SSC-192

NOTCH BRITTLENESS AFTER PRESTRAINING

SHIP STRUCTURE COMMITTEE

January 1969

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ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U.S. COAST GUARD HEADQUARTERS
WASHINGTON, D.C. 20591

January 1969

Dear Sir:

Concurrently with basic research efforts devoted to studying the microstructure behavior of steel, the Ship Structure Committee sponsored a project at Brown University to relate the macroscopic behavior of steel to its mechanical characteristics. The results indicate that steels can be adversely affected by straining at temperatures normally expected during fabrication or rolling.

Herewith is a copy of the final report on the project prepared by C. Mylonas and S. Kobayashi entitled *Notch Brittleness After Prestraining*.

This report is being distributed to individuals and groups associated with or interested in the work of the Ship Structure Committee. Comments concerning this report are solicited.

Sincerely yours,

D. B. Henderson

D. B. Henderson
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-192

Final Report

on

Project SR-158

"Macrofracture Fundamentals"

to the

Ship Structure Committee

NOTCH BRITTLENESS AFTER PRESTRAINING

by

C. Mylonas and S. Kobayashi

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Contract NObs 88294

U. S. Coast Guard Headquarters
Washington, D. C.

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ABSTRACT

Notched plates and bars prestrained in compression or extension, before or after notching, at 70°F or 550°F were tested to fracture in tension at -16 F. It was found that a catastrophic reduction of ductility could be caused by small prestrains. Uniform longitudinal or transverse prestraining by as little as 0.05 at 70°F reduced the initial ductility of notched bars by a factor of 4 or more. Hot prestraining was even more damaging: the greatest drop in the ductility at -16°F was caused by prestrains of only 0.025 at 550°F. These testsindicate that the "brittle" behavior of mild steel structures results from some damaging prior history of straining. Accordingly the proper selection of steels should be based on their resistance to embrittlement by suitable straining rather than on their properties in the initial undamaged state. The presented testing methods offer a great control over the steel ductility. They would be useful both in steel assessment and in the investigations of the factors influencing the resistance of steel to fracture.

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INTRODUCTION

An extensive series of tests was begun after the conclusion of Drucker [1,2] that low average stress fracture of mild steel structures under static loading should indicate a reduction or exhaustion of the initial ductility. After many unsuccessful attempts, low average stress fractures were systematically produced in the laboratory with symmetrically side-notched plates subjected first to in-plane compression across the common notch axis and then to tension at -16°F [3-9]. Sufficiently precompressed plates fractured at an average stress about 30% of the initial yield point, or developed arrested cracks at an even lower stress, occasionally as low as 10% of yield, but then would not fracture further till the stress was raised to the point of general yielding. Most tests were made with 10 in. square, 3/4 in. thick plates of project "E" steel, but similar results were obtained with other steels [10] and also with an ABS-B steel.

The reduction of ductility by precompression by amounts causing low stress "brittle" fracture was further studied with bars precompressed axially and then turned into standard specimens and tested in tension [6-9,11,12] and with bars subjected to reversed bending [7-9,13-18]. The ductility in tension (natural strain at fracture) was found to change little until the compressive prestrain reached a narrowly defined value, the exhaustion limit, at which it dropped abruptly to values of the order of 0.01 (1%). The exhaustion limit was of the order of 0.50 for bars prestrained at room temperature, but only about 0.25 in bars prestrained at about 550°F [9,12,15,16,18,19]. The exhaustion limit varied with steel quality, reflecting the resistance to embrittlement by prestraining. Although embrittling strains of 0.50 are not unlikely at the root region of cracks, flaws, or notches of real structures, the smooth bar tests were considered unrealistic because they lacked the constraint or triaxiality developing in the vicinity of discontinuities, a well known factor reducing the ductility. Tests were accordingly made with axially and uniformly compressed bars with subsequently machined deep circumferential grooves [12]. The extension at fracture was found to decrease rapidly with prestrain. At prestrains as small as 0.05 to 0.10 it was a small fraction (1/4 or less) of the extension of unstrained bars. The circumferentially grooved specimen should be seen as a small part of a large structure, the part at which fracture may start. The load-carrying capacity of structures with some ductility is not directly related to the stress at the crack or notch, which is always high, but to its ability to elongate without fracture so as to enable the rest of the structure to carry a higher stress. Therefore, the elongation at fracture of the notched specimens is of paramount importance because it provides a realistic measure of the resistance of a structure to fracture and of the "embrittlement" or damage caused by prestraining.

A number of factors affect the extension at fracture of notched parts, or "notch ductility", such as the strain and temperature history, the severity of the constraint, and of course several metallurgical factors. The present tests were designed to study the influence of the constraint severity and of the prestrain temperature and direction. The following tests were made, all with ABS-B steel, finally tested in tension at -16°F.

I. Plate Tests

a) Plates with symmetric side notches precompressed at 70°F after notching.

b) Plates compressed uniformly in their plane and subsequently side notched.

II. Bars with Circumferential Grooves

a) Uniformly axially compressed bars (70°F) with subsequently machined deep circumferential grooves of 0.003, 0.010 or 0.030 in. notch radii (completion of earlier tests).

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.

b) As in a) but precompressed transversely and tested longitudinally.

c) As in a) but prestrained in longitudinal extension.

d) As in a) but subjected to axial precompression at 550°F.

e) Bars with grooves machined first, compressed axially at 70°F.

III. Bars with Symmetric Side Notches

a) Uniformly axially compressed bars (70°F), subsequently side-notched with root radii of 0.003, 0.010 or 0.030 in. and tested in reversed tension.

b) As in a) but transversely compressed.

c) As in a) but precompressed at 550°F.

IV. Notched Reversed Bend Tests

2. NOTCHED PLATE TESTS

a. Plates notched after prestraining. Precompression of the notched plates and testing in tension was done as in earlier tests [2-4,8,9]. ABS-B steel plates (composition and properties in Tables I and II) 3/4 in. thick and 10 in. square, with 1.5 in. deep notches milled with a sharp cutter (middle square of Fig. 1) were supported laterally and subjected to in-plane compression perpen-

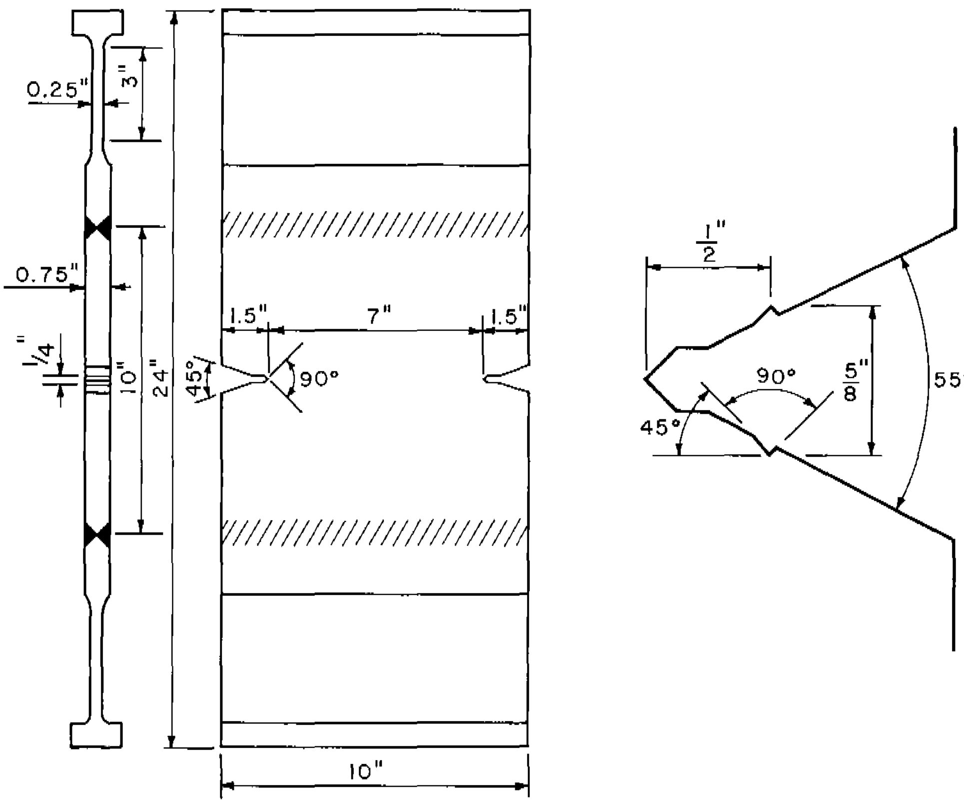

Fig. 1 Notched Plate.

dicular to the notch axis. The amount of precompression was measured by the shortening of a 1.15 in. gage length across the notch roots. The prestrained plates were aged for 2 hours at 300°F and welded to special pulling heads which would act as plastic hinges and reduce any eccentricity of loading [4]. Welding was done on a special jig for ensuring alignment, and the fillets were made with small passes applied on alternating faces so as to prevent warping. Special precautions were taken to keep the area between notches below 330°F. Thermocouples were mounted close to the notches, and the plates were covered with 2 in. thick plastic foam insulation and kept in a freezer at -25°F. The plates with their insulating cover could be quickly mounted in the dovetailing heads of a hydraulic testing machine and tested at a rate of 50 klb/min within 10 to 14 minutes, when their temperature had reached -16° ± 1°F over the significant area. Figure 2 shows the mounted test plate with insulation removed, fitted with extensometers used in later tests.

The results are given in Table III and Fig. 3, where the ratio of the average stress at a complete fracture or arrested crack to the initial yield point is plotted against the contraction over the 1.15 in. gage length on the side of the fracture initiating notch. A separate indication is given for fracture without prior audible cracking; for arrested cracks; for fractures after earlier cracks; or for no-fracture. Vertical lines join the points representing early crack and subsequent cracks, fracture or interruption of a single test. With face contractions below about 0.040 in. low stress fracture was impossible or unlikely; with about 0.040 to 0.060 in. fracture occurred systematically at an average stress around 70% of yield; with about 0.065 in. and over one or more arrested cracks occurred at average stress between 9 and 20%. As has already been observed [4], plates with arrested cracks would not fracture again until the average stress was increased considerably, sometimes almost to the flow limit. By using-up the highly prestrained notch region without achieving the propagation conditions, arrested cracks actually result in a strengthening of the structure. This would appear as an explanation of the existence of several arrested cracks in safely operating ships [19-21].

b. Plates notched after uniform prestraining. The prevention of buckling

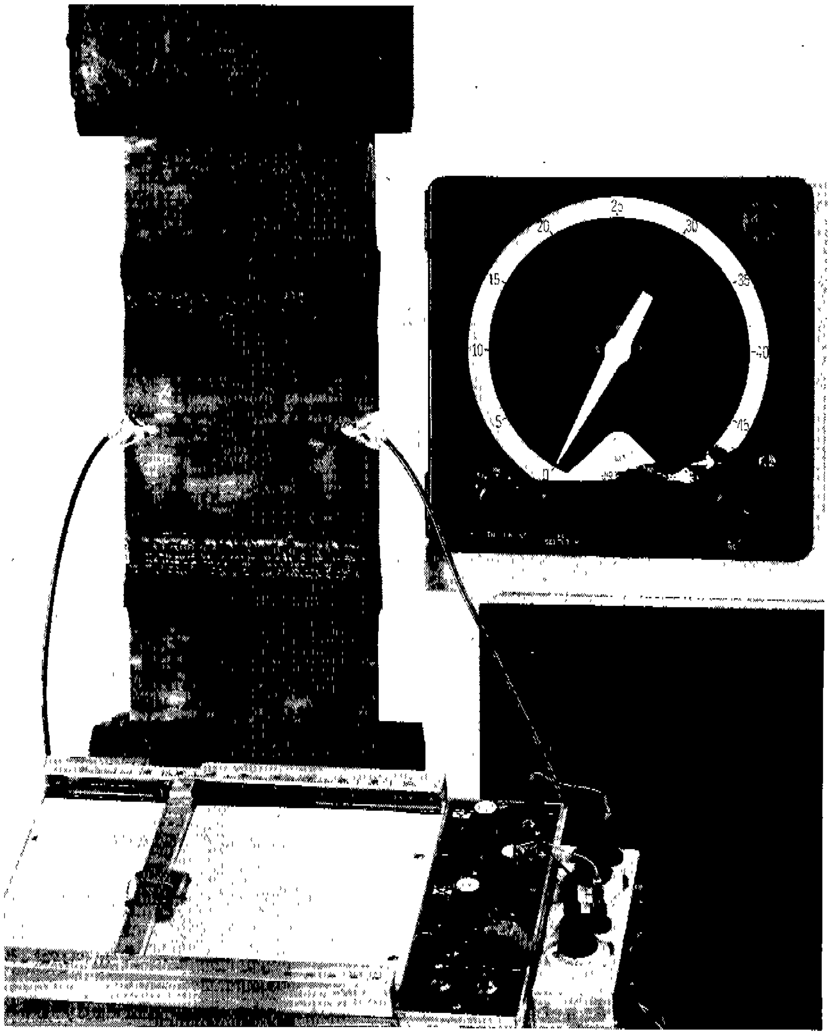

Fig. 2 Notched Plate With Extensometers And Autographic Equipment.

TABLE III ABS-B STEEL BRITTLE-FRACTURE TESTS OF 10-IN-WIDE PLATES WITH MACHINED NOTCHES PRESTRAINED IN COMPRESSION AFTER NOTCHING.

Plate	Avg. face compr. on 1-in. at notch root (10^{-3} in.)[a]	Avg. net compr. stress (ksi)	Test temperature (°F)	Average net tension: Max. applied (ksi)[b]	Average net tension: Max. applied % of yield	Average net tension: At significant crack % of yield
1	14	35.4	-16	> 30.0	> 89	
2	16	36.4	-16	> 30.0	> 89	
4	25	38.2	-16	> 30.0	> 89	
6	26-26	38.2	-16	29.0	85	
3	39	38.2	-16	> 32.1	> 95	
5	41-40	39.1	-16	23.2	68	
7	55-55	40.0	-18	25.6	75	
8	55-55	40.0	-16	23.2	68	
13	70-70	47.6	-16	18.0	56	12
12	72	47.6	-16	> 17.0	> 50	9;14
9	84	50.5	-16	> 30.0	> 89	14;18
10	86-85	50.5	-16	> 28.1	> 83	13;18;77
11	98-99	52.5	-16	15.2	45	
14	103	52.5	-16	> 20.0	> 59	14;20

a. First number for side of crack initiation, whenever applicable.
b. Stress at fracture unless preceeded by > signifying that no complete fracture occurred.

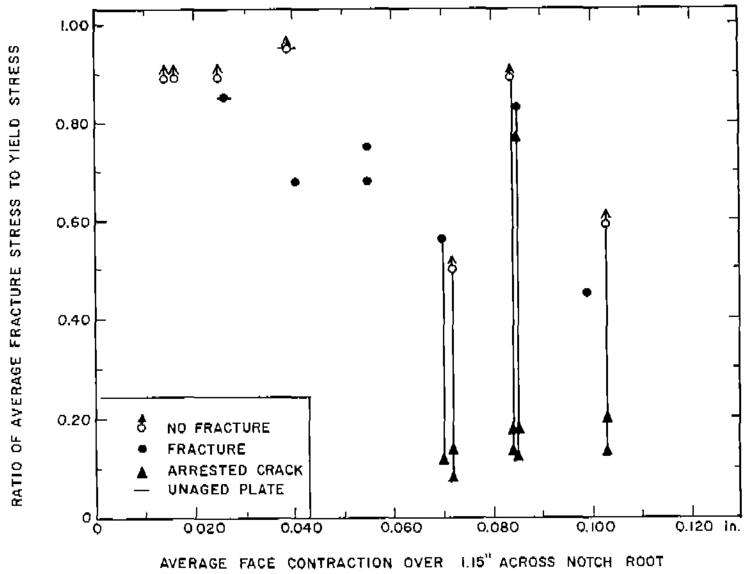

Fig. 3 Tests At -16°F Of 10 in. ABS-B Plates Compressed After Notching Initial Yield Stress 34 ksi.

during in-plane compression into the plastic region presented much greater difficulties with smooth than with notched plates which yielded only locally. The unnotched plates yielded more or less uniformly throughout their volume and shortened by the full amount of the prestrain. An initial plate size 28 x 7 x 0.75 in. was chosen so as to allow for shortening and expansion up to longitudinal strains of 0.50 or more. At first lateral support was provided only over the faces in the hope that no in-plane buckling would occur. The support consisted of two 24 x 12 x 2 in. aluminum plates sandwiching the compressed plate and bolted against each other by 8 bolts along their longitudinal edges (Fig. 4), which extended be-

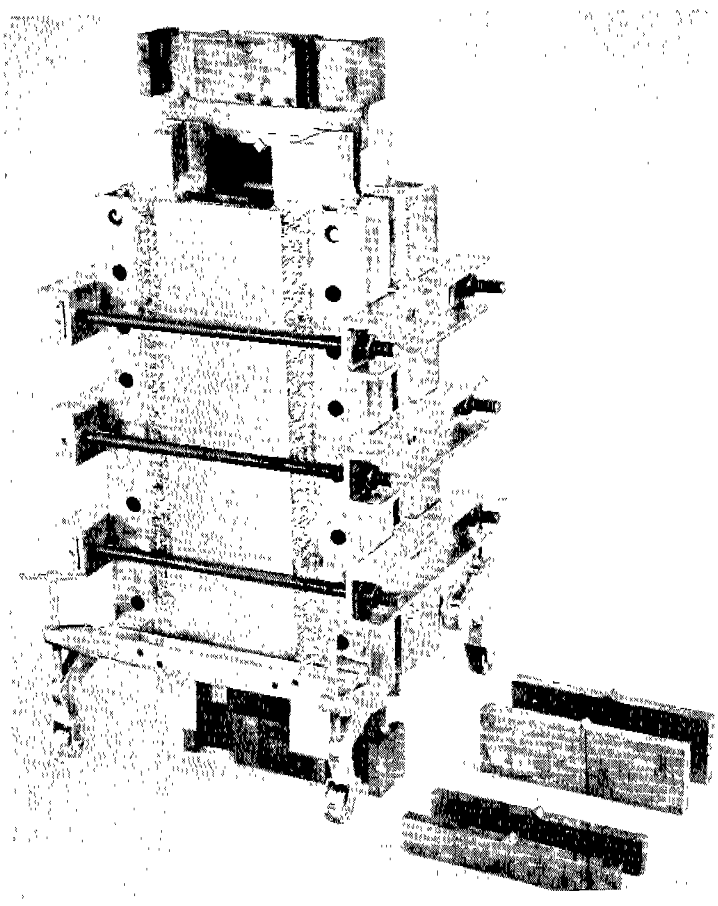

Fig. 4 Lateral Support of 28 x 7 x 0.75 In Plates Compressed Longitudinally By 0.30.

yond the steel plate. In addition each plate was stiffened longitudinally with two welded 5 in. deep aluminum I-beams and when these proved insufficient, with 3/4 in. thick plates and angles welded over the I-beams and onto the edges of the 2 in. thick sandwich plates. The whole jig was mounted on retracting casters so as to be easily moved and positioned in the compression machine. The I-beams protruded above and below, leaving a gap between opposite faces which received the thin end of the compression head. The protruding beams acted also as guides against any out-of-plane motion of the whole jig. The compression heads rested by their broad bases on the compression plattens. At first the thin ends of the compression heads were smooth and straight, but at a prestrain of about 20% and a load of about 600 000 lb., in-plane buckling by lateral sliding at the compressed edges occurred in a quarter-wave mode (Fig. 5, right). This presents some interest as an instability problem with plastic action, large strains and frictional forces. The edges of compressed plate and compressing head were then notched at their middle so as to accommodate a square "key" and prevent sliding, as shown in Fig. 4 at top center. Additional extension plates with a raised central point (Fig. 4, bottom right) were also made for continuing the compression when the plate would shorten. However, at an only slightly higher load, in-plane buckling started again in a half-wave mode without sliding of the ends (Fig. 5, middle right). In-plane lateral supports had then to be used. They consisted of three adjustable screws on each edge supported by short channels held in pairs by long horizontal bolts (Fig. 4). These edge stops, as well as the 16 bolts holding the aluminum plates together, had to be in turn loosened and lightly re-tightened after each increase of prestrain by about 0.02. This permitted reaching a prestrain of 0.30, when the compressed plate began buckling in several out-of-plane ripples of about 5 in. wavelength. Prevention of this buckling would have needed a considerably stiffer lateral support than could be achieved with the existing jig. Accordingly only 4 plates were prestrained, two by 0.20 and two by 0.30. One of each is shown at the left of Figure 5.

Fig. 5 Compressed And Buckled Plates.

The compressed plates were cut into two squares of the largest possible size (7 5/8 to 8 1/4 in.), which were machined to a thickness of 3/4 in. and notched symmetrically as in Fig. 1. The ratio of notch depth to plate width was the same as in the older 10 in. square plates, but the sides of the notches had two small broached grooves 1/2 in. from the root for mounting the extensometers measuring the extension at the shoulders up to fracture, as shown in Figures 1 and 2. The extensometer outputs were recorded on a two-pen X-Y recorder (or $X\text{-}Y_1\text{-}Y_2$ recorder). The single pen X-Y recorder shown in Fig. 2, normally used in the grooved bar tests of the next paragraph, was only used with plate No. 50. The load was recorded on the X-axis and the two extensometer outputs were fed to the Y_1- and Y_2- pens. The test results are shown in Table IV. Two relatively low stress fractures were obtained, at an average stress of 91% of $\sigma_{0.1}$ with plate No. 53 prestrained by 0.20, and at 74% of $\sigma_{0.1}$ with plate No. 50 prestrained by

0.30. Two more plates prestrained by 0.20 and one by 0.30 did not fracture at loads between 95% and 105% of $\sigma_{0.1}$. Nevertheless, the permanent extension at fracture was small. Plate 52 (0.20) which fractured after two tests at 106% of $\sigma_{0.1}$ had extensions of about 0.008 and 0.005 in. at the two notches; plate 53 (0.20) had about 0.0055 on both. With Plate 50 (0.30) the permanent extensions could not be measured as easily because a single pen X-Y recorder was used to plot the extensions at the two notches, but judging from the total deflections the permanent appeared to be very small, about 0.002 on one side and negligible on the other. Direct comparison with the first series of plates compressed after notching is not very meaningful, as the earlier plates had an unknown and probably very high prestrain and hardening at the notch root, and also an increased notch

TABLE IV ABS-B STEEL FRACTURE TESTS OF UNIFORMLY PRECOMPRESSED PLATES NOTCHED AFTER STRAINING.

Plate	Prestrain	Net Area sq. in.	Elong. at Shoulders 10^{-3} in.				Stress % of $\sigma_{0.1}$	$\sigma_{0.1}$ ksi	Remarks
			Total		Permanent				
			Y_1	Y_2	Y_1	Y_2			
52	0.20	0.755x5.220=3.94	~5.0 12.0	~4.0 8.2	5.3	2.5	~ 64% >101%	58	a No fracture
		Aged again and re-tested	~6.5 9.9	~6.4 9.3	2.9	2.3	~105% 106%	58	a b b Fracture
53	0.20	0.748x5.210=3.90	8.6	7.1	5.5	5.4	91%	58	Fracture
56	0.20	0.753x5.415=4.08	~3.9 ~4.2 4.7	~3.5 ~3.7 4.2	1.8	1.3	~ 88% ~ 91% > 95%	58	c c No fracture
51	0.30	0.740x5.790=4.31	6.2	3.8	~2	~1	67%	64	Fract. at weld
		Welded and re-tested	~6.5 9.7	~5.5 14.5	3.2	6.1	74% 105%		a b b No fracture
50	0.30	0.753x5.800=4.36	5	8	(~2)[d]	(~5)[d]	74%	64	Fracture

a. Onset of large plastic straining.
b. Additional extension, over any permanent extension of prior loading.
c. Small irregularities of graph, possibly indicating small arrested cracks.
d. Estimated from total.

acuity. Furthermore in the earlier tests only the fracture loads were measured but not the extension. In general a uniform precompression of the order of 0.20 to 0.30 causes fracture at stresses as low as with notched plates compressed to a contraction of about 0.025 to 0.055 on 1 in. at the notch root, but not as low as with a contraction of 0.070 in. or more.

As seen in the circumferentially grooved tests [12] the extension at fracture is a much better indication of the brittle or ductile behavior than the average stress. In several instances the behavior was brittle (very low extension) although the stress exceeded the flow limit based on $\sigma_{0.1}$. The shoulder extension at fracture of plate No. 50 is comparable with the very small extension of circumferentially grooved bars of equal uniform prestrain (0.30) [12]. Plates No. 53 (0.20) and 52 (0.20) have larger extensions than the corresponding bars, probably reflecting the smaller degree of constraint in the plates and perhaps their smaller notch acuity.

In view of the shortage of ABS-B plate of this batch and of the difficulty in prestraining by more than 0.30, the plate tests were stopped and the remainder of the uniformly prestrained plates was used for bars cut and tested transversely to the precompression.

3. BARS WITH CIRCUMFERENTIAL GROOVES

a. Uniform axial compression at 10°F. All bars had an initial cross-section of 0.75 in. square and a length of about 9 in. with axis parallel to the direction of rolling. They were compressed axially at 70°F in the machine described in reference [9], and artifically aged for 1.5 hours at 300"F. Deep and sharp circumferential grooves of 0.003, 0.010 or 0.030 in. notch radius were milled in such a way as to avoid straining of the narrowed section, as shown in Fig. 6 and described in detail in reference [12]. Earlier tests had been made with a net diameter (grooved section) of about 0.375 in. (net area about

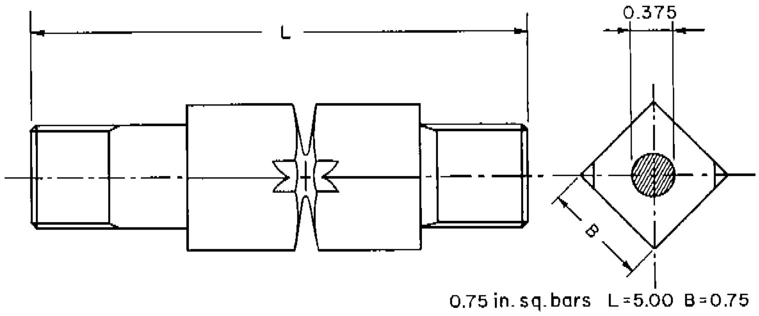

Fig. 6a Grooved Specimen.

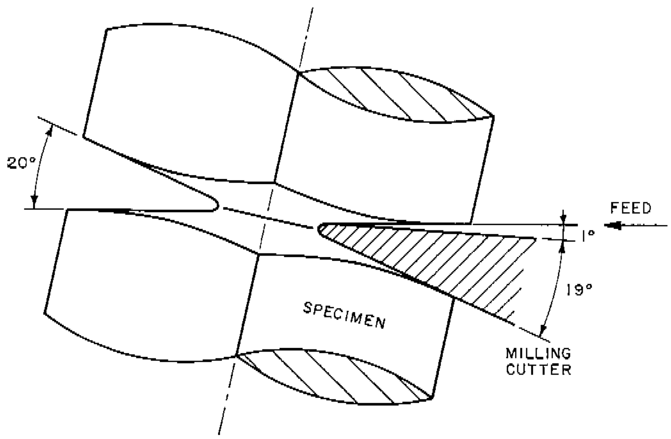

Fig. 6b Detail Of Groove Machining.

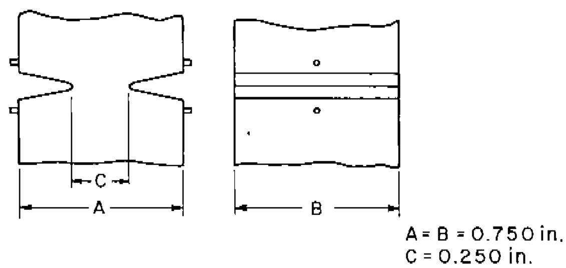

Fig. 6c Symmetrically Side-Notched Specimen.

0.110 sq. in.). The present tests were with a net diameter of about 0.300 or 0.450 in. (areas about 0.065 or 0.159 sq. in.) for a check on the influence of gross to net area. The grooved bars were fitted with a specially constructed extensometer for measuring the extension at the shoulders up to fracture (Fig. 7) and were tested in tension at -16°F. The load-extension curves, plotted on an X-Y recorder, were substantially linear and reversible up to a high load, although localized plastic strains certainly occurred within this range. Several checks by unloading showed that departure from linearity in the loading curve corresponded to gross permanent axial extension at the shoulders. Consequently it was possible to determine the permanent deformation at fracture from the loading curve. The average net stress and the total extension at the shoulders at frac-

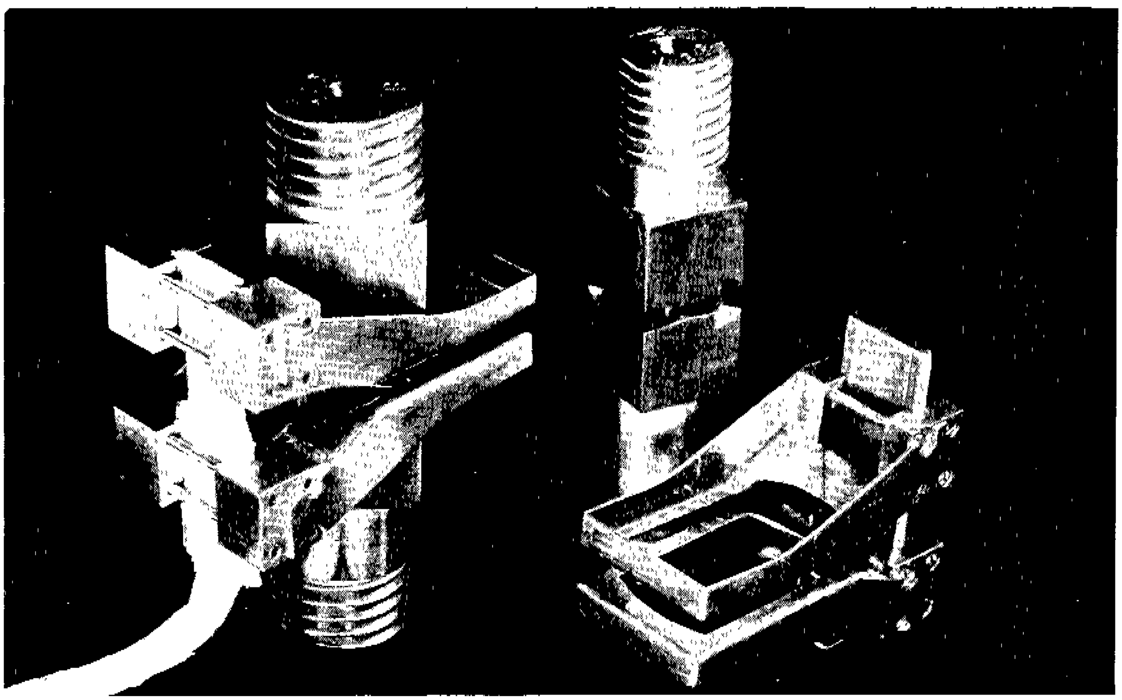

Fig. 7 Grooved Bars With Extensometer.

ture are given in Table V and are plotted against the prestrain in Fig. 8. An important aspect of Fig. 8 (left) is the comparison of the fracture stress with the 0.1% offset yield strength ($\sigma_{0.1}$) and with the 2.68 $\sigma_{0.1}$ flow limit for the 20 degree deeply circumferentially grooved specimen [12]. As judged by the fracture stress the behavior is certainly ductile when the stress is lower than the flow limit which happens at prestrains of about 0.20 or more. The extension at fracture, however, is a better indication of the ductile-brittle transition [12]. As seen in Fig. 8 (right), the extension at fracture is substantial in unstrained bars (0.17 to more than 0.50 in. depending on the notch radius) but drops to 1/4 or less these values at prestrains as low as 0.05 to 0.10.

TABLE V ABS-B STEEL BARS GROOVED CIRCUMFERENTIALLY AFTER UNIFORM AXIAL PRECOMPRESSION AT 70°F EXTREME NET AREAS TENSION TESTS AT -16°F.

Bar	Pre-strain	Notch Radius (in.)	Root Dia. (in.)	Net Area (in.^{2})	Elong. at Fracture 0.001 in.		Av. Stress ksi	
					Total	Plastic	At Fract.	Flow Limit
285	0	0.003	0.2865	0.0645	>40.0	–	110	100
286	0	0.003	0.2805	0.0618	>40.0	-	118	
287	0.05	0.003	0.3015	0.0714	5.0	3.9	136	115
288	0.05	0.003	0.3005	0.0709	3.3	2.3	117	
289	0.10	0.003	0.2980	0.0697	6.4	5.3	158	138
290	0.10	0.003	0.3020	0.0716	5.2	4.1	156	
291	0	0.003	0.4485	0.1580	Extensometer came off		103	100
292	0	0.003	0.4470	0.1569	30.8	29.0	101	
293	0.05	0.003	0.4490	0.1583	6.2-12.3*	10.1	112-122*	115
294	0.05	0.003	0.4480	0.1576	7.0-15.0	13.8	113-124*	
295	0.10	0.003	0.4510	0.1598	3.6- 9.8*	8.4	114-140*	138
296	0.10	0.003	0.4490	0.1583	3.3-10.8*	9.4	112-143*	

* Fracture preceded by earlier crack.

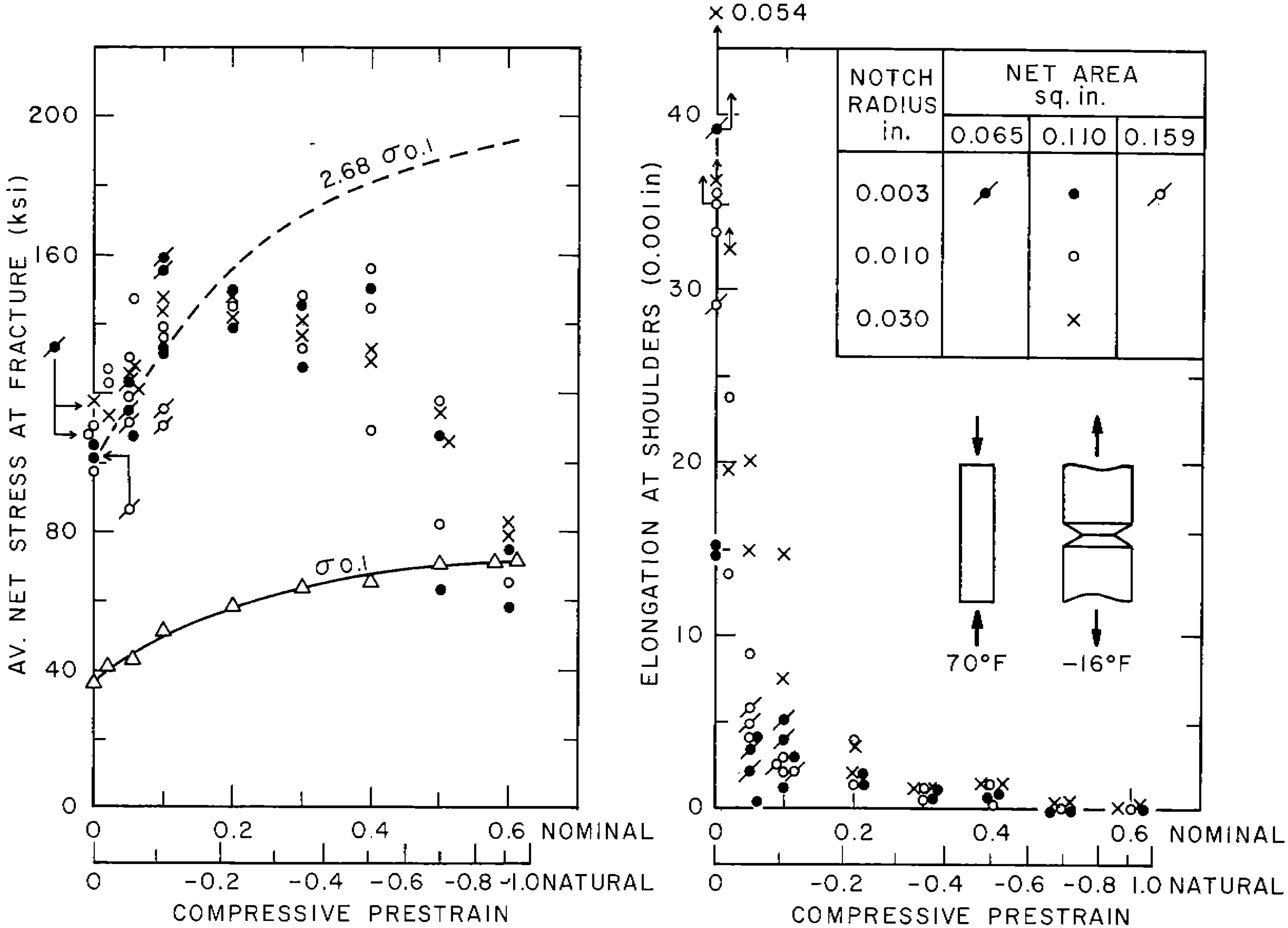

Fig. 8 Bars Axially Precompressed At 70°F, Grooved And Tested At -16°F.

The old and new results are very similar for all net sections, showing that the fracture behavior was insensitive to variations of the ratio of net to gross area (grooved to full section) from about 1:8 to about 1:3, hence that the grooves used in the main series of Fig. 8 (area ratio about 1:5) were not too shallow.

b. Uniform transverse compression at 70°F; axial tension tests at -16°F. Bars of 0.75 in. square cross-section and suitable length (3 in. or more) were cut with their axes transverse to the direction in which the plates of paragraph 2 were compressed by 0.20 and 0.30. In addition smaller plates were compressed in the direction of rolling to strains of 0.05 and 0.10 and were cut into bars, similar to the previous ones, with their length transverse to precompression and rolling. After artificial aging some of these bars were machined into standard 0.505 tension specimens for the determination of the raised yield strength, true stress and natural strain at fracture. Table VI gives the results of the

TABLE VI ABS-B STEEL STANDARD TENSION TESTS AT -16°F AFTER UNIFORM LATERAL PRECOMPRESSION AT 70°F.

Bar	Prestrain	0.1% Offset Stress ksi	Fracture		$\sigma_{0.1}$ (ksi) for same long. prestrain
			Nat. Strain	True Stress ksi	
B-800	0	36.5	1.00	139	36-38
B-801	0	39.4	1.00	138	
B-802	0.05	59.2	0.89	134	42.5-43.5
B-803	0.05	62.3	0.89	138	
B-804	0.10	67.2	0.88	137	51.4-51.8
B-805	0.10	68.2	0.86	139	
B-322	0.20	79.3	0.66	131	58-59
B-326	0.30	87.1	0.63	134	63-64
B-806	0.30	88.9	0.74	132	63-64

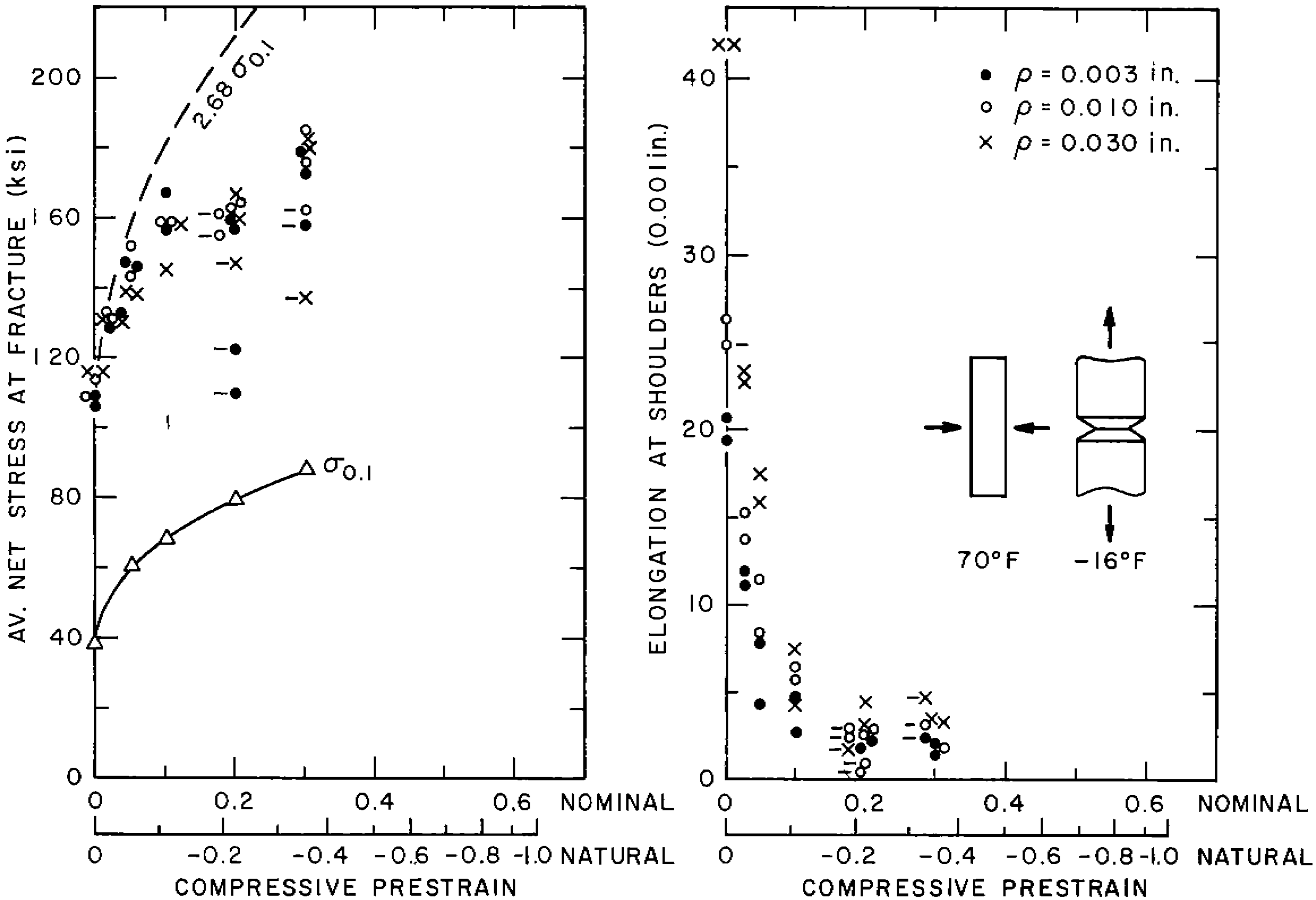

Fig. 9 Bars Laterally Precompressed At 70°F, Grooved And Tested At 16°F.

TABLE VII ABS-B STEEL BARS GROOVED CIRCUMFERENTIALLY AFTER UNIFORM LATERAL PRECOMPRESSION AT 70°F TENSION TESTS AT -16°F.

Bar	Pre-strain	Notch Radius (in.)	Root Dia. (in.)	Net Area (in.^{2})	Elong. at Fracture 0.001 in.		Av. Stress ksi	
					Total	Plastic	At Fract.	Flow Limit
B-437	0	0.003	0.373	0.1093	21.6	20.7	109	103
B-438		0.003	0.3765	0.1113	20.3	19.4	106	
B-439		0.010	0.380	0.1134	25.8	24.9	109	
B-440		0.010	0.3765	0.1113	27.4	26.3	114	
B-441		0.030	0.373	0.1093	42.0	41.0	115	
B-442		0.030	0.372	0.1087	42.0	41.0	115	
B-443	0.025	0.003	0.373	0.1093	13.1	11.9	133	—
B-444		0.003	0.367	0.1058	12.3	11.1	129	
B-445		0.010	0.376	0.1110	16.4	15.2	132	
B-446		0.010	0.377	0.1116	14.8	13.7	133	
B-447		0.030	0.3745	0.1102	23.8	22.6	131	
B-448		0.030	0.376	0.1110	24.4	23.2	130	
B-350	0.05	0.003	0.3745	0.1102	5.8	4.4	146	163
B-351		0.003	0.3665	0.1055	9.2	7.9	147	
B-352		0.010	0.3785	0.1125	9.5	8.2	152	
B-353		0.010	0.3720	0.1087	12.6	11.3	144	
B-354		0.030	0.3765	0.1113	17.0	15.8	138	
B-355		0.030	0.3775	0.1119	18.6	17.3	138	
B-356	0.10	0.003	0.3770	0.1116	6.2	4.8	167	181
B-357		0.003	0.3760	0.1110	4.4	2.8	157	
B-358		0.010	0.3710	0.1081	7.3	5.8	159	
B-359		0.010	0.3715	0.1084	7.9	6.5	159	
B-360		0.030	0.3740	0.1099	8.7	7.3	158	
B-361		0.030	0.3745	0.1102	5.7	4.3	145	
B-362	0.20	0.003	0.3720	0.1087	3.6	2.0	157	212
B-363		0.003	0.3745	0.1102	4.0	2.4	159	
B-364		0.010	0.3760	0.1110	4.2	2.7	163	
B-365		0.010	0.3765	0.1113	4.5	2.9	164	
B-366		0.030	0.3725	0.1090	4.7	3.1	159	
B-367		0.030	0.3750	0.1104	6.2	4.6	166	
B-368	0.30	0.003	0.3735	0.1096	4.0	2.2	179	236
B-369		0.003	0.3605	0.1021	3.4	1.6	173	
B-370		0.010	0.3750	0.1104	5.0	3.4	185	
B-371		0.010	0.3760	0.1110	3.8	2.0	176	
B-372		0.030	0.3735	0.1096	5.0	3.2	180	
B-373		0.030	0.3720	0.1087	5.3	3.4	182	
B-309+	0.20	0.003	0.3765	0.1113	1.8	0.6	110	212
B-318+		0.003	0.3720	0.1087	2.2	1.0	122	
B-317+		0.010	0.3715	0.1084	4.5	3.0	161	
B-320+		0.010	0.3735	0.1096	3.9	2.6	157	
B-321+		0.030	0.3745	0.1102	3.5	1.9	147	
B-324+	0.30	0.003	0.3765	0.1113	3.2*-4.4	2.6	158*-173	236
B-323+		0.010	0.3725	0.1090	3.6*-5.1	3.5	162*-171	
B-325+		0.030	0.3760	0.1110	2.6*-6.2	4.7	137*-168	

+ From large compressed plates

* First crack

transversely compressed bars and for comparison the $\sigma_{0.1}$ stress for longitudinal compression as found in earlier tests [12]. Transverse and longitudinal yield stress are identical in unstrained but aged bars, and slightly larger than the typical values of Table II. In strained bars, however, the transverse $\sigma_{0.1}$ value is appreciably larger than the longitudinal. The $\sigma_{0.1}$ and $2.68\ \sigma_{0.1}$ curves for transversely prestrained bars are shown in Fig. 9 (left). The remaining bars were circumferentially grooved to a diameter of about 0.375 in. and a notch radius of 0.003, 0.010 or 0.030 in. (Fig. 6). The stress and the permanent elongation at the shoulder at fracture are given in Table VII and plotted against the prestrain in Fig. 9. The results are similar to those of longitudinally prestrained bars (Fig. 8). Unstrained and very lightly strained bars reach a fracture stress equal to the $2.68\ \sigma_{0.1}$ flow limit; highly prestrained bars fracture at a stress lower than $2.68\ \sigma_{0.1}$. The transition, however, is at a prestrain of about

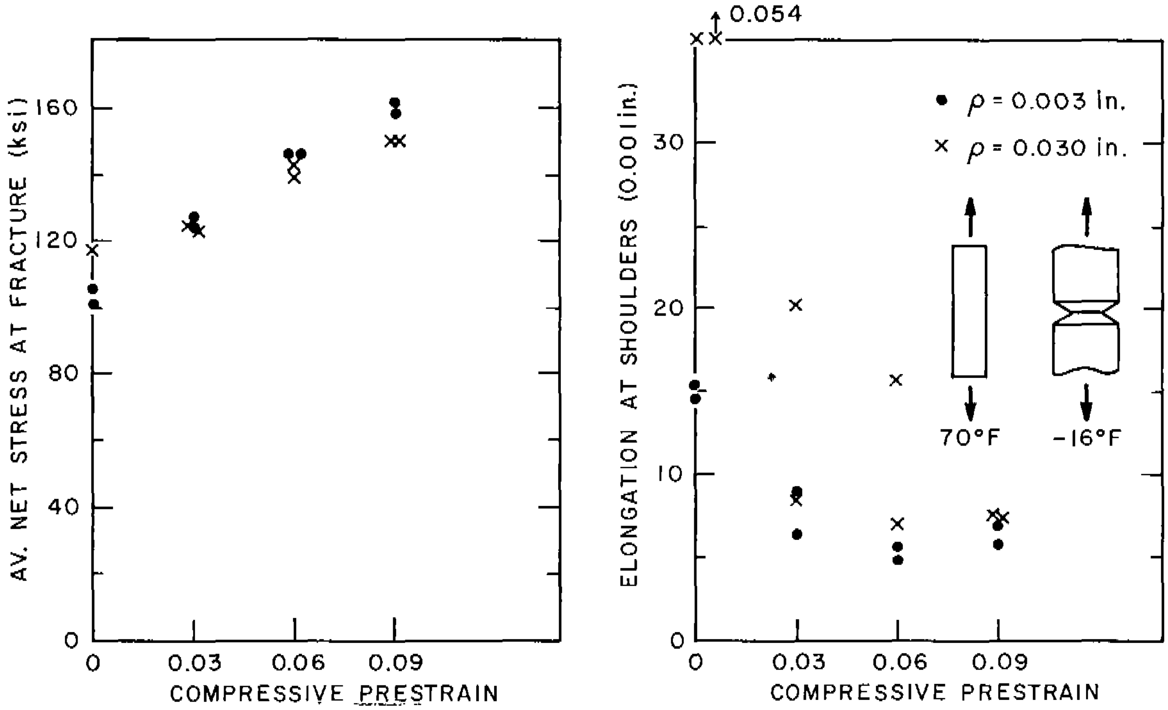

Fig. 10 Bars Axially Prestretched At 70°F, Grooved and Tested At -16°F.

0.05, instead of about 0.20 for longitudinal prestrain, but it is so gradual that no great importance can be attached to this difference. It is also interesting to note that at a transverse prestrain of 0.30 the fracture stress curve appears to be still rising (Fig. 9, left) whereas for longitudinal prestrain it is falling or at most remaining horizontal (Fig. 8, left).

The fracture extension changes with prestrain in an almost identical manner in bars with transverse and longitudinal prestrain (Fig. 10 and 8, right). At prestrains of 0.05 to 0.10 the extension drops to about 1/4 or 1/5 the value for unstrained bars.

c. Uniform axial extension at 70°F; axial tests at -16°F. For comparison some bars were permanently deformed in tension before grooving. Smooth bars of 3/4 in. cross-section, 9 in. long were gripped at their ends in the usual wedge grips of a tension machine and pulled to strains of 0.03, 0.06 or 0.09. Higher strains were avoided for fear of non-uniform straining. The bars were aged, grooved as in Fig. 6a with notch radii of 0.003 or 0.030 in., and tested in tension at -16°F exactly as the precompressed bars. The results are given in Table VIII and Fig. 10. Tests for the 0.1% offset yield strength after prestretching and aging could not be made, but it is clear that the fracture stress follows the same pattern as before, beginning at or above the 2.68 flow limit at zero prestrain (100 ksi) and rising with the prestrain at low prestrain values (Note: Fig. 10 has a more extended prestrain scale than all other similar graphs). The elongation at fracture also follows the usual pattern, i.e. falls rapidly to a small fraction of its initial value, even at prestrains as low as 0.03 to 0.09. Here, however, the reduction is of the order of 1/3 instead of 1/4 to 1/5.

TABLE VIII ABS-B STEEL BARS GROOVED CIRCUMFERENTIALLY AFTER UNIFORM AXIAL EXTENSION AT 70°F.

Bar	Pre-strain	Notch Radius (in.)	Root Dia. (in.)	Net Area (in.^{2})	Elong. at Fracture 0.001 in.		Average Fracture Stress ksi
					Total	Plastic	
B-413	0.03	0.003	0.376	0.1110	10.4	9.0	124
B-414		0.003	0.377	0.1116	7.6	6.2	127
B-415		0.030	0.3765	0.1113	21.2	20.0	123
B-416		0.030	0.3735	0.1096	10.0	8.6	124
B-417	0.06	0.003	0.3765	0.1113	7.0	5.6	146
B-418		0.003	0.375	0.1104	6.3	4.9	146
B-419		0.030	0.372	0.1087	8.5	7.0	139
B-420		0.030	0.375	0.1104	17.1	15.6	143
B-421	0.09	0.003	0.3755	0.1107	8.6	7.0	161
B-422		0.003	0.374	0.1099	7.4	5.9	158
B-423		0.030	0.375	0.1104	9.2	7.8	149
B-424		0.030	0.363	0.1035	9.1	7.5	149

d. Hot uniform axial compression. The hot axial compression of the 9.00 x 0.75 x 0.75 in. bars was produced in the special machine described in an earlier report (Fig. 12a,b of ref. 18), after a modification permitting a single stroke compression without change of plungers. After preheating to 550°F in a separate oven, each bar was quickly inserted in the hot dies of the compression machine, compressed to the required strain in at most one minute, and dropped in boiling water. The bars were then machined to standard tension specimens and were tested at -16°F. This method was used for prestrains of 0.20 and less, not tested before, and of 0.30 and 0.40 for comparison with corresponding earlier tests by the method of step-by-step compression [18]. The results are given in Table IX. The 0.1% offset strength of bars prestrained by the same amount at room temperature is given in the last column for comparison.

TABLE IX ABS-B STEEL STANDARD TENSION TESTS AT -16°F AFTER UNIFORM AXIAL PRECOMPRESSION AT 550°F.

Bar	Prestrain	0.1% Offset Stress ksi	Fracture		$\sigma_{0.1}$ (ksi) for same cold prestrain
			Nat. Strain	True Stress ksi	
0.1	0	38.6	1.16	142.9	36-38
0.2	0	38.6	1.19	147.2	
5.1	5	42.7	1.11	146.8	42.5-43.5
5.2	5	46.8	1.09	147.4	
10.1	10	54.5	1.00	145.6	51.4-51.8
10.2	10	57.5	1.02	150.6	
20.1	20	63.6	1.00	149.8	58-59
20.2	20	65.0	0.96	148.3	
30.1	30	70.3	0.92	157.9	63-64
30.2	30	72.3	0.88	159.7	
B-5[b]	0.30	73	0.82	141	63-64
B-6[b]	0.30	76	0.85	141	
B-7[b]	0.30	68	0.88	146	
B-8[b]	0.30	67	0.90	145	
40.1	40	71.7	0.90	161.7	66-67
40.2	40	72.7	0.93	156.6	
B-1[a]	0.41	72	0.77	137	66-67
B-2[a]	0.41	69	0.75	147	
B-3[a]	0.41	71	0.83	143	
B-4[a]	0.41	66	0.90	155	

a. Precompressed at 527°F in 4 steps over a period of 7 to 40 minutes.
b. Precompressed at 530°F in 4 steps over a period of 12 to 44 minutes.

Bars prestrained in the same manner at 550°F were also grooved circumferentially as before and tested in tension at -16°F. The results for prestrains up to 0.30 and a notch radius of 0.003, 0.010 or 0.030 in. are given in Table X and Fig. 11. Up to prestrains of about 0.05 or 0.10 the fracture stress (Fig. 11, left) is again higher than the 2.68 $\sigma_{0.1}$ flow limit of perfectly plastic bars of the same yield strength. At prestrains of about 0.10 and higher the

TABLE X ABS-B STEEL BARS GROOVED CIRCUMFERENTIALLY AFTER UNIFORM COMPRESSION AT 550°F TENSION TESTS AT -16°F.

Bar	Pre-strain	Notch Radius (in.)	Root Dia. (in.)	Net Area (in.^{2})	Elong. at Fracture 0.001 in.		Av. Stress ksi	
					Total	Plastic	At Fract.	Flow Limit
B-407	0	0.003	0.3755	0.1107	30.4	29.6	117	100
B-408		0.003	0.3755	0.1107	31.0	29.2	122	
B-409		0.010	0.378	0.1122	36.4	35.4	119	
B-410		0.010	0.3725	0.1090	46.0	45.0	120	
B-411		0.030	0.376	0.1110	31.0	30.0	123	
B-412		0.030	0.3755	0.1107	46.8	45.8	118	
B-401	0.025	0.003	0.375	0.1104	5.5	4.7	129	
B-402		0.003	0.3745	0.1102	4.4	3.5	118	
B-403		0.010	0.3745	0.1102	9.0	8.0	137	
B-404		0.010	0.376	0.1110	8.6	7.6	133	
B-405		0.030	0.375	0.1102	32.3	31.3	134	
B-406		0.030	0.375	0.1102	23.8	22.6	142	
B-375	0.05	0.003	0.3745	0.1102	5.2	4.3	138	120
B-376		0.003	0.3755	0.1107	2.4	1.3	116	
B-377		0.010	0.3760	0.1110	2.3	0.9	112	
B-378		0.010	0.3760	0.1110	2.5	1.4	117	
B-379		0.030	0.3745	0.1102	5.8	4.7	136	
B-380		0.030	0.3750	0.1104	5.7	4.6	142	
B-381	0.10	0.003	0.3755	0.1107	2.3	1.0	126	150
B-382		0.003	0.3750	0.1104	1.7	0.5	110	
B-383		0.010	0.3755	0.1107	2.6	1.3	137	
B-384		0.010	0.3750	0.1104	2.9	1.7	143	
B-385		0.030	0.3760	0.1110	5.8	4.4	160	
B-386		0.030	0.3740	0.1099	5.0	3.7	160	
B-387	0.20	0.003	0.3745	0.1102	2.1	0.7	138	172
B-388		0.003	0.3740	0.1099	2.2	0.8	136	
B-389		0.010	0.3745	0.1102	2.1	0.7	134	
B-390		0.010	0.3755	0.1107	1.2	0	90	
B-391		0.030	0.3740	0.1099	2.9	1.5	146	
B-392		0.030	0.3745	0.1102	2.5	1.1	138	
B-393	0.30	0.003	0.3760	0.1110	1.7	0.2	116	191
B-394		0.003	0.3755	0.1107	1.9	0.6	119	
B-395		0.010	0.3750	0.1104	2.1	0.7	130	
B-396		0.010	0.3745	0.1102	1.2	0	102	
B-397		0.030	0.3755	0.1107	1.8	0.4	121	
B-398		0.030	0.3755	0.1107	2.3	0.7	136	

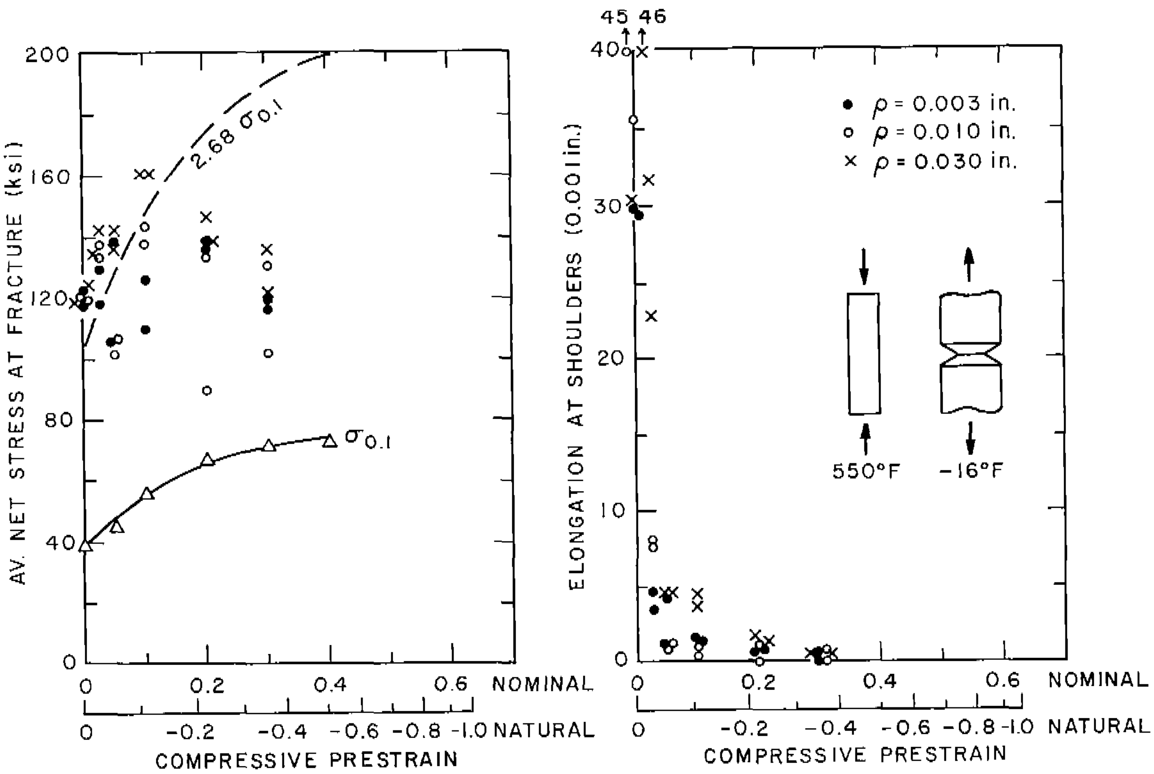

Fig. 11 Bars Axially Precompressed At 500°F, Grooved And Tested At - 16°F.

fracture stress drops well below the corresponding 2.68 $\sigma_{0.1}$ flow limit. The reduction of the fracture stress seems to occur at smaller prestrains, about half as small as with similar bars prestrained at 70°F. Indeed if expanded to about twice its present width, the whole Fig. 11 left (hot prestrain) would become almost identical with Fig. 8 left (cold prestrain). Hot prestrain causes about the same $\sigma_{0.1}$ and notched fracture stress as cold prestrain twice as large. This is in agreement with an earlier conclusion that the exhaustion limit (compressive prestrain needed to cause brittleness in subsequent tension) in hot straining was only half as big as in cold straining [15,16,9], and emphasizes the importance of the hot straining occurring during welding.

The permanent extension at the shoulders (Fig. 11, right) drops again very quickly with increasing prestrain. For the 0.003 in. notch radius the drop to about 1/6th or less the unstrained value occurs already at a hot prestrain of only 0.025. For the 0.010 in. radius the drop is to about 1/4th at 0.025 and to 1/10th or less at 0.05. For the 0.030 in. radius the extension drops to 2/3 the unstrained value at 0.025 prestrain and to about 1/10th at 0/05. The results are very similar with those of similar cold strained bars (Fig. 8, right), but the drop of ductility appears to be even more sudden, especially for the less acute notches of 0.030 and 0.010 in. radii. It again appears that hot prestraining causes greater embrittlement than an equal cold straining.

e. Axial (non-uniform) compression of already grooved bars. In these tests the bars had the circumferential grooves machined first and were subsequently precompressed axially and artificially aged. Twelve grooved bars were prepared but only six could be prestrained and tested. The compression of the remaining six bars was to be chosen on the basis of the first results, but the tests were

TABLE XI ABS-B STEEL BARS GROOVED CIRCUMFERENTIALLY AND THEN COMPRESSED AXIALLY AT 70°F TENSION TESTS AT -16°F.

Bar	Pre-strain	Notch Radius (in.)	Root Diameter in.		Elong. at Fracture 0.001 in.		Av. Stress ksi	
			As Machined	After Compression	Total	Plastic	At Fract.	Flow Limit for Initial Yield Stress
B-425	0.005	0.003	0.376	0.378	19.2	18.5	118.8	100
B-426		0.010	0.3745	0.377	28.0	27.2	123.5	
B-427		0.030	0.3725	0.376	44.0	43.2	126	
B-428	0.015	0.003	0.374	0.382	3.6	2.8	94.3	
B-429		0.010	0.3765	0.3845	7.4	6.6	108.5	
B-430		0.030	0.373	0.385	42.4	41.6	132	

interrupted.

The results are shown in Table XI and Fig. 12, which is completed with the unstrained test data from Fig. 8. Precompression causing contractions of 0.005 and 0.015 in. at the shoulder do not appear to cause any significant reduction in the fracture stress with any notch radius. The extension at fracture, however, is about 1/5th the unstrained value at a shoulder contraction of 0.015 in. for notch radii of 0.003 and 0.010 in. but is unchanged for the 0.030 radius. The shoulder contraction of 0.005 in. has no significant effect on the fracture stress with any of the notch radii. These tests although incomplete confirm that brittle-

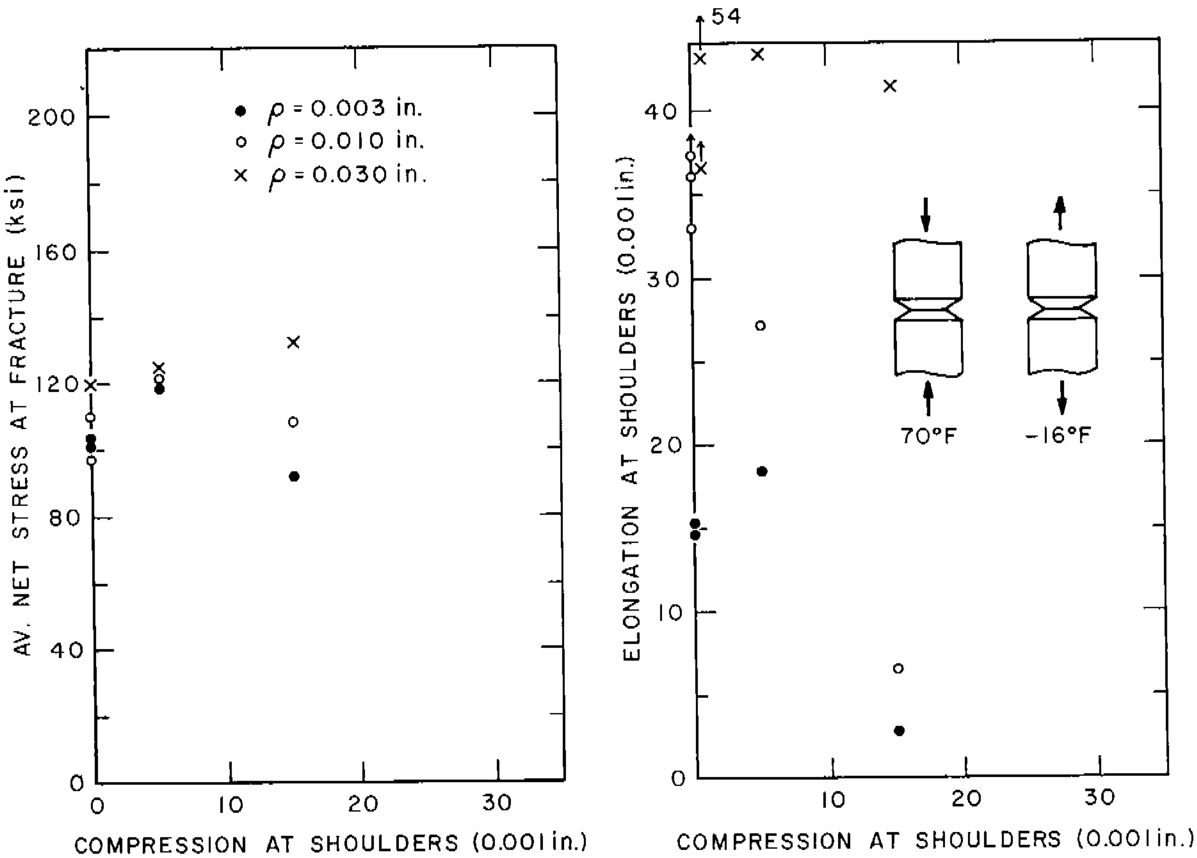

Fig. 12 Bars Grooved First, Axially Precompressed At 70°F, Tested At -16°F.

ness is better indicated by the deformation than by the average stress at fracture, as has already been discussed earlier [12]. If the gross simplifying assumption is made that the highly strained region at the root of the notch has a length (in the axial direction) proportional to the radius of curvature, it would be concluded that equal peak strains would develop in grooved bars at contractions proportional with the radius of curvature. Since the bars of 0.010-in. notch radius are "brittle" (low extension at fracture) at a prestrain contraction of 0.015-in., the bars of 0.030-in. notch radius should be "brittle" at a three times higher shoulder contraction, or about 0.045-in. Likewise the bar of 0.003-in. notch radius should have been brittle at 1/3 this contraction or about 0.005 in., but this does not appear to be so. More tests of this nature should reduce any spurious results of scatter in the present limited tests, and should greatly help in the study of the size effect in fracture.

3. BARS WITH SYMMETRIC SIDE NOTCHES

Symmetrically side-notched bar tests were made for comparison with the circumferentially grooved bars, especially as to their relative degrees of constraint. Compression and aging was carried out exactly as with the corresponding bars with grooves and the notches were machined with the same milling cutters (Fig. 6c). The extensometer measuring the extension at the shoulders up to fracture was modified so as to be mounted on 0.010-in. pins inserted at the center line of the notched faces about 0.025 in. from the edge of each notch (Fig. 6c). As is well known, conditions of plane strain are difficult to achieve in bars with deep symmetric side notches [21]. This is clearly shown by the average net stress at the moment when large deformations occur in comparison with the flow limits in <u>plane stress</u> and <u>plane strain</u> for perfectly plastic material. The flow limit in <u>plane stress</u> (thin bars) is equal to the yield stress σ_o in simple tension; in plane strain (thick bars) it is $2.57\sigma_o$ for deep notches of zero included angle, or about $2.4\ \sigma_o$ for 20° [23]. The governing factor is the ratio B:C of bar thickness to net width at the notch section [22]. Even at a ratio of about 7:1 large deformations occurred at a load well below the plane strain limit [23]. With the usually reported notched test specimens having a ratio of about 2 the conditions are very close to plane stress with little lateral constraint. Only at very low loads and elastic stresses do such relatively "thin" specimens develop plane strain constraints in the region of the notch root away from the faces, as then it is the ratio of thickness to notch radius which need be large [22]. By extension, plane strain will also prevail at slightly higher loads when the yield zones are small. As the loading increases, however, the yield regions grow and the severity of the constraint diminishes from plane strain to plane stress, as has been recently confirmed by Hahn [25], and its influence on fracture is reduced. The purpose of the present tests is to study the remaining ductility after prestraining which diminishes with increasing constraint severity. Therefore, it was important to have the strongest possible conditions of constraint constant throughout the whole test. This could be achieved if conditions close to plane strain prevailed throughout the whole process of loading up to general yielding or fracture. "Thick" specimens were obviously required (large B:C ratios, Fig. 6c). The thickness B was limited to 0.75 in. (thickness of parent plate) and the width C was chosen after preliminary tests with 0.750-in. square bars notched to a net width of 0.375, 0.250, or 0.125-in., i.e. with ratios B:C of 2, 3, or 6, either unstrained or compressed axially by 0.20 at 70°F. All bars had the same notch root radius of 0.003 in. The preliminary results are shown with those of all cold axially compressed bars in Table XII but are marked for easy distinction. Of the bars with 0.375-in. net width (B:C = 2), the two of zero prestrain either stripped or broke at the

TABLE XII ABS-B STEEL BARS NOTCHED ON SIDES AFTER UNIFORM AXIAL COMPRESSION AT 70°F TENSION TESTS AT -16°F.

Bar	Pre-strain	Notch Radius 10^{-3} in.	Root Width in.	B/C	Elong. at Fracture 0.001 in. Total	Plastic	Av. Stress ksi At Fract.	Th. Flow Limit $2.4\ \sigma_{0.1}$
B-297[+]	0	0.003	0.375	2	14.6*->40.0	>39.2	64.0*>78.2	89
B-298[+]		0.003	0.375		>53.0	>52.2	>82.3	
B-300[+]	0.20	0.003	0.373		> 4.0	> 2.9	>109.7	140
B-301[+]	0	0.003	0.254	3	24.8*-54.0	23.0*	86*-94	89
B-302[+]		0.003	0.250		51.0	49.0	93	
B-303[+]	0.20	0.003	0.246		10.0	8.6	130	140
B-304[+]		0.003	0.245		14.4	13.0	135	
B-305[+]	0	0.003	0.124	6	23.6*-25.1	24.3	117*-116	89
B-306[+]		0.003	0.129		17.1*-21.8	21.0	103*-104	
B-625	0.05	0.003	0.124	6	10.6	9.6	135	103
B-626		0.003	0.1235		6.8	5.8	130	
B-627		0.010	0.124		5.8	4.8	126	
B-628		0.010	0.124		8.8	7.8	128	
B-629		0.030	0.126		14.4	13.4	125	
B-630		0.030	0.1265		8.7	7.7	124	
B-631	0.10	0.003	0.125	6	7.7	6.7	148	124
B-632		0.003	0.125		9.1	8.1	152	
B-633		0.010	0.125		9.7	8.7	151	
B-634		0.010	0.123		5.8	4.7	143	
B-635		0.030	0.1255		8.1	7.0	132	
B-636		0.030	0.1275		6.7	5.8	133	
B-307[+]	0.20	0.003	0.123	6	6.2	5.2	155	140
B-308[+]		0.003	0.129		5.2	4.2	152	
B-637	0.20	0.003	0.1245	6	5.2	4.0	162	140
B-638		0.003	0.125		7.6	6.4	165	
B-639		0.010	0.123		5.8	4.5	153	
B-640		0.010	0.124		6.0	4.8	161	
B-641		0.030	0.1295		5.7	4.5	141	
B-642		0.030	0.127		5.3	4.1	141	
Bar	Pre-strain	Notch Radius 10^{-3} in.	Root Width in.	B/C	Total	Plastic	At Fract.	Th. Flow Limit $2.4\ \sigma_{0.1}$
B-643	0.30	0.003	0.1255	6	4.9	3.5	163	153
B-644		0.003	0.1235		8.0	6.8	173	
B-645		0.010	0.1260		7.1	5.9	170	
B-646		0.010	0.1235		6.6	5.4	171	
B-647		0.030	0.124		4.6	3.4	153	
B-648		0.030	0.123		5.4	4.2	154	

[+] Preliminary tests with various values B:C.

* Early crack noise or diagram irregularity. In bar B-297 this was caused by stripping of the threads.

threads of the pulling heads at average net stresses of about 80 ksi (less than the plain strain flow limit of 89 ksi) with large permanent extensions (0.040 to 0.050 in.); the third, prestrained by 0.20, withstood the highest load of the testing machine (30.5 klb) at a stress of 110 ksi (less than the plane strain flow limit of 140 ksi) without fracture or large extension. The bars of 0.250-in. net width (B:C = 3) developed large extensions and reached the plane strain flow limit when unstrained, but fractured just under the flow limit with much smaller extension when prestrained by 0.20. The bars of 0.125-in. net width (B:C = 6) reached or exceeded the theoretical flow limit whether strained by 0 or 0.20, but showed large strains only when unstrained: those prestrained by 0.20 extended much less, only half as much as the corresponding bars of 0.250 in. width.

The bars of 0.125-in. net width (B:C = 6) developed higher stress and smaller extension at fracture, hence appreciably greater constraint than the next wider 0.250-in. bars, and were chosen for all other tests with side-notched bars.

a. Bars with uniform axial precompression at 70°F. The results of the tension test at -16°F of bars uniformly prestrained by 0.005, 0.10, 0.20 or 0.30 and notch radii of 0.003, 0.010 or 0.030-in. are given in Table XII and in the graphs of Fig. 13.

b. Bars with uniform lateral precompression at 70°F. The corresponding test results of laterally precompressed bars are given in Table XIII and Fig. 14.

c. Bars with uniform axial precompression at 550°F. The corresponding results are shown in Table XIV and Fig. 15.

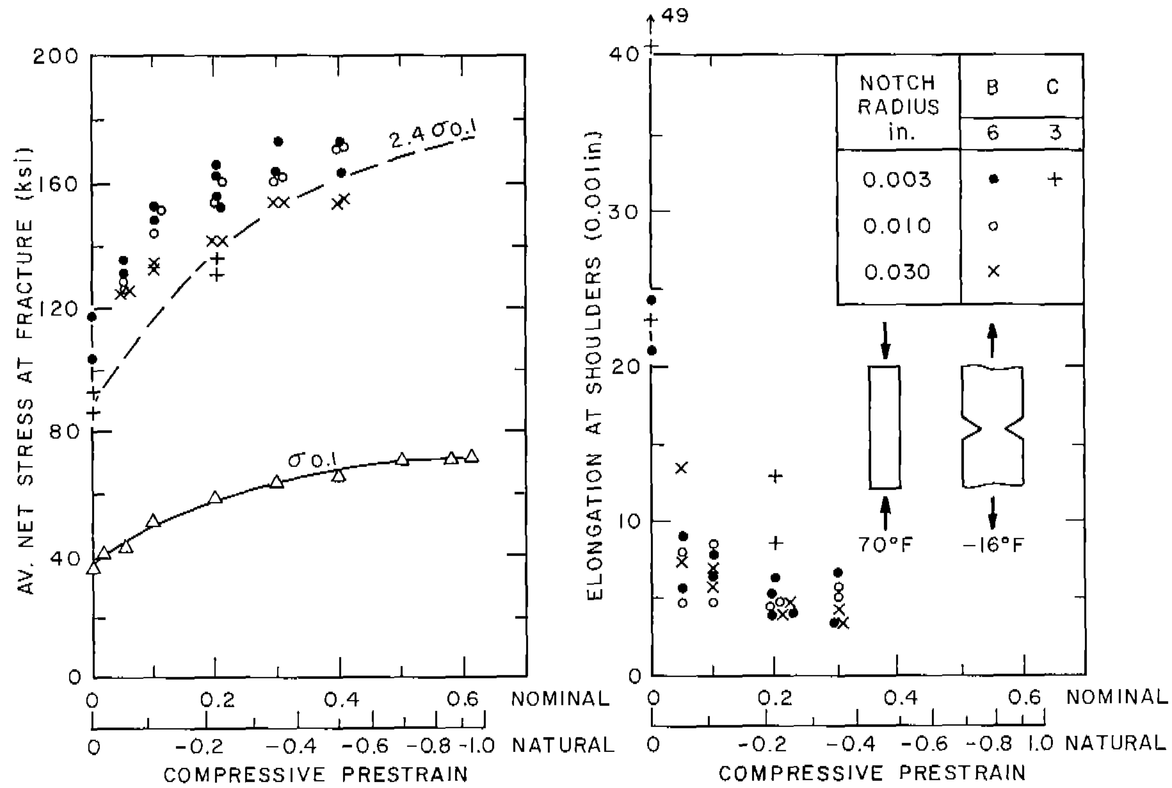

Fig. 13 Bars Axially Precompressed At 70°F, Side - Notched And Tested At - 16°F.

Each of the Figures 13-15 contains two graphs: one of average net fracture stress vs. prestrain (left) and another of permanent fracture extension at the shoulders vs. prestrain (right). The left graph shows also the 0.1% offset yield strength after compression and aging and the theoretical 2.4 $\sigma_{0.1}$ flow limit for an equivalent perfectly plastic material. All graphs are remarkably similar to those of circumferentially grooved bars of corresponding conditions of prestrain, especially the relation of the fracture stress to their flow limit curve. The only recognizable difference appears in the fracture extension graph of axially cold strained bars, where the side notches show somewhat larger ex-

TABLE XIII ABS-B STEEL BARS NOTCHED ON SIDES AFTER UNIFORM LATERAL COMPRESSION AT 70°F TENSION TESTS AT -16°F.

Bar	Pre-strain	Notch Radius 10^{-3} in.	Root Width in.	$\frac{B}{C}$	Elong. at Fracture 0.001 in.		Av. Stress ksi	
					Total	Plastic	At Fract.	Th. Flow Limit $2.4\ \sigma_{0.1}$
B-687	0	0.003	0.119	6	18.0	17.3	108	91
B-689		0.010	0.1265		18.8	18.1	107	
B-690		0.010	0.1235		20.0	19.3	118	
B-691		0.030	0.125		20.4	19.7	103	
B-692		0.030	0.1255		19.9	19.2	111	
B-693	0.025	0.003	0.1255	6	11.6	10.6	118	
B-694		0.003	0.1255		11.2	10.2	126	
B-695		0.010	0.125		13.1	12.1	118	
B-696		0.010	0.125		12.2	11.2	121	
B-697		0.030	0.1265		12.4	11.4	114	
B-698		0.030	0.126		11.9	10.9	114	
B-600	0.05	0.003	0.1255	6	7.8	6.8	133	146
B-601		0.003	0.1275		7.5	6.4	128	
B-602		0.010	0.126		7.8	6.7	132	
B-603		0.010	0.123		9.0	7.9	131	
B-604		0.030	0.124		8.3	7.1	126	
B-605		0.030	0.1235		8.1	7.0	129	
B-606	0.10	0.003	0.1245	6	5.2	4.0	143	163
B-607		0.003	0.127		5.2	4.0	142	
B-608		0.010	0.1245		4.7	3.5	139	
B-609		0.010	0.1245		5.8	4.6	143	
B-610		0.030	0.1245		5.8	4.6	134	
B-611		0.030	0.125		7.2	6.0	135	
B-612	0.20	0.003	0.126	6	3.5	2.1	154	190
B-613		0.003	0.129		2.8	1.4	146	
B-614		0.010	0.1265		4.2	2.6	152	
B-615		0.010	0.125		3.8	2.4	153	
B-616		0.030	0.125		4.2	3.0	147	
B-617		0.030	0.124		3.8	2.6	146	
B-618	0.30	0.003	0.127	6	3.6	2.0	172	211
B-619		0.003	0.137		3.7	2.1	164	
B-620		0.010	0.125		3.8	2.2	167	
B-621		0.010	0.124		3.1	1.5	166	
B-622		0.030	0.126		5.0	3.4	160	
B-623		0.030	0.125		3.9	2.4	157	

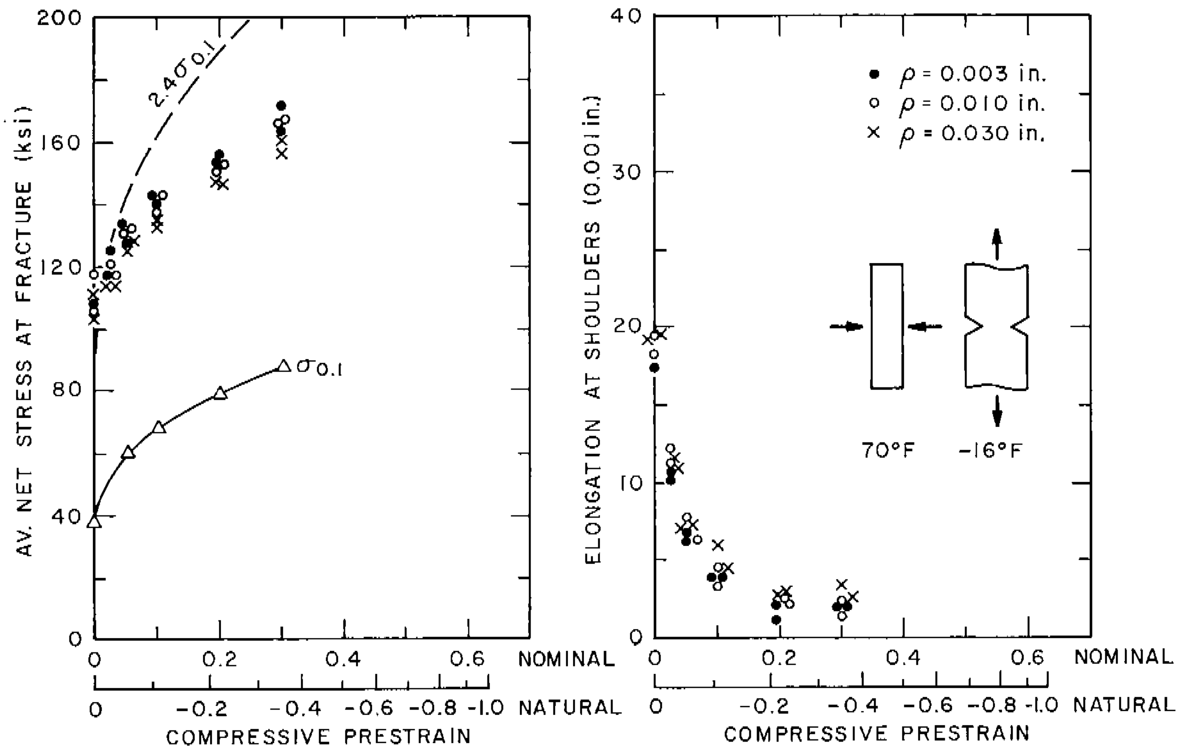

Fig. 14 Bars Laterally Precompressed At 70°F, Side - Notched And Tested At -16°F.

tension than the circumferential grooves (compare Fig. 14 and 8) at all prestrains, except at zero prestrain. It is not clear whether this should be attributed to a difference in constraint severity in the two types of bars. The question is complicated by the obvious behavior changes from face to center of the side-notched bars. The regions close to the faces show much less cleavage and obviously more lateral contraction (smaller deformed width C) than the center. It appears probable that in some instances the center region cracked first. In view also of the size difference (grooved diameter 0.375 in: net width C 0.125 in.) very close comparisons are meaningless.

TABLE XIV ABS-B STEEL BARS NOTCHED ON SIDES AFTER UNIFORM AXIAL COMPRESSION AT 550°F TENSION TESTS AT -16°F.

Bar	Pre-strain	Notch Radius 10^{-3} in.	Root Width in.	B/C	Elong. at Fracture 0.001 in.		Av. Stress ksi	
					Total	Plastic	At Fract.	Th. Flow Limit $2.4\ \sigma_{0.1}$
B-675	0	0.003	0.125	6	25.0	24.2	112	93
B-676		0.003	0.125		21.8	21.1	109	
B-677		0.010	0.143		28.6	27.8	106	
B-678		0.010	0.125		29.4	28.6	111	
B-679		0.030	0.1265		30.4	29.6	99	
B-680		0.030	0.1265		25.6	24.8	102	
B-681	0.025	0.003	0.1245	6	5.3	4.5	119	—
B-682		0.003	0.125		5.0	4.2	118	
B-683		0.010	0.1255		7.0	6.2	117	
B-684		0.010	0.123		6.6	5.8	116	
B-685		0.030	0.129		15.0	14.2	115	
B-686		0.030	0.1265		16.0	15.2	123	
B-650	0.05	0.003	0.1265	6	3.1	2.2	128	107
B-651		0.003	0.1260		3.2	2.2	124	
B-652		0.010	0.1240		4.2	3.4	132	
B-653		0.010	0.1240		3.1	2.8	130	
B-654		0.030	0.1265		4.0	3.0	124	
B-655		0.030	0.1255		3.2	2.2	118	
B-656	0.10	0.003	0.1250	6	3.5	2.5	146	134
B-657		0.003	0.127		1.7	0.7	119	
B-658		0.010	0.1235		3.2	2.0	148	
B-659		0.010	0.124		3.0	1.8	141	
B-660		0.030	0.128		2.6	1.4	137	
B-661		0.030	0.128		3.6	2.4	137	
B-662	0.20	0.003	0.1255	6	2.2	0.9	142	154
B-663		0.003	0.1265		2.6	1.2	151	
B-664		0.010	0.125		2.3	0.9	149	
B-665		0.010	0.124		2.2	1.0	143	
B-666		0.030	0.1265		3.0	1.6	155	
B-667		0.030	0.128		2.6	1.3	141	
B-668	0.30	0.003	0.125	6	1.4	0.0	113	170
B-669		0.003	0.128		2.2	0.9	147	
B-670		0.010	0.125		1.6	0.4	144	
B-671		0.010	0.125		1.8	0.4	133	
B-672		0.030	0.127		2.0	0.6	134	
B-673		0.030	0.128		2.8	1.4	156	

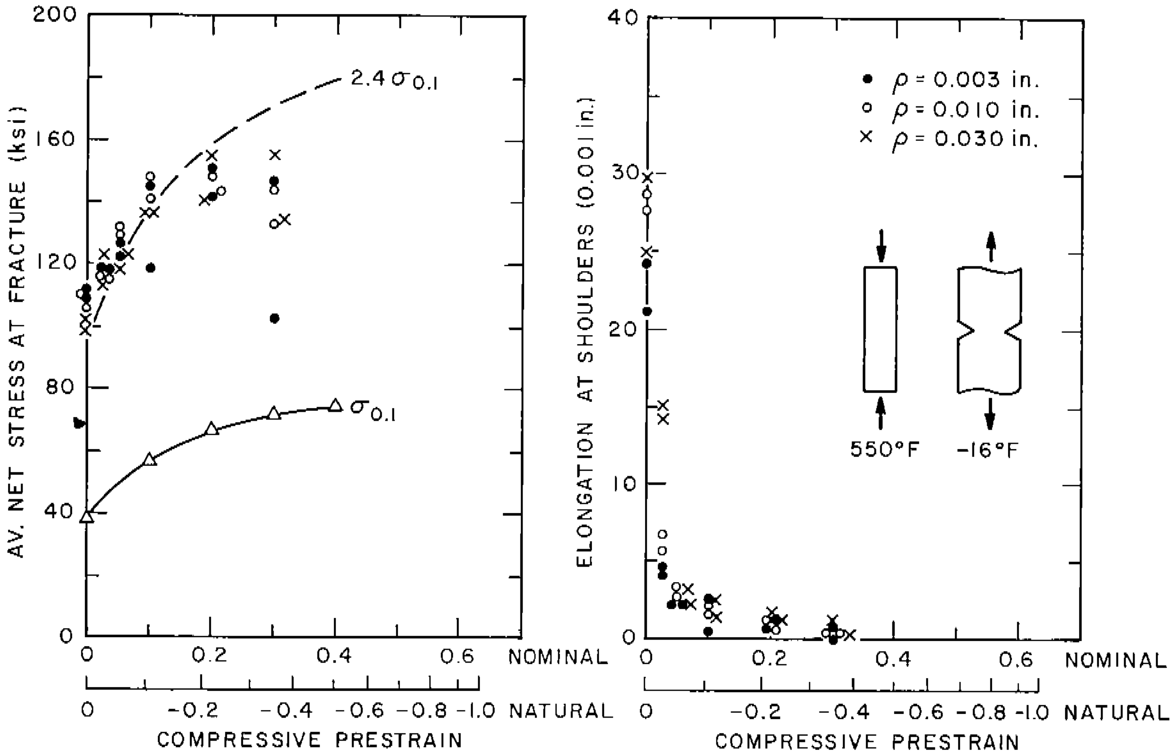

Fig. 15 Bars Axially Precompressed At 550°F, Side - Notched And Tested At -16°F.

CONCLUSION

A. The present tests prove that a catastrophic reduction of ductility of mild steel may be caused by small prestrains. The extension at the shoulders of grooved or notched bars has been reduced to about 1/4 or 1/5 its initial value by a uniform cold compressive or extensional prestrain of about 0.05 or a uniform hot prestrain of about 0.025, or by a compression of the already notched bars by only 0.015 in. at the shoulders.

B. Axial cold (70°F) or hot (550°F) precompression, cold pre-extension and lateral cold precompression have a generally similar effect, but hot precompression appears to be more damaging than cold. The hot prestrain causing the ductility drop to about 1/4 - 1/5 its initial value is only about half the corresponding cold prestrain.

C. The circumferentially grooved bar appears to be a better test specimen than the side notched bar which shows a variation of behavior from center to faces.

D. The notched 3/4 in. thick plates needed larger prestrains than the notched or grooved bars, probably because of their smaller constraint as they were much thinner than the bars hence developed conditions closer to plane stress. However, the embrittling in-plane compression of already notched plates was only about three times that of circumferentially grooved bars (0.040 in. or more vs. 0.015 in.).

E. The presented testing method offers great control over the ductility or embrittlement of the steel, and great sensitivity to factors such as geometry, notch severity and temperature. It appears very promising for studying many more factors affecting ductility and brittle fracture, especially the most important ones of repeated strain reversals, of specimen size and speed of loading.

F. As amply shown structural mild steels can develop "brittle" fractures only after some damaging strain history during fabrication, use or repair. Accordingly the proper selection of steels to withstand brittle fracture should be based on their resistance to embrittlement by straining, rather than on any property in their "initial" state. The higher the prestrain (cold or hot) a steel can withstand without showing brittleness in subsequent notched tension testing, the "tougher" it is.

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13. ABSTRACT

Notched plates and bars prestrained in compression or extension, before or after notching, at 70°F or 550°F were tested to fracture in tension at -16°F. It was found that a catastrophic reduction of ductility could be caused by small prestrains. Uniform longitudinal or transverse prestraining by as little as 0.05 at 70°F reduced the initial ductility of notched bars by a factor of 4 or more. Hot prestraining was even more damaging: the greatest drop in the ductility at -16°F was caused by prestrains of only 0.025 at 550°F. These tests indicate that the "brittle" behavior of mild steel structures results from some damaging prior history of straining. Accordingly the proper selection of steels should be based on their resistance to embrittlement by suitable straining rather than on their properties in the initial undamaged state. The presented testing methods offer a great control over the steel ductility. They would be useful both in steel assessment and in the investigations of the factors influencing the resistance of steel to fracture.

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