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APPENDIX A

THE PROPERTIES AND MICROSTRUCTURE OF SPRAY-QUENCHED THICK-SECTION STEELS

by

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The Properties and Microstructure of Spray-Quenched Thick-Section Steels

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ABSTRACT. With the increasing use of thick-section quenched and tempered steels for nuclear and chemical reactors, there is a definite need for information on the properties of some of the newer low-alloy high-strength steels when given such thick-section heat treatment. Of particular interest are yield and tensile strengths attainable, the notch toughness to be expected, the plastic fatigue strengths available and the kinds of microstructure that appear to be characteristic of these thicknesses.

In the program reported here, four quenched and tempered heavy-section steels—A212 Grade B, A533 Grade B, A542 and A543—were studied in the simulated 6-in. thick and 12-in. thick quenched, tempered and stress-relieved condition. Specimens taken from these simulated heavy sections were evaluated to provide a characterization of the properties and structure of heavy-section, heat-treated, low-alloy steels.

The results show that increasing the section size from 6 to 12 in. produced no important changes in strength, notch toughness or fatigue resistance in these steels in the quenched, tempered and stress-relieved condition. When comparing 1-in. thick plate with the heavy sections, strength decreased only modestly while notch toughness decreased substantially. Because of their initial good toughness, however, the alloy steels still exhibited transition temperatures below −10° F. The fatigue and elevated temperature properties of the steels were similar to those found in thinner sections of equivalent tensile strength. The results of the microstructure study confirmed the mechanical property tests in that little difference in microstructure was observed between the 6-in. and 12-in. conditions.

Introduction

In view of the recent trend to larger pressure vessels for the higher operating pressures and temperatures of the nuclear power and chemical industries, considerable effort has been expended in the development of new materials and heat treatment procedures for large heavy-walled reactor vessels. In the past, these vessels have been of carbon or low-alloy steels and the heat treatment most commonly used has been normalizing and stress relieving. Current industrial practice is moving away from these more established materials and procedures because of both economics and safety. As the size and requirements of the newer vessels have increased, so has the wall thickness required to meet these demands with the conventional materials at hand. With this increase in wall thickness, both strength and toughness are decreased and fabrication costs are increased. It is to be expected, then, that both new materials and heat treatments should be developed for such heavy-walled vessel applications. In practice, these two developments are complementary. The new materials available for these vessels are of significantly greater hardenability than those previously used. This makes quenching and tempering treatments more desirable than with conventional steels because in heavy sections where accelerated cooling can do little to improve, for example, a carbon steel, the higher alloy steels respond to produce microstructures representing improved strength and toughness. The use of such steels has already been shown to be of advantage in section sizes up to 4 in. both from the standpoint of strength and notch toughness.[1-3] In section sizes over 4 in., some industrial experience has already been obtained. However, a program surveying some of the newer and more promising materials in a systematic manner had not been done. Therefore, the program described in this paper was undertaken to provide such a survey of four of the newer heavy-walled pressure-vessel materials.

In this program, four steels—A212 Grade B (in the quenched and tempered condition), A533 Grade B, A542 and A543—all of which are of potential use in heavy-walled vessels, were compared in heavy-section sizes. It was believed that four properties are of interest in a study of the response of low-alloy steels to accelerated cooling in heavy sections. The first of these is yield and tensile strength at room and elevated temperatures. The advantage of the steels must be realized by practical increases in both yield and tensile strength in the center thicknesses of heavy-section plates if they are to be attractive. The extent to which such increases can be maintained as section size increases becomes an important question.

A second area of importance, indeed a critical one from the safety standpoint, is the kind of

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toughness properties that can be expected as a result of quenching and tempering of a heavy-section low-alloy steel plate. It has been shown that a favorable balance of both strength and toughness can be maintained in thinner-section low-alloy plates; to what extent can this be maintained as section sizes increase? Because of the importance of this area, the notch toughness tests conducted in this program were supplemented by plane-strain fracture toughness evaluations on A533B, A542, and A543 by Westinghouse, and notch tensile tests were conducted on the A212B and A533B by Syracuse University. Heat-treated material from this program was furnished to them for this purpose. The results of these tests are reported separately in this *Bulletin*.

A third area of interest in this study is the fatigue resistance of the steels in the 1000 to 100,000 cycle failure range. While few failures in pressure vessels have been directly attributed to fatigue, the role of fatigue in initiating cracks that lead to failures cannot be ignored in vessel design.

The fourth area of interest in the study of the steels is the influence of the cooling treatments on the microstructures that are produced by the quenching and tempering of heavy sections. Microstructure may appear to be of secondary interest when mechanical property data are known. Since properties of alloy plates are strongly influenced by microstructure, the evaluation of microstructures produced by the heat treatment of heavy-section plate can give valuable clues to the combinations of steels and treatments that are required in order to produce useful properties as section size is increased.

The study reported in this paper must be considered limited in scope in that it includes data from single heats of only four typical steels. However, the specimens were cut from both the quarter point and center thickness locations of commercially-produced heavy plates and thus the investigation provides coordinated data on the characteristics of commercially-produced low-alloy high-strength steels when heat treated for heavy-section service. It should therefore serve as a useful guide for the further development of suitable steels for heavy-section applications.

Materials

Four steels with actual or potential use in heavy-walled pressure vessels were included in the experimental study. These were A212 Grade B, A533 Grade B, A542, and A543. The chemical compositions of these steels are listed in Table 1. The four steels were obtained as heavy thickness production plates, as indicated. Both quarter- and center-section chemical analyses were done on these production plates and are listed in Table 1. Because of the thickness of these plates, it was possible to perform duplicate mechanical property tests on both center- and quarter-thickness positions to reveal any differences in the behavior of materials from these locations. Therefore, there were essentially eight sources of material for testing, i.e., center- and quarter-thickness locations in four different steels. The as-received properties of the plates are listed in Table 2.

Heat Treatment

In order to produce data useful in evaluating the suitability of the four quenched and tempered steels to heavy-section service, it was necessary to heat treat the plates to reproduce heavy-section quenched and tempered microstructures. It can be seen from Table 1 that the plates as-received were from 6¼ to 8 in. in thickness. Since this initial thickness insured that the plates were representative of heavy sections in chemistry and rolling practice it was decided to cut ¾-in. thick test plates from the center thickness and quarter thickness positions of the original plates and to heat treat these test plates in such a manner as to match the cooling rate from austenitizing that would be characteristic of two typical plate thicknesses—6 in. and 12 in. In order to select cooling rates appropriate for these thicknesses, a large body of both calculated and experimental data on cooling rates during the quenching of heavy-section plates was obtained and studied.[4–6] These data are summarized in Fig. 1. Since relatively few of the experimental cooling rate data available were obtained on large-size heavy-section plates, and dip as well as spray quenching may be

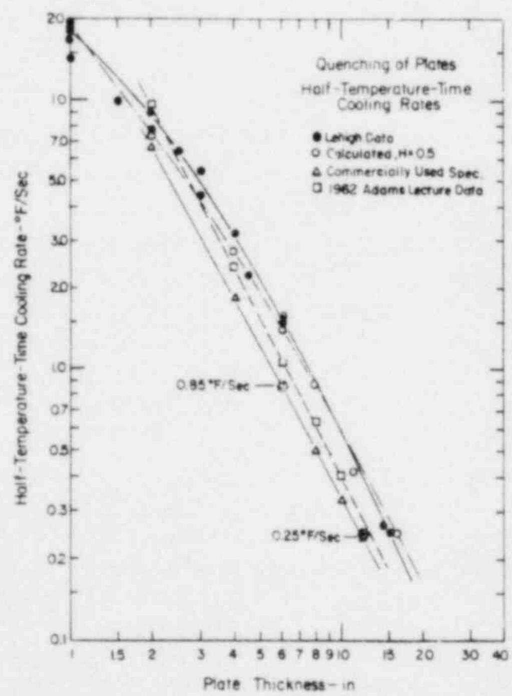

Fig. 1—Cooling rates in plates quenched from austenitizing

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Table 1—Compositions and Heat-Treatment Temperatures for the Heavy-Section Steels

Steel	*C*	*Mn*	*P*	*S*	*Si*	*Ni*	*Cr*	*Mo*	*Cu*	*Al*	*As received thickness, in.*	*Treatment temperatures*
A212B												
Ladle	.25	.70	.012	.037	.23	.15	.07	...	.16	.037	6¼	Austenitizing 1650° F 1 hr
Quarter	.27	.72	.007	.025	.24	.12	.08	<.01	.15	.020		Tempering 1200° F 8 hr
Center	.28	.73	.007	.025	.24	.13	.08	<.01	.16	.019		Stress relief 1100° F 24 hr
A533B												
Ladle	.20	1.28	.019	.030	.21	.53	.15	.52	.27	.031	7¼	Austenitizing 1650° F 1 hr
Quarter	.19	1.26	.024	.028	.25	.52	.13	.52	.30	.022		Tempering 1200° F 8 hr
Center	.18	1.25	.024	.025	.24	.52	.13	.51	.29	.025		Stress relief 1100° F 24 hr
A543												
Ladle	.17	.32	.013	.017	.28	3.65	1.86	.48	...	...	8	Austenitizing 1575° F 1 hr
Quarter	.16	.34	.014	.020	.27	3.60	1.89	.53	.07	.004		Tempering 1200° F 8 hr
Center	.15	.32	.013	.020	.28	3.55	1.85	.50	.06	<.004		Stress relief 1100° F 24 hr
A542												
Ladle	.14	.46	.010	.020	.28	.25	2.35	.99	.19	.024	7½	Austenitizing 1750° F 1 hr
Quarter	.15	.46	.013	.024	.31	.21	2.32	1.14	.23	.006		Tempering 1200° F 8 hr
Center	.15	.46	.013	.027	.30	.22	2.34	1.11	.22	.006		Stress relief 1100° F 24 hr

Table 2—As-Received Mechanical Properties[a] of the Heavy-Section Steels

Material	*Heat treatment*	*Yield str. ksi*	*Tensile str. ksi*	*% El. (2 in.)*	*% R of A*	*Charpy V-notch energy, ft-lb*
A212B	Aust. 1650° F, water quench, tempered 1225° F, 6 hr, stress relieved 1125° F, 20 hr, furnace cool	41.7	74.2	33	...	at 10° F—41, 40, 40
A533B	Aust. 1575° F, water quench, tempered 1225° F, 4 hr, stress relieved 1125° F, 30 hr, furnace cool	69.4	89.9	27	66.2	at 10° F—37, 35, 38
A542	Aust. 1700° F, water quench, tempered 1175° F, 7 hr, air cool	94.7	111.4	19	60.5	at 10° F—23, 30, 24
A543	Double quenched and tempered	96.1	119.1	16.8	44.5	at 10° F—60, 60, 70, 74 at −120° F—35, 36, 38, 34

[a] Longitudinal properties, quarter thickness.

employed for accelerated cooling of heavy plates, it was thought wise to select generally conservative values for cooling rates attainable from quenching. The cooling rates selected to represent the 6-in. and 12-in. thicknesses were 0.85° F/sec and 0.25° F/sec, respectively, and are indicated on Fig. 1. These two cooling rates were then reproduced in the ¾-in. thick test plates by simulated cooling treatments.

The material received for the program was in the form of plates approximately 10½ in. wide by 24 in. long by the plate thickness (6–8 in.). These were cut into two sections approximately 10½ in. by 18 in. by the thickness and 10½ in. by 6 in. by the thickness. The plates were then sectioned along the thickness dimension and ¾-in. thick slices were removed at both quarter-thickness positions and two ¾-in. thick slices were removed on either side of the center-thickness position. These plates were then heat treated as indicated in Table 1. A system of aluminum foil baffles was used to retard the cooling of the plates from austenitizing to the degree necessary to produce the desired cooling rates. This system varied somewhat with the size of the test plate, but basically consisted of cooling the smaller plates in an aluminum foil lined box of dimensions 12 in. × 16 in. × 24 in. with internal baffles adjusted to obtain the desired cooling rate. The cooling rates were obtained for the larger plates by using aluminum foil baffles set at experimentally determined distances from a free hanging plate. Thermocouples were attached to the plates before austenitizing to monitor the cooling rates during the "quenching" cycle. Since some variation in cooling rates did occur, only plates with cooling rates within 0.05° F/sec of that selected were used in the experimental study. To reduce edge effects, approximately 1½ in. was removed from the test plate edges before specimens were machined.

The tempering treatment given to the plates (Table 1) was designed to simulate the typical treatment given to a heavy-section plate. Since heavy-section plates often receive one or more long stress-relief treatments during fabrication operations, it was also felt desirable to include a heavy-section stress-relief treatment, followed by a cooling rate from stress-relief as specified by the ASME Boiler and Pressure Vessel Code for a 12-in. thick plate. The test plates were accordingly stress-relieved for 24 hr at 1100° F followed by cooling at a rate of approximately 40° F per hr to 600° F. In order to determine if this slow cooling treatment from stress-relief was deleterious to toughness, some plates were cooled at a rate of 240° F per hour (approximating the air cooling of a heavy-section plate) to study the effect of this cooling treatment.

Testing Schedule

The schedule of tests for each of the four steels at quarter- and center-thickness and at two cooling rates (6-in. and 12-in. thickness simulations) included room- and elevated-temperature tension tests, Charpy V-notch and drop weight tests, and cantilever bending fatigue tests. In addition to these mechanical property tests, photomicrographs were prepared of each of the four steels in the simulated 6-in. and 12-in. conditions at various stages in their heat treatment.

The tension tests were performed in air on longitudinal 0.252-in. diam tension test specimens with 1.0 in. gage length. Tests were performed at room temperature and at elevated temperatures up to 1100° F. A strain rate of 0.05 in./minute was used for all tests. Center- and quarter-thickness specimens of all four steels at both cooling rates were tested at room temperature and 200° F. Center-thickness specimens of both cooling rates were tested at 400° F, 800° F, and 1000° F, while quarter-thickness specimens of both cooling rates were tested at 600° F, 900° F and 1100° F. The temperature during the elevated temperature tests was controlled to within ±5° F. At least two specimens were tested for each condition at each temperature and the results averaged.

The impact tests were standard Charpy V-notch and standard specimen type P-2 drop-weight tests.[7] The Charpy test data were evaluated for the 15 ft-lb energy transition temperature, the 15 mil expansion transition temperature, the 50% shear fracture appearance transition temperature and the upper shelf energy value. The drop-weight test was evaluated for the nil ductility temperature. All Charpy impact specimens were parallel to the plate rolling direction and were notched transverse to the plate surface. Each Charpy series consisted of from 15–30 specimens.

The low-cycle fatigue tests consisted of constant deflection bending tests (R = −1) on standard Lehigh cantilever-bend fatigue specimens. This specimen is 18 in. long by 2½ in. wide by ½ in. in thickness in the test section. The range of testing included total strain ranges producing failures between 1000 and 200,000 cycles. Both the total strain ranges for the first visible cracking of the specimen and for complete separation of the specimen were recorded. Because of the size of these specimens, it was necessary to run transverse rather than longitudinal specimens in the fatigue portion of the study.

Results and Discussion

With regard to the data obtained in this study, it is important to keep in mind that the program is made up of single-heat data only for the four steels involved and provides no statistical information. On the other hand, the heats used in the study are commercially-produced heavy-section steels and therefore do represent material taken from heats of acceptable commercial quality. Moreover, the real value of the program lies not so much in the specific levels of strength and toughness obtained, as in the comparative behavior of the various steels and in the general response of the steels to heat treatment in heavy sections.

Tensile Properties

The results of the room- and elevated-temperature tension tests for the four steels may be found in Table 3 and in Figs. 2 to 9. For three of the four steels tested the difference in cooling rate between the 0.85° F/sec (6-in.) condition and the 0.25° F/sec (12-in.) condition did not produce any appreciable difference in mechanical properties. For A212B, A542 and A543, the largest difference in either yield or tensile strength observed between the two cooling rates for a given position was about 3% increase in strength for the 6-in. material while for a majority of the cases this difference was even smaller. For A533 Grade B, however, there was a difference of about 10% in yield strength and 5% in tensile strength between the two conditions, the 6-in. material once again being the stronger.

In terms of general strength level, the A212 Grade B is by far the weakest of the four steels, with a yield strength less than half that of A542 or A543, and a tensile strength about 65% that of A542 or A543. The A533 Grade B lies approximately in the mid-range between these two values. It should be noted that when given either the 6-in. or 12-in. treatment, the A533 Grade B, A542 and A543 all meet Class 1 specifications for these grades while the A212 Grade B would be below minimum specifications in the quarter-thickness material for either thickness.

In general, there was but little difference in strength properties between the two plate positions, reflecting the general uniformity of compositions shown in the chemical analysis of Table 1. For two steels, A533 Grade B and A542, the mid-thickness specimens were somewhat stronger, while for the other two, A212 Grade B and A543, the quarter-thickness specimens were stronger. These differences were no more than about 5% in yield strength and 3% in tensile strength for any of the steels. The only apparent segregation of alloy elements or carbon evident in Table 1 occurred in A543 where the quarter-section chemistry is richer in nickel, chromium and molybdenum.

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Table 3—Room- and Elevated-Temperature Tensile Properties of the Heavy-Section Steels

Steel and condition	*0.2% offset yield point-ksi*	*Ultimate tensile strength-ksi*	*% elongation in 1 in.*	*% reduction of area*
		Room Temperature		
A212B				
6 in. Quarter[a]	39.6	67.6	40.5	64.9
6 in. Center	42.2	70.8	36.0	62.9
12 in. Quarter[b]	40.1	68.3	38.0	64.1
12 in. Center	42.6	71.6	35.5	60.7
		200° F		
6 in. Quarter	42.4	70.0	30.0	65.1
6 in. Center	43.7	71.8	29.0	64.7
12 in. Quarter	40.7	69.2	28.0	66.9
12 in. Center	41.7	70.7	29.0	64.8
		400° F		
6 in. Center	30.9	64.1	29.5	63.6
12 in. Center	30.5	60.9	33.0	64.5
		600° F		
6 in. Quarter	23.3	63.6	33.5	61.0
12 in. Quarter	24.4	66.6	24.0	62.5
		800° F		
6 in. Center	23.4	53.5	35.5	71.6
12 in. Center	21.7	49.0	45.0	78.2
		900° F		
6 in. Quarter	20.5	39.5	41.0	83.2
12 in. Quarter	21.0	40.8	38.0	79.9
		1000° F		
6 in. Center	18.6	31.7	39.0	80.9
12 in. Center	18.6	30.8	43.0	85.0
		1100° F		
6 in. Quarter	16.4	25.1	36.0	84.5
12 in. Quarter	16.3	25.9	37.0	82.5
		Room Temperature		
A533B (Class I)				
6 in. Quarter	70.0	88.7	28.0	69.5
6 in. Center	68.2	85.9	27.0	71.2
12 in. Quarter	64.1	84.6	29.0	68.8
12 in. Center	59.0	80.6	34.0	70.1
		200° F		
6 in. Quarter	64.8	82.5	25.0	69.3
6 in. Center	63.4	79.8	21.0	69.7
12 in. Quarter	56.7	77.5	28.0	68.0
12 in. Center	49.9	70.0	29.0	70.6
		400° F		
6 in. Center	60.4	80.7	22.5	...
12 in. Center	45.8	68.4	23.5	66.4
		600° F		
6 in. Quarter	58.1	83.6	21.0	60.0
12 in. Quarter	48.5	78.9	23.0	58.0
		800° F		
6 in. Center	56.7	78.0	20.0	68.9
12 in. Center	40.4	71.1	26.5	66.3
		900° F		
6 in. Quarter	51.7	64.6	22.0	73.8
12 in. Quarter	41.4	58.4	28.0	74.9
		1000° F		
6 in. Center	47.5	54.8	...	80.1
12 in. Center	34.4	47.7	...	79.4
		1100° F		
6 in. Quarter	44.2	45.5	26.0	81.4
12 in. Quarter	36.1	39.8	38.0	82.6

Steel and condition	*0.2% offset yield point-ksi*	*Ultimate tensile strength-ksi*	*% elongation in 1 in.*	*% reduction of area*
		Room Temperature		
A542 (Class I)				
6 in. Quarter	94.2	111.4	20.0	68.6
6 in. Center	94.2	112.2	21.0	70.4
12 in. Quarter	92.9	110.5	21.0	72.4
12 in. Center	93.7	111.4	16.0	63.2
		200° F		
6 in. Quarter	101.5	113.4	20.0	72.1
6 in. Center	100.1	112.0	19.0	71.7
12 in. Quarter	98.8	112.3	15.0	62.[illegible]
12 in. Center	98.3	111.6	15.0	66.9
		400° F		
6 in. Center	95.2	111.5	13.0	62.5
12 in. Center	91.2	111.1	14.0	61.6
		600° F		
6 in. Quarter	79.4	98.3	14.0	60.0
12 in. Quarter	74.3	92.3	14.0	62.6
		800° F		
6 in. Center	82.7	96.2	16.0	64.8
12 in. Center	83.1	88.6	15.0	62.8
		900° F		
6 in. Quarter	75.0	82.4	17.0	64.5
12 in. Quarter	71.1	79.4	16.5	64.6
		1000° F		
6 in. Center	70.0	74.7	22.0	77.3
12 in. Center	70.5	75.1	...	65.4
		1100° F		
6 in. Quarter	58.7	63.3	21.0	75.1
12 in. Quarter	58.4	60.7	19.0	75.8
		Room Temperature		
A543 (Class I)				
6 in. Quarter	86.5	106.4	25.0	71.0
6 in. Center	86.3	103.4	28.0	68.9
12 in. Quarter	86.3	103.2	25.0	72.6
12 in. Center	84.0	101.2	27.0	69.5
		200° F		
6 in. Quarter	83.0	99.5	21.5	71.1
6 in. Center	85.0	101.5	23.0	70.8
12 in. Quarter	75.4	91.0	21.0	71.8
		400° F		
6 in. Center	75.9	93.5	21.0	73.3
12 in. Center	71.6	87.4	19.5	68.7
		600° F		
6 in. Quarter	72.3	89.5	20.0	67.5
12 in. Quarter	72.5	92.0	20.0	66.8
		800° F		
6 in. Center	68.1	92.3	20.0	68.8
12 in. Center	70.4	83.5	20.0	68.4
		900° F		
6 in. Quarter	62.6	72.2	25.0	77.3
12 in. Quarter	64.1	72.7	24.0	78.7
		1000° F		
6 in. Center	57.0	62.0	32.5	84.2
12 in. Center	57.3	60.7	21.0	83.8
		1100° F		
6 in. Quarter	48.2	52.8	27.0	87.6
12 in. Quarter	47.0	49.5	...	87.7

[a] Cooling rate 0.85° F/sec, quarter thickness.
[b] Cooling rate 0.25° F/sec, quarter thickness.

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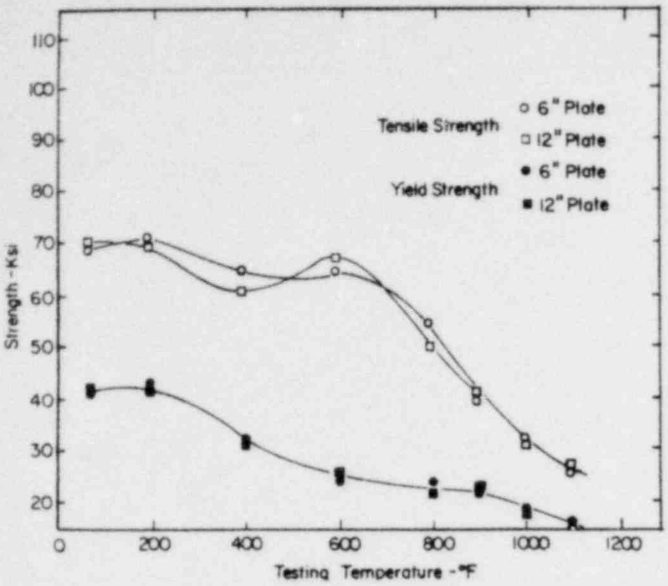

Fig. 2—The influence of temperature on the yield and tensile strength of quenched and tempered A212B

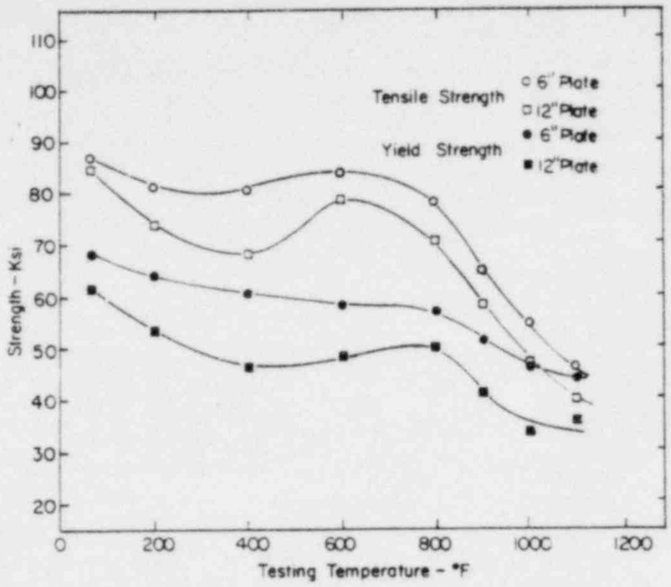

Fig. 4—The influence of temperature on the yield and tensile strength of A533B

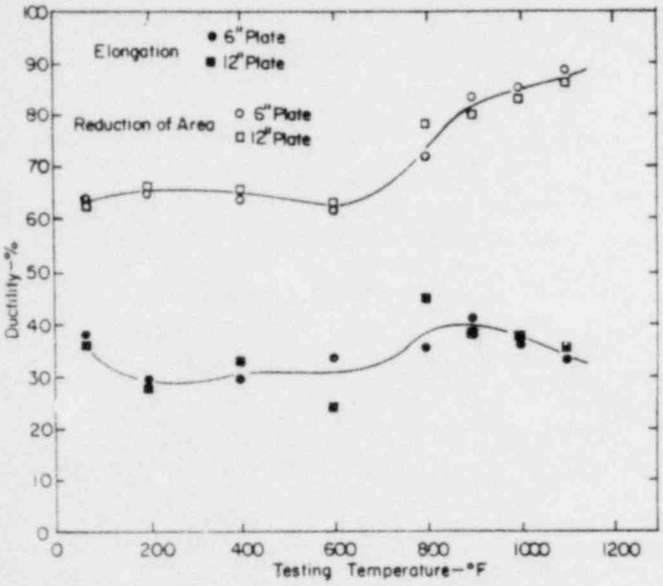

Fig. 3—The influence of temperature on the elongation and reduction of area of quenched and tempered A212B

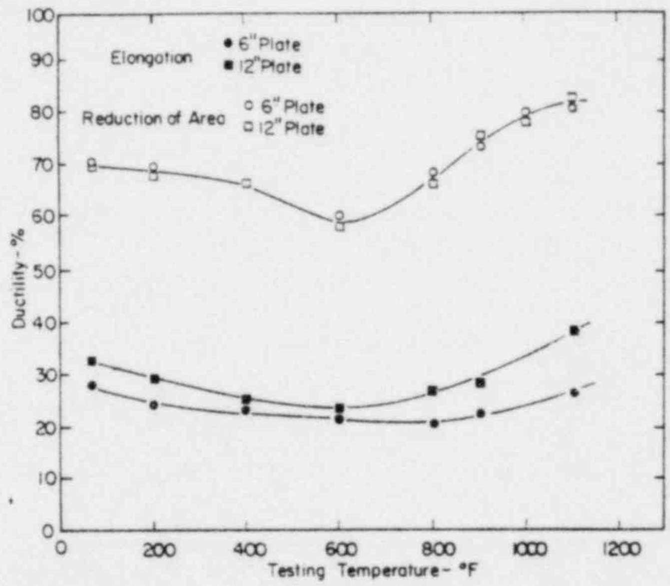

Fig. 5—The influence of temperature on the elongation and reduction of area of A533B

The room-temperature tensile ductilities of the four steels reflect, inversely, the tensile properties of the steels. Those materials and conditions with the lowest strength generally had the highest tensile ductility. The variations in ductility in the same steel with different conditions of treatment were small compared to those between steels. The dutility of the A212 Grade B was almost twice that of the A542 while A533 Grade B and A543 were intermediate.

The elevated-temperature tensile properties of the steels, found in Figs. 2 to 9, show that all of the steels tend to have aging reactions between room temperature and 800° F that cause their tensile strength curves to remain relatively high up to 800° F. For two materials, A212 and A533, the loss in tensile strength is only about 5% at 600° F compared to room temperature. The loss in yield strength at this temperature is about 40% for the A212 Grade B and about 20% for A533 Grade B. For A542 and A543, the tensile strength loss at 600° F is somewhat greater, about 15%, but the initial room temperature strength of these steels is high enough to more than offset the increased loss. The loss in yield strength of A542 and A543 at 600° F is also about 15%. Above 800° F the yield and tensile strengths of all of the steels appear to decrease sharply to values at 1100° F that are approximately 50% of the room temperature values. These eight figures (Figs. 2–9) include data from both center- and quarter-thickness specimens (as may be seen from Table 3) and both cooling rates. No apparent trends due to section position appeared in the curves and the

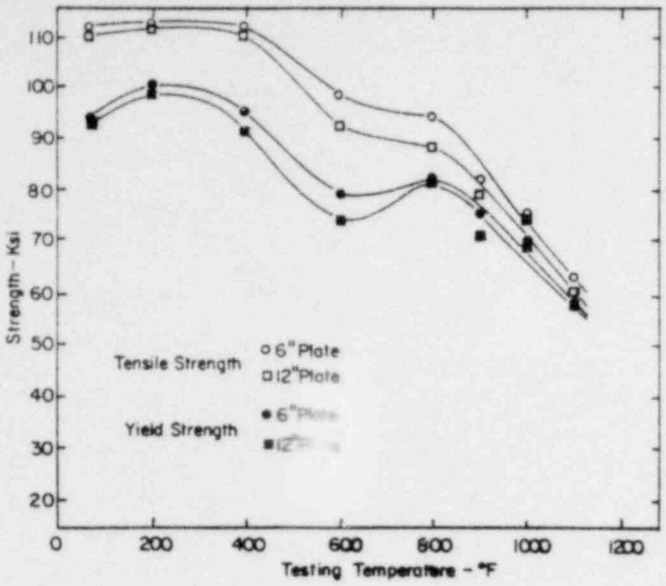

Fig. 6—This influence of temperature on the yield and tensile strength of A542

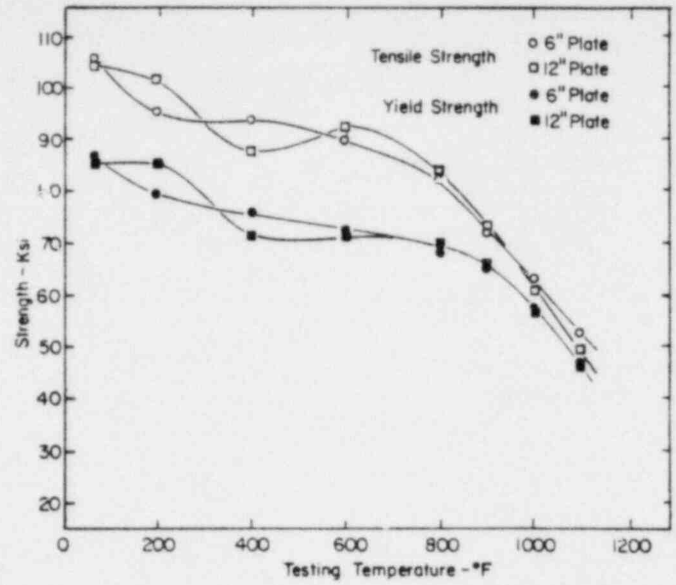

Fig. 8—The in luence of temperature on the yield and tensile strength of A543

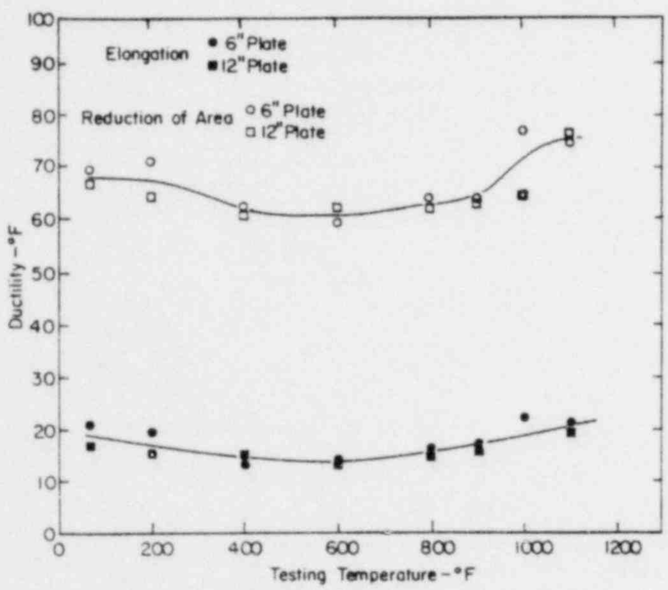

Fig. 7—The influence of temperature on the elongation and reduction of area of A542

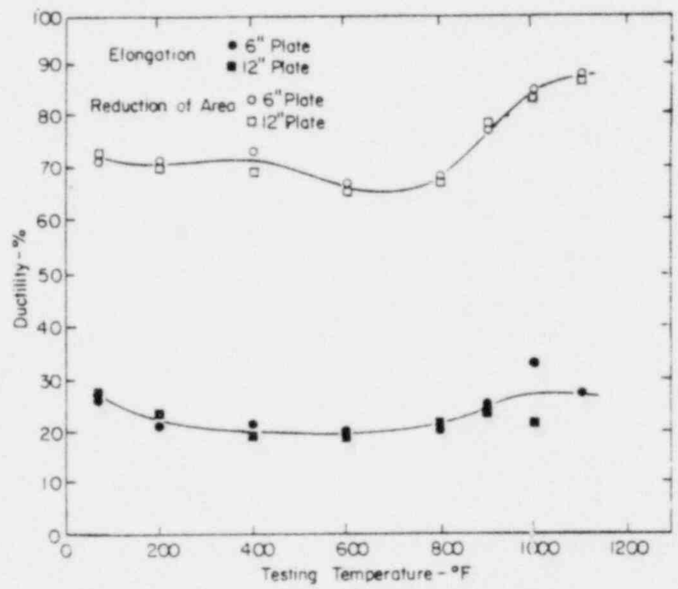

Fig. 9—The influence of temperature on the elongation and reduction of area of A543

points are plotted without differentiating them. Some differences due to cooling rate are apparent. For A533 Grade B, and to a lesser extent A542, the differences in strengths observed for the two cooling rates are more pronounced at elevated temperatures. In these two cases the faster cooled (6-in. thick) plate holds some strength advantage. For the A543 and to a lesser extent A212, the aging characteristics of the two different cooling conditions are somewhat different but neither condition holds a distinct advantage.

The elevated-temperature ductilities continue to reflect inversely the trends observed in the strength curves. The ductilities generally continue to remain ranked in the same order as at room temperature, while aging peaks in the strength curves are mirrored by ductility minima in the same temperature range.

Impact Properties

The summarized Charpy impact test results and the drop-weight test results for the four steels are found in Tables 4 and 5 and Figs. 10 and 11. The Charpy impact test curves are found in Figs. Al to A20. The Charpy impact tests results generally confirm the tension test results with respect to the influence of section location. There was little or no effect in A212 Grade B or A533 Grade B, while for A542 and A543 a decrease of about 10° F in Charpy V-notch 15 ft-lb or 15 mil transition temperature for the quarter-section location was noted. For A212 Grade B and A533 Grade B there was also little influence of cooling rate on toughness. For A542 and A543 a measurable improvement in 15 ft-lb or 15 mil transition temperature exists in the 6-in. plate as compared to the 12-in. plate. In A542 this amounts to

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Table 4—Charpy V-Notch Impact Test Data

Chemistry and cooling rate	Trans. temp. °F 15 ft-lb	Trans. temp. °F 15 mils	Trans. temp. °F 50% shear	NDT fix energy ft-lb	Shelf energy ft-lb
A212 Grade B					
6 in. Plate center[a]	+28	0	+90	9	61
6 in. Plate RC center	+22	−10	+90	...	...
6 in. Plate quarter[b]	+28	−2	+108	9	77
6 in. Plate RC quarter	+24	−10	+90	...	...
12 in. Plate center	+32	−4	+90	10	61
12 in. Plate RC center	+28	+2	+94	...	...
12 in. Plate quarter	+32	−2	+105	10	74
12 in. Plate RC quarter	+16	−14	+84	...	...
A533 Grade B					
6 in. Plate center	−28	−56	+34	17	88
6 in. Plate RC center	−28	−60	+54	...	...
6 in. Plate quarter	−28	−46	+38	15	80
6 in. Plate RC quarter	−24	−48	+56	...	...
12 in. Plate center	−20	−48	+60	18	79
12 in. Plate RC center	−24	−56	+54	...	...
12 in. Plate quarter	−16	−40	+68	16	75
12 in. Plate RC quarter	−26	−54	+60	...	...
A542					
6 in. Plate center	−66	−72	+90	20	70
6 in. Plate RC center	−44	−48	+110	...	...
6 in. Plate quarter	−70	−78	+72	20	86
6 in. Plate RC quarter	−50	−54	+90	...	...
12 in. Plate center	−26	−38	+102	16	53
12 in. Plate RC center	−44	−50	+62	...	...
12 in. Plate quarter	−36	−48	+80	16	93
12 in. Plate RC quarter	−50	−52	+44	...	...
A543					
6 in. Plate center	−120	−134	−50	17	77
6 in. Plate RC center	−150	−160	−70	...	...
6 in. Plate quarter	−130	−136	−38	20	71
6 in. Plate RC quarter	−180	−192	−86	...	...
12 in. Plate center	−94	−112	−46	12	69
12 in. Plate RC center	−164	−172	−58	...	...
12 in. Plate quarter	−110	−120	−50	15	70
12 in. Plate RC quarter	−176	−184	−96	...	...

[a] Center thickness position.
[b] Quarter thickness position.
RC — Cooled at 240° F/hr from stress relief — all others cooled at 40° F/hr.; 12 in. plate cooled at 0.25° F/sec from austenitizing, 6 in. plate cooled at 0.85° F/sec from austenitizing.

about 35° F, while for A543 it amounts to about 20° F.

The use of a rapid cooling treatment from stress-relief is seen to substantially improve the impact resistance of only one steel—A543. For this steel, decreases in the 15 ft-lb or 15 mil transition temperature of between 6° F to 70° F were

Table 5—Drop-Weight Test Data

Steel	Energy required (ft-lb)	NDT (°F) 6 in. Plates Center chem.	NDT (°F) 6 in. Plates Quarter chem.	NDT (°F) 12 in. Plates Center chem.	NDT (°F) 12 in. Plates Quarter chem.
A212 Grade B	285	0	0	+10	+10
A533 Grade B	333	−20	−10	−10	−10
A542	380	−30	−40	−20	−30
A543	380	−110	−110	−110	−110

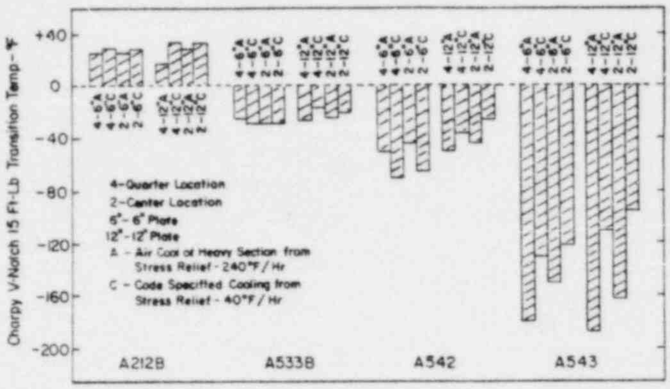

Fig. 10—The Charpy V-notch impact test results for the four heavy section steels

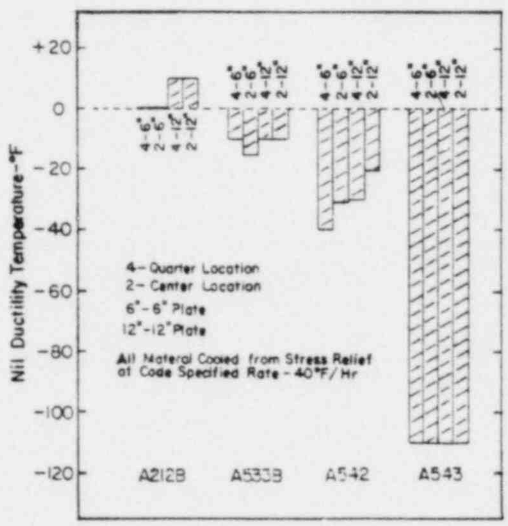

Fig. 11—The drop weight test results for the four heavy section steels

observed, with the largest improvements occurring in the 12-in. plate specimens. The response of A542 to the rapid cooling treatment from stress relief was mixed while for the other steels a very slight improvement was noted.

In general, the A543 has markedly superior notch toughness to any of the other steels in the program and A212 Grade B had the poorest toughness of the four steels. A difference in transition temperature of over 100° F separates these two extremes while A533 Grade B and A542 are in the intermediate range. Both of these latter steels have transition temperatures more than 40° F lower than the A212 Grade B.

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The drop-weight test data, presented in Table 5 and Fig. 11, show no response to section location or cooling rate from austenitizing for A533 Grade B and A543 steels. Only A542 steel shows much influence of cooling rate or location, as the 6-in. thickness material is superior to the 12-in. and the quarter section is superior to the center section.

The results of the drop-weight tests confirm the over-all results of the Charpy impact tests as the steels show the same relative behavior in both tests. The NDT temperatures are slightly higher than the Charpy 15 ft-lb transition temperature for A533 Grade B, A542 and A543, as indicated by the higher NDT "fix" energy listed in Table 4, while for A212 Grade B the NDT temperature is lower than that for the 15 ft-lb criterion in the Charpy test.

Fatigue Tests

The fatigue test data obtained for the four steels are found in Table 6 and Figs. A21 to A24. The response of the four steels to fatigue conditions follows the pattern normally expected of low-alloy high-strength steels. The higher-strength steels have superior fatigue resistance in the 100,000 cycle failure region, while the lower-strength but more ductile steels are superior in the low-cycle region. The levels of fatigue life attained in these tests are comparable to those found in equal-strength lighter-section plate.

Microstructures

The microstructures of the four project steels are seen in Figs. 12 to 15. The A212 Grade B steel (Fig. 12) consists of fairly coarse aggregates of ferrite and pearlite, with the difference in cooling rate from austenitization resulting in no significant difference in microstructure. Tempering and stress relieving resulted in some spheroidization of the pearlitic carbides. The microstructure of the A533 steel (Fig. 13) consists largely of ferrite and low-temperature transformation products, reflecting the microsegregation occurring during cooling, with the enriched austenite remaining after the ferrite precipitates, finally transforming to areas of high-carbon high-alloy martensite or bainite. The ferrite precipitation and resulting microsegregation is markedly more pronounced at the 12-in cooling rate than at the 6-in. cooling rate. The microstructure of the A542 steel (Fig. 14) consists predominantly of a mixture of upper and lower bainite, with little apparent difference between the microstructures of the specimens cooled at the 6-in. and 12-in. cooling rates. The microstructure of the A543 steel (Fig. 15) appears to consist predominantly of lower bainite, with some upper bainite, although the amount of transformation to upper bainite is significantly less than occurred in the A542 steel. The occurrence of substantial spheroidization during tempering and stress relieving is apparent from the microstructures of the three alloy steels, but differences in microstructure between the specimens slowly cooled and rapidly cooled from stress relieving are not revealed by the light microscope, even though a substantial difference in Charpy impact behavior exists for these two conditions.

Comparison of Light- and Heavy-Section Behavior

It may be helpful to compare the properties of the four steels in the heavy-section sizes studied in the program with the properties which were obtained in previous programs for these steel grades treated to represent quenched and tempered, and normalized and tempered, plates of relatively light section. Figures 16 and 17 summarize the tensile and Charpy test properties representative of plates ranging from less than 1-in. to 15-in. thickness on the basis of cooling rate from austenitizing. For the most part the tensile properties show a gradual loss of strength as thickness is increased. The notch toughness uniformly decreases with greater thickness; but A212 and A543 show a progressive loss, while A533 and A542 sustain most of the loss of toughness as sections are increased to about 4 in., above which relatively little change is incurred.

Summary

The results of the study of the four heavy-section steels can be summarized as follows:

1. There were no important changes in strength, notch toughness, or fatigue resistance produced by the reduction of cooling rate during quenching when the section size is increased from 6 in. to 12 in. in A212 Grade B, A533 Grade B, A542, or A543 steels tested in the quenched, tempered and stress-relieved condition.

2. The property most affected by increase of the section thickness from 1-in. to the 6 to 12 in. range is notch toughness. Rises of 50 to 100° F in transi-

Table 6—Plastic Fatigue Resistance of the Heavy-Section Steels

		Total strain range—%					
		3/16 in. Crack			Failure		
Steel	*Condition*	*5000 cyc*	*10,000 cyc*	*50,000 cyc*	*5000 cyc*	*10,000 cyc*	*100,000 cyc*
A212B	12 in. Center and quarter chem.	0.75	0.60	0.36	1.20	0.92	0.39
A533B	6 in. and 12 in. center and quarter chem.	0.71	0.59	0.37	0.82	0.68	0.40
A542	12 in. Center and quarter chem.	0.80	0.69	0.50	0.95	0.79	0.49
A543	12 in. Center and quarter chem.	0.79	0.65	0.50	0.96	0.78	0.48

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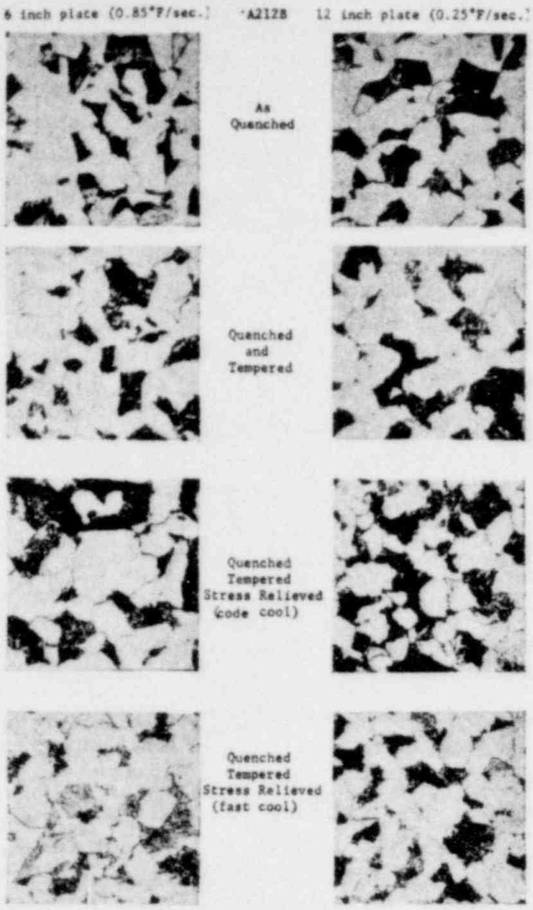

Fig. 12—The microstructure of A212B (Nital etch, × 500)

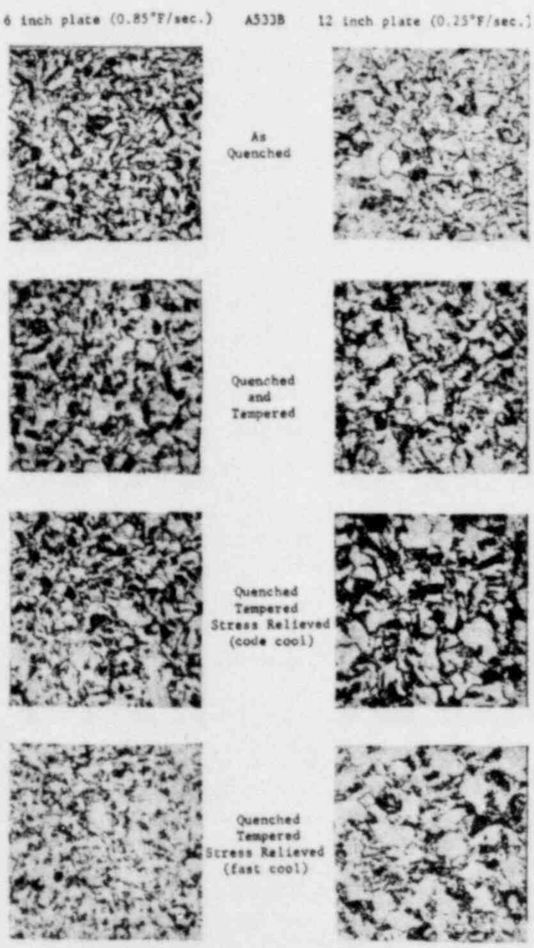

Fig. 13—The microstructure of A533B (Nital etch, × 500)

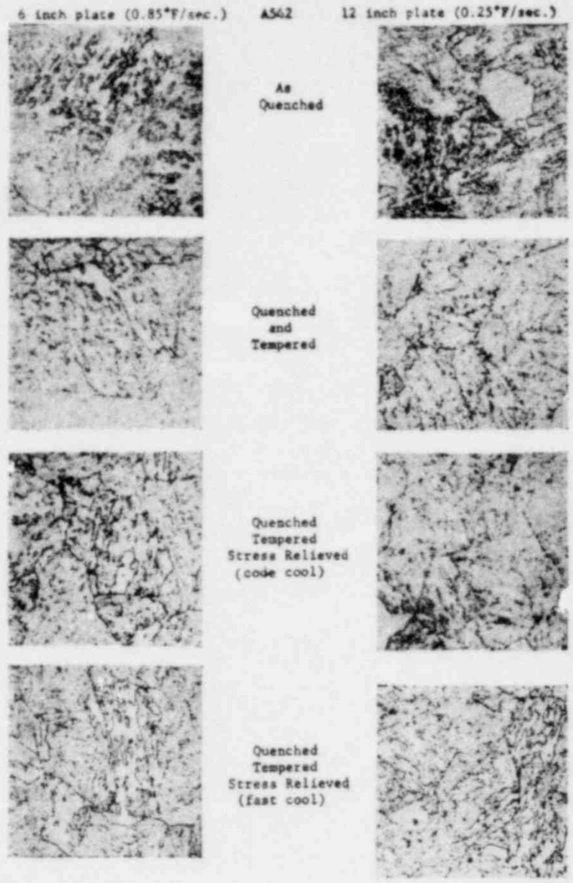

Fig. 14—The microstructure of A542 (Nital etch, × 500)

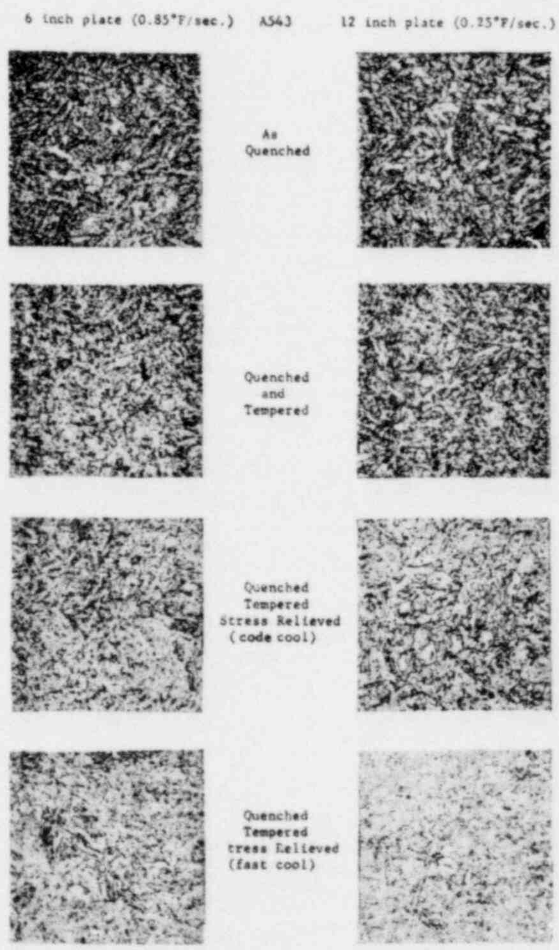

Fig. 15—The microstructure of A543 (Nital etch, × 500)

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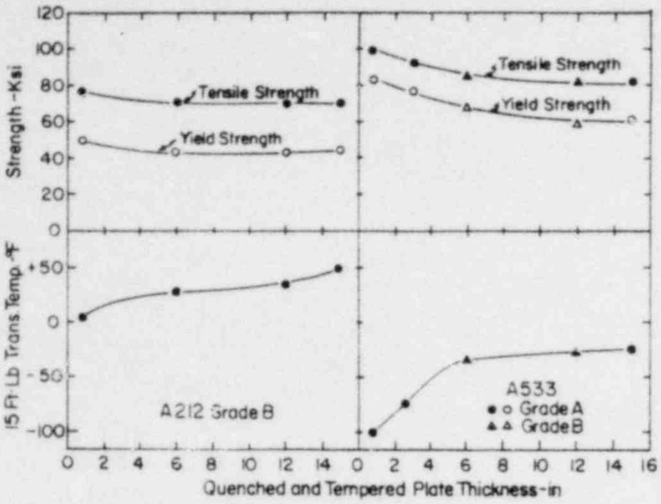

Fig. 16—The strength and toughness of A212B and A533 as influenced by simulated plate thickness.

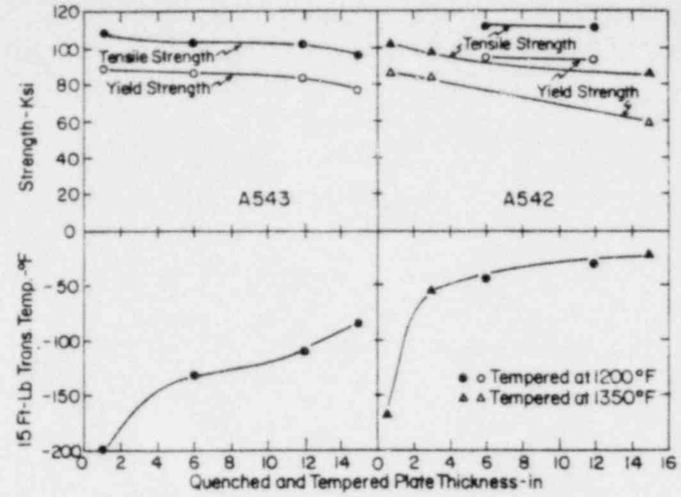

Fig. 17—The strength and toughness of A542 and A543 as influenced by simulated plate thickness

tion temperature were observed in these steels. Fortunately, the alloy steels display transition temperatures below −10° F even in heavy sections. The notch toughness of the A543 steel was markedly superior to that of the other steels treated at cooling rates corresponding to the thicknesses of either 6 or 12 in.

3. The fatigue properties of the steels matched those of steels with similar tensile properties developed in lighter sections. The allowable strain range for a fatigue life of 100,000 cycles correlated well with tensile strength, while the strain range for 5000 cycles appeared to be related principally to the ductility of the steel (as observed in previous work).

4. The elevated-temperature tension tests indicated about the same characteristics in these steels as those observed in thin-gage steels, including the strain-aging phenomena in the 400–800° F temperature range. For A533 Grade B and A542, the 6-in. thick plate material was superior to the 12-in. plate material at elevated temperatures to 1000° F.

5. Metallographic examination generally substantiated the small differences in properties observed between specimens cooled at the rate to be expected in a 6-in. section and those cooled to match a 12-in. section.

Acknowledgment

The authors are grateful to the members of the Materials Division of the Pressure Vessel Research Committee for their advice and guidance, and to PVRC for support of the investigation. They wish also to express their appreciation to the Foster-Wheeler Corp. which contributed extensive services in the preparation of the test plates.

References

1. Gross, J. H., and Stout, R. D., "The Performance of High-Strength Pressure-Vessel Steels in Heavy Sections," *Welding Jnl.*, **35** (3), Research Suppl., 115-s to 119-s, 1956.
2. Gross, J. H., and Stout, R. D., "Properties and Weldability of High-Strength Pressure-Vessel Steels in Heavy Sections," *Ibid.*, **36** (3), Research Suppl., 157-s to 167-s, 1957.
3. Gross, J. H., Kottcamp, E. H., and Stout, R. D., "Effect of Heat Treatment on the Microstructure and Properties of Pressure-Vessel Steels," *Ibid.*, **37** (4), Research Suppl., 160-s to 168-s, 1958.
4. Lorentz, R. E., Jr., "Utilization of Quenching and Tempering for Improvement in Properties of Low Alloy Steels in Heavy Thicknesses for Welded Construction," *Ibid.*, **41** (10), Research Suppl., 433-s to 447-s, 1962.
5. Kottcamp, E. H., Canonico, D. A., and Stout, R. D., "Prediction of the Properties of Heavy-Section Pressure-Vessel Steels From End Quench Tests," *Ibid.*, **38** (4), Research Suppl., 350-s to 354-s, 1962.
6. Stout, R. D., "Higher-Strength Steels for Welded-Structures," *Ibid.*, **39** (7), Research Suppl., 273-s to 283-s, 1960.
7. Puzak, P. P., and Pellini, W. S., "Standard Method for NRL Drop Weight Test," NRL Report 5831, 1962, United States Naval Research Laboratory, Washington, D. C.

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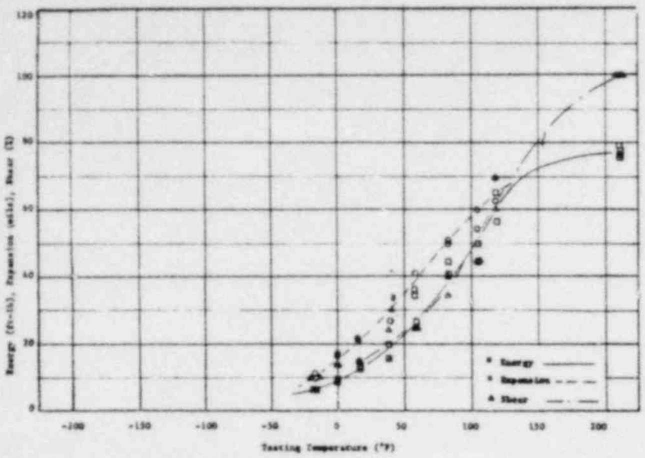

Fig. A1—Charpy V-notch impact data for code-stress-relieved A212B, 6 in. plate, quarter location

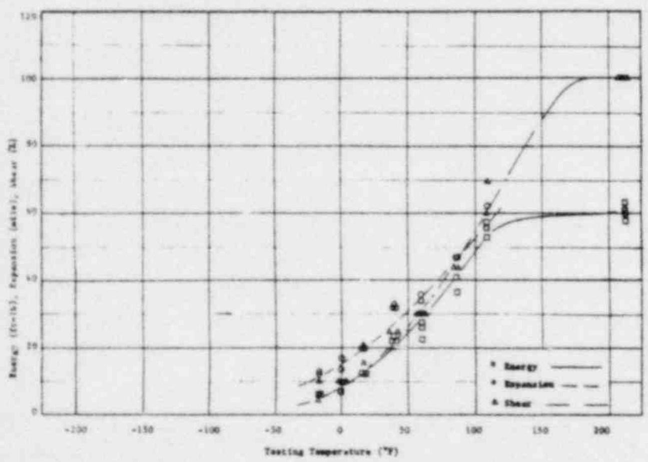

Fig. A2—Charpy V-notch impact data for code-stress-relieved A212B, 6 in. plate, center location

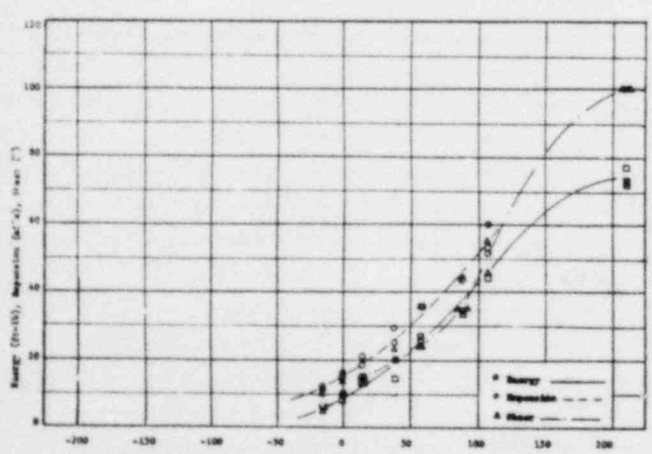

Fig. A3—Charpy V-notch impact data for code-stress-relieved A212B, 12 in. plate, quarter location

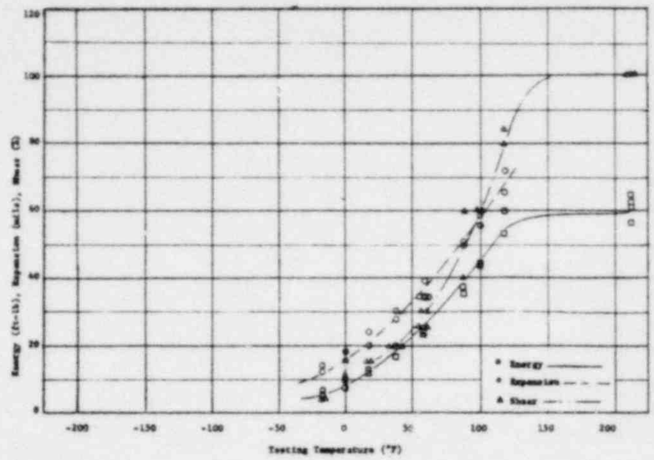

Fig. A4—Charpy V-notch impact data for code-stress-relieved A212B, 12 in. plate, center location

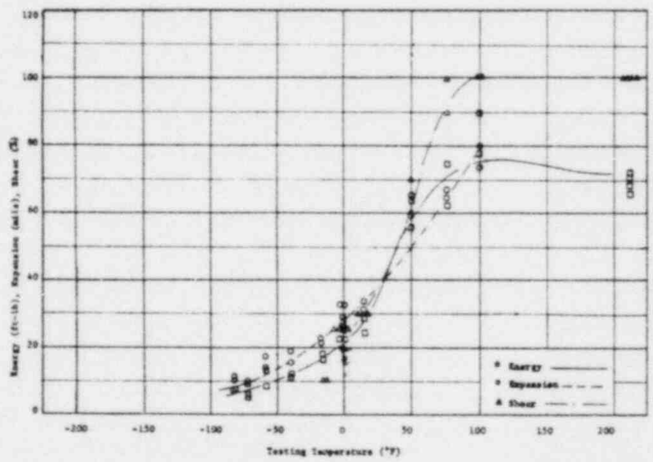

Fig. A5—Charpy V-notch impact data for code-stress-relieved A533B, 6 in. plate, quarter location

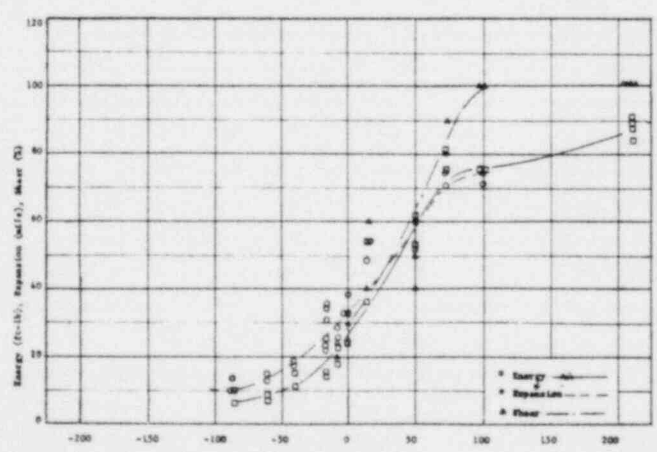

Fig. A6—Charpy V-notch impact data for code-stress-relieved A533B, 6 in. plate, center location

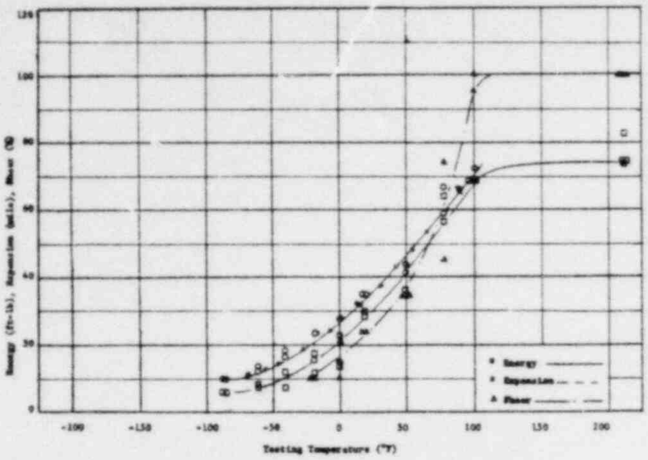

Fig. A7—Charpy V-notch impact data for code-stress-relieved A533B, 12 in. plate, quarter location

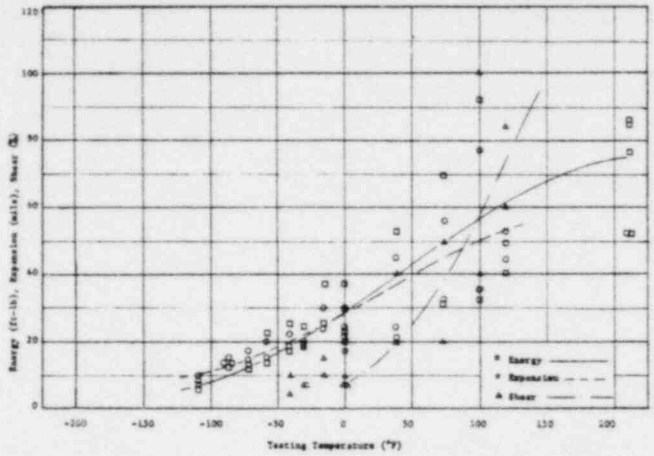

Fig. A10—Charpy V-notch impact data for code-stress-relieved A542, 6 in. plate, center location

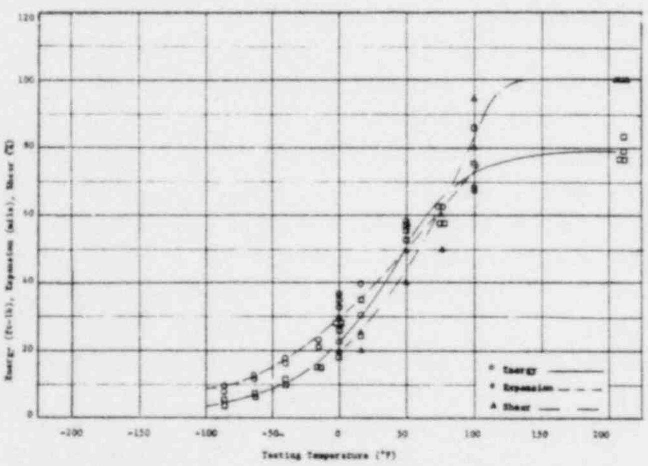

Fig. A8—Charpy V-notch impact data for code-stress-relieved A533B, 12 in. plate, center location

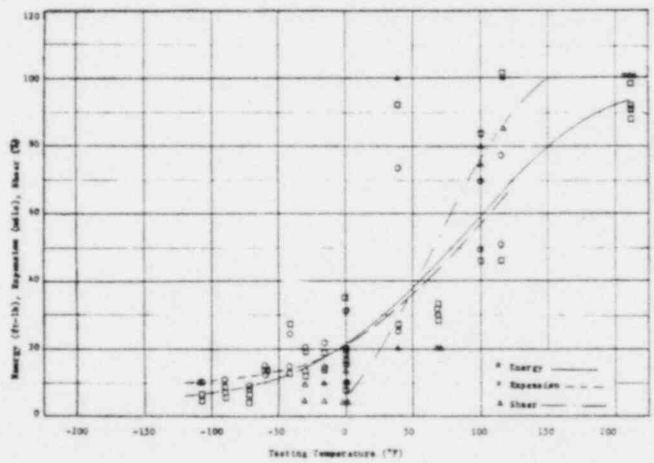

Fig. A11—Charpy V-notch impact data for code-stress-relieved A542, 12 in. plate, quarter location

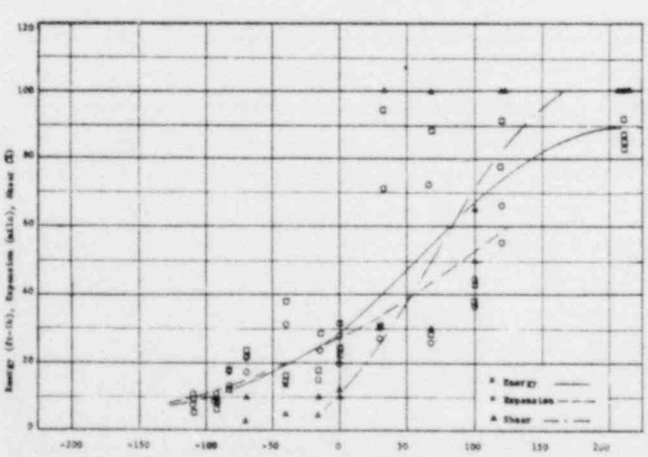

Fig. A9—Charpy V-notch impact data for code-stress-relieved A542, 6 in. plate, quarter location

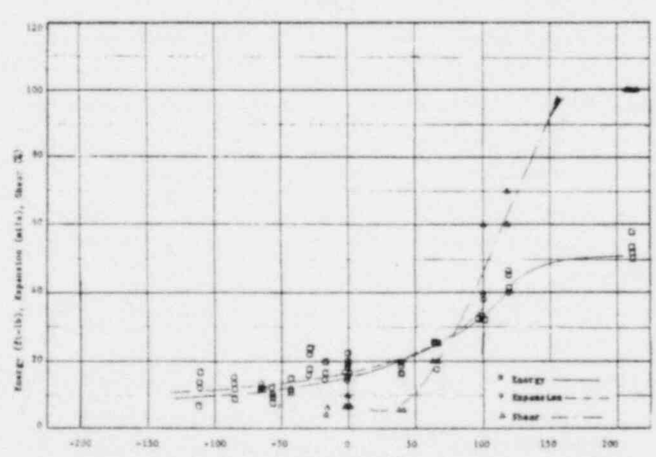

Fig. A12—Charpy V-notch impact data for code-stress-relieved A542, 12 in. plate, center location

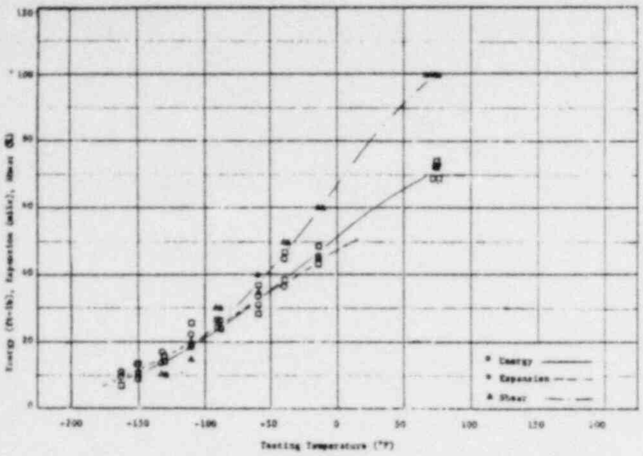

Fig. A13—Charpy V-notch impact data for code-stress-relieved A543, 6 in. plate, quarter location

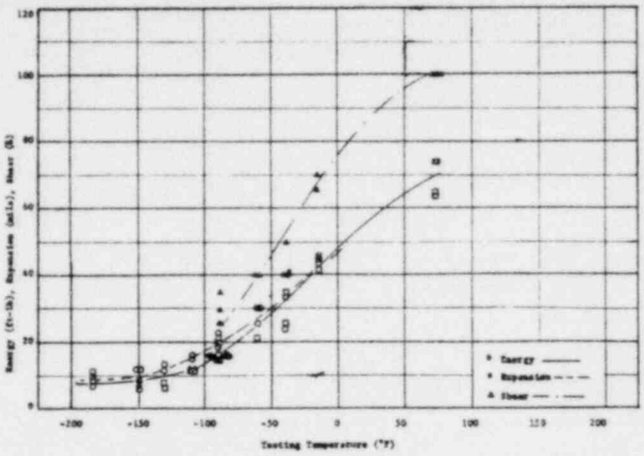

Fig. A16—Charpy V-notch impact data for code-stress-relieved A543, 12 in. plate, center location

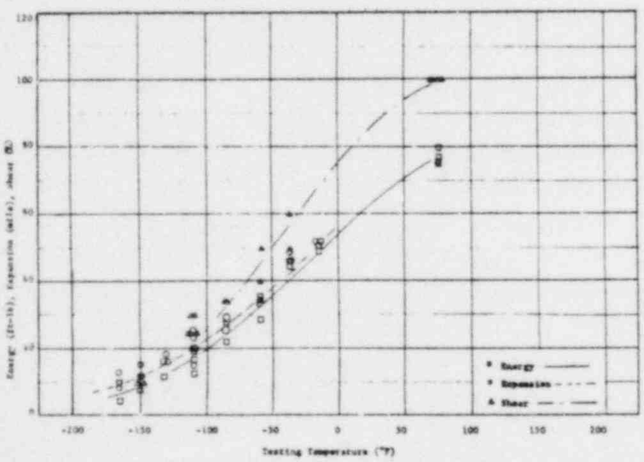

Fig. A14—Charpy V-notch impact data for code-stress-relieved A543, 6 in. plate, center location

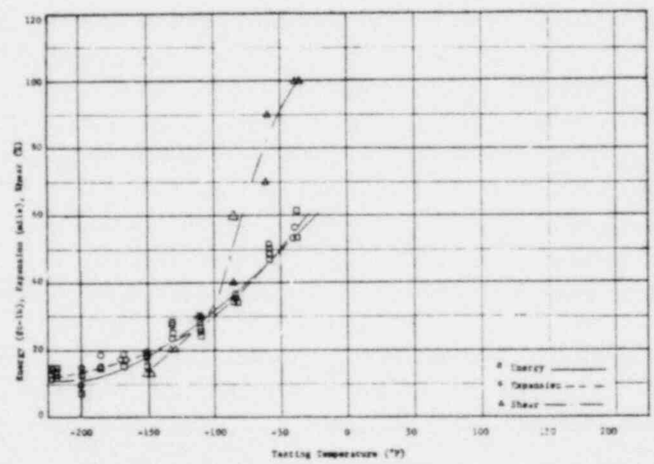

Fig. A17—Charpy V-notch impact data for stress relieved and air cooled A543 6 in. plate, quarter location

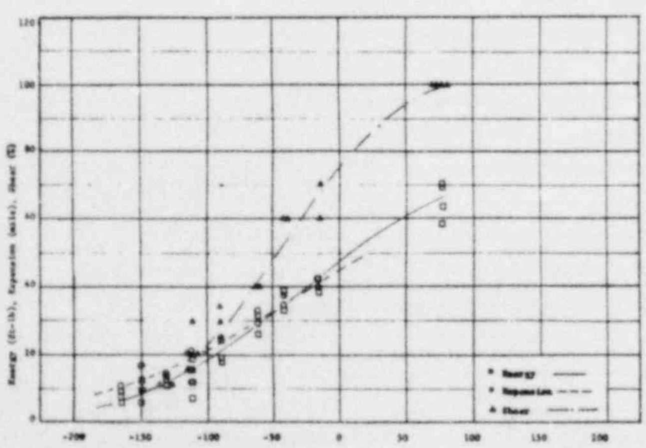

Fig. A15—Charpy V-notch impact data for code-stress-relieved A543, 12 in. plate, quarter location

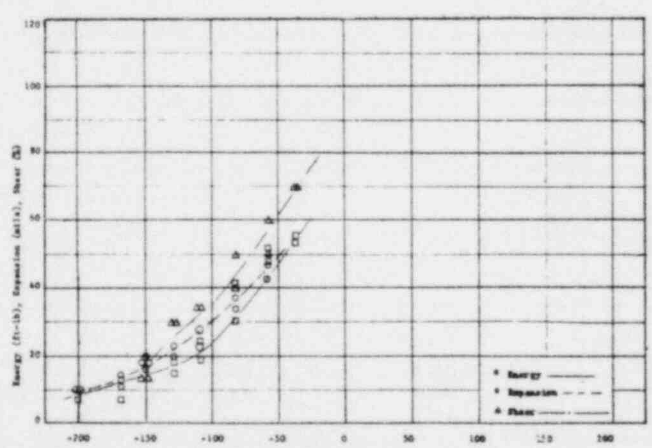

Fig. A18—Charpy V-notch impact data for stress relieved and air cooled A543 6 in. plate, center location

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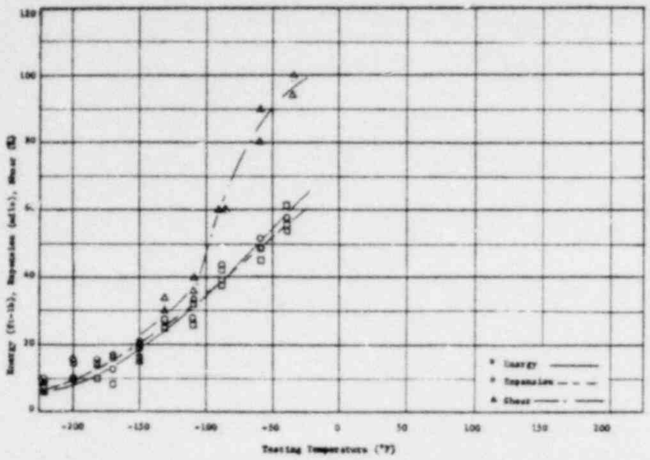

Fig. A19—Charpy V-notch impact data for stress relieved and air cooled A543 12 in. plate, quarter location

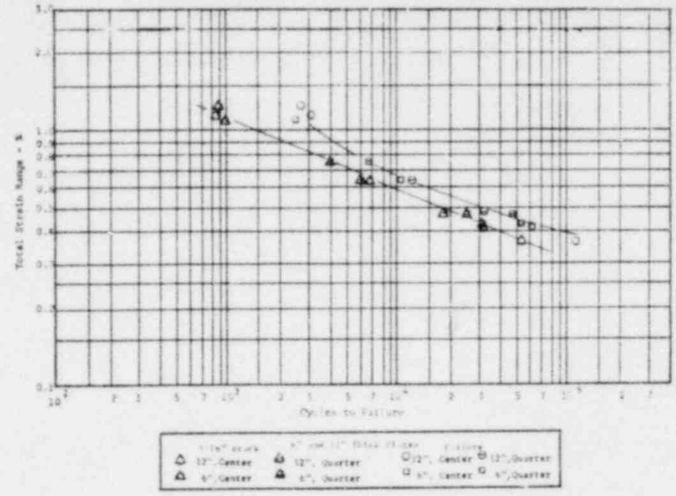

Fig. A22—Plastic fatigue data for heavy-section A533B

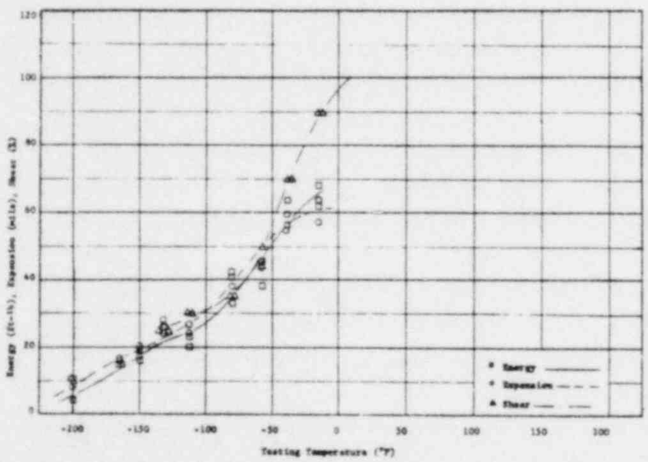

Fig. A20—Charpy V-notch impact data for stress relieved and air cooled A543 12 in. plate, center location

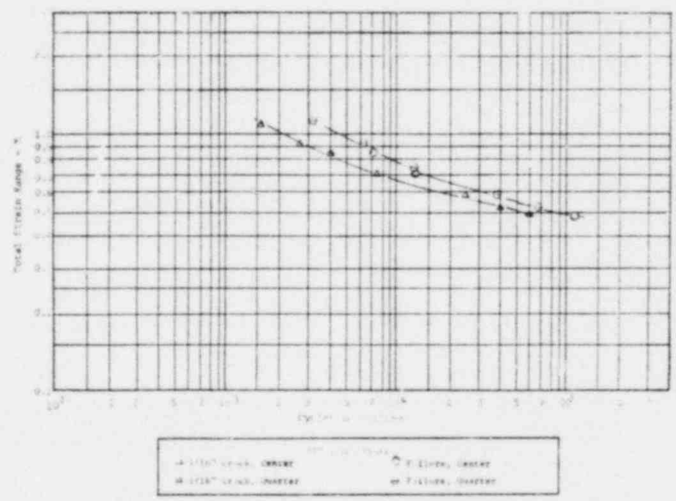

Fig. A23—Plastic fatigue data for heavy-section A542

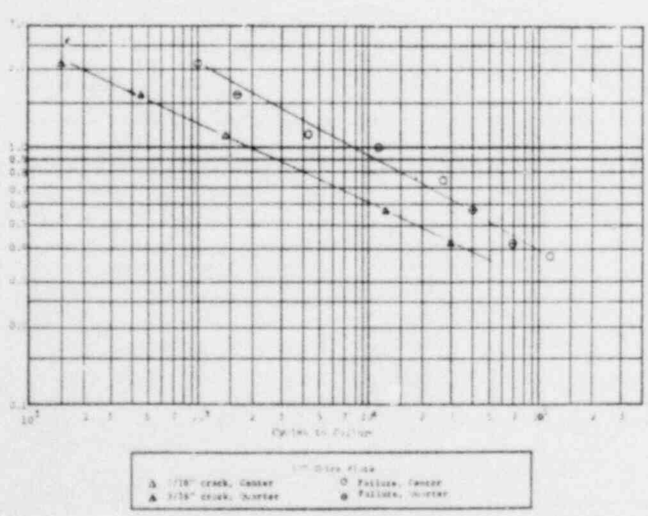

Fig. A21—Plastic fatigue data for heavy-section A212B

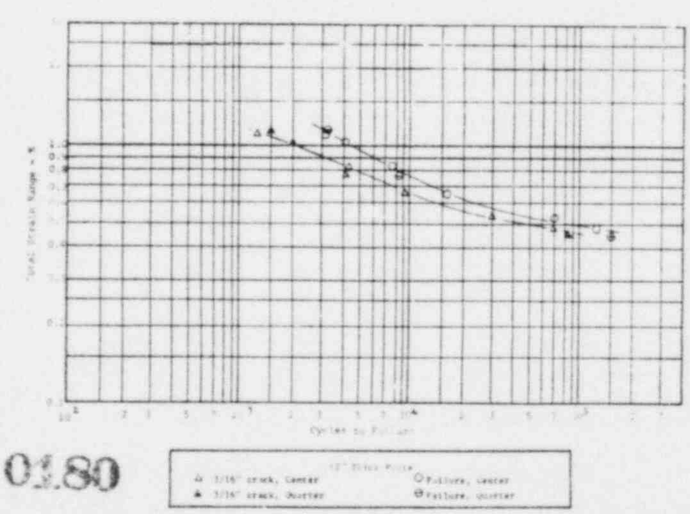

Fig. A24—Plastic fatigue data for heavy-section A543