

The data in Table 2 and Figure 6 show both the marked reduction in strain with increase in size and the loss of ductility in the full-size specimen at 100°F.

Specimen Number 6 yielded at a lower load than the other specimens because the notch size was considerably greater. However, there is no explanation at this time for the lower yield strength of Specimens 3 and 5.

The fracture surfaces of Specimens 2 through 6 are shown in Figure 7. Specimen 4 and Specimen 6 were both tested at 100°F but

FIGURE 6. STRESS-STRAIN CURVES FOR THE LONGITUDINAL 6-INCH-THICK
FLAWED TENSILE SPECIMENS

FIGURE 7. FRACTURE SURFACES OF THE LONGITUDINAL 6-INCH-THICK
FLAWED TENSILE SPECIMENS

behaved quite differently. The larger notch in Specimen 6 was believed by some to cause the flat fracture but this explanation was hard for others to accept. Specimen Number 7 was tested at 100°F to settle the debate and the fracture surface is shown in Figure 8. The ductile behavior of Specimen Number 4 is still unexplained and a study of the grain structures of all the specimens is being performed to see if a significant variation exists. It is noteworthy that Specimens 4 and 6 were machined from HSST plate 01 and were only a few feet apart. Specimen 7 was machined from HSST plate 03.

2. Transverse Specimens

Three transverse specimens were cut from HSST plate 03 and tested at 100°F, 130°F and 220°F. The data for these tests are presented in Table 2 and stress-strain curves are presented in Figure 9. One may note again the reduction of ductility with temperature. As expected, the yield strength and ultimate strength of the transverse specimens is less than the values for longitudinal specimens tested at the same temperature.

The fracture surface of the three transverse specimens is shown in Figure 10. The large shear lips on the 220°F specimen are not quite as predominant as those on the longitudinal specimen and the 130°F specimen resembles Specimen Number 4 tested at 100°F. The appearance of the fracture surface of Specimens 7 and 8, both tested at 100°F are almost identical.

FIGURE 8. THE FRACTURE SURFACE OF LONGITUDINAL SPECIMEN NUMBER 7
AFTER TESTING AT 100°F

FIGURE 9. STRESS-STRAIN CURVES FOR THE TRANSVERSE 6-INCH-THICK
FLAWED TENSILE SPECIMENS COMPARED WITH CURVES
FOR LONGITUDINAL SPECIMENS

FIGURE 10. FRACTURE SURFACES OF THE THREE TRANSVERSE 6-INCH-THICK
FLAWED TENSILE SPECIMENS

V. CONCLUSIONS

One may note several expected trends in the data presented in this paper. (1) There is a marked reduction in ductility with size, (2) there is a significant temperature effect on ductility and (3) the performance of the transverse specimens is inferior to the performance of the longitudinal specimens.

The degree of effect of size, temperature and rolling direction is somewhat masked by the variation in material properties within the HSST plates. It is difficult to evaluate the difference in performance between Specimen Number 2 and Specimen Number 9, both tested at 220°F, when the yield strength of Specimen 9 was significantly lower than the other two transverse specimens. Did the metallurgical factors affecting yield strength also affect ultimate strength and elongation? There is also a possibility that the difference in performance between Specimen Number 4 and Specimen Number 6 may be explained by material property variation and this possibility is being investigated.

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