SSC-235

EFFECT OF TEMPERATURE AND STRAIN UPON SHIP STEELS

SHIP STRUCTURE COMMITTEE

1973

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SR 199
18 JUL 1973

Two of the goals of the Ship Structure Committee involve the development of improved criteria for the application of shipbuilding materials and the development of improved techniques and guidance for ship construction. This report contains the first results of a study of flame straightening of high strength steel plates which was undertaken in furtherance of both of these goals. Research in this area is continuing with a study of shipyard application of flame straightening techniques. It is expected that the results of that study will be published in a subsequent Ship Structure Committee report.

Comments on this report would be welcomed.

W. F. Rea

W. F. REA, III
Rear Admiral, U. S. Coast Guard
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SSC-235

Final Technical Report

on

Project SR-199, "Forming Parameter Effects"

EFFECT OF TEMPERATURE AND STRAIN UPON SHIP STEELS

by
R. L. Rothman and R. E. Monroe

under
Department of the Navy
Naval Ship Engineering Center
Contract No. N00024-71-C-5088

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U.S. Coast Guard Headquarters
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ABSTRACT

The effects of flame straightening and both hot and cold forming upon material properties of hot rolled, normalized, and quenched and tempered steels were investigated. Flame straightening was studied by first simulating the effects of time at temperature upon the tensile and impact properties of seven steels. Straightening was then performed within the determined limits upon 4-foot-square plates which had been distorted by welding them into a rigid frame. As a result of these studies, it is recommended that flame straightening with appropriate controls be allowed as an acceptable process for distortion removal for both normalized and quenched and tempered steels.

Simulations of outer fiber strain resulting from both hot and cold forming were conducted to determine the effects of temperature and strain upon properties. In general, it was found that either tensile or impact properties were reduced to some degree by most operations.

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INTRODUCTION

Many of the fabrication procedures used in shipyards have been developed for mild steel plate. This steel is by far the most frequently used construction material in shipbuilding and will continue to be so. However, the use of higher strength steels is becoming greater as the newer designs become more demanding in their materials requirements. This program was undertaken to determine if certain fabrication procedures can be applied to (1) high-strength, hot-rolled steel, (2) normalized steel, and (3) quenched and tempered steel. The particular fabrication procedures studied were flame straightening and plate forming.

Flame straightening has been used successfully for years to remove the distortion in weldments of mild steel. The process requires the skillful application of heat to cause plastic shape changes. A torch is used to heat the steel to a "dull red". The accuracy in temperature possible by using color criteria depends on the judgment of the operator and whether the work is performed in a dark compartment or in bright sunlight, but, since mild steel is relatively tolerant of fabrication variations, exact temperature control is not necessary. In contrast, quenched and tempered steels owe their properties to a series of specific heat treatments to control the metallurgical structure. If these steels are heated above the lower critical temperature this structure changes, and their properties become degraded as demonstrated during previous research on this subject under Ship Structure Committee Project SR-185. Degradation will also occur if the steel is over tempered without exceeding the lower critical. Consequently, current requirements forbid flame straightening on any high-strength steel. Since no alternative straightening procedure exists, the shipyard is forced to remove distortion by a cutting and rewelding procedure. The objective of this program with respect to flame straightening was to determine if this process could be used on heat-treated steels. To accomplish this objective, the effects of temperature were first determined through simulations, and the results were then applied to the actual flame straightening of large plates.

Plate forming is done both at elevated temperatures and at ambient temperatures. In considering whether hot forming can be applied to heat-treated steels one must again consider the effects of temperature and must add the second variable of strain. The forming studies conducted during this program were simulations of the effects of forming upon specific regions of the plate. Forming introduces a strain distribution into the plate ranging from tensile to compressive so that the study of one strain level cannot describe the change in properties of the entire plate due to forming. The greatest strains occur at the outer fibers of the plate, so the effect of forming strain will be greatest there. Consequently, the strain levels were chosen to represent these regions. Both tensile and compressive strains were applied to see if one side of the formed plate presents greater potential problems than the other. Samples were strained at elevated temperatures and room temperature as a further comparison of hot forming versus cold forming.

The experiments performed are presented and discussed under three categories: Elevated Temperature Simulations encompasses the work performed on both flame straightening and hot-forming simulations; Room Temperature Simulations covers the simulations of cold forming; and Flame Straightening contains all work on the actual flame straightening of restrained plates.

EXPERIMENTAL PROCEDURES

Materials

The steels used in this program were as follows:

1. (1) As-rolled: ABS-B, ABS-C, and ASTM A441
2. (2) Normalized: ASTM A537-A
3. (3) Quenched and tempered: ASTM A537-B, NAXTRA-100, and T-1.

The chemical compositions of these seven steels are shown in Table I. All were received in 1/2-inch plate thickness. As indicated by the titles of the steels, two were bought to ABS specifications, three were bought to ASTM specifications, and two were proprietary grades. It was found necessary to use proprietary grades rather than similar ASTM grades for two steels because of availability. The steels ABS-B, ABS-C, A441, A537-A, and A537-B were ultrasonically inspected by the producer prior to shipment.

The plates used in the flame-straightening studies were 48 inch x 48 inch. The material used in the simulation experiments varied in size according to the need as described in appropriate sections of this report.

TABLE I. STEEL CHEMICAL COMPOSITIONS.

	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	V	Zr	B
ABS Grade B	.12	.91	.010	.016	.06							
ABS Grade C	.15	.76	.010	.016	.22							
A441	.15	1.10	.011	.014	.21				.22	.05		
A537 Grade A	.19	1.17	.011	.010	.34	.17	.14	.06	.16			
A537 Grade B	.17	1.14	.010	.010	.36	.15	.14	.06	.17			
NAXTRA-100	.18	.86	.012	.019	.49	.59		.21			.10	.0007
T-1	.17	.91	.008	.016	.22	.60	.79	.48				

All compositions are in weight percent: ladle analysis
Heat treatments are as follows:
A537-A Normalized at 1650 F
A537-B Austenitized at 1650 F, Water Quenched, and Tempered at 1240 F
NAXTRA-100 Austenitized at 1650 F, Water Quenched, and Tempered at 1220 F
T-1 Austenitized at 1660 F, Water Quenched, and Tempered at 1270 F.

Elevated Temperature Simulations

Samples were heated at elevated temperatures to simulate both flame straightening and hot forming. Time and temperature were variables for both simulations, and, in addition, a strain at temperature was given to the hot-forming samples.

All elevated temperatue simulations were performed on Gleeble Model 510 equipment. This device is a programmable thermal-mechanical testing machine which can strain samples in either tension or compression while they undergo a preset thermal cycle. The sample is held between two sets of copper jaws which supply current for resistance heating and provide a restraining force. A thermocouple is percussively welded to the sample to monitor and control temperature. For Charpy specimens, the location of the control thermocouple corresponded to the midpoint of the subsequent notch. Because of the resistance heating, the temperature is uniform through the thickness of the sample. The temperature can be controlled to ± 15 F at 1300 F* over a 2-in. length of the sample with the 6-in. jaw spacing used in this study for tensile samples. The load cell has a 10,000-pound capacity. A more detailed description of the equipment and procedures appears in Appendix A.

Flame-Straightening Simulation

Both Charpy and tensile samples were prepared by holding at a controlled temperature for a fixed time. The blanks for Charpy samples used in these experiments were .455 in. x .5 in. x 6 in.; the .455-in. dimension was ground before heating to achieve good electrical contact with the copper jaws. After the thermal cycle, these blanks were machined into Charpy samples for testing. Tensile samples were 12-in. long with a 2-in. gage; the gage had a .500-in. width and a .430-in. thickness. They were machined before the thermal cycle and were tested with no further machining.

The thermal cycles applied consisted of 15 seconds to bring the samples to temperature, between 30 and 300 seconds at temperature, and an air cool to ambient temperature. Some samples were water quenched to ambient after the appropriate hold time. The holding temperatures used varied between 800 and 1300 F. No load was applied to any of the samples in the flame-straightening simulation.

Hot-Forming Simulation

Except for the application of a strain, the specimens and procedures used in the hot-forming simulations were the same as those used in the flame-straightening simulation. The heat-up time was 15 seconds, the hold time at temperature was 600 seconds, and the samples were air cooled to room temperature.

---

* All temperatures are in degrees Farenheit.

The strain was read directly from the sample by connecting a dial gage between two points on the sample which were not heated appreciably during the temperature cycle. Therefore, the change in length measurement could be made continually during the straining and was independent of any slippage which occurred between the sample and the jaws. Gage marks were placed on the sample, and length measurements were made before and after the load-temperature cycle as a check on the dial-gage readings -- complete agreement was found. Final machining of Charpy and tensile samples was performed after cycling.

The magnitudes of strain used were 2 and 5 percent based on the change in length of the zone heated into the visible range. This strain definition was chosen as representative of the outer fiber strain in a plate due to bending. The corresponding measured strains based on reduction in area of the samples are listed below.

Temperature	Direction of Strain	Magnitude of Strain Based on Change in Length, percent	Reduction in Area, percent
1300	Tensile	5	8
1300	Compressive	5	9
1300	Tensile	2	4
1300	Compressive	2	4
1100	Tensile	5	7
1100	Compressive	5	8

The Charpy notch was always placed at the point of maximum change in area. For the cold-forming simulations, the strains administered were identical as measured by either change in length or change in area.

In addition to the samples heated to 1300 and 1100 F for subsequent room temperature testing, it was desired to check the ductility of certain steels at 550. The Gleeble load-cell capacity was less than that necessary to test full-sized samples at 550, so A537-B, NAXTRA-100, and T-1 samples were prepared in 0.165-in. thicknesses. These samples were taken to temperature and pulled in tension to obtain a 0.100-in. change in length over the 2-in. gage section which is comparable to the 5 percent strain used in the hot-forming simulation.

Room Temperature Simulations

To simulate cold forming, samples were strained specified amounts at room temperature. The load was then removed, and the samples held at ambient temperature for between 18 and 24 days before testing.

Tensile Prestrain

Both tension and Charpy samples were prepared with tensile prestrain at room temperature. The specimen configurations used for prestraining both types of samples were essentially the same. A tensile sample of 12-in. length, 2-in. gage, and approximately 1/2-in. width and thickness was pulled the specified amount, and the load released. After sitting at room temperature for 18 to 24 days, the sample was tested to fracture in tension. The gage for the Charpy samples was 2.3 in. so that the grips could be cut off after prestraining, and the resulting 1/2-in. x 1/2-in. x 2.165-in. bar was machined into a Charpy sample.

Prestrains of either 2 or 5 percent were administered. No reduction in area occurred in room temperature simulations.

Compressive Prestrain

Only Charpy samples were prepared with compressive prestrain. Specimen blanks .420 in. x 420 in. x 2.3 in. were prestrained either 2 or 5 percent in compression. After prestraining, the blanks were machined into Charpy samples.

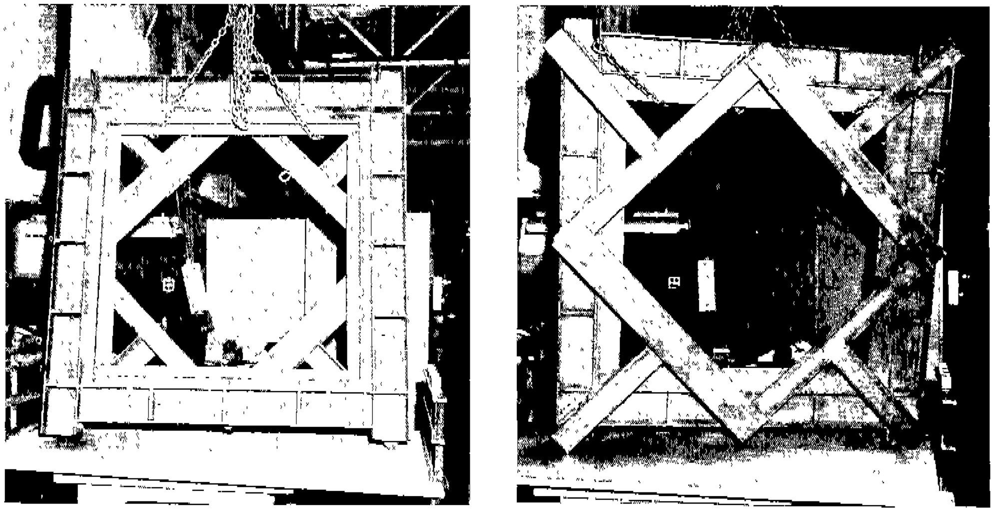
Flame Straightening

The experimental details involved in constructing the frame, welding a plate into the frame to create distortion, and removing the distortion by flame heating are described below.

Frame

The requirements of a frame for the intended application were: that it prevent movement of the plate in its plane; that it be sufficiently rigid against motion out of the plane so that little frame motion could occur in the vertical direction; that plate distortion out of the plane could be introduced by welding; and that the frame be reusable. Two views of the frame which met these requirements are shown in Figure I. Structural I-beams of 6-in. web and flange dimensions and 3/8-in. member thickness were used to prevent motion in the plane. Gusset plates 5/8-in. thick were added to the I-beams, and angles were also used to stiffen the frame against out-of-plane motion. Two different sizes of angles were used as follows:

Web width	5 in.	4 in.
Flange width	5 in.	4 in.
Plate thickness	1/2 in.	3/8 in.



A. Front View

B. Back View

FIGURE 1. FRAME USED IN PROGRAM

A 2-in.-wide transition plate was welded to the frame at the center of the inner flange of the I-beams to facilitate plate removal after the completion of each flame-straightening experiment. The experimental plates were joined to the frame by butt welding to this transition plate.

Welding

Essentially the same procedure was used for welding all plates into the frame. Both the sample plate and the transition plate of the frame were cut and ground to a 60 degree bevel. The plate was then placed in the frame, tacked, and welded. All welding was done manually using the following electrodes:

E 7016 for ABS-B and ABS-C

E 8016-B2 for A441, A537-A, and A537-B

E 11018-M for NAXTRA-100 and T-1.

Three centered passes were used to fill the groove with 1/8-in., 5/32-in., and 3/16-in. electrodes used for succeeding passes. If a greater amount of distortion was desired than that created by the three passes, overwelding was done with 3/16-in. electrodes. A distortion of approximately 1/8 inch was obtained for all plate as measured at the center. NAXTRA-100 and T-1 were given a 250 degree preheat before each welding operation; all other steels were welded at ambient temperature.

Heat Application

Spot heating was used in this program because it was felt that this type of heating could be controlled more easily than line heating. The oxyacetylene torch used had an Oxweld 100 A3 tip. Heated spots were typically 2 in. in diameter. During the heating of each spot, the temperature was monitored with temperature indicating crayons. The heating-simulation studies presented later in this report showed that a temperature as high as 1300 maintained for 5 minutes would not degrade the tensile and impact properties of the steels. However, the temperature could be controlled to within a few degrees in the simulation, and this is clearly impossible with torch heating. The following considerations should be observed in selecting and measuring an operating temperature for torch heating in a shipyard:

(1) The temperature should be measured from the side of the plate on which the heating is being performed.

(2) Though no information is available on the effect of a thin surface region heated above the transformation temperature on properties, one should avoid the creation of such a region.

(3) One must measure the plate temperature and not the flame temperature.

(4) Since the torch must be removed in order to measure temperature, a reduction in surface temperature will occur between torch removal and temperature measurement, and this must be taken into account.

(5) A worker using a torch can easily overheat the plate so a margin of error must be included in the selection of operating temperature.

(6) Higher temperature generally results in greater shape change.

Several temperature ranges were examined, and it was decided that the measured range of $900 \leq T \leq 1050$ met the above requirements. After heating, the flame was removed and temperature-indicating crayons corresponding to the extremes of the range were applied to insure the temperature was between the two. It is emphasized that this temperature range was measured after removing the torch, and the maximum surface temperature could easily have exceeded 1050. A temperature range of $1050 \leq T \leq 1250$ was found to result in some surface transformation, and a temperature range of $800 \leq T \leq 1000$ was found to give less plate motion.

All flame-straightening experiments presented in this report were conducted using a measured plate temperature range of $900 \leq T \leq 1050$.

Straightening Procedure

The plate was tacked and measured. The first two weld passes were completed, and measurements were taken after the plate had cooled to room temperature. The third weld pass was deposited, and measured after cooling. A minimum distortion of approximately 1/8 inch of vertical plate motion measured at the center of the plate relative to the as-tacked plate measurement was desired. For those plates where this amount of distortion occurred after the three weld passes, the straightening procedure was begun. If the distortion after three passes was less than desired, overwelding was performed until the desired distortion occurred.

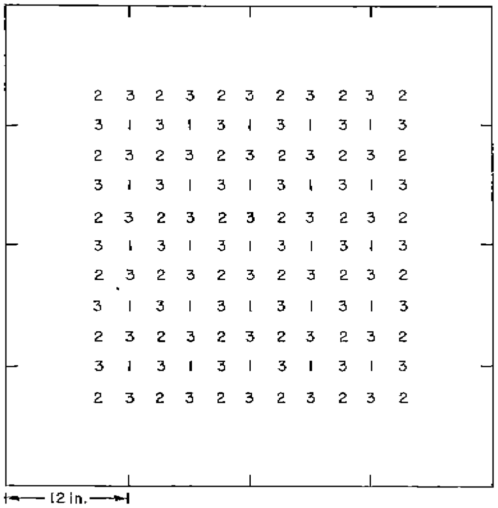
The spots were heated in patterns, and the distortion was measured after the completion of each separate pattern. The first three patterns used are shown in Figure 2. Pattern 1 consisted of 25 spots, Pattern 2 of 36 spots, and Pattern 3 of 60 spots. When the plate returned to its as-tacked height, the heating was stopped. If it had not reached this position after the first three patterns, further heating was done. Each plate was straightened until it either returned to its as-tacked position or insufficient unheated metal was available for further spots. In some plates spots which had been heated previously were reheated to determine if repetition could be used.

After each individual spot had reached the desired temperature range as measured by the temperature crayons, it was spray quenched with water. Heating of the succeeding spot was not begun until after the surface of the heated spot had been quenched to a temperature below the boiling point of water. The sequence used was to heat each spot in order in a given row, but adjoining rows were never heated successively so that heat build-up in the plate could be minimized. Figure 3 shows the plate and frame after Patterns 1 and 2 had been completed.

After all spot heating was completed, the plate was flame cut from the frame, and a final distortion measurement was made on the frame. The plates were then cut into mechanical property samples. The spots for the complete pattern of Figure 2 were approximately 2 in. in diameter and 1 in. apart so that the entire Charpy samples and gage lengths of tensile samples could be prepared from material entirely within the spot. Samples taken from between the spots were approximately 1/2 in. in width and the edges of these samples were approximately 1/4 in. from the nearest spot.

Distortion Measurement

Plate distortion was measured perpendicular to the plane of the plate by a dial gage which was mounted independent of the frame and plate. Measurements were made on plate and frame after tacking, after both two and three weld passes (and after overwelding when performed) after each individual spot heating pattern, and of the frame after the plate was cut out. A total of 6 points were measured on the frame (at each corner and the center of two sides) and 25 points were measured on the plate. The measuring points on the plate coincided with the locations of Pattern 1 spots shown in Figure 2.



2	3	2	3	2	3	2	3	2	3	2
3	1	3	1	3	1	3	1	3	1	3
2	3	2	3	2	3	2	3	2	3	2
3	1	3	1	3	1	3	1	3	1	3
2	3	2	3	2	3	2	3	2	3	2
3	1	3	1	3	1	3	1	3	1	3
2	3	2	3	2	3	2	3	2	3	2
3	1	3	1	3	1	3	1	3	1	3
2	3	2	3	2	3	2	3	2	3	2
3	1	3	1	3	1	3	1	3	1	3
2	3	2	3	2	3	2	3	2	3	2

Pattern 1 - 25 spots
Pattern 2 - 36 spots
Pattern 3 - 60 spots

FIGURE 2. SPOT HEATING PATTERNS USED

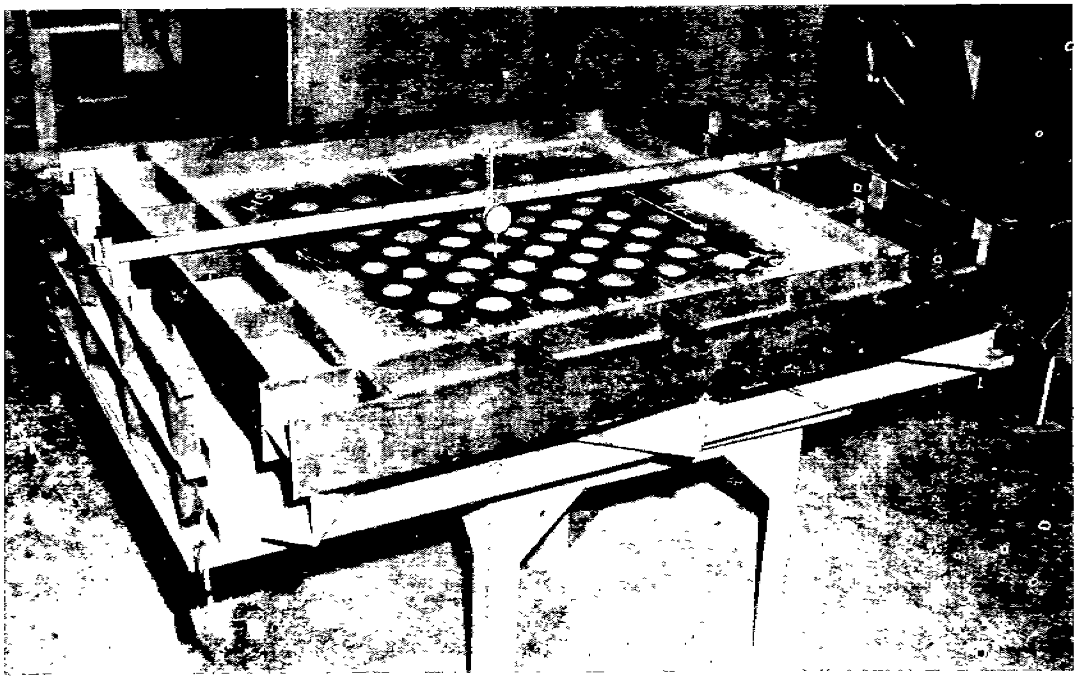


FIGURE 3. PLATE AND FRAME AFTER COMPLETION OF PATTERNS 1 AND 2

Mechanical Testing

The tensile and Charpy V-Notch tests were conducted in a straightforward manner. All specimens were longitudinal; i.e., long dimension oriented parallel to the final rolling direction. Tensile tests were conducted at a constant strain rate of 0.005 in./in./sec.

The following numbers of samples were prepared and tested:

(1) Flame-straightening simulations--one tensile and eight Charpys for each condition for all steels except A-441 for which 32 Charpys were tested for each condition.

(2) Hot-forming simulations--two tensiles and eight Charpys for each condition.

(3) Cold-forming simulations--one tensile and eight Charpys for each condition.

(4) Flame-straightened plates--two tensiles and 16 Charpys from the spots of each plate; two tensiles and eight Charpys from the area between spots in selected plates.

Where eight Charpys were prepared for a given condition, each was tested at a separate temperature to define the transition curve. For those conditions where 16 (or 32) Charpys were prepared, two (or four) were tested at each of eight temperatures. All Charpys were full size and notched perpendicular to the plate surface.

RESULTS

The experimental results which follow are grouped into elevated temperature simulations, room temperature simulations, and flame straightening of plates. The flame-straightening simulations are important both to establish the limitations on actual straightening and to provide base-line data at zero strain for the hot-forming simulations.

Tensile test results are reported in terms of yield strength, ultimate strength, and elongation in 2 in. Charpy results are reported in terms of upper shelf energy, temperature at which 50 percent of the upper shelf energy was absorbed (T_{50}) and 20 ft-lb temperature. Some indicator of the shift of the transition curve was needed, and since the lower shelf was not reached at -150 for some steels, the 50 percent temperature was selected. The shift in the 50 percent temperature was checked against the shift in the temperature at which the mean energy between the upper shelf and the lower shelf occurred for several tests, and the results agreed well. The 20 ft-lb temperature is not a good criterion for toughness; it is tabulated in this report only because of custom and is not used in the data analysis in any way. Similarly, the ultimate tensile strength is reported, but is not applied in the analysis.

TABLE II. RESULTS OF ELEVATED TEMPERATURE SIMULATIONS FOR ABS-B STEEL

Treatment		Charpy Results			Tensile Results		
Temperature (F), Time (sec)	Applied Strain	Upper Shelf (ft-lb)	T_{50} (F)	20 Ft-Lb Temperature (F)	σ_Y (ksi)	Elongation (% in 2 in.)	σ_T (ksi
As-received	None	112	44	-10	38.5	36	64.0
1300, 30	None	122	41	-16	--	--	--
1300, 300	"	128	60	-8	41.2	35.0	62.8
1300, 300, Quench	"	145	74	5	42.4	37.0	66.0
1100, 30	"	114	24	-11	--	--	--
1100, 300, Quench	"	112	42	0	--	--	--
800, 30	"	123	42	-20	--	--	--
800, 300	"	128	30	-33	--	--	--
1300, 600	5% tensile	117	59	8	43.6	37.5	65.1
1300, 600	5% compressive	123	89	42	44.0	33.0	65.6
1100, 600	5% tensile	104	73	24	--	--	--
1100, 600	5% compressive	110	55	8	--	--	--

TABLE III. RESULTS OF ELEVATED TEMPERATURE SIMULATIONS FOR ABS-C STEEL

Treatment		Charpy Results			Tensile Results		
Temperature (F), Time (sec)	Applied Strain	Upper Shelf (ft-lb)	T_{50} (F)	20 Ft-Lb Temperature (F)	σ_Y (ksi)	Elongation (% in 2 in.)	σ_T (ksi
As-received	None	103	-16	-53	44.4	41.0	66.1
1300, 30	"	102	5	-34	--	--	--
1300, 300	"	102	20	-16	45.2	34.0	64.9
1300, 300, Quench	"	99	31	6	45.9	32.5	67.0
1100, 30	"	96	10	- 26	--	--	--
800, 30	"	100	7	-18	--	--	--
800, 300	"	98	21	-33	--	--	--

TABLE IV. RESULTS OF ELEVATED TEMPERATURE SIMULATIONS FOR A441 STEEL

Treatment		Charpy Results			Tensile Results		
Temperature (F), Time (sec)	Applied Strain	Upper Shelf (ft-lb)	T_{50} (F)	20 Ft-Lb Temperature (F)	σ_Y (ksi)	Elongation (% in 2 in.)	σ_T (ksi)
As-received	None	107	15	-29	57.7	34.5	78.3
1300, 30	"	106	12	-25	--	--	--
1300, 300	"	109	28	-30	59.3	29.0	77.3
1300, 300, Quench	"	101	45	9	59.6	28.5	79.4
1100, 30	"	103	25	-50	--	--	--
800, 30	"	104	25	-30	--	--	--
800, 300	"	103	51	-30	--	--	--

It is difficult to set standards for changes in properties which should be considered degrading. The allowable change in properties should be judged in terms of the actual structure for which the steel is intended rather than in an abstract sense. For example, a shift of 100 degrees in T_{50} is large indeed, but if the shift occurred from -150 to -50 it might not be important to a ship application, whereas a 30 degree shift in another steel from 20 to 50 degrees would be most significant. The following guidelines are applied in this report as a basis for comparison:

> A shift of 20 degrees in T_{50} is considered to be significant.
>
> A shift of 15 percent in upper shelf energy or elongation is considered to be significant.
>
> A shift of 15 percent in yield strength is considered significant for lower strength steels. A shift of 10 percent is considered significant for NAXTRA-100 and T-1.

Elevated Temperature Simulations

The results of the elevated temperature simulations are tabulated in Tables 2 through 8. The results are summarized below.

1. ABS-B. Among the flame-straightening samples (no applied strain), the only significant change in properties occurred for the series quenched from 1300. For this series, the Charpy T_{50} curve shifted 30 degrees to higher temperatures and the upper shelf increased by 33 ft-lb with no significant change in tensile properties. For all of the rest of the flame-straightening simulations at 1300, 1100, and 800, the change in either tensile or impact properties was minimal. Among the hot-forming samples, significant shifts to higher temperatures occurred in the Charpy curves for the compressive strain at 1300 and the tensile strain at 1100. The yield strengths increased after straining at 1300, but because this increase was less than 15 percent it is not considered significant; elgonations were unchanged.

2. ABS-C. Only flame-straightening simulations were conducted on this steel. A loss in elongation occurred after 300 seconds at 1300 for both air cooled and quenched samples. All of the treatments at 1300, 1100, and 800 shifted the Charpy curves significantly to higher temperatures with no change in upper shelf level.

3. A441. Only flame-straightening simulations were conducted for this steel. Four Charpy samples were tested at each of eight temperatures to define the curve. These results showed a significant increase in T_{50} after quenching from 1300 and after 300 seconds at 800. The tensile elongation was slightly reduced after simulations at 1300.

TABLE V. RESULTS OF ELEVATED TEMPERATURE SIMULATIONS FOR A537-A STEEL

Treatment		Charpy Results			Tensile Results		
Temperature (F), Time (sec)	Applied Strain	Upper Shelf (ft-lb)	T_{50} (F)	20 Ft-Lb Temperature (F)	σ_Y (ksi)	Elongation (% in 2 in.)	σ_T (ksi)
As-received	None	90	1	-48	55.1	33.5	87.4
1300, 30	"	90	-59	-91	—	—	—
1300, 300	"	90	-50	-82	58.6	30.5	82.6
1300, 300, Quench	"	90	-5	-43	62.2	30.5	83.8
1100, 30	"	85	-60	-78	—	—	—
800, 30	"	88	-25	-72	—	—	—
800, 300	"	88	-40	-85	—	—	—
1300, 600	5% tensile	89	-18	-70	61.6	29.0	82.9
1300, 600	5% compressive	89	4	-60	60.5	28.3	82.5
1100, 600	5% tensile	83	-5	-40	—	—	—
1100, 600	5% compressive	83	-12	-30	—	—	—

TABLE VI. RESULTS OF ELEVATED TEMPERATURE SIMULATIONS FOR A537-B

Treatment		Charpy Results			Tensile Results		
Temperature (F), Time (sec)	Applied Strain	Upper Shelf (ft-lb)	T_{50} (F)	20 Ft-Lb Temperature (F)	σ_Y (ksi)	Elongation (% in 2 in.)	σ_T (ksi)
As-received	None	140	-106	< -150	65.0	34.5	81.0
1300, 30	"	158	-70	< -150	—	—	—
1300, 300	"	156	-88	< -150	66.2	28.0	80.5
1300, 300, Quench	"	154	-135	< -150	68.1	30.5	85.2
1100, 30	"	140	-73	< -150	—	—	—
1100, 300, Quench	"	140	-98	< -150	—	—	—
800, 30	"	140	-106	< -150	—	—	—
800, 300	"	152	-101	< -150	—	—	—
1300, 600	5% tensile	158	-104	-143	67.5	29.8	80.5
1300, 600	5% compressive	168	-78	< -150	67.8	28.3	80.5
1100, 600	5% tensile	146	-88	< -105	—	—	—
1100, 600	5% compressive	150	-80	< -105	—	—	—

TABLE VII. RESULTS OF ELEVATED TEMPERATURE SIMULATIONS FOR NAXTRA-100

Treatment		Charpy Results			Tensile Results		
Temperature (F), Time (sec)	Applied Strain	Upper Shelf (ft-lb)	T_{50} (F)	20 Ft-Lb Temperature (F)	σ_Y (ksi)	Elongation (% in 2 in.)	σ_T (ksi)
As-received	None	55	-94	-123	115.5	22.0	121.7
1300, 30	"	60	-98	-138	—	—	—
1300, 300	"	60	-98	-138	103.5	18.5	113.8
1300, 300, Quench	"	64	-115	-148	107.2	18.0	116.5
1100, 30	"	56	-111	-136	—	—	—
1100, 600	"	55	-94	-126	—	—	—
900, 30	"	55	-84	-110	—	—	—
900, 600	"	55	-84	-114	—	—	—
800, 30	"	55	-94	-112	—	—	—
800, 300	"	55	-94	-122	—	—	—
1300, 600	5% tensile	75	-148	< -150	95.8	17.3	109.2
1300, 600	5% compressive	77	-102	< -150	93.6	17.0	108.6
1100, 600	5% tensile	68	< -105	< -105	—	—	—
1100, 600	5% compressive	65	-105	< -105	—	—	—

TABLE VIII. RESULTS OF ELEVATED TEMPERATURE SIMULATIONS FOR T-1 STEEL

Treatment		Charpy Results			Tensile Results		
Temperature (F), Time (sec)	Applied Strain	Upper Shelf (ft-lb)	T_{50} (F)	20 Ft-Lb Temperature (F)	σ_Y (ksi)	Elongation (% in 2 in.)	σ_T (ksi)
As-received	None	56	-138	-147	98.2	24.0	110.0
1300, 300	"	57	< -150	< -150	98.7	21.5	110.0
1300, 300, Quench	"	56	< -150	< -150	98.7	22.5	110.0
1100, 300	"	56	-138	< -150	--	--	--
800, 300	"	56	-138	< -150	--	--	--
1300, 600	5% tensile	62	< -150	< -150	86.5	18.8	102.4
1300, 600	5% compressive	58	< -150	< -150	82.4	18.3	101.2
1300, 600	2% tensile	65	< -150	< -150	--	--	--
1300, 600	2% compressive	63	< -150	< -150	--	--	--
1100, 600	5% tensile	60	< -105	< -105	--	--	--
1100, 600	5% compressive	58	< -105	< -105	--	--	--

4. A537-A. Among the flame-straightening simulations, the Charpy curves were all shifted large amounts to lower temperatures with the singular exception of the insignificant change in the samples quenched from 1300. Decreases in T_{50} of up to 61 degrees were measured with no change in upper shelf. Tensile properties were unaffected. The results of the hot-forming simulations showed no significant changes in any parameter.

5. A537-B. The flame-straightening simulations conducted for 30 seconds at both 1300 and 1100 showed shifts in T_{50} of approximately 35 degrees to higher temperatures; the samples quenched from 1300 gave a shift in T_{50} of the same magnitude but to lower temperatures. There were no significant changes in other Charpy curves or in the measured tensile properties for flame-straightening simulations. Among the hot-forming simulations, the samples given a compressive strain showed significant increases in T_{50} whereas those given tensile strains did not. The compressive strain at 1300 resulted in a 28 ft-lb increase in the upper shelf. Complete Charpy curves for the hot-forming simulations are shown in Figure 4. The tensile properties were unaffected.

6. NAXTRA-100. The flame-straightening simulations resulted in no significant change in any parameter. The hot-forming simulations resulted in a significant increase in upper shelf energy and, in the case of the tensile strain at 1300, a significant decrease in T_{50}. Complete Charpy curves are shown in Figure 5. Both yield and elongation were reduced by straining at 1300 for both tensile and compressive strains.

7. T-1. The flame-straightening simulations showed no significant change in any parameter. The hot-forming simulations at 1300 resulted in no change in Charpy curves, but did give a reduction in yield strength and elongation.

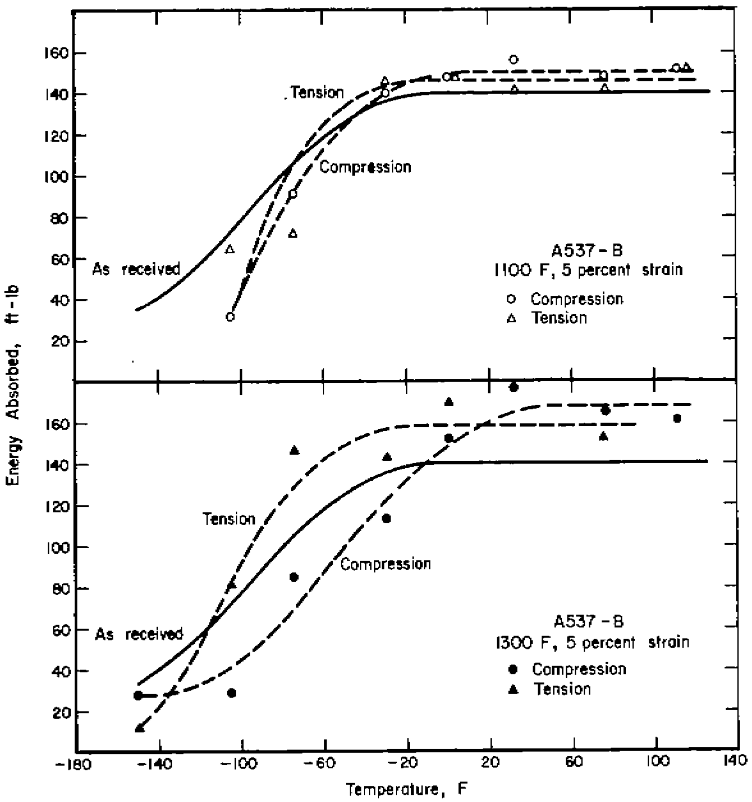


FIGURE 4. CHARPY RESULTS OF A537-B HOT-FORMING SIMULATIONS

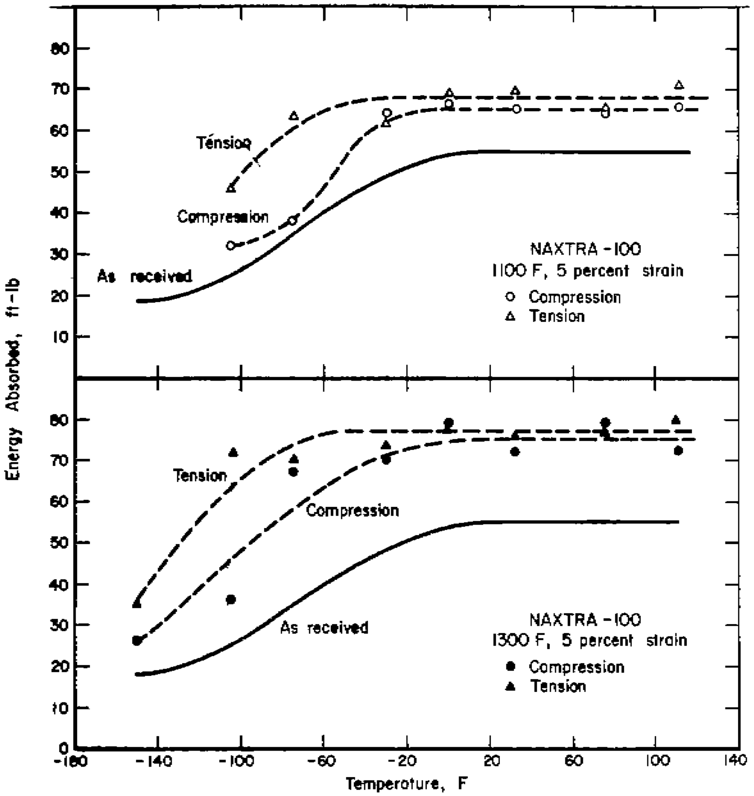


FIGURE 5. CHARPY RESULTS OF NAXTRA-100 HOT-FORMING SIMULATIONS

" 2% compressive 55 <-150 <-150 - - -

Loading at 550 F

A brief qualitative investigation was conducted to see if certain steels became embrittled at 550 degrees. Two samples each of A537-B, NAXTRA-100, and T-1 were strained at temperature in the Gleeble with the following results.

1. A537-B. One sample was pulled to failure and showed a reduction in area of 57 percent at the fracture. Testing of the other sample was terminated after 5 percent elongation was obtained in the 2-in. gage length.

2.-NAXTRA-100. Testing of two samples was terminated after obtaining a uniform elongation of 5 percent in the 2-in. gage.

3. T-1. Testing of one sample was terminated after obtaining a uniform elongation of 5 percent in the 2-in. gage. The other sample fractured in a nonheated area outside of the gage after 5 percent elongation was reached in the gage section.

Room Temperature Simulations

The results of the room temperature simulations are presented in Table 9.. Figures 6 and 7 show the complete Charpy transition curves for A537-B, NAXTRA-100, and T-1 as examples of the data from these experiments. The results are summarized as follows:

1. ABS-B. The Charpy curve was essentially unaffected by the 5 percent compressive strain, but was shifted 40 degrees to higher temperatures by the 5 percent tensile strain. The yield strength was increased

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Flame Straightening

The measurements of distortion at the plate center during the flame-straightening experiments are summarized in Table 10. The spot patterns referred to appear in Figure 2. The term "distortion" as used in this table refers to the increase in plate height above that measured after tacking. Movement, therefore, represents distortion removal and is positive when the distortion has been reduced. All of the data shown are for plates straightened in the measured temperature range $900 \leq T \leq 1050$ with each spot being spray quenched before beginning heating the next spot. In general, the corners of the frame moved 0.060 in. after welding in the plate, and they remained in approximately the same position during flame straightening. After the plate was cut out, the frame was remeasured, and it was found to return to within about 0.015 in. of its original preweld position.

Two observations can be made from the data in Table 10.

(1) The vertical movement obtained by heating a pattern identical to one which had been heated previously is always very small or in the opposite direction compared to the movement obtained due to the first heating. To illustrate:

Steel	Movement Due to First Heating Of Pattern 1, in.	Movement Due to Second Heating Of Pattern 1, in.
ABS-B	0.042	0.004

TABLE IX . RESULTS OF ROOM TEMPERATURE SIMULATIONS

Steel	Applied Strain	Charpy Results Upper Shelf (ft-lb)	T_{50}	20 ft-lb Temperature	Tensile Results σ_Y (ksi)	Elongation (% in 2 in.)	σ_T (ksi)
ABS-B	as received	112	44	-10	38.5	36	64.0
"	5% tensile	105	84	50	67.7	31.5	71.2
"	5% compressive	117	43	8	-	-	-
"	2% tensile	-	-	-	51.8	37.0	67.7
A537-A	as received	90	1	-48	55.1	33.5	87.4
"	5% tensile	74	28	-7	84.2	27.0	92.1
"	5% compressive	81	29	7	-	-	-
"	2% tensile	-	-	-	67.0	31.5	89.2
A537-B	as received	140	-106	<-150	65.0	34.5	81.0
"	5% tensile	134	-60	-114	86.0	24.5	89.5
"	5% compressive	140	-115	<-150	-	-	-
"	2% tensile	142	-102	<-150	71.8	28.5	84.0
"	2% compressive	152	-90	<-150	-	-	-
NAXTRA-100	as received	55	-94	-123	115.5	22.0	121.7
"	5% tensile	31	-83	-50	133.5	13.0	134.5
"	5% compressive	59	-56	-96	-	-	-
"	2% tensile	-	-	-	124.5	19.0	129.2
T-1	as received	56	-138	-147	98.2	24.0	110.0
"	5% tensile	51	-131	-143	115.0	20.0	115.0
"	5% compressive	55	-124	-134	-	-	-
"	2% tensile	55	<-150	<-150	102.7	22.0	112.7
"	2% compressive	55	<-150	<-150	-	-	-

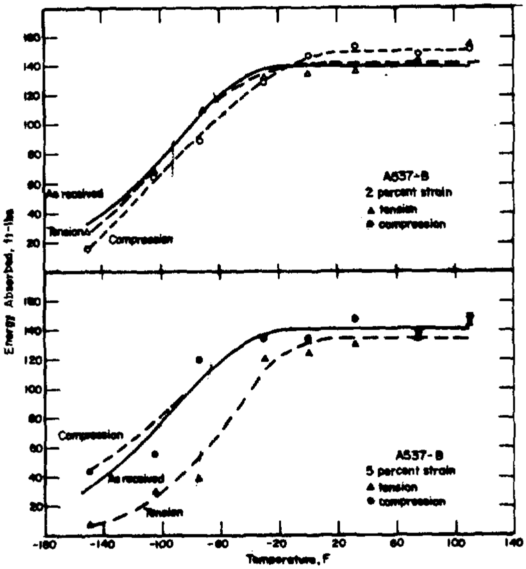

FIGURE 6. CHARPY RESULTS OF A537-B ROOM TEMPERATURE SIMULATIONS

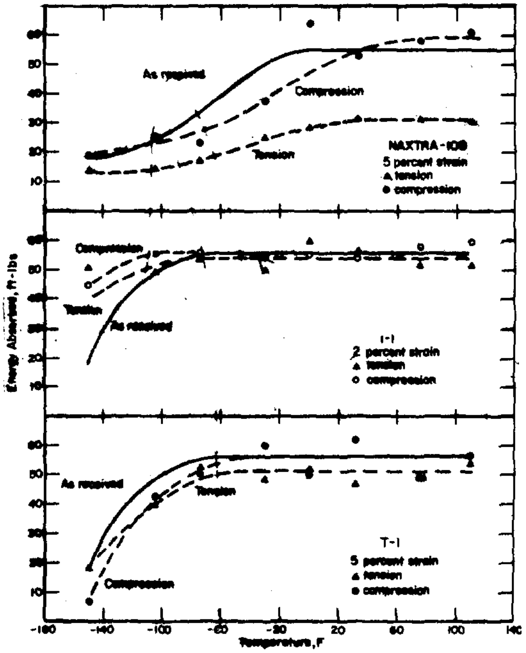

FIGURE 7. CHARPY RESULTS OF T-1 AND NAXTRA-100 ROOM TEMPERATURE SIMULATIONS

Flame Straightening

The measurements of distortion at the plate center during the flame-straightening experiments are summarized in Table 10. The spot patterns referred to appear in Figure 2. The term "distortion" as used in this table refers to the increase in plate height above that measured after tacking. Movement, therefore, represents distortion removal and is positive when the distortion has been reduced. All of the data shown are for plates straightened in the measured temperature range $900 \leq T \leq 1050$ with each spot being spray quenched before beginning heating the next spot. In general, the corners of the frame moved 0.060 in. after welding in the plate, and they remained in approximately the same position during flame straightening. After the plate was cut out, the frame was remeasured, and it was found to return to within about 0.015 in. of its original preweld position.

Two observations can be made from the data in Table 10.

(1) The vertical movement obtained by heating a pattern identical to one which had been heated previously is always very small or in the opposite direction compared to the movement obtained due to the first heating. To illustrate:

Steel	Movement Due to First Heating Of Pattern 1, in.	Movement Due to Second Heating Of Pattern 1, in.
ABS-B	0.042	0.004
A-441	0.036	-0.018
NAXTRA-100	0.010	0.002
T-1	0.029	-0.002*

(2) The amount of plate movement for different steels due to spot heating by identical procedures is related to the yield strength of the material. The lower strength steels give maximum movement. This is illustrated by Figure 8.

After spot heating was completed on each plate, mechanical property specimens were cut from it. Two random spots were mounted and polished in cross section for metallographic examination from which it was determined that none of the plates heated in the measured temperature range of $900 \leq T \leq 1050$ had been heated above the lower critical temperature. The results of the tensile and impact tests on samples taken from these plates are shown in Table 11.

Figure 9 shows the actual Charpy data for both as-received and flame-straightened samples from six steels. The effects of flame straightening upon the properties of the steels as compared to the as-received condition are summarized as follows:

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*Patterns 1 and 2 combined.

TABLE X. FLAME STRAIGHTENING OF STEEL PLATES MEASURED AT PLATE CENTER

Treatment	Distortion,[a] in.	Movement,[b] in.
ABS-B		
After welding	.136	-
Heating Pattern 1 (25 spots)	.094	.042
Heating Pattern 2 (36 spots)	.055	.039
Reheating Pattern 1 (25 spots)	.051	.004
Reheating Pattern 2 (36 spots)	.040	.011
Heating Pattern 3 (60 spots)	.015	.025
Net movement[c]		.121
A441		
After welding	.130	-
Heating Pattern 1 (25 spots)	.094	.036
Heating Pattern 2 (36 spots)	.072	.022
Heating Pattern 3 (60 spots)	.032	.040
Reheating Pattern 1 (25 spots)	.050	-.018
Reheating Pattern 2 (36 spots)	.054	-.004
Heating additional spots (100 spots)	.028	.026
Reheating Pattern 1 (25 spots)	.029	-.001
Net movement		.101
A537-A		
After welding	.146	-
Heating Pattern 1 (25 spots)	.100	.046
Heating Pattern 2 (36 spots)	.073	.027
Heating Pattern 3 (60 spots)	.027	.046
Net movement		.119
A537-B		
After welding	.102	-
Heating Pattern 1 (25 spots)	.059	.043
Heating Pattern 2 (36 spots)	.040	.019
Heating Pattern 3 (60 spots)	.001	.039
Net movement		.101
NAXTRA-100		
After welding	.138	-
Heating Pattern 1 (25 spots)	.128	.010
Heating Pattern 2 (36 spots)	.114	.014
Heating Pattern 3 (60 spots)	.090	.024
Repeat Pattern 1 (25 spots)	.088	.002
Repeat Pattern 2 (36 spots)	.080	.008
Heat additional spots (52 spots)	.089	-.009
Repeat Patterns 1 and 2 (61 spots)	.080	.009
Net movement		.048
T-1		
After welding	.134	-
Heating Pattern 1 (25 spots)	.105	.029
Heating Pattern 2 (36 spots)	.097	.008
Heating Pattern 3 (60 spots)	.057	.040
Reheating Patterns 1 and 2 (61 spots)	.059	-.002
Heating additional spots (100 spots)	.013	.018
Net movement		.121

(a) Distortion is the increase in plate height as measured at the center compared to the height measured after tacking.

(b) Movement is the decrease in distortion as measured at the plate center.

(c) Net movement is the total decrease in distortion at the plate center after the completion of all spot heating.

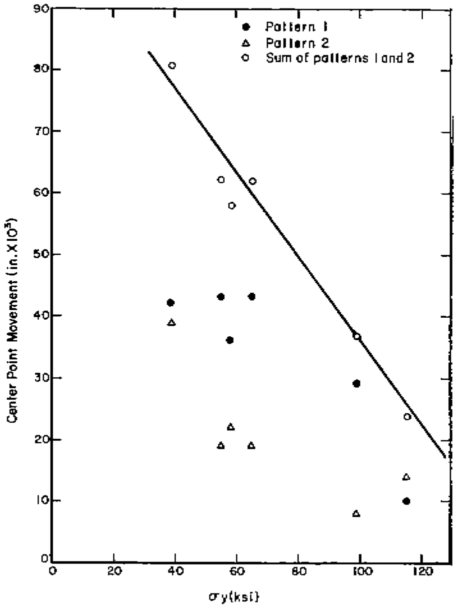

FIGURE 8. DISTORTION REMOVAL FOR PATTERNS 1 and 2 AS A FUNCTION OF YIELD STRENGTH
(The line is drawn through points representing the sum of Patterns 1 and 2.)

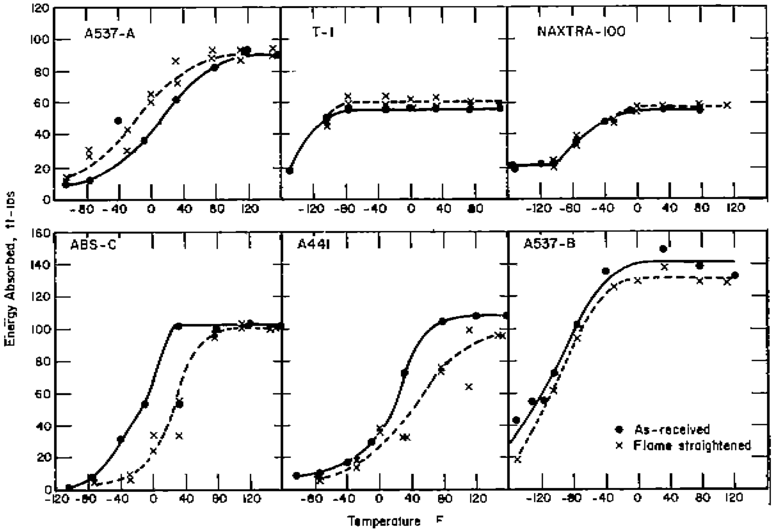

FIGURE 9. CHARPY TESTS ON AS-RECEIVED AND FLAME-STRAIGHTENED SAMPLES

TABLE XI. EFFECT OF FLAME STRAIGHTENING ON MECHANICAL PROPERTIES

	Charpy Results			Tensile Results		
Steel	Upper Shelf (ft-lb)	T_{50}	20 ft-lb Temperature	σ_Y (ksi)	Elongation (pct in 2 in.)	σ_T
ABS-C (as received)	103	-16	-53	44.4	41.0	66.1
" (on spots)	100	30	-3	43.9	32.0	67.1
A-441 (as received)	107	15	-29	57.7	34.5	78.3
" (on spot)	95	35	-20	53.3	28.0	80.5
A537-A (as received)	90	1	-48	55.1	33.5	87.4
" (on spot)	90	-28	-85	-	-	-
A537-B (as received)	140	-106	<-150	65.0	34.5	81.0
" (on spot)	130	-101	<-150	68.4	27.5	87.0
" (between spots)	136	-102	<-150	66.6	28.0	85.1
NAXTRA-100 (as received)	55	-94	-123	115.5	22.0	121.7
" (on spot)	56	-94	-123	116.3	21.5	124.4
" (between spots)	55	-94	-123	115.1	20.5	123.1
T-1 (as received)	56	-138	-147	98.2	24.0	110.0
(on spots)	60	<-105	<-105	110.3	23.5	120.8

1. ABS-C. The Charpy curve was shifted to higher temperatures by 46 degrees with no change in the upper shelf. Yield and tensile strength are unchanged; elongation was reduced from 41 to 32 percent.

2. A441. The Charpy curve was shifted to slightly higher temperatures but this change is not considered significant. Yield and tensile strength are unchanged; elongation was reduced.

3. A537-A. The Charpy curve was shifted 29 degrees to lower temperatures with no change in upper shelf.

4. A537-B. There was no change in the Charpy curve from samples taken either on or between spots. A reduction in elongation occurred.

5. NAXTRA-100. No change in Charpy or tensile properties either on or between spots was found.

6. T-1. No significant change in Charpy properties occurred. A slight increase in yield strength occurred with no change in elongation.

DISCUSSION

Forming Simulations

The results of the forming simulations are summarized in Table 12. The rules used to define a significant change in parameters are repeated in the table. When one of the two principal parameters (upper shelf or T_{50} for impact tests; yield strength or elongation for tensile tests) was changed and the other was not, the test results are interpreted in terms of the change. For example, if T_{50} were increased but the upper shelf were unchanged, the impact properties would be considered to be reduced.

As-Rolled Steel. Forming simulations were made for ABS-B steel. The significant property changes due to hot-forming simulations were shifts to higher temperatures of the impact transition curves after compressive strain at 1300 and tensile strain at 1100. Since no significant changes in properties resulted from these temperatures for samples with no applied strain (the flame-straightening simulations), this reduction of impact properties is due to strain. The transition temperature of samples given equivalent tensile strains in the cold-forming simulation increased by a corresponding amount. The tensile properties were actually enhanced by cold forming.

It is not possible to assess the importance of this reduction in impact properties to ship applications since there are no specific impact requirements for this steel. No distinction between cold and hot forming can be made on the basis of either the static or the dynamic tests.

TABLE XII. SUMMARY OF RESULTS OF FORMING SIMULATIONS*

Steel	Temperature, (F)	Strain, (Percent)	Impact Properties		Tensile Properties	
			Tensile Strain	Compressive Strain	Tensile Strain	Compressive Strain
ABS-B	1300	5	unchanged	reduced	unchanged	unchanged
"	1100	5	reduced	unchanged	--	--
"	75	5	reduced	unchanged	improved	--
"	75	2	--	--	improved	--
A537-A	1300	5	unchanged	unchanged	unchanged	unchanged
"	1100	5	unchanged	unchanged	--	--
"	75	5	reduced	reduced	reduced	--
"	75	2	--	--	improved	--
A537-B	1300	5	unchanged	reduced	unchanged	unchanged
"	1100	5	unchanged	reduced	--	--
"	75	5	reduced	unchanged	reduced	--
"	75	2	unchanged	unchanged	reduced	--
NAXTRA-100	1300	5	improved	improved	reduced	reduced
"	1100	5	improved	improved	--	--
"	75	5	reduced	reduced	reduced	--
"	75	2	--	--	unchanged	--
T-1	1300	5	unchanged	unchanged	reduced	reduced
"	1300	2	unchanged	unchanged	--	--
"	1100	5	unchanged	unchanged	--	--
"	75	5	unchanged	unchanged	reduced	--
"	75	2	unchanged	unchanged	unchanged	--

* The following criteria have been applied to evaluate the effects of the forming sumulations upon material properties.

A shift of 20 degrees in T_{50} is considered to be significant.

A shift of 15 percent in upper shelf energy and elongation is considered to be significant.

A shift of 15 percent in yield strength is considered significant for lower strength steels. A shift of 10 percent is considered significant for NAXTRA-100 and T-1.

Normalized Steel. Forming simulations were made for A537-A steel. The hot-forming simulations on this steel resulted in no significant change in properties. Cold-forming simulations resulted in 30 degree increases in the transition temperature for both tensile and compressive strains of 5 percent. A loss in ductility was observed after 5 percent tensile strain at 75 degrees but the resultant ductility was well above the 22 percent minimum elongation in 2 inches specified by ASTM.

These results indicate hot forming is to be preferred over cold forming for A537-A.

Quenched and Tempered Steel. Forming simulations were conducted on A537-B, NAXTRA-100, and T-1.

For A537-B, the transition temperatures were increased after compressive strain at both 1300 and 1100 in the hot-forming simulation, but not after tensile strain. In the cold-forming simulations, an increase in transition temperature occurred after 5 percent tensile strain and not after 2 percent tensile or up to 5 percent compressive strain. Elongation was reduced after cold tensile strain, but it was still well above the ASTM minimum requirement of 22 percent.

These results for A537-B indicate that compressive strain at elevated temperatures causes a reduction in impact properties, but tensile strain does not. Tensile strain at 75 degrees reduces the impact properties, but compressive strain does not.

For NAXTRA-100, hot-forming simulations improved the impact properties and decreased the tensile properties. These property changes are related to the applied strain since no such changes occurred as a result of temperature alone. The cold-forming simulations resulted in a decrease in tensile and impact properties after both tensile and compressive strains.

For T-1, the hot-forming simulations reduced the tensile properties, but had no effect upon impact properties. The cold-forming simulations did not degrade the properties with the exception of a small loss in elongation with 5 percent tensile strain.

The qualitative studies at 550 showed no embrittlement for A537-B, NAXTRA-100, or T-1.

Flame Straightening

Process

The basis of flame straightening is a controlled application of thermal expansion to cause net plastic deformation. In order to obtain plastic strain, the yield strength must be exceeded. The amount of thermal expansion resulting from heating any low-alloy steel to a given temperature can be considered constant since the coefficient of thermal expansion varies little. The amount of plastic strain available for use in straightening is therefore that portion of the thermal strain which exceeds the strain at yield. This then explains why the amount of flame straightening accomplished is a function of the yield strength of the steel (Figure 8). In principal, any steel can be flame straightened by increasing the temperature, but metallurgical considerations limit the maximum temperature to below the lower critical. Therefore, as the yield strength of the steel increases, the usefulness of flame straightening as a process for distortion removal decreases.

It was observed that, if a series of spots were reheated, little, if any, net straightening occurred. This effect probably occurs because the surface of the spots was left in a residual state of compression after the first flame application. Consequently, in order to achieve the plastic deformation required for straightening, the thermal expansion strain would have to exceed the yield strain plus the residual compressive strain.

Flame straightening can be accomplished with or without a quench. The deciding factor of whether or not to quench is dependent on the stress state within the plate. If the distorted plate is welded into a structure, the stresses exerted by the structure on the plate are the cause of the distortion. If one heats a large area of the plate, this area will be weaker than the cold metal surrounding it. Consequently, the ability of this area to resist the applied stresses will be reduced, and the distortion will be increased. The importance of quenching is, therefore, to keep the area heated in flame straightening small enough to prevent further distortion. Quenching each spot allows one to heat many spots in a short time without allowing any heat buildup in the plate which would reduce the resistance of the plate to the acting stresses. Were it not for the time consideration, one could heat one spot and allow it to air cool before proceeding to the next spot so that the net straightening would be the same as if quenching had been employed. If the plate is not under any stress, quenching would probably not be needed.

Flame straightening has been discussed in this report in terms of spot heating. This pattern of heat application is the easiest to understand and control. However, line heating in which quenching occurs continuously behind the torch can be considered to be a continuous application of spot heating. Therefore, all of the preceding discussion applies equally to line heating.

Properties

As-Rolled Steel. Both as-rolled steels, ABS-C and A441, showed decreases in ductility after flame straightening. This decrease is compared to the appropriate specification below:

Elongation in 2 Inches

	As-received	Flame Straightened	Specification Requirement
ABS-C	41.0	32.0	22.0 (ABS)
A441	34.5	28.0	18.0 (ASTM)

Hence both steels will pass requirements for elongation. ABS-C showed the only significant reduction in impact properties of all steels studied with a 46 degree increase in Charpy transition temperature. Since there is no pertinent requirement for this parameter, the evaluation is not as simple as for elongation. Flame straightening has always been permitted for as-rolled carbon steels with no required qualification tests. These steels were included in this program to furnish a base line with which to judge the heat-treated steels yet ABS-C was the only steel for which impact properties were reduced by flame straightening.

Normalized Steel. The normalized steel A537-A showed no loss in properties due to flame straightening. Consequently, flame straightening is an acceptable fabrication process for this steel.

Quenched and Tempered Steels. The three quenched and tempered steels studied, A537-B, NAXTRA-100, and T-1, were not affected by flame straightening at the heated spots, or, in the case of A537-B and NAXTRA-100, between the spots. The only measured change in properties was a reduction in elongation from 34.5 percent to 27.5 percent for A537-B; however, since the ASTM specification for this steel requires only 22 percent elongation, the as-straightened properties meet the requirements in this instance. Since NAXTRA-100 and T-1 are proprietary steels, they are not subject to ASTM requirements; however, since no reduction in properties occurred, it can be concluded that flame straightening should be permitted in these steels.

CONCLUSIONS

The conclusions reached in this program are of necessity based on the specific plates studied. No generally accepted criteria to specify the permissible reduction in property exists. For some steels where a significant loss in properties occurred, the criteria used to judge the severity of this degradation were the applicable specifications of the appropriate classification body (ABS or ASTM). If the as-received properties of the steels had been only slightly above the specified maximum, the degradation could have been sufficient for the steel to fail to meet the requirements; hence, this type of criterion should only be used with caution.

It is worthy of note that the properties of the heat-treated steels were more stable to heating than those of the as-rolled steels.

If the forming simulations are judged on the basis that no reduction in properties is allowed, the only conclusive result is that hot forming is to be preferred over cold forming for A537-A steel. In general, warm forming at 1100 F appears to be preferred over cold forming for 5 percent strain.

The following conclusions have been reached regarding flame straightening:

(1) Flame straightening can be applied as a distortion removal process to both normalized and quenched and tempered steels with no reduction in static or dynamic properties. Its use should be permitted under controlled conditions in shipyards.

(2) Flame straightening can be accomplished within the temperature range of $900 \leq T \leq 1050$ as measured by temperature-indicating crayons with no metallurgical transformation of the steel.

(3) The usefulness of flame straightening as a distortion removal process decreases as the yield strength of the steel increases.

(4) Quenching should be employed as a part of the flame-straightening process for plates under stress.

(5) No useful straightening can be obtained by reheating a spot which has previously been heated.

(6) No reduction in properties occurs at areas adjacent to the heated region.

Comments on Flame-Straightening Practice

In general, the procedures for flame straightening of high-strength steel are similar to those currently used to flame straighten hot-rolled steel with the important addition of temperature control. For spot heating either type of steel one should heat the convex side of the plate in an array of spots such as that shown in Figure 2. The arrangement of the spots should be made in intermixed patterns similar to those shown in the figure so that the heating can be terminated after any pattern when the distortion has been removed. A typical spot spacing for a single pattern is around 6 inches.

The specific heating and quenching equipment is not critical. The torch should be selected with the thought in mind that the plate temperature must be controlled; this will tend to dictate a smaller torch. An Oxweld 100 A3 torch tip was used successfully in this program. The peak temperature of the heated spot on the plate should lie between 900 and 1050 F. During heating, the temperature should be periodically monitored by lifting the torch and quickly making simultaneous marks with temperature-indicating crayons corresponding to 900 and 1050 F. Heating is completed when a temperature of 900 degrees is indicated. A temperature of 1050 F should never be reached. Once 900 degrees has been reached, the water quench should be applied immediately and held on the spot until no further steam is seen. Once the spot has been quenched, heating can be begun on the next spot.

The only guiding factor for selecting spot sequence is that a build-up of heat in the plate should not be allowed to occur. For this reason, adjoining rows were never heated successively in this program so that quenched material had additional time to cool. The spots were heated in order within a single row.

APPENDIX A

THE USE OF THE GLEEBLE FOR ELEVATED-TEMPERATURE SIMULATIONS

This appendix is included to present greater detail on the Gleeble techniques used for elevated-temperature simulations than appears in the body of the report.

Figure A shows a Charpy blank in the Gleeble load-cell configuration employed for tensile prestrain to simulate hot forming. The sample itself (A) is 0.455 in. x 0.5 in. x 6 in.; the 0.455-in. dimension was machined before heating to provide good electrical contact with the wedge blocks (B). The wedge blocks are made of copper-based Mallory 3 alloy. Item C is a two-piece bolted clamp used to provide additional gripping of the sample. The dial gage (D) is mounted on the sample itself through the pins (E) so that the change in length can be observed continuously independent of any possible slippage in the jaws. These pins are both in the cooler region of the sample; an insulated tip was used in the dial-gage arm to prevent any current flow through the gage itself. The jaws (F) are water cooled; the electrical current flows from the jaws to the wedge blocks and through the sample. The indicated jaw spacing of 2 inches was used for all Charpy samples.

A chromel-alumel thermocouple, shown welded to the center of the sample is used to control the sample heating. If compressive loading were desired, the only configuration change necessary would be to insert additional blocks between the bolted clamps and the back of the jaws. For flame-heating simulations which required no load, the tensile configuration was used.

The thermal cycle used for both flame-straightening simulations and hot-forming simulations consisted of a linear rise from ambient to the desired temperature over a 15-second interval. The hold time at temperature was dependent upon the particular experiment. The cooling cycle occurred at the natural rate for all samples except those quenched where a water quench was employed.

The load was applied near the end of the hold cycle. The right jaw in the figure is movable, and the left is locked in position. When loading began, the change in length was monitored continuously by the dial gage, and when the desired elongation had been accomplished both the load and the heating current were turned off simultaneously. Provisions were made for the jaws to remain movable during cooling so that thermal contraction could occur. Measurements of length and cross section were made before and after the Gleeble cycle for all specimens; the measured length changes were in agreement with that indicated by the dial gage.

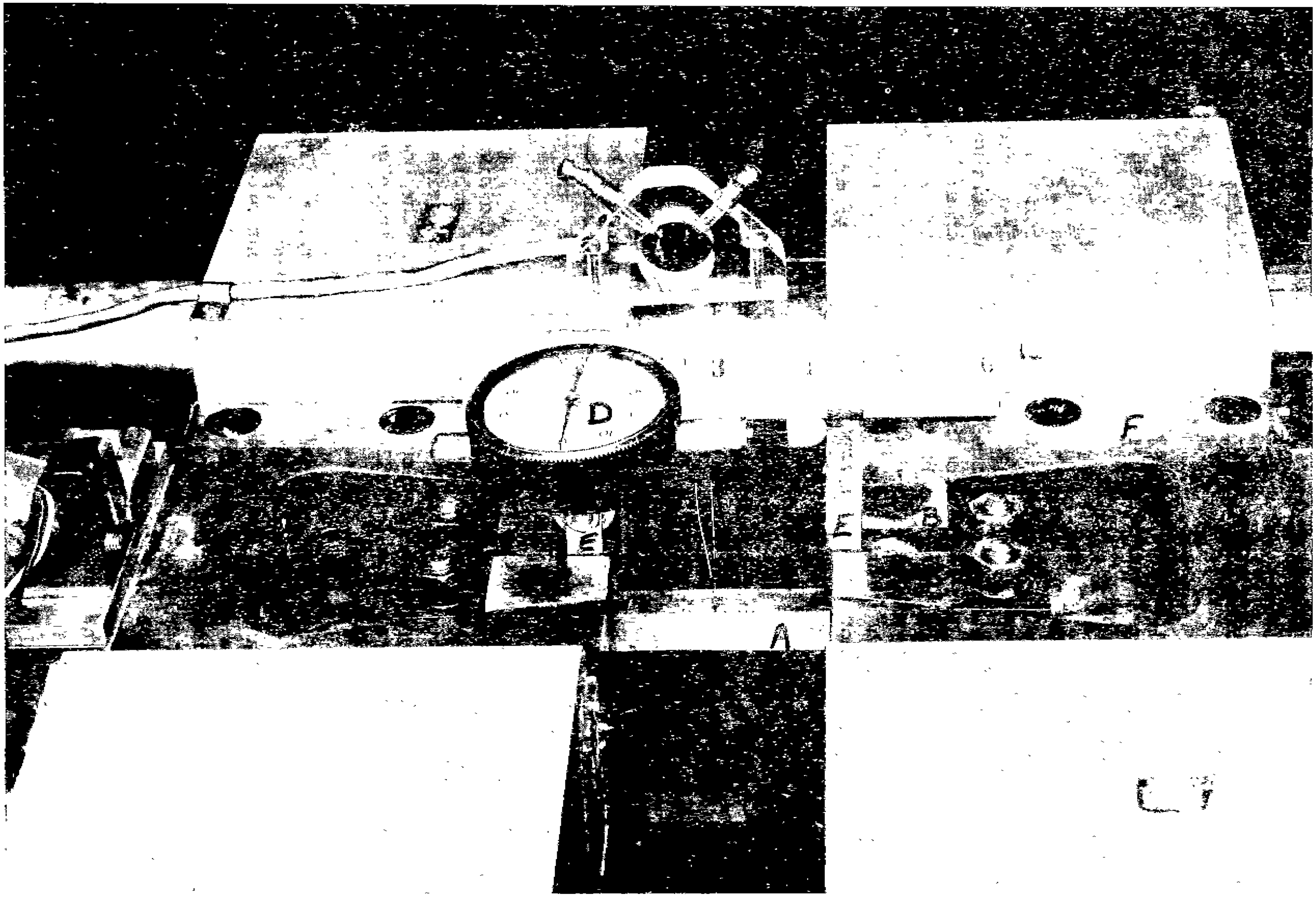

FIGURE A-1. SPECIMEN IN THE GLEEBLE IN THE TENSILE CONFIGURATION

APPENDIX B

SPOT HEATING AT OTHER TEMPERATURES

During the course of this investigation, straightening experiments were conducted on plates in addition to those reported in the body of the report. These additional experiments were conducted to study the effects of temperature and spot pattern in a semiquantitative manner, so as to develop proper procedures. The spot locations did not necessarily correspond to that shown in Figure 2 of the text. Most of these additional plates were spot heated at $800 \leq T \leq 1000$; one was heated at $1050 \leq T \leq 1250$. The 1050 - 1250 temperature range was dropped from consideration after metallographic examination revealed some transformation had occurred at the surface. The results of these experiments are summarized for completeness in the accompanying Table B, which follows the format used for Table 10 in the text.

TABLE B-I. ADDITIONAL FLAME-STRAIGHTENING EXPERIMENTS AS MEASURED AT PLATE CENTER

Treatment	Distortion,(a) in.	Movement,(b) in.
	ABS-C ($800 \leq T \leq 1000$)	
After welding	.038	--
Heating 25 spots	.008	.030
Heating 16 spots	.016	.024
Net movement(c)		.054
	A537-A ($800 \leq T \leq 1000$)	
After welding	.059	--
Heating 25 spots	.045	.014
Heating 16 spots	.025	.020
Heating 40 spots	-.014	.039
Net movement		.073
	A537-B ($800 \leq T \leq 1000$)	
After welding	.100	--
Heating 25 spots	.063	.037
Heating 24 spots	.039	.024
Heating 40 spots	.005	.034
Net movement		.095
	NAXTRA-100 ($800 \leq T \leq 1000$)	
After welding	.110	--
Heating 25 spots	.087	.023
Heating 16 spots	.076	.011
Heating 40 spots	.045	.031
Reheating 25 spots	.040	.005
Reheating 16 spots	.035	.005
Net movement		.074
	T-1 ($800 \leq T \leq 1000$)	
After welding	.049	--
Heating 25 spots	.043	.006
Heating 16 spots	.032	.011
Heating 40 spots	.012	.020
Net movement		.037
	NAXTRA-100 ($1050 \leq T \leq 1250$)	
After welding	.107	--
Heating 25 spots	.069	.038
Heating 32 spots	.058	.011
Reheating 13 spots	.029	.029
Net movement		.078

(a) Distortion is the increase in plate height as measured at the center compared to the height measured after tacking.

(b) Movement is the decrease in distortion as measured at the plate center.

(c) Net movement is the total decrease in distortion at the plate center after the completion of all spot heating.

DOCUMENT CONTROL DATA - R & D

(*Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified*)

1. ORIGINATING ACTIVITY (*Corporate author*) Battelle Memorial Institute Columbus, Ohio	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Effect of Temperature and Strain Upon Ship Steels

4. DESCRIPTIVE NOTES (*Type of report and inclusive dates*)

5. AUTHOR(S) (*First name, middle initial, last name*)

R. L. Rothman and R. E. Monroe

6. REPORT DATE March, 1973	7a. TOTAL NO. OF PAGES 29	7b. NO. OF REFS 0
8a. CONTRACT OR GRANT NO. N00024-71-C-5088 b. PROJECT NO. SR-199 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (*Any other numbers that may be assigned this report*) SSC-235	

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY (Ship Structure Committee) Naval Ship Systems Command

13. ABSTRACT

The effects of flame straightening and both hot and cold forming upon materials properties of hot-rolled, normalized, and quenched and tempered steels were investigated. Flame straightening was studied by first simulating the effects of time at temperature upon the tensile and impact properties of seven steels. Straightening was then performed within the determined limits upon 4-foot-square plates which had been distorted by welding them into a rigid frame. As a result of these studies, it is recommended that flame straightening with appropriate controls be allowed as an acceptable process for distortion removal for both normalized and quenched and tempered steels.

Simulations of outer fiber strain resulting from both hot and cold forming were conducted to determine the effects of temperature and strain upon properties. In general, it was found that either tensile or impact properties were reduced to some degree by most operations.

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Flame straightening						
Plate forming						
Ship construction						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

Security Classification

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