SSC-167

Restoration of Ductility of Hot or Cold Strained ABS-B Steel by Heat Treatment at 700 to 1150°F

by

C. MYLONAS AND R. J. BEAULIEU

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April 1965

Dear Sir:

In order to study the effect of gross strain upon the mechanical and metallurgical properties of steel and to relate those variables to steel embrittlement, the Ship Structure Committee is sponsoring a project at Brown University entitled "Macrofracture Fundamentals." Herewith is a copy of the Fourth Progress Report, SSC-167, Restoration of Ductility of Hot or Cold Strained ABS-B Steel by Heat Treatment at 700 to 1150°F by C. Mylonas and R. J. Beaulieu.

The project is conducted under the advisory guidance of the Ship Hull Research Committee of the National Academy of Sciences-National Research Council.

Comments on this report would be welcomed and should be addressed to the Secretary, Ship Structure Committee.

Sincerely yours,

John B. Oren

John B. Oren
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-167

Fourth Progress Report
of
Project SR-158
"Macrofracture Fundamentals"

to the

Ship Structure Committee

RESTORATION OF DUCTILITY OF HOT OR COLD STRAINED ABS-B STEEL BY HEAT TREATMENT AT 700 TO 1150°F

by

C. Mylonas and R. J. Beaulieu

Brown University
Providence, Rhode Island

under

Department of the Navy
Bureau of Ships Contract NObs 88294

Washington, D. C.
National Academy of Sciences-National Research Council
April 1965

ABSTRACT

The severe embrittlement caused by a suitable history of strain and temperature has been confirmed also for steel conforming to ABS-B classification. Steel prestrained in compression by about 50% at 70 F and subsequently tested in tension fractures at an extensional strain of the order of 1%. Prestraining at 550 F by even 25% can cause brittleness in extension at -16 F. Local severe embrittlement of this nature has been shown to be the basic cause of the static initiation of brittle failure of structures at low average stress. This is confirmed by service failures, whose origin is frequently traced to cold worked areas, or to the hot strained regions of defects close to welds.

It is shown that a suitable heat treatment can restore appreciable ductility to steel embrittled by hot or cold straining. The duration of heating decreases with the temperature, but increases very rapidly with the amount of prestrain. To each temperature corresponds a limiting prestrain for which heat treatment becomes impractically long. Cold strained steel requires considerably longer heat treatment and higher temperatures (1000-1200 F) than hot strained steel (700-1000 F). Approximate time-temperature-prestrain curves have been experimentally determined.

The results confirm that a major beneficial effect of the so-called "thermal stress-relieving" treatment is a restoration of the ductility of locally embrittled steel.

CONTENTS

Page

1. INTRODUCTION 1
2. EXHAUSTION LIMITS OF ABS-B STEEL 2
2a. Material 2
2b. Testing Method 2
2c. Warm Prestraining 4
3. RESTORATION OF DUCTILITY BY HEATING 6
3a. Heat Treating Procedure 6
3b. Description of the Tests 7
3c. Test Results 7
3d. Tentative Explanation of the "worst" Prestraining Temperature 9
4. CONCLUSIONS 17
REFERENCES 19

INTRODUCTION

The understanding of the mechanism of brittle fracture of structures was greatly advanced by the fundamental observations of Wells (1,2) and the analysis of Drucker (3), which related the overall static behavior of a structure to the amount of plastic deformation at the most severely strained region. Typically brittle failures *under static central loading are those* occurring before the incidence of general yielding of the cross-section, when the plastic strains at the root of cracks or notches are relatively small and the average stress smaller that yield. Conversely a ductility smaller than needed at the roots of cracks or notches when *general yielding begins*, should cause fracture at an average stress level lower than yield, hence brittle fractures. Ordinary structural steels tested in the laboratory, however, had been found to have sufficient ductility so as to avoid low static stress fracture in spite of cracks and a low temperature. Consequently, it became clear that service fractures occurring under static loading at low average stress indicated a loss or reduction of the initial ductility of structural steel in the regions of cracks or notch roots. This has been experimentally verified by deliberately damaging the steel so as to reduce its ductility at the notch roots in order to obtain fractures at low average stress. The reduction of ductility was achieved in the laboratory by prestraining notched plates in compression. (4-6) When subjected to subsequent tension these essentially unwelded plates fractured at an average net stress as low as 10% of yield. Extensive research (4-16) with prestrained notched plates, bent beams, and axially compressed bars, has shown that the ductility of steel depends on the whole history of prior strain and temperature, and may be drastically exhausted by cold straining of a closely determined amount, and far more easily by straining at about 500-600°F. The exhaustion of ductility caused by suitable straining appears as a major factor in the mechanism of static brittle fracture initiation. This is in striking agreement with the general finding that service failures are initiated in cold-worked regions or at defects close to welds, where complex hot straining occurs.

Brittle fracture initiation close to welds was first simulated in the laboratory by Greene (19) with plates butt-welded along edges containing prepared notches. Similar tests were systematized by Wells (1,2,20) and with many variations by *several other investigators* (21-30). The early cracks and failures of these plates have been mostly attributed to the strong longitudinal residual tension of the thermally contracting region adjacent to the weld. A strong argument in favor of this view has been the prevention of fracture by the so-called "thermal stress-relieving" operation which consists of heating to about 1200°F. Nevertheless, opinions vary widely on the subject of the influence of residual stresses (6,13,18,30,31). With our present knowledge it is readily seen that the local embrittlement resulting from the complex hot straining during the welding cycle is the most likely cause of the test plate failures at the welded-over notches, and of service failures originating close to welds (12).

Increasing attention has been given in the last years to the importance of the embrittlement caused by the history of strain and temperature, particularly in the vicinity of welds (18,25,26,32). The change of ductility of the parent plate near a weld has been confirmed by hardness measurements (33), and by tension (34) and impact tests (35) of notched specimens taken at various distances from the weld. A number of independent investigators starting from different points of view have studied various aspects of the influence of the history of strain and temperature on the properties of steel (36-56). Notable among these is the work of Körber, Eichinger, and Möller, (36) which had escaped the attention of all subsequent investigators.

If the cause of the failures originating at discontinuities near welds or in cold worked regions is the embrittlement caused by hot or cold straining, the highly beneficial effect of the so-called "thermal stress relieving treatment" should be a restoration, at least in part, of the ductility of the steel. "Mechanical stress relieving" (21,41) may also restore some ductility as shown by instances of strain-softening (39,40). Heat treatment at temperatures higher than 1100-1200°F is employed after forming or spinning.

Lagasse and Hoffmans (45-47) have confirmed that steel sheet embrittled by cold forming could be made sufficiently ductile by heating at about 1100 F, i.e. at the stress relieving temperature. A small number of preliminary tests (15) with E-, ABS-C and A-7 type steel embrittled by cold compression supported this view.

The purpose of the present tests is to study the relation between the required duration and temperature of heat treatment and the amount and temperature of prestrain. Besides their practical usefulness for "stress relieving", the results could give some indication on the nature of the processes involved in the restoration of ductility and on the physical causes of the initial embrittlement. The precision of the tests depended on the ability to produce controlled embrittlement, and to heat rapidly to the desired temperature so as to avoid significant influences of the intermediate temperatures. Controlled prestrain was effectively produced with the reversed bent test. The rapid heating was achieved by immersion in a lead bath.

2. EXHAUSTION LIMITS OF ABS-B STEEL

2a. Material. The bars used in all tests were cut in the direction of rolling from 3/4 in. plates conforming to ABS Class B specifications, of the same heats as plates tested at the National Bureau of Standards. Composition and properties are shown in Tables I and II.

2b. Testing Method. Exhaustion limits in cold-straining. The reversed bent test

TABLE I. COMPOSITION OF ABS-B STEEL.

	C	Mn	P	S	Si	Ni	Cu	Cr	Al	N
Minimum	0.14	0.91	0.009	0.018	0.041	0.021	0.051	0.023	0.02	0.004
Maximum	0.18	1.07	0.012	0.028	0.056	0.040	0.096	0.031	0.03	0.006
Typical	0.14	1.04	0.011	0.018	0.056	0.023	0.083	0.031	0.02	0.004
	0.15	0.94	0.009	0.027	0.046	0.040	0.094	0.023	0.02	0.005

TABLE II. PROPERTIES OF ABS-B STEEL.

	Yield Point ksi	Ultim. Strength ksi	Elong. (8") %	Finish Temp. °F	Ferrite Grain Size	°F			Nil Duct. Temp. °F Center	Fibrous	
						T_{V10}	T_{V15}	T_{V20}		50% °F	10% °F
Maximum	32.6	57.9	31.0	1600	7.8	-30	-24	-13	-20	24	-22
Minimum	35.7	63.9	33.0	1725	8.2	-5	6	18	-10	39	-10
Typical	33.8	58.4	33.0	1640	7.8	-5	6	18	-10	37	-14
	35.7	59.8	32.0	1600	8.1	-11	2	+11	-10	28	-15

From 12 analyses and 6 tests by the Nat. Bureau of Standards on pieces taken from plates of the same heat as used in the present tests.

(13,14) was employed throughout the present investigation. Bars of dimensions 9 x 1.00 x 0.75 in. are bent at first slightly in four point loading (Fig. 1a), and then more in longitudinal compression till they buckle and bend by various amounts (Fig. 1b). This is referred to as the prestrain or initial bending. The final test consists of pulling the bars open in a reversed bending action (figures 1c and 2). The compressive prestrain ε_o at the intrados (which is one of the as-rolled surfaces of the steel plate) is calculated from the radius of curvature R and the bar thickness h

$$\varepsilon_o = h/(2R+h)$$

As was found with tests of other steels, bars prestrained above a certain limit are brittle and fracture in reverse bending at small strains and low loads. Bars prestrained below this limit have sufficient ductility so as not to fracture even when pulled open by large amounts, corresponding to large extensional strains and high loads. The prestrain causing the sudden reduction of ductility is referred to as the exhaustion limit. The great convenience of the reversed-bend tests is the ease with which the exhaustion limit may be determined by simple measurement of the load at fracture. As shown in Figure 3 (right) bars prestrained at 70°F by more than 0.55 (55%) and aged (1 1/2 hours at 300°F) cracked or fractured in subsequent reversed bending at 70°F under loads well below 3000 lb. On the contrary bars prestrained below 0.55 did not break at loads well above 5000 lb. Bars withstanding the arbitrary load of 5000 lb. are called ductile; those breaking at loads below 5000 lb. are brittle. Any other load limit higher than about 3000 lb. would give the same exhaustion limit of 0.55 for these conditions of testing. The exhaustion limit is usually determined within a strain of ±0.02 or less. For bars prestrained at 70°F, aged and tested at -16°F the exhaustion limit lies between

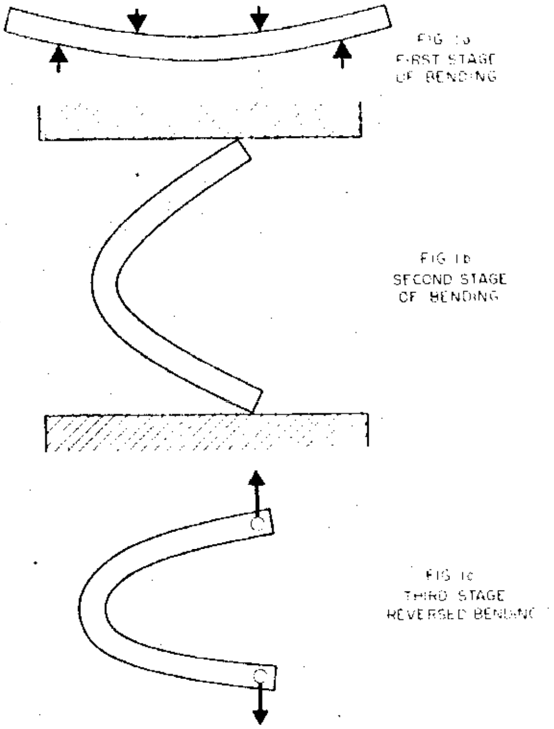

FIG. 1. SCHEMATIC BENT BAR TESTING.

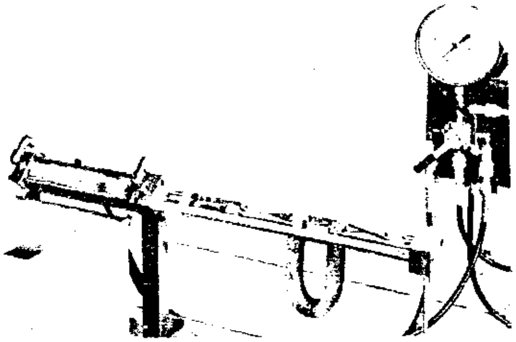

FIG. 2. HORIZONTAL TESTING MACHINE FOR BENT BARS IMMERSED IN COOLING BATH. (TANK MOVED TO THE LEFT).

0.45 and 0.48 (Fig. 3, left). The detailed results of 62 tests plotted in Figure 3 are given in Table III.

During final testing, all bars were immersed in a liquid bath. This reduced the localized heating caused by plastic work, provided the test was slow, and eliminated the convection heating of bars tested at -16°F. A special horizontal hydraulic testing machine was built for this purpose (Fig. 2). The legs of the U-shaped bars are upright and the lower curved part hangs inside a cooling tank (moved to the left in Figure 2). Water was used for the tests at 70°F, and glycerine at 60% concentration for the tests at -16°F. Glycerine was not found to affect significantly the results.

The exhaustion limit is a sensitive indicator of the influence of many variables on the embrittlement of steel. A reduction of the exhaustion limit indicates a stronger embrittling action, since a lower prestrain exhausts the ductility to the point of brittleness. An increase of the exhaustion limit indicates a less embrittling action. Thus, aging and low testing temperatures reduce the exhaustion limit.

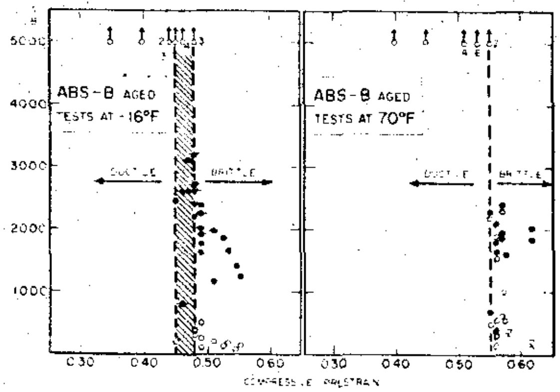

FIG. 3. EXHAUSTION LIMITS OF ABS-B STEEL INITIALLY BENT AT 70° AND AGED.

2c. Warm prestraining. As discussed elsewhere (12,15) the easier embrittlement caused by straining at about 500 to 600°F is related with the initiation of brittle fracture at defects close to welds. The most embrittling temperature and the corresponding reduced exhaustion limit may prove useful indications of how prone a steel is to such embrittlement.

Bars were prestrained at various temperatures up to 850°F. After heating in

TABLE III. EXHAUSTION LIMIT OF BARS OF ABS-B STEEL PRESTRAINED AT 70° AND AGED.

TESTS AT -16°F		
Strain	Test Load (lb.)	
	Arr. Crack	Fracture
.35		*
.40		*
.45		*
.45		*
.45		*
.45	200	2650
.46		*
.46		*
.46		*
.46		2600
.46		*
.46		600
.47		3100
.47		2600
.48		3200
.48	300	2600
.48		*
.48		2600
.48		*
.48		2700
.48	300	2200
.48		*
.49		3830
.49		1975
.49	100	2400
.49	500	1750
.49	250	1650
.49		[illegible]
.53	100	1850
.53	100	1550
.53	100	1445
.60	[illegible]	1235

TESTS AT 70°F		
Strain	Test Load (lb.)	
	Arr. Crack	Fracture
.40		*
.45		*
.51		*
.51		*
.51		*
.52		*
.51		*
.51		*
.53		*
.53		*
.53		*
.53		*
.55		*
.55	500	[illegible]
.55		*
.55	2200	2300
.56	300	[illegible]
.56	1550	[illegible]
.56	150	[illegible]
.56	1900	[illegible]
.56	550	[illegible]
.56	300	1455
.57	650	[illegible]
.57	550	[illegible]
.57	2300	[illegible]
.57	1000	[illegible]
.62	200	[illegible]
.62	100	[illegible]

* No fracture at 5000 lb., equivalent to over 80 ksi.

an oven to the required temperature the bars were given the initial four-point bending (Fig. 1a), and after reheating for about 30 min., they were bent to the required radius and left to cool. One or more days later they were tested in reversed bending (Figures 1c and 2) at 70°F or -16°F. The results of 76 tests at 70°F and of 82 tests at -16°F are given in Tables IV a, b, and V a, b, and in graph form in Figures 4 and 5, where the temperature of prestrain is plotted against the amount of prestrain, and the behavior of the bars in subsequent tension is marked by a black circle when brittle, and by an open circle when ductile (i.e. when no fracture had occurred under 5000 lb. or more). A "worst" temperature range exists around 550°F, for bars tested at 70° as well as -16°F.

TABLE IV (a) and (b).

EXHAUSTION LIMIT OF BARS OF ABS-B STEEL PRESTRAINED HOT AND TESTED AT 70° F.

BAR	INITIAL BEND		TEST LOAD (lb)		FRACTURE STRESS
	Strain	°F	Arr. Crack	Fracture	$4P/\pi d^2$ ksi
B 6	0.23	500		+	+
B 7		500		+	+
B 46	0.24	550		+	+
B 47		550		+	+
B 4	0.27	450		+	+
B 5		450		+	+
B 14		550		3510	
B 15		550		+	+
B 1		650		+	+
B 2		650		+	+
B 52	0.30	450		+	+
B 53		450		+	+
B 48		550		3510	77.5
B 49		550		+	+
B 54		650		+	+
B 55		650		+	+
B 32	0.33	450		+	+
B 33		450		2060	45.4
B 16		550		+	+
B 17		550	1440	1650	-
B 68		550		+	+
B 69		550		2100	43.6
B 34		650		+	+
B 35		650		+	+
B 8		700		+	+
B 9		700		+	+
B 42	0.35	550		2060	45.9
B 43		550		+	+
B 38	0.37	400		+	+
B 39		400	820	2890	-
B 28		450	1650	2060	-
B 29		450		2060	48.6
B 70		550	1030	2270	-
B 71		550	620	1650	-
B 58		550	1240	1650	-
B 59		550	1650	2060	-
B 26		650	1130	1440	-
B 27		650	1130	1440	-
B 36		700		3090	77.[illegible]
B 37		700		1650	38.9
B 56		800		+	+
B 57		800		+	+

+ No fracture at 5000 lb., equivalent to over 80 ksi.

TABLE IV (b)

BAR	INITIAL BEND		TEST LOAD (lb)		FRACTURE STRESS
	Strain	°F	Arr. Crack	Fracture	$4P/\pi d^2$ ksi
B 10	[illegible]	300		+	+
B 11		300		+	+
B 22		400		2060	[illegible]
B 23		400		+	+
B 74		500	1650	3520	-
B 75		500	[illegible]	2440	-
B 24		700	1440	2650	-
B 25		700		[illegible]	48.1
B 40		750		2250	[illegible]
B 41		750		[illegible]	47.9
B 12		800		+	+
B 13		800		+	+
B 60	0.48	250		+	+
B 61		250		+	+
B 44		300	620	2130	+
B 45		300		+	+
B 64		400	2030	[illegible]	
B 65		400	1440	[illegible]	-
B 72		550	210	2040	-
B 73		550	210	2330	-
B 78		700	2030	2680	-
B 79		700		3710	
B 30		800		+	+
B 31		800		2690	[illegible]
B 62		850		+	+
B 63		850		+	+
B 20	0.54	250	3500	3040	-
B 21		250	1100	2060	-
B 66		400	210	1440	-
B 67		400	820	1650	-
B 76		650	1850	3300	-
B 77		650		2820	
B 50		1000		+	+
B 51		1000		+	+

+ No fracture at 5000 lb., equivalent to over 80 ksi.

TABLE Va.

EXHAUSTION LIMIT OF BARS OF ABS-B STEEL PRESTRAINED HOT AND TESTED AT -16° F.

BAR	INITIAL BEND		TEST LOAD (lb)		FRACTURE STRESS
	Strain	°F	Arr. Crack	Fracture	$4P/\pi d^2$ ksi
B 058	0.20	550		+	+
B 059		550		+	+
B 046	0.22	550		4330	91.5
B 047		550		4540	87.4
B 06	0.23	500		+	+
B 07		500		4950	75.0
B 048		550	1850	1690	-
B 049		550		3320	76.[illegible]
B 056		600		+	+
B 057		600		4540	95.5
B 038	0.24	400		+	+
B 039		400		+	+
B 030		450		3720	70.7
B 031		450		2270	49.0
B 052		550		3510	72.0
B 053		550		1850	[illegible]
B 032		650	1240	1650	-
B 033		650		3510	70.0
B 036		700		+	+
B 037		700		+	+
B 060	0.27	400		+	+
B 061		400		+	+
B 04		450		820	
B 05		450		+	+
B 062		550		2060	
B 063		550		1850	
B 02		650		3710	92.0
B 03		650		3420	83.0
B 022		700		2490	51.1
B 023		700		+	+
B 064	0.30	300		+	+
B 065		300		+	+
B 068		400		2490	
B 069		400		1850	
B 078		450		2370	51.0
B 079		450		2890	67.0
B 070		550		1650	
B 071		550		1240	
B 026		650		1850	49.0
B 027		650		2690	62.6
B 040		750		+	+
B 041		750		3920	87.2
B 066		800		+	+
B 067		800		+	+

+ No fracture at 5000 lb., equivalent to over 80 ksi.

TABLE Vb. EXHAUSTION LIMIT OF BARS OF ABS-B STEEL PRESTRAINED HOT AND TESTED AT -16° F.

BAR	INITIAL BEND		TEST LOAD (lb)		FRACTURE STRESS
	Strain	°F	App. Crack	Fracture	[illegible]/bd² ksi
B 072	0.34	300		*	*
B 073		300		*	*
B 074		400		3300	72.8
B 075		400		3370	82.8
B 018		550		2880	56.7
B 019		550		3510	70.9
B 09		700		2060	45.2
B 39		700		3510	77.8
B 034		800		2680	59.4
B 035		800		2890	58.[illegible]
B 076		850		*	*
B 077		850		*	*
B 044	0.37	300		*	*
B 045		300		2890	60.0
B 070		400	206	1440	
B 021		400	635	1440	-
B 042		800		3920	95.6
B 043		800		3500	81.5
B 078	0.40	300		*	*
B 079		300		*	*
B 080		400		1850	43.9
B 081		400		1290	47.9
B 082		550		2890	
B 083		550		2480	
B 012		800		3870	92.0
B 013		800		3500	77.4
B 084		850		*	*
B 085		950		3090	72.5
B 054		900		*	*
B 055		900		*	*
B 016	0.44	250		*	*
B 017		250		*	*
B 010		300	1230	1650	34.0
B 011		300	1440	1650	35.9
B 086		800	410	1130	
B 097		800		1950	
B 014		900		3300	79.8
B 015		900		2480	60.[illegible]
B 024		1000		*	*
B 025		1000		*	*

* No fracture at 5000 lb., equivalent to over 80 ksi.

The prestrain at the "worst" temperature causing brittleness at 70°F, is just over half the prestrain at room temperature (about 0.32 as compared to 0.55). For tests at -16°F the difference is even more pronounced: the prestrain at the "worst" temperature is less than half that at 70°F (about 0.22 as compared to about 0.47).

As the prestrain temperature rises above about 600°F, the exhaustion limit increases again, showing a weaker embrittling effect. Above about 900° the exhaustion limit is higher than at room temperature.

3. RESTORATION OF DUCTILITY BY HEATING

3a. Heat treating procedure. Preliminary tests have shown (15) that oven heating produces a very slow temperature rise in the bars. Cold bars would reach the oven temperature in about 30 minutes. This long heating time obscured the time-temperature relationship for heat treatment. A more rapid electrical resistance heating was tried. A 2 volt 4000 amp. current from a modified lighting transformer with a single turn secondary

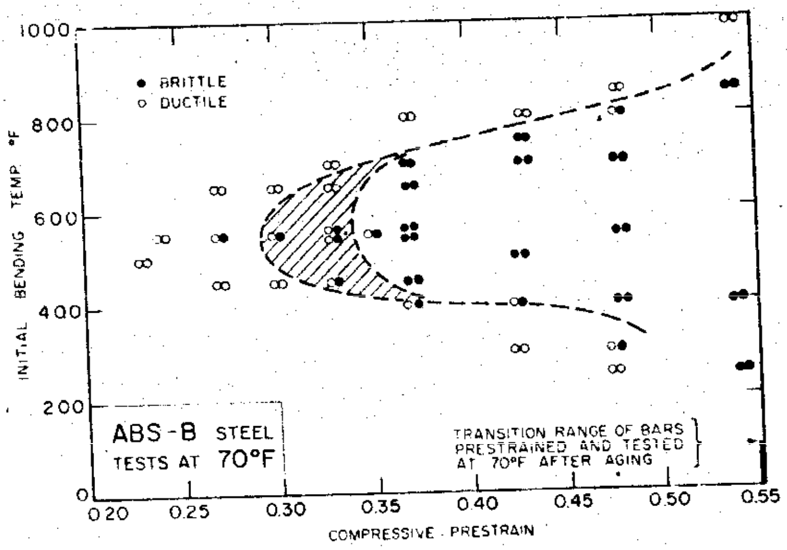

FIG. 4. EXHAUSTION LIMITS OF ABS-B STEEL INITIALLY BENT HOT.

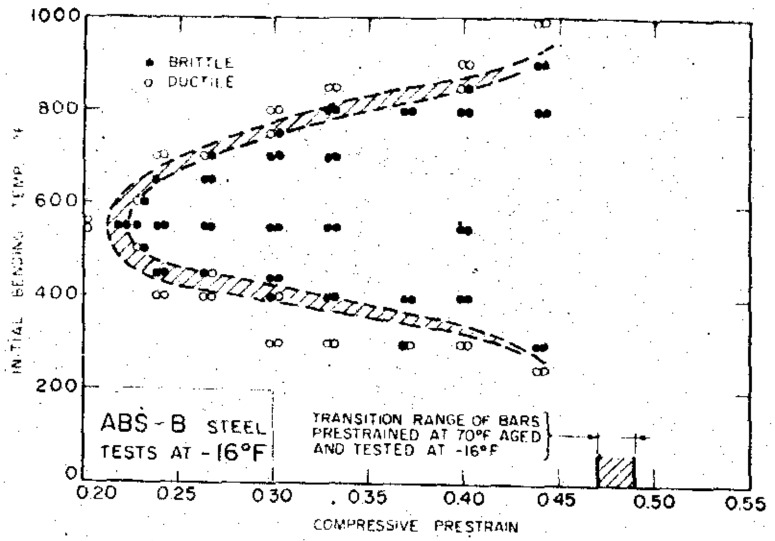

FIG. 5. EXHAUSTION LIMITS OF ABS-B STEEL INITIALLY BENT HOT.

winding was passed through the bent bars held in special clamps. The temperature was measured with thermocouples on the specimens, and was found to reach the desired level in less than 3 minutes, but non-uniform heating resulted, with a hot region at the intrados. The only satisfactory method of uniform and rapid heating was by immersion of the prestrained bars in a commercial lead bath thermostatically controlled to within 5°F. The bars were first immersed partially, with the legs of the U-shaped bars in the lead bath and the intrados outside. Three minutes later, when the intrados had been heated to about 100°F below the bath temperature, and the lead bath had recovered its set temperature, the bars were totally immersed, and in two more minutes were within 5 degrees of the bath temperature. This was taken as the beginning of the heat treating period in all tests. The effect of the short heating time below the test temperature is negligible. For example, bars bent cold to a prestrain of 0.55 and tested at -16°F, were made ductile by a heating of about 10 minutes at 1150°F, 20 minutes at 1100°F and not even 2 hours at 1050°F (Figures 8 and 9). The rate of restoration of ductility decreases quite rapidly when the temperature drops.

3b. Description of the tests. The tests included bars strained at 70°F and at the "worst" temperature of 550°F, and tested after heat treatment at 70° and at -16°F. The bars were prestrained by various amounts above the exhaustion limit for the specific conditions of each test, so that without heat treatment they should have all been brittle. With bars prestrained at 70°F the exhaustion limit was about 0.55 for tests at 70°F, and about 0.45-0.48 at -16 F: and with bars prestrained at 550 F it was about 0.30-0.35 for tests at 70 F and about 0.21-0.22 for tests at -16 F.

The duration of heat treatment varied from 3 to 120 minutes. Temperatures between 1000 and 1150 F for cold strained bars, and between 700 to 1000 F for hot strained bars were tried.

3c. Test results. The results of 206 tests of cold strained bars and 311 hot strained bars are given in Tables VI to XXII. The results are also plotted in the graphs of Figures 6 to 16, according to temperature of prestrain, of heat treatment, and of test. In these figures the heat treating time

TABLE VI. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 70 F HEAT TREATED AT 1000 F; TESTED AT 70 F.

BAR	PRE-STRAIN	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
		°F	Minutes	Arr. Crack	Fracture	$6M/bd^2$ ksi
639	0.56	1000	3	-	2300	
640			3	-	+	+
641			5	-	+	+
642			5	-	+	+
649	0.57	1000	3	-	4200	
650			3	-	2600	
637			5	-	+	+
638			5	-	+	+
633			10	-	+	+
634			10	-	+	+
643	0.59	1000	15	2500	3050	-
644			15		1600	
631			30	-	3100	
632			30	-	+	+
659			60	-	+	+
660			60	-	4800	
651*	0.60	1000	30	-	2500	
652*			30	-	2300	
687*			60	-	2600	
688*			60	-	5050	
719*			120	-	2900	
720*			120	-	4900	
675*	0.62	1000	90	-	4600	
676*			90	-	3100	

+ No fracture at 5000 lb., equivalent to over 80 ksi.

* Shorter bars. Highest load is 6300 lb., equivalent to over 80 ksi.

TABLE VII. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 70 F HEAT TREATED AT 1050 F; TESTED AT 70 F.

BAR	PRE-STRAIN	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
		°F	Minutes	Arr. Crack	Fracture	$6M/bd^2$ ksi
657	0.56	1050	3	-	2100	
658			3	-	1650	
621			5	-	+	+
622			5	-	+	+
671	0.57	1050	5	-	+	+
672			5	-	4900	
661	0.59	1050	8	-	2700	
662			8	-	4500	
635			15	-	+	+
636			15	1200	1600	-
623			30	-	+	+
624			30	-	+	+
711*	0.60	1050	15	-	6150	
712*			15	-	5500	
721*			30	-	*	*
722*			30	-	3300	
743*			60	-	5770 x	-
744*			60	-	5460 x	-
751*			90	-	4740	76.8
752*			90	-	3300 x	-
757*			90	-	4950	71.5
758*			90	-	4950	69.0
723*	0.62	1050	30	-	5800	
724*			30	-	5200	
745*			120	-	2600 x	-
746*			120	-	2800 x	-
677*	0.63	1050	30	-	3100	
678*			30	-	4700	
683*			60	-	4400 x	
684*			60	-	4720 x	

+ No fracture at 5000 lb., equivalent to over 80 ksi.

* Shorter bars. Highest load is 6300 lb., equivalent to over 80 ksi.

x Pre-existing crack, as shown by discolored part of fracture surface.

TABLE VIII. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 70 F HEAT TREATED AT 1100 F; TESTED AT 70 F.

BAR	PRE-STRAIN	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
		°F	Minutes	Arr. Crack	Fracture	$6M/bd^2$ ksi
623	0.56	1100	3	-	+	+
610			3	-	1900	
605			5	-	+	+
606			5	-	2300	
603			10	-	+	+
604			10	-	+	+
627	0.57	1100	8	-	+	+
628			8	-	+	+
615			15	-	+	+
616			15	-	+	+
607			30	-	+	+
608			30	-	+	+
667			60	-	+	+
668			60	-	+	+
665	0.59	1100	8	-	+	+
666			8	-	4500	
625			15	-	+	+
626			15	-	4100	
613			30	-	+	+
614			30	-	+	+
611			60	-	+	+
612			60	-	+	+
673*	0.60	1100	30	-	3200 x	-
674*			30	-	6100	
703*			30	-	2500 x	-
704*			30	-	*	*
759*	0.61	1100	60	-	3300 x	-
760*			60	-	4950	76.5
689*	0.62	1100	60	-	4600	
690*			60	-	4900	
717*			120	-	5900	88.6
718*			120	-	*	*

+ No fracture at 5000 lb., equivalent to over 80 ksi.

* Shorter bars. Highest load is 6300 lb., equivalent to over 80 ksi.

x Pre-existing crack, as shown by discolored part of the fracture surface.

is plotted against the amount of prestrain, which is always higher than the corresponding exhaustion limit shown in the legend. Bars deforming without fracture under a load up to or beyond 5000 lb. are termed ductile and are represented by open circles. Bars fracturing at lower loads are termed brittle and are represented by full circles. To produce prestrains of 0.60 or more (cold strained bars) it was found necessary to shorten the bars, otherwise their legs would touch during bending. These shorter bars are indicated by an asterisk in Tables VI to XII, and were tested to the calculated equivalent load of 6300 lb. It was also found that some of the most highly strained bars had developed cracks before the final test, as was obvious from discolored areas of the fracture surfaces. These bars are marked by the sign x and are not taken under consideration.

TABLE IX. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 70 F HEAT TREATED AT 1150 F; TESTED AT 70 F.

BAR	PRE-STRAIN	HEAT TREATMENT °F	HEAT TREATMENT Minutes	TEST LOAD (lb) App. Crack	TEST LOAD (lb) Fracture	FRACTURE STRESS $4P/\pi d^2$ ksi
617	0.57	1150	3		+	+
618			3		+	+
669	0.59	1150	5		+	+
670			5		+	+
629			10		+	+
630			10		+	+
619			20		2400	
620			20		+	+
701*	0.60	1150	5		5900	74.7
702*			5		4000 x	-
761*	0.61	1150	15		2470 x	-
762*			15		+	+
691*	0.62	1150	15		3000	-
692*			15		3300	-
753*			15		3090	-
754*			15		2990	-
679*			30		+	+
680*			30		+	+
715*	0.63	1150	30		5800	74.6
716*			30		3050 x	-
755*			30		5360	71.6
756*			30		2880	57.6
729*			60		2800 x	-
730*			60		2800 x	-
747*			60		3190 x	-
748*			60		2580	-
693*	0.65	1150	15		4000	
694*			15		5850	57.4
699*			30		2800	-
700*			30		2700	-
731*			30		+	+
732*			30		+	+

+ No fracture at 5000 lb., equivalent to over 80 ksi.

* Shorter bars. Highest load is 6300 lb., equivalent to over 80 ksi.

x Pre-existing crack, as shown by discolored part of fracture surface.

TABLE X. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 70 F HEAT TREATED AT 1000 F & 1050 F, TESTED AT -16 F.

BAR	PRE-STRAIN	HEAT TREATMENT °F	HEAT TREATMENT Minutes	TEST LOAD (lb) App. Crack	TEST LOAD (lb) Fracture	FRACTURE STRESS $4P/\pi d^2$ ksi
043	0.49	1000	30		4640	
044			30		3040	
087			60		4120	92.1
088			60		2880	71.7
091			120		3090	74.6
092			120		3090	78.3
033	0.51	1000	30		2840	
034			30		4540	
045			60		4740	
046			60		2830	
073			120		4430	97.4
074			120		3920	67.7
021	0.55	1000	60		2440	
022			60		3030	
035			120		4740	
036			120		3090	
063	0.49	1050	3		+	+
064			3		+	+
051	0.51	1050	3		+	+
052			3		+	+
047			8		+	+
048			8		+	+
037			15		+	+
038			15		+	+
023			30		+	+
024			30		+	+
093	0.53	1050	8		4430	88.4
094			8		4540	85.1
085			15		3390	79.7
086			15		+	+
081			30		+	+
082			30		+	+
077			60		+	+
078			60		+	+
025	0.55	1050	60		2480 x	-
026			60		4540	
039			120		4950	
040			120		4850	

+ No fracture at 5000 lb., equivalent to over 80 ksi.

x Pre-existing crack, as shown by discolored part of fracture surface.

The scatter of the results is considerably greater and the transition from brittle to ductile less sharp than with non heat-treated bars. There are indications that the ductility is restored gradually during heating. Although the loads appear to increase gradually with heating time up to 5000 lb. (or 6300 lb. for the shorter bars), very rarely did fractures occur at the higher loads (up to 7000 lb.) at which the bars were frequently tested. The 5000 lb. (or 6300 lb.) still shows the restoration of an appreciable ductility, with extensional strains well over 0.10.

In spite of scatter, the results indicate an unexpected dependence of the least necessary duration of heating on the amount of prestrain. Approximate curves of the minimum heating time needed to restore the ductility have been plotted as functions of prestrain, except for the heat treating temperature of 850°F. (Fig. 14, above), where the scatter was too great. The heating time increases so rapidly with prestrain, that an effective cut-off prestrain appears to exist beyond which restoration of ductility, if at all possible, would not be practical. It is not known whether any deterioration of the steel under prolonged heating contributes to this effect. The collected curves for all straining, heat treating, and testing temperatures are shown in Figure 17. The unexpected dependence of heating time on amount of prestrain, and its expected inverse dependence on heat treating temperature are clearly indicated. This is also shown in Fig. 18 where the approximate minimum heat treating time is plotted against the heat treating temperature for various constant prestrains at 550°F.

3d. A tentative explanation of the "worst" prestraining temperature. A very

TABLE XI. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 70 F HEAT TREATED AT 1100 F; TESTED AT -16 F.

BAR	PRE-STRAIN	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
		°F	Minutes	App. Crack	Fracture	4M/bd² ksi
041	0.51	1100	3		+	+
042			3		+	+
027			5		+	+
028			5		+	+
05			10		+	+
06			10		+	+
067	0.53	1100	5		+	
068			5		3300	
059			10		+	+
060			10		+	+
04	0.55	1100	15		4540	
010			15		4740	
01			30		+	+
02			30		+	+
049	0.57	1100	30		4330	
050			30		4430	
053			60		+	+
054			60		+	+
011	0.59	1100	30		4430	
012			30		4330	
013			30		2480 x	-
014			30		2370 x	-
057			60		4020	
058			60		4740	
029			60		2480	
030			60		+	+
097			90		4330	75.0
098			90		2060 x	-
095			120		3710 x	-
096			120		+	+

\+ No fracture at 5000 lb., equivalent to over 80 ksi.

x Pre-existing crack, as shown by discolored part of fracture surface.

TABLE XII. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 70 F HEAT TREATED AT 1150 F; TESTED AT -16 F.

BAR	PRE-STRAIN	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
		°F	Minutes	App. Crack	Fracture	4M/bd² ksi
07	0.51	1150	3		+	+
08			3		+	+
061	0.53	1150	3		+	+
062			3		+	+
015	0.55	1150	5		2890	
016			5		2680	
03			10		+	+
04			10		+	+
089	0.57	1150	10		4130	
090			10		+	+
017			20		+	+
018			20		3710	
069			30		2600 x	-
070			30		+	+
079			30		2320 x	-
080			30		2670 x	-
071	0.59	1150	30		4130	80.5
072			30		+	+
055			30		2660 x	-
056			30		2660 x	-

\+ No fracture at 5000 lb., equivalent to over 80 ksi.

x Pre-existing crack, as shown by discolored part of fracture surface.

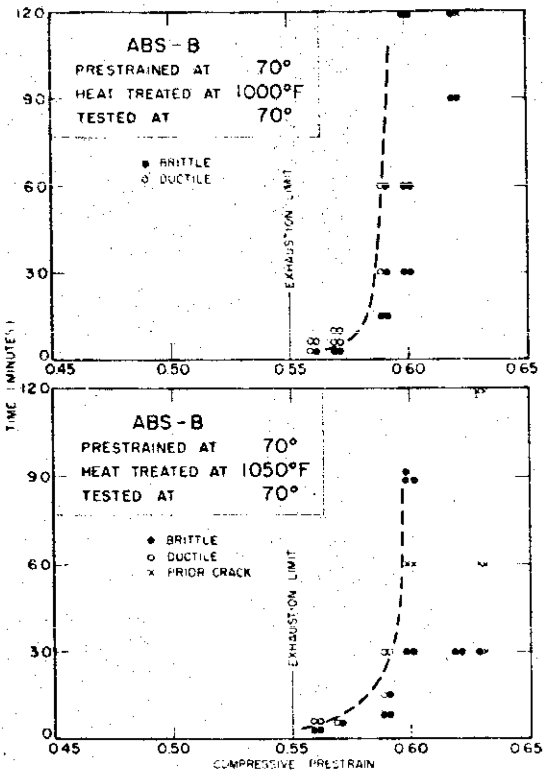

FIG. 6. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 70 F. HEAT TREATMENT AT 1000 & 1050 F; TESTS AT 70 F.

interesting though not altogether unexpected result is the restoration of ductility of hot strained bars at temperatures as low as 700°F. As shown in Figure 13 and Table XVII, bars prestrained a little above the exhaustion limit and heat treated at 750°F and 700°F for periods of 1 or 2 hours, may be ductile at -16°F. Likewise heat treatment at 750°F for 1-2 hours restores ductility at 70°F to bars strained just over the exhaustion limit at 550°F (Table XIII). Some ductility is very likely restored even in shorter heating periods, or at slightly lower temperatures, though not sufficient to enable the bars to withstand the full straining caused by a 5000 lb. load. An explanation may then be offered for the existence of a "worst"

TABLE XIII. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 550 F; HEAT TREATED AT 750 & 800 F; TESTED AT 70 F.

Bar	Pre-strain	Heat Treatment		Max. Load (lb)		Max. Nom. Stress
		°F	Minutes	Appr. Crack	Fracture	[illegible] ksi
[illegible]	0.37	750	60	-	3600	[illegible]
[illegible]			60	-	[illegible]	[illegible]
[illegible]			120	-	[illegible]	[illegible]
[illegible]			120	-	*	*
[illegible]	0.37	800	5	1250	[illegible]	-
[illegible]			[illegible]	-	[illegible]	*[illegible]
[illegible]			10	-	[illegible]	[illegible]
[illegible]			10	-	[illegible]	[illegible]
[illegible]			20	-	[illegible]	
[illegible]			20	-	*	*
[illegible]			30	-	*	*
[illegible]			30	-	*	*
[illegible]	0.40	700	[illegible]	-	1850	43.5
[illegible]			20	-	[illegible]	[illegible]
[illegible]			40	-	3300	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			50	[illegible]	[illegible]	-
[illegible]			50	-	*	*
[illegible]			120	-	*	*
[illegible]			120	-	*	*
[illegible]	0.43	[illegible]	60	-	3090	72.3
[illegible]			40	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	
[illegible]			[illegible]	-	3300	
[illegible]			120	-	[illegible]	
[illegible]			[illegible]	-	[illegible]	

* No fracture at [illegible] lb., equivalent to over 60 ksi

TABLE XIV. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 550 F; HEAT TREATED AT 850 & 900 F; TESTED AT 70 F.

[illegible]	[illegible]	[illegible]		[illegible]		[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ksi
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]

[illegible]

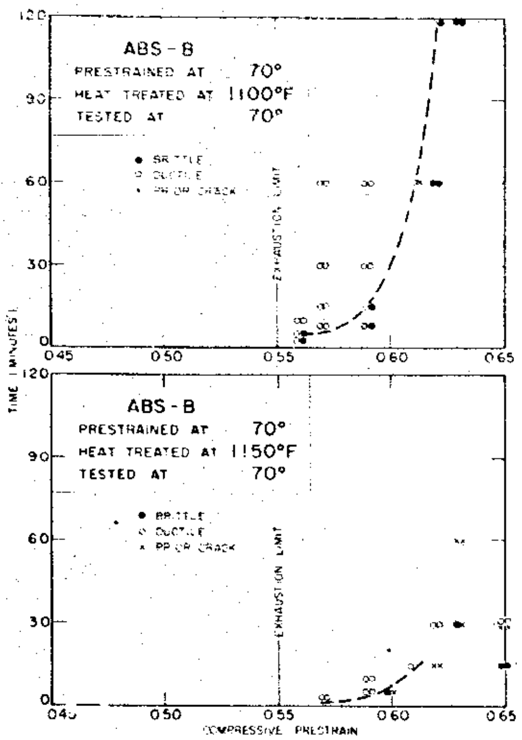

FIG. 7. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 70 F. HEAT TREATMENT AT 1100 & 1150 F; TESTS AT 70 F.

temperature around 550°F at which the exhaustion limit is least, and for the rapid increase of exhaustion limit as the prestraining temperature is raised above 600°F (Figures 4 and 5). The strain hardening, aging, and embrittlement appear to increase with the temperature, at least up to a point. Simultaneously a recovery or restoration of ductility appears to occur above a certain temperature and to become faster as the

TABLE XV. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 550 F HEAT TREATED AT 950 & 1000; TESTED AT 70 F.

BAR	PRE-	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
	STRAIN	°F	Minutes	Arr. Crack	Fracture	[illegible] ksi
[illegible]	[illegible]	[illegible]	3	-	*	*
[illegible]			3	-	*	*
[illegible]	0.[illegible]	[illegible]	[illegible]	-	3[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	-
[illegible]			[illegible]	-	*	*
[illegible]	0.4[illegible]	950	[illegible]	-	*	*
[illegible]	0.[illegible]			-	1550	[illegible]
[illegible]	0.26		10	-	*	
[illegible]	0.[illegible]		[illegible]	-	*	*
[illegible]	0.[illegible]		[illegible]	-	*	*
[illegible]	0.[illegible]		12	-	*	*
B-316	0.[illegible]	950	20	-	3[illegible]	
[illegible]			20	-	3920	
[illegible]			40	-	3[illegible]	[illegible]
[illegible]			40	-	2260	[illegible]
[illegible]			60	-	*	*
[illegible]			60	-	*	*
[illegible]	0.[illegible]	1000	3	-	*	*
[illegible]	0.[illegible]		3	-	*	*
[illegible]	0.[illegible]		3	-	*	*
[illegible]	0.[illegible]		3	-	*	*
[illegible]	0.[illegible]		5	-	[illegible]	[illegible]
[illegible]	0.[illegible]		5	-	*	*
[illegible]	[illegible]	[illegible]		-	1650	
[illegible]				-	2650	
[illegible]			[illegible]	-	*	
B-313			10	-	*	*
B-202	[illegible]	1000	10	-	*	*
B-203	[illegible]		10	-	*	*
[illegible]	0.[illegible]		10	-	4250	
B-227			10	-	2500	[illegible]
[illegible]			20	-	*	*
[illegible]			20	-	[illegible]	[illegible]
[illegible]			30	-	*	*
[illegible]			30	-	2600	[illegible]
[illegible]			40	1250	[illegible]	*
[illegible]			40	-	*	*
[illegible]	[illegible]	[illegible]	60	[illegible]	1[illegible]	-
[illegible]	0.[illegible]		60	[illegible]	[illegible]	-

* No fracture at [illegible] lbs., equivalent to over [illegible] ksi

TABLE XVI. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 550 F HEAT TREATED AT 1050 F; TESTED AT 70 F.

BAR	PRE-	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
	STRAIN	°F	Minutes	Arr. Crack	Fracture	lb/in^2 ksi
B-216	0.[illegible]	1050	3	-	*	*
B-217			3	-	*	*
B-200	0.[illegible]	1050	3	-	*	*
B-201			3	-	*	*
B-206	0.[illegible]	1050	3	-	*	*
B-207			3	-	*	*
B-258	0.[illegible]	1050	3	-	1670	39.6
B-259			3	-	*	*
B-222	0.[illegible]	1050	5	-	3300	78.9
B-223			5	-	*	*
B-210			10	-	*	*
B-211			10	-	*	*
[illegible]	0.[illegible]	1050	5	-	1850	45.7
[illegible]			5	-	2680	[illegible]
[illegible]			10	-	2620	
[illegible]			10	-	*	*
B-228	0.[illegible]	1050	10	-	2580	62.7
B-229			10	-	1210	29.4
B-220			20	-	2650	65.6
B-221			20	-	*	
B-342	0.[illegible]	1050	40	620	1660	-
B-343			40	-	*	*

* No fracture at 5000 lb., equivalent to over 80 ksi

TABLE XVII. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 550 F; HEAT TREATED AT 700-800 F; TESTED AT -16 F.

BAR	PRE-	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
	STRAIN	°F	Minutes	Arr. Crack	Fracture	[illegible] ksi
B-305	0.24	[illegible]	30	-	[illegible]	[illegible]
B-306			30	-	[illegible]	[illegible]
B-307			60	-	[illegible]	[illegible]
B-308			60	-	[illegible]	[illegible]
B-369			120	-	*	*
[illegible]			120	-	*	*
[illegible]	0.[illegible]	[illegible]	60	-	[illegible]	[illegible]
B-310			60	-	[illegible]	[illegible]
[illegible]	0.24	750	20	-	[illegible]	[illegible]
[illegible]			20	-	[illegible]	[illegible]
[illegible]			60	-	*	*
B-374			60	-	*	*
[illegible]			120	-	*	*
B-372			120	-	*	*
B-315	0.27	750	30	-	4860	101.[illegible]
B-316			30	-	[illegible]	[illegible]
B-365			60	-	*	*
B-366			60	-	4640	
B-353			120	-	*	*
B-354			120	-	2260	[illegible]
B-232	0.24	800	5	-	[illegible]	[illegible]
B-233			5	-	2260	[illegible]
B-234			10	-	*	*
B-235			10	-	[illegible]	
B-242	0.27	800	10	-	[illegible]	[illegible]
B-243			10	-	*	*
B-217			20	-	[illegible]	[illegible]
B-218			20	-	3600	[illegible]
B-375			60	-	[illegible]	71.[illegible]
[illegible]			60	-	*	*
[illegible]	0.30	800	10	-	[illegible]	
[illegible]			10	-	2260	
B-283			20	-	*	*
B-284			20	-	[illegible]	[illegible]
B-311			30	-	*	[illegible]
B-312			30	-	[illegible]	[illegible]
[illegible]			120	-	[illegible]	[illegible]
B-380			120	-	[illegible]	[illegible]
B-257	0.33	800	20	-	*	*
B-255			20	-	[illegible]	
B-323			60	1440	[illegible]	-
B-324			60	-	2650	[illegible]
B-355			120	-	*	*
B-356			120	1440	1440	-

TABLE XVIII. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 550 F HEAT TREATED AT 850 F; TESTED AT -16 F.

BAR	PRE-	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
	STRAIN	°F	Minutes	Arr. Crack	Fracture	[illegible] ksi
[illegible]	0.24	850	3	-	[illegible]	[illegible]
[illegible]			3	-	[illegible]	[illegible]
[illegible]			5	-	[illegible]	[illegible]
[illegible]			5	-	*	*
B-344			15	-	*	*
[illegible]			15	-	*	*
[illegible]	0.27	850	10	-	[illegible]	[illegible]
[illegible]			10	-	*	*
[illegible]	0.30	850	[illegible]	-	[illegible]	
[illegible]			[illegible]	-	[illegible]	
[illegible]			20	-	*	*
[illegible]			20	-	*	*
[illegible]	0.33	850	20	-	[illegible]	
[illegible]			20	-	*	*
[illegible]			30	-	[illegible]	[illegible]
[illegible]			30	-	[illegible]	[illegible]
[illegible]			60	-	[illegible]	77.2
[illegible]			60	-	[illegible]	[illegible]
[illegible]			120	-	*	*
[illegible]			120	-	[illegible]	[illegible]
B-331	0.36	850	30	-	[illegible]	[illegible]
B-332			30	-	[illegible]	[illegible]
B-333			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			120	-	[illegible]	[illegible]
[illegible]			120	-	[illegible]	[illegible]
[illegible]	0.39	850	60	-	[illegible]	[illegible]
[illegible]			60	-	[illegible]	[illegible]

* No fracture at 5000 lbs., equivalent to over [illegible] ksi

TABLE XIX. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 550 F HEAT TREATED AT 900 F; TESTED AT -16 F.

BAR	PRE-STRAIN	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
	[illegible]	°F	Minutes	App. Crack	Fracture	[illegible] ksi
[illegible]	[illegible]	[illegible]	[illegible]	-	*	[illegible]
[illegible]				-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	0.33	[illegible]	5	-	[illegible]	
B-277			[illegible]	-	[illegible]	
[illegible]			[illegible]	-	*	*
[illegible]			15	-	[illegible]	
B-321			[illegible]	-	*	*
B-322			[illegible]	-	[illegible]	65.5
[illegible]			30	-	[illegible]	[illegible]
[illegible]			35	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]

* No fracture at [illegible] lb., equivalent to over [illegible] ksi

TABLE XX. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 550 F HEAT TREATED AT 950 F; TESTED AT -16 F.

BAR	PRE-STRAIN	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
	[illegible]	°F	Minutes	App. Crack	Fracture	[illegible] ksi
[illegible]	[illegible]	[illegible]	3	-	[illegible]	[illegible]
[illegible]			3	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	70.7
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	950	[illegible]	-	[illegible]	
[illegible]			[illegible]	-	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	[illegible]	[illegible]	*
[illegible]			[illegible]	*	*	*
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	63.0
[illegible]			[illegible]	-	[illegible]	63.3
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*

* No fracture at [illegible] lb., equivalent to over [illegible] ksi

TABLE XXI. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 550 F HEAT TREATED AT 1000 F; TESTED AT -16 F.

BAR	PRE-STRAIN	HEAT TREATMENT		TEST LOAD (lb)		FRACTURE STRESS
	STRAIN	°F	Minutes	App. Crack	Fracture	[illegible] ksi
[illegible]	[illegible]	1000	[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	1000	[illegible]	-	[illegible]	
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	1000	[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	1000	[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	1000	[illegible]	-	*	*
B-211			[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	1000	[illegible]	-	*	*
B-352			[illegible]	-	*	*
[illegible]	[illegible]	1000	[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	
[illegible]	[illegible]	1000	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			90	-	[illegible]	[illegible]
[illegible]	[illegible]	1000	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]		[illegible]	[illegible]

* No fracture at [illegible] lb., equivalent to over [illegible] ksi

TABLE XXII. RESTORATION OF DUCTILITY OF BARS OF ABS-B STEEL PRESTRAINED AT 550 F HEAT TREATED AT 1050 F; TESTED AT -16 F.

BAR	PRE-STRAIN	HEAT TREATMENT		TEST LOAD (lb)		[illegible]
	STRAIN	°F	Minutes	App. Crack	Fracture	[illegible] ksi
[illegible]	[illegible]	[illegible]	[illegible]	-	*	*
B-201			3	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	1050	[illegible]	-	*	*
[illegible]			3	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-	*	*
[illegible]			[illegible]	-	[illegible]	[illegible]
[illegible]			[illegible]	-	[illegible]	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	*	*
[illegible]			[illegible]	-	*	*
[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	
[illegible]			[illegible]	-		

* No fracture at [illegible] lb., equivalent to over [illegible] ksi

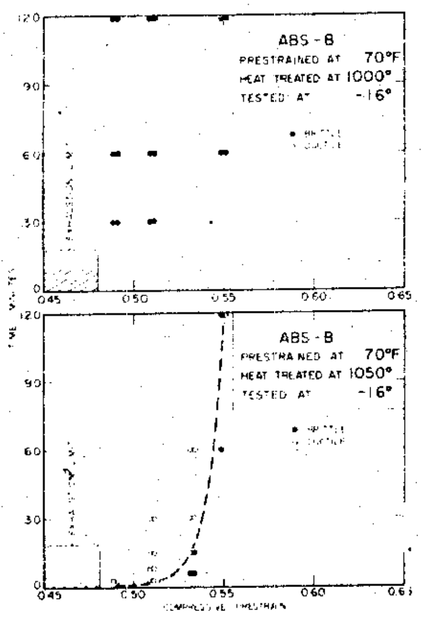

FIG. 8. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 70 F HEAT TREATMENT AT 1000 & 1050 F; TESTS AT -16 F.

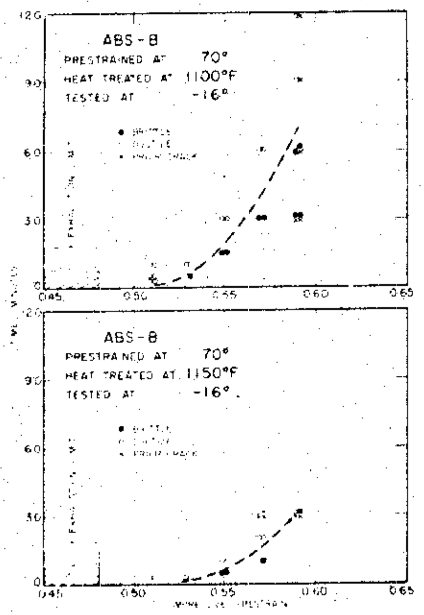

FIG. 9. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 70 F HEAT TREATMENT AT 1100 & 1150 F; TESTS AT -16 F.

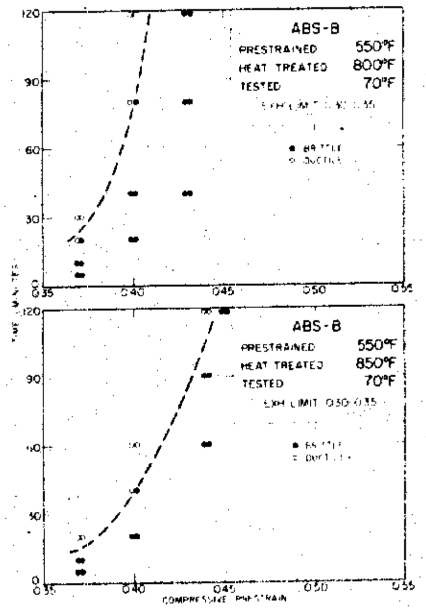

FIG. 10. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 550 F HEAT TREATMENT AT 800 & 850 F; TESTS AT 70 F.

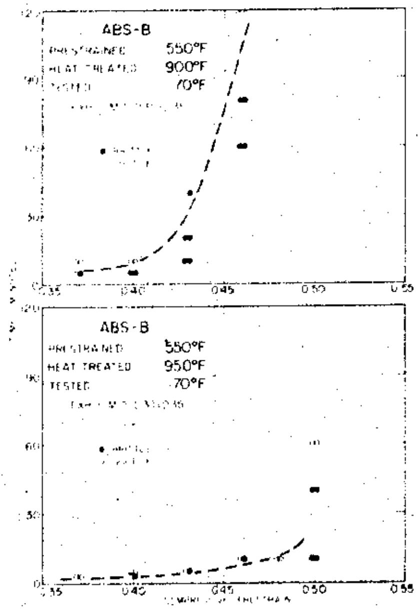

FIG. 11. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 550 F HEAT TREATMENT AT 900 & 950 F. TESTS AT 70 F.

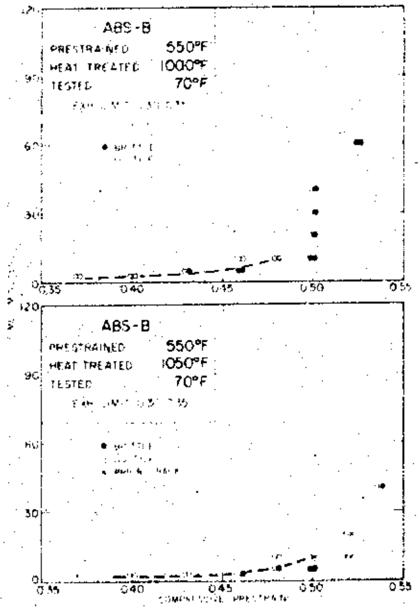

FIG. 12. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 550 F HEAT TREATMENT AT 1000 & 1050 F; TESTS AT 70 F.

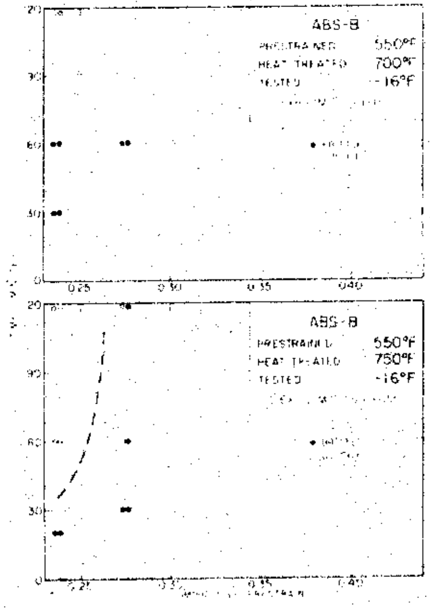

FIG. 13. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 550 F HEAT TREATMENT AT 700 & 750 F; TESTS AT -16 F.

temperature rises. The final behavior of the steel should be governed by the net effect of the two counteracting influences. Under the present test conditions the two influences cause the worse embrittlement at about 550°F. Above this temperature the rate of recovery is stronger and restores more ductility than is exhausted. A gain of restoration over exhaustion of a few per cent for every 50° F. is sufficient to produce the shape of the curves of Figures 4 and 5.

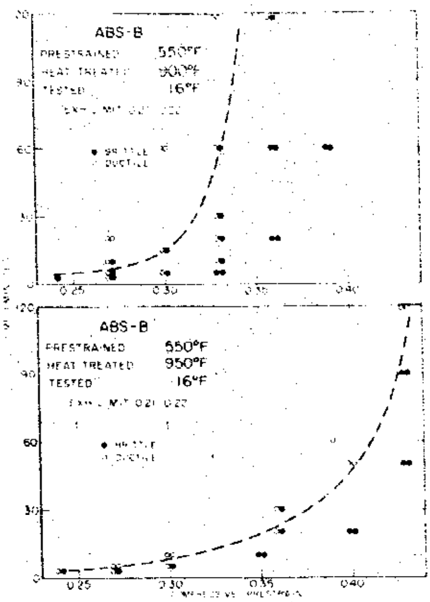

FIG. 15. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 550 F HEAT TREATMENT AT 900 & 950 F; TESTS AT -16 F.

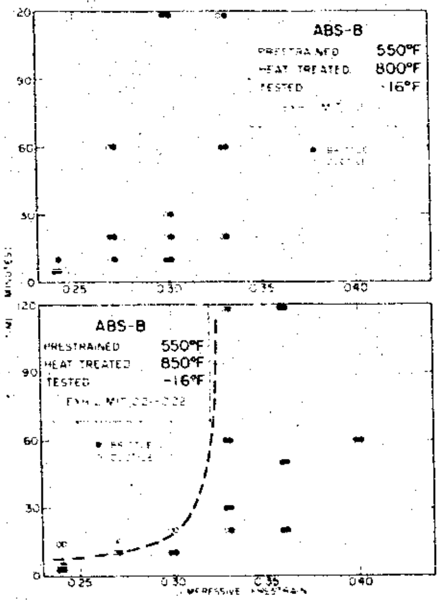

FIG. 14. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 550 F HEAT TREATMENT AT 800 & 850 F; TESTS AT -16 F.

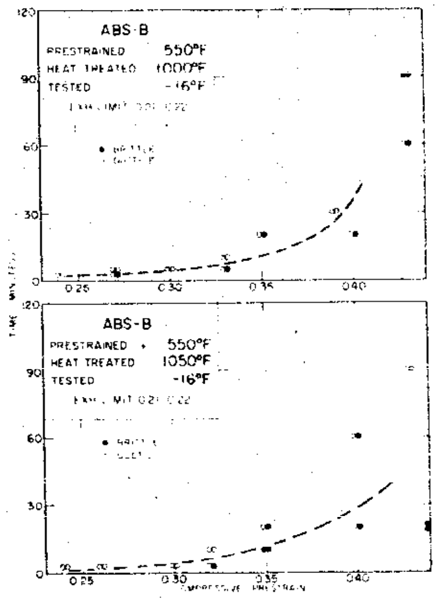

FIG. 16. RESTORATION OF DUCTILITY AFTER PRESTRAIN AT 550 F HEAT TREATMENT AT 1000 & 1050 F; TESTS AT -16 F.

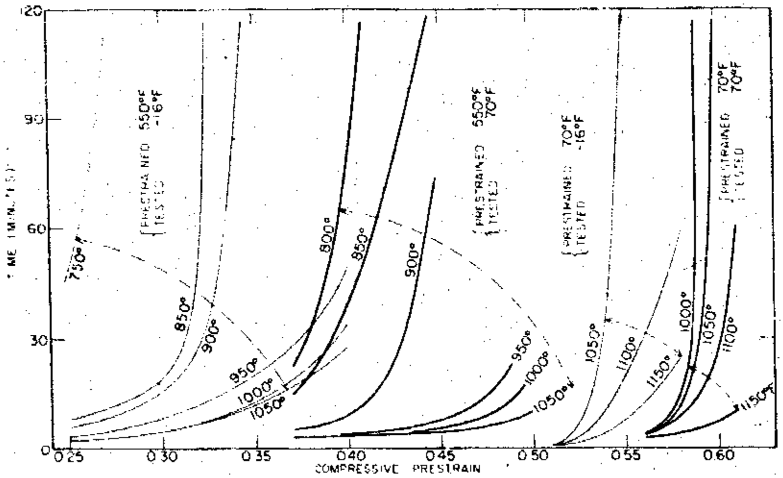

FIG. 17. APPROXIMATE CURVES OF MIN. HEAT TREATING TIME VS. PRESTRAIN FOR ABS-B STEEL BARS PRESTRAINED AT 70 AND 550 F AND TESTED AT 70 AND -16 F.

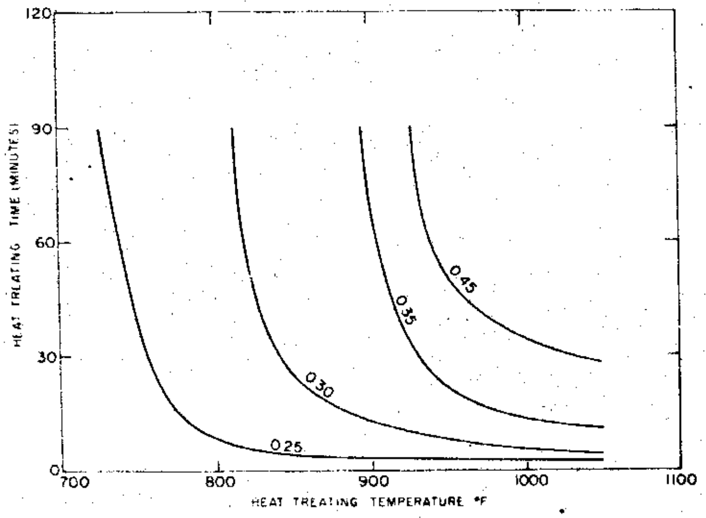

FIG. 18. APPROXIMATE CURVES OF MINIMUM HEAT TREATING TIME VS. TEMPERATURE FOR ABS-B STEEL BARS PRESTRAINED BY CONSTANT AMOUNTS AT 550 F AND TESTED AT -16 F.

4. CONCLUSIONS

It has been found that ABS-B steel, like other steels studied in the past, suffers a sudden reduction of the extensional ductility at a narrowly determined limit of compressive prestrain. The exhaustion limit was determined for prestraining at 70^{0} and -16^{0}F. A "worst" prestraining temperature was again found at about 550^{0}F, where the exhaustion limit was about half as high as at 70^{0}F.

Heat treatment at temperatures above 1000° F of bars embrittled by cold straining was found to restore sufficient ductility to permit extensional strains of over 0.10 (10%) without fracture. The required duration of heating was found to increase very rapidly with the amount of prestrain, so that at each of the tested temperatures a practical cut-off prestrain existed, beyond which impractically long heating times appeared to be needed. The required heat treating time decreased rapidly as the temperature was raised.

Restoration of ductility was much faster and could be achieved at considerably lower temperatures in bars which had been *embrittled* by *prestraining* at 550°F than at 70°F. Bars prestrained little beyond the exhaustion limit at 550°F could be made ductile in two hours even at 700°F. It appears that the process of restoration of ductility takes place continuously and gradually during heat treatment, and that some restoration of ductility may occur even in short heating cycles and at lower temperatures than 700°F. The "worst" prestraining temperature would then appear to result from the most unfavorable net effect of two opposite tendencies, namely the embrittlement by straining and aging, and the rate of recovery, both of which appear to increase with temperature.

It may be concluded that suitable heat treatment can restore sufficient ductility to prevent brittle failures, but requires a specified time which depends not only on the temperature but also quite strongly on the type and *amount of prestrain* embrittlement. The experimentally determined time-temperature-prestrain curves with ABS-B steel indicate the following trends:

A. Restoration of ductility is easier in hot than in cold strained bars.

B. Some restoration of ductility appears to occur even at 700°, and maybe even less, for hot strained bars.

C. The required heating time increases with the amount of prestrain, and becomes impractically long beyond a certain limiting prestrain.

D. An increase of temperature reduces the required heating time and increases the limiting prestrain.

E. Heating for about 1/2 to 1 hour at 1050°F or more would seem necessary for bars strained hot, and at 1150°F or more for bars strained cold. It is not known, however, if these heat treatments are sufficient for the most severe prestrains.

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13. ABSTRACT The severe embrittlement caused by a suitable history of strain and temperature has been confirmed also for steel conforming to ABS-B classification. Steel prestrained in compression by about 50% at 70°F and subsequently tested in tension fractures at an extensional strain of the order of 1%. Prestraining at 550°F by even 25% cause brittleness in extension at -16°F. Local severe embrittlement of this nature has been shown to be the basic cause of the static initiation of brittle failure of structures at low average stress. This is confirmed by service failures, whose origin is frequently traced to cold worked areas, or to the hot strained regions of defects close to welds.

It is shown that a suitable heat treatment can restore appreciable ductility to steel embrittled by hot or cold straining. The duration of heating decreases with the temperature, but increases very rapidly with the amount of prestrain. To each temperature corresponds a limiting prestrain for which heat treatment becomes impractically long. Cold strained steel requires considerably longer heat treatment and higher temperatures (1000-1200°F) than hot strained steel (700-1000°F). Approximate time-temperature-prestrain curves have been experimentally determined.

The results confirm that a major beneficial effect of the so-called "Thermal stress-relieving" treatment is a restoration of the ductility of locally embrittled steel.

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