SSC-173

Exhaustion of Ductility Under Notch Constraint Following Uniform Prestraining

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ADDRESS CORRESPONDENCE TO:

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August 1966

Dear Sir:

In order to study the effect of gross strain upon the mechanical and metallurgical properties of steel and to relate these variables to steel embrittlement, the Ship Structure Committee is sponsoring a project at Brown University entitled "Macrofracture Fundamentals." Herewith is a copy of the Fifth Progress Report, SSC-173, Exhaustion of Ductility under Notch Constraint Following Uniform Prestraining by C. Mylonas, S. Kobayashi and A. E. Armenakas.

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

SSC - 173

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

to the
Ship Structure Committee

EXHAUSTION OF DUCTILITY UNDER NOTCH CONSTRAINT FOLLOWING UNIFORM PRESTRAINING

by
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Brown University
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under

Department of the Navy
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Washington, D. C.
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ABSTRACT

An earlier analysis and tests (1-4) have shown that commercial mild steels under static loading do not fracture in a brittle manner unless damaged by a suitable history of straining. Notched and then compressed plates have fractured in subsequent tension at loads as low as 10% of the limit load and precompressed smooth bars at strains as low as 0.01. The comparison of average net fracture stress with the flow limit stress was shown to be an excellent criterion of brittle or ductile behavior of mild steel structures, when only loads and general stress levels are known.

The purpose of the present work is to measure the amount of uniform precompression of ABS-B and Project E-steel resulting in brittle fracture under the strong constraint of a subsequently machined severe circumferential groove. The elongation at the shoulders, measured with a special extensometer, was found to be a far more sensitive measure of brittleness than the average fracture stress. Prestrains as low as 0.05 caused a reduction of the elongation at the shoulders from about 0.017 - 0.050 in. to about 0.003 - 0.006 in. At low prestrains average fracture stress equaled or exceeded the theoretical flow limit of 2.68 $\sigma_{0.1}$, where $\sigma_{0.1}$ is the 0.1% offset yield stress in simple tension at the same prestrain. At a prestrain of 0.20 the fracture stress fell below the flow limit and at 0.60 it was close to $\sigma_{0.1}$. The conditions of fracture at a notch in a strain hardening material are discussed. The total plastic elongation of a region surrounding a sharp notch in prestrained steel determines whether or not fracture will be initiated in large structures, hence is a direct and realistic measure of the remaining ductility and provides an excellent test of the material's resistance to embrittlement.

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1. INTRODUCTION

Research on brittle fracture in the last ten years at Brown University, summarized and extended in references (1-4) which discuss also numerous related publications, has shown the importance of the prior history of strain and temperature of mild steel on its susceptibility to the initiation of brittle fracture. In essence, attention is focussed on the strains developing near a notch or crack of a structure at various stages of loading. Localized yielding begins at the notch roots at low loads, but is contained within elastic regions. The plastic strains are hence small. They increase slowly with the load up to the flow limit or limit load for an ideally plastic material. Unrestricted plastic flow then occurs. At such strains the real material locally strain hardens and fractures. With work-hardening materials no flow limit exists, and the transition from low to high plastic strains is more gradual. If the strain hardening curve is not too steep, the overall deformations are found to increase distinctly more rapidly at loads close to the flow limit of an equivalent perfectly plastic material. With steeper strain-hardening no distinct demarkation exists between brittle and ductile behavior, but a reasonably high average net stress or total deformation may be adopted as a useful criterion, as discussed later.

The total ductility of the material at the notch, under the local conditions of triaxial stress, will determine the maximum load which may be reached. With a total available ductility equal or larger than that required at the limit load or at the chosen load or deformation limit, the behavior will be ductile (high load); with less available than required ductility low load fracture (brittle fracture) will occur. Accordingly the sufficiency or not of the ductility at a notch is shown by the magnitude of the applied load or average net stress as compared with the limit load or the agreed limit.

The application of this criterion showed a surprising difference between laboratory and service fractures. Commercial mild steels in their initial undamaged state had sufficient ductility to avoid brittle fracture initiation under static loading in spite of the deepest notches and temperatures below brittle transition, whereas the steels of the service structures did not. It was concluded that, in the latter case, local embrittlement had occurred, probably during fabrication or service.

The validity of the above theories was demonstrated by the achievement of low static stress (brittle) fracture initiation in unwelded steel after a local reduction of the ductility. This was best done with symmetrically notched plates of mild steel (E-steel, ABS-C, ABS-B and others) cooled below the sharpy V-notch transition range and tested in central static tension. Unless deliberately damaged these plates withstood loads of limit intensity. Sufficient in-plane compressive prestraining perpendicular to the notch axis followed by accelerated aging resulted in static initiation of fracture at loads considerably lower than the flow limit, as low as 1/10th of this limit.

The cause of this change from ductile to brittle behavior was shown to be a reduction or exhaustion of the initial ductility at the notches caused by compressive prestraining followed by aging, but the magnitude of the compressive strains was unknown. The strongly variable strain distribution at a sharp notch could not be easily calculated, neither could its peak at the notch be measured. Only with axially precompressed bars and with bent bars, permitting easy strain measurements, could damage be related to prestrain. The straining action was reversed for final testing causing tension in place of compression and was continued up to fracture. It was found that the strain at fracture, hence the ductility, remained high up to a well defined limiting prestrain around 0.50 to 0.70 (50% to 70%), at which it dropped suddenly to very low values, of the order of 0.01 (1%). This limit, defined as the exhaustion limit in simple compression followed by tension, was usually determined to within 0.02 or better, and depended on the steel and the severity of the conditions of prestraining or final testing. Strain aging, as rolled surfaces and low test temperatures lowered the exhaustion limit. Prestraining in compression at about 550°F followed by cold final testing caused embrittlement at half the prestrain required with cold prestraining. Furthermore hot straining in extension embrittled the steel in subsequent tension. Heating for various periods at 700°F to 1200°F raised the exhaustion limit, i.e. caused some restoration of ductility (5). The value of the exhaustion limit indicates the susceptibility of steel to embrittlement and has been suggested as an indication of resistance to brittle fracture.

These results show the importance of all the prior history of strain and temperature and substantiate the previous analysis of the problem of static fracture initiation. They also provide qualitative explanations of the initiation of fracture in service. In effect initiation of service fractures has mostly been traced to regions of stress concentration which have been either cold strained, or lie close to welds, where complex hot straining had occurred.

For a quantitative assessment of the susceptibility to fracture, however, it is necessary to relate the reduced ductility to the ductility at a notch, and the damaging prestrain to the prestrains which may occur in a real structure. The effect of prestrain on the ductility required at a notch was investigated in the present tests with prestrained and then notched bars of ABS-B and Project E-steel.

2. DAMAGE BY PRESTRAINING

The damage at a notch of a plate under in-plane compression certainly does not occur under uniaxial compression as in the precompressed or bent bars, but under a variable three-dimensional stress, as e.g. at cracks or notches, or during punching or shearing, which are known to lead to brittle fracture. Consideration of the flattening and alignment of flaws, or of strain hardening at the squashed edges of flaws (3), indicate that simple compression may produce the type of simple prestrain causing the most embrittlement in subsequent tension in the same direction. Embrittlement may be easier, however, with a more complicated strain history. Certain sequences of straining and aging are known to cause embrittlement at smaller total strains; others may be discovered. Embrittlement by hot straining and by the complex longitudinal and transverse straining at a defect close to a weld during and after welding are such examples. Another example of a complex strain history is low cycle fatigue, or the application of a small number of longitudinal strain reversals. Axially loaded waisted bars showed an extensional ductility linearly decreasing with the cumulative average strain (6). On the contrary some reversed bend tests had shown no cumulative effect over 3 reversals.

Further search is obviously needed for a possible strain and temperature history which could occur during fabrication, service, or repair, and be more damaging than simple compression. As already discussed, however, embrittlement or ductility must not be assessed in simple tension but under the condition at the notch. It is thus proposed first to develop a test which will indicate when simple compression causes insufficient ductility under notch conditions, and then to use it to find more easily embrittling types of straining.

3. DUCTILITY AT A NOTCH

Except for the precompressed notched plate tests, all other tests consisted of simple uniaxial compression (with some uniaxial hot extension tests) followed by uniaxial tension to fracture. These tests were quite successful as simple and rapid methods of embrittling the steel, but they did not reproduce either the stress or the strain conditions of a notch at fracture. Straining at the root of very sharp notches though very localized may be quite severe even in the case of brittle fracture. Brittle behavior may therefore be possible after a considerably smaller compressive prestrain than required to reduce the fracture strain of smooth bars to 0.01 (4). Another observation shows that straining at a notch is quite different than in simple tension. Simple compression-tension tests showed an essentially unimpaired ductility up to prestrains of the order of 0.50 or more and a more or less abrupt reduction of ductility at this prestrain limit. If ductility in simple tension had been the governing factor, notched bars of uniformly prestrained material should also show an appreciably unchanged behavior up to prestrains of about 0.50, and should be very brittle only above this limit. This did not seem reasonable, and as shown by the present tests is quite incorrect. Brittleness in notched bars appears at a much lower compressive prestrain than in smooth bars.

This difference may be attributed to the stress state at the notch which differs strongly from simple tension. At the root surface of a deep notch the stress state is biaxial, but within a short depth triaxial tension builds up even while the behavior is elastic. When the flow limit is approached, triaxiality and longitudinal stress increase considerably, especially at the center of a deeply grooved section (3), but at low loads by far the largest stress is found at or close to the surface and is caused by the strong straining and work hardening. Triaxiality therefore cannot be a very important factor in most brittle fractures. In intermediate situations the maximum stress could be at a small depth from the surface where some moderate triaxiality can develop. It may be found that the intermediate situations are the most frequent and practically important and that the additional brittleness due to a moderate triaxiality superimposed on the prior damage by prestraining is sufficient to cause brittle fracture, hence is an important factor in the difference observed between smooth and notched bars.

The previous qualitative discussion became necessary because of our present inability to analyze exactly the problem of brittle fracture, i.e. by a comparison of the locally required ductility with the available material ductility under the conditions of stress at the notch. This can be exactly done if the problem of the stress and strain distribution around a notch in a material of the specific anisotropic strain-hardening law caused by prestraining is solved. This in turn requires the prior determination of the highly anisotropic strain-hardening law (tensorial) after prestraining. The exact solution of these problems would be a tremendous undertaking, impossible at this time. However, an indication of sufficiency or insufficiency of the ductility may be obtained without a separate calculation of available and required ductility, from tests of notched specimens, as is further discussed in paragraph 4.

The previous discussion about ductility does not imply a tacit assumption of a strain criterion of fracture. It is the strain under the local stress condition which governs. Both stress and strain and also strain history are important. Fracture may be caused by a very high stress reached by work hardening and constraints which develop at large strains in materials with slow strain hardening, or at low strains in materials with steep strain hardening. Stress is an intuitively clearer cause of fracture, but the growth of stress to a presumed limiting value is best seen as the result of suitable straining. Obviously, through the strain hardening law and the history of straining, the "conditions of fracture" could be expressed in terms of either stress or strain or in terms of both.

4. TEST OF DUCTILITY UNDER NOTCH CONSTRAINT

According to the previous discussion ductility must be assessed with prestrained and then notched specimens. Deep circumferential notches of various degrees of sharpness were considered advantageous (Fig. 6), as they offer maximum constraint and high requirements of ductility. A delicate point is how to assess the ductility or brittleness of deeply notched bars of strain hardening materials. When large ductility is available without much strain-hardening, the flow limit based on the yield stress σ_o in simple tension indicates the incidence of large strains (1-4). The theoretical flow limit stress for deep circumferential grooves of zero included angle is 2.85 times the yield stress σ_o in simple tension (7). An approximate correction for the present grooves with a 20° included angle, may be based on the corresponding change of flow limit in symmetrically notched bars in plain strain (8). The modified flow limit stress σ_L is about 2.68 σ_o. The prestrained bars, however, are not perfectly plastic but strain harden. They also have a substantially raised yield strength (0.1% offset) in simple tension. As discussed in the Introduction, a high load or a large total deformation will be chosen as limiting criterion. The flow limit $A\sigma_L$ corresponding to the 0.1% offset yield strength $\sigma_{0.1}$ (where A is the net area) appears as a suitable load limit. If little or no strain hardening occurs this flow limit should indicate the incidence of large strains. If strain hardening with sufficient ductility occurs, the actual stress over a substantial part of the region will rise more than without strain hardening, hence could correspond to a load larger than $A\sigma_L$. With steeper strain hardening and less ductility the stress at fracture may be very high in narrow regions of stress concentration but low over the rest of the section, so that the total load may be either higher or lower than the flow limit $A\sigma_L$. With increasing steepness of strain hardening fracture will occur at a continuously decreasing load tending to $A\sigma_{0.1}/n$ (n is the elastic factor of stress concentration), i.e. to a value 2.68n times smaller than $A\sigma_L$. It may be concluded that fracture at or below the flow limit based on the 0.1% yield strength is a sure indication of insufficient ductility. Insufficiency may also exist at loads higher than the flow limit, but cannot be distinguished with certainty. For relatively ductile materials it might be more realistic to base the flow limit on the 0.2% or 0.5% or 1% offset yield strength, because such strains could be expected to occur throughout the yielding region. A correspondingly higher criterion would then be reached. It has even been suggested (9) that the flow limit based on the ultimate strength of smooth bars (load divided by original area) should be used for judging the behavior of notched bars. The flow limit 2.68 $A\sigma_{0.1}$ based on the 0.1% offset strength was nevertheless chosen as a safe (hence sufficient) criterion of brittleness for all degrees of strain hardening, but it should be kept in mind that it is not also a necessary criterion. Brittleness may exist without necessarily showing as a fracture stress lower than the flow limit.

Among the many reported series of tests with notched bars, one is of special interest (10). These tests were made with bars of a normalized medium carbon steel, a quenched and tempered chrome steel and an aluminum alloy, with circumferential grooves 0.5 to 7.5 mm deep, a root diameter of 5 or 15 mm and a notch radius giving an elastic factor of stress concentration from 1 to 5. The average net fracture stress was at first found to increase considerably with the notch sharpness, then gradually to diminsh, eventually below even the yield stress for the tempered steel. These results are presented as a deviation from the notions of strength based on elasticity and stress concentration, without any reference to plasticity. An obvious explanation may be given on the basis of flow limit and increasing demands on ductility as the notch severity increases. The net fracture stress reached with the ductile steel is of interest: it is 1.75 times the ultimate strength for bar-to-root diameters of 3 or 4 at stress concentrations above 3; for bar-to-root diameters of 2 it is 1.6 times the ultimate strength. Assuming the ultimate to be about 1.5 times the 0.1% offset stress the above maximum stresses may be written as about 2.6 $\sigma_{0.1}$ and 2.4 $\sigma_{0.1}$ respectively, both of which are close to the flow limit.

As already mentioned the fracture load level was used as an indirect measure of ductility for convenience, since loads are more easily measured and more frequently known than deformations. A direct indication of the ductility of notched bars is their elongation at fracture. The required deformation for ductile behavior is unknown and depends on the structure. The ductile notched bar itself need elongate only as much as required to reach the flow limit. No solution for the strains of this elasto-plastic problem exists, but the elongation of the notched region may be accepted to be very small. If the grooved bar is seen as the region at the tip of a crack of a larger structure, the required elongation must be much larger: the notch region reaches a high stress quickly but must keep yielding till the remainder of the larger section also reaches a high stress. A practical answer to the question of required amount of elongation may be based on the observation that unprestrained mild steel has the required ductility. A substantial reduction of the elongation at fracture below that of the unstrained bars will be taken as an indication of brittleness. Fortunately the test indicated a rapid transition from the large deformation of unstrained steel (about 0.015 to 0.050 in. depending on root radius) to much smaller values (0.005 or less) at a compression ratio of 0.10 or smaller. The amount of precompression causing embrittlement is easily definable. It is noteworthy that the drop of elongation at fracture occurs at lower prestrains than the reduction of the average fracture stress below the flow limit.

It has been suggested (9) that the deformation at fracture of notched bars should be compared with the total elongation of a perfectly plastic material deforming and continuous necking down to a point. For rectangular bars in plain strain the total theoretical elongation would then be as large as the bar width; for a notched bar in plane strain the elongation would be equal to half the width of the net section. For circumferentially grooved bars in tension no suitable flow field or elongation has been found. It should be noted that flow limit calculations do not determine the deformations uniquely (e.g. theoretically several necks or a long neck could form equally well in a tension bar). Furthermore the suggested limits of deformation are far too high for

TABLE I TYPICAL COMPOSITION AND PROPERTIES OF STEELS

Steel	Element, per cent									Yield Strength psi	Ultimate Tensile Strength psi	Elongation per cent		Charpy Impact	
	C	Mn	P	S	Si	Cn	Ni	Cr	Mo			In 8 in.	In 2 in.	ft-lb	Temp. deg. Fahr.
E	0.20	0.33	0.013	0.020	0.01	0.18	0.15	0.09	0.02	32 000	65 000	36	30	15 to 3.3	55 to -11
ABS-B	0.14	1.04	0.011	0.018	0.056	0.083	0.023	0.031		33 800	58 400	33		20 to 10	18 to -5
	0.15	0.94	0.009	0.027	0.046	0.094	0.040	0.023		35 700	59 800	32		20 to 10	11 to -11

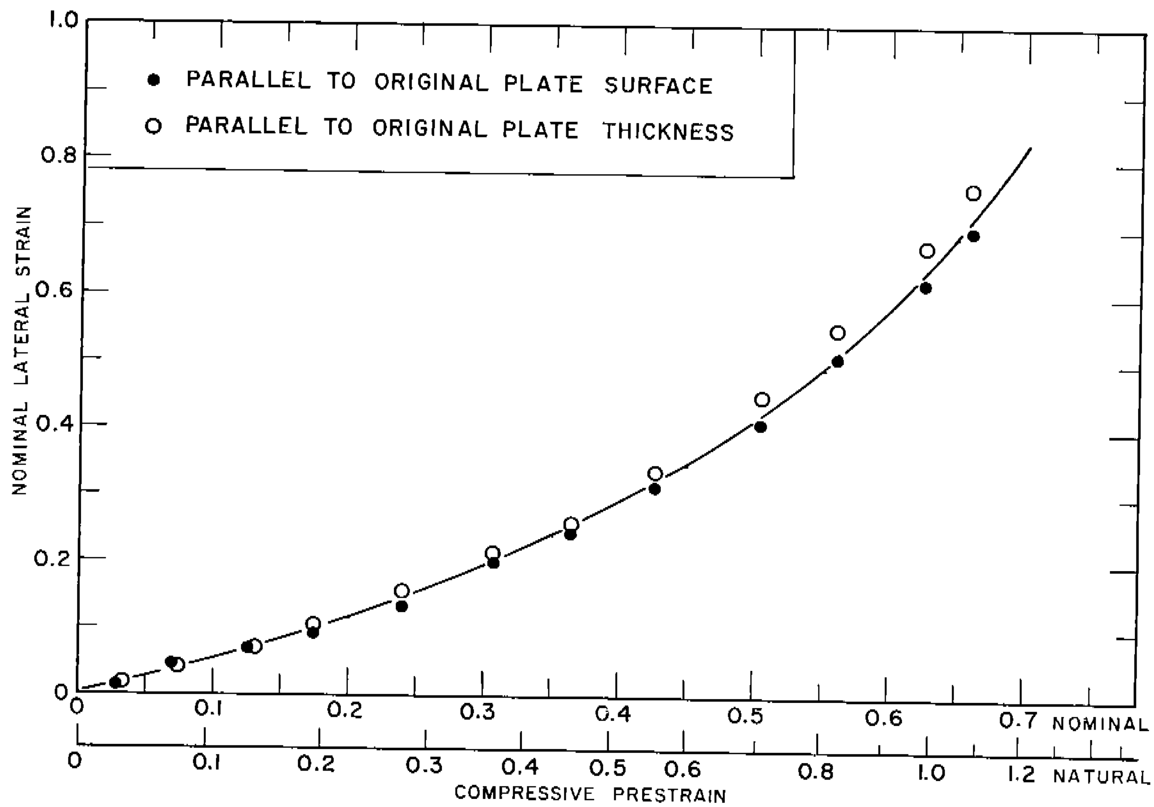


Fig. 1. Lateral Expansion of Axially Compressed Bars of ABS-B Steel

practical purposes, five to ten times higher than those of the most ductile bars.

The 0.1% offset yield strength $\sigma_{0.1}$ needed in the calculation of the flow limit was found from axial tests of smooth bars compressed longitudinally, as described in the next paragraph. The values of $\sigma_{0.1}$ and of the true stress and natural strain at fracture were determined for various compression ratios up to 0.70, and permit the comparison of notched and unnotched ductility and strength.

5. AXIALLY COMPRESSED SMOOTH BARS

The work hardening and the reduction of ductility in tension caused by prior axial compression has already been studied for E-steel (4). Further tests with ABS-B steel have now been made, for a comparison of notched with unnotched ductility and for obtaining the 0.1% offset yield strength needed in the notch bar calculations. Bars of ABS-B steel (properties in Table I) were cut from $\frac{3}{4}$-in. thick as-rolled plates. They had a $\frac{3}{4}$-in. square cross-section and a length (in the direction of rolling) of 9.75-in. for the smaller prestrains and 12-in. for the highest. The bars were axially compressed while being held by V-guides against lateral buckling, as reported earlier (4). The longest bars were compressed in the hot-compression machine (without heating), which will be described in a later report. The bars remained straight and square during compression except for a trace of barreling over a length of $\frac{1}{2}$ to $\frac{3}{4}$-in. at both ends. The lateral expansion in directions parallel and perpendicular to the original plate surface together with the curve of isotropic lateral expansion calculated for a constant volume are shown in figure 1 as functions of prestrain. The expansion parallel to the plate thickness was some 8 to 10% larger than parallel to the plate surface. The deformation was equivoluminal up to prestrains of about 0.50. At higher prestrains the volume appeared to increase up to about

TABLE II ABS-B STEEL

BARS AXIALLY COMPRESSED AT 70°F AND AGED TESTED IN TENSION AT -16°F

Bar B-Steel	Prestrain	0.1% Offset Stress ksi	Fracture	
			Nat. Strain	True Stress ksi
B-268	0	36.0	1.13	146
B-269	0	38.6	1.13	140
B-270	0.02	40.4	1.11	141
B-271	0.02	39.9	1.10	145
B-272	0.055	42.7	1.06	144
B-273	0.055	43.5	1.11	138
B-258	0.10	51.4	1.06	195
B-259	0.10	51.8	1.05	152
B-260	0.20	58.0	1.06	153
B-261	0.20	58.9	1.02	151
B-262	0.30	64.0	1.05	156
B-263	0.30	63.2	1.02	154
B-264	0.40	65.3	1.05	163
B-265	0.40	66.0	1.09	166
B-266*	0.40	67.0	1.05	157
B-267*	0.40	66.2	1.02	151
B-116	0.50	70.1	0.93	155
B-132	0.58	71.1	0.82	153
B-148	0.61	71.7	0.89	164
B-169	0.66	65.0	0.65	135
B-170	0.66	65.2	0.62	132
B-400	0.75	67.0	+	92
B-401	0.75	66.0	+	94
B-404	0.75	66.0	0.01	102
B-405	0.75	69.0	0.01	93
B-402**	0.75	45.4	+	96
B-403**	0.75	44.2	0.41	118

* *Aged after machining* ** *Unaged* + *Fracture at fillet*

TABLE III ABS-B STEEL

BARS AXIALLY COMPRESSED AT 70°F AND AGED TESTED IN TENSION AT 70°F

Bar B-Steel	Prestrain	0.1% Offset Stress ksi	Fracture	
			Nat. Strain	True Stress ksi
B-410	0	34.8	1.22	142
B-411	0	35.2	1.19	139
B-250	0.10	46.5	1.06	140
B-251	0.10	47.4	1.08	140
B-252	0.20	57.9	1.07	147
B-253	0.20	56.7	1.05	142
B-254	0.30	61.9	1.09	151
B-255	0.30	62.6	1.09	152
B-256	0.40	65.5	1.08	158
B-257	0.40	63.5	1.16	160
B-108	0.50	65.9	0.92	155
B-124	0.58	67.8	0.90	160
B-140	0.61	67.0	0.80	149
B-155	0.66	63.0	0.72	135
B-156	0.66	63.1	0.72	138

4%. This may be easily accounted for by the small barreling at the ends which is more pronounced at the larger prestrains and extends over a proportionally larger part of the whole length. Accordingly at large compressions the strain calculated by the shortening of the bars may be lower than the actual value by about 0.02.

All bars were subjected to accelerated aging (330°F for 2 hours) and were machined to standard tension specimens of 0.505-in. diameter. The threaded heads of bars compressed more than by 0.50 were of 1.00 in. diameter, because some low stress fractures had occurred at the threads of the standard $\frac{3}{4}$ -10 specimen heads. Great care was taken to avoid heating or straining of the bars during machining. The specimens were tested at 72°F and at -16°F in a small tension machine described earlier (4) which could be immersed in a cooling bath. Load-elongation curves were autographically plotted on an X-Y recorder from a load cell in series with the specimen and an LVDT extensometer. At a strain of 0.01 the extensometer was removed while the test continued to fracture. The true fracture stress was found from the load at fracture and the neck diameter, and the natural strain at fracture was calculated on the assumption of constancy of volume during plastic straining.

The results are given in Tables II and III. In addition the results of tests with E-steel aged without stressing, selected from earlier reports (4) and completed with a few new tests, are shown in Tables IV and V for comparison with ABS-B tests and with grooved E-steel tests described later. The fracture strain has also been plotted against compressive prestrain for all tests (Figures 2 and 3). Both steels show a remarkable lack of any reduction of ductility for prestrains up to about 0.40 to 0.50. ABS-B steel gave fracture strains between 1.05 and 1.15, appreciably more than the 0.7 to 0.8 of E-steel. At prestrains between 0.5 and about 0.6 for E-steel, or 0.65 to 0.75 for ABS-B, the ductility gradually fell to about $\frac{2}{3}$ the initial value. The ductility then dropped to very small values at prestrains between 0.61 and 0.68 for E-steel and about 0.75 for ABS-B steel at -16°F.

A comparison between reversed axial and bend tests showed two significant differences which required a check or explanation: a) The exhaustion limits for both steels were considerably higher in reverse axial tests than in bend

TABLE IV PROJECT E-STEEL

BARS AXIALLY COMPRESSED AT 70°F AND AGED TESTED IN TENSION AT -16°F

Bar B-Steel	Prestrain	0.1% Offset Stress ksi	Fracture	
			Nat. Strain	True Stress ksi
E-01	0	41	0.94	125
E-500	0.10	42	0.99	131
E-264	0.20	57	0.86	138
E-265	0.20	56	0.93	150
E-275	0.30	60	0.91	145
E-276	0.30	64	0.92	150
E-284	0.40	63	0.96	150
E-285	0.40	63	0.86	138
E-210	0.50	67	0.82	159
E-217	0.50	65	0.83	146
E-242	0.58	66	0.66	139
E-249	0.58	67	0.01	83
E-255	0.61	67	0.65	134
E-192	0.61	72	0.71	147
E-143	0.61	-	0.01	85
E-145	0.61	-	0.56	157

TABLE V PROJECT E-STEEL

BARS AXIALLY COMPRESSED AT 70°F AND AGED TESTED IN TENSION AT 70°F

Bar B-Steel	Prestrain	0.1% Offset Stress ksi	Fracture	
			Nat. Strain	True Stress ksi
E-00	0	36	0.89	111
E-501	0.10	44	0.96	118
E-7	0.10	-	0.74	110
E-6	0.15	-	0.79	110
E-16	0.20	-	0.71	120
E-502	0.20	53	0.89	125
E-24	0.30	-	0.73	113
E-39	0.31	56	0.87	132
E-35	0.37	57	0.98	113
E-16	0.38	60	0.81	131
E-20	0.40	-	0.66	111
E-42	0.40	58	0.85	131
E-3	0.41	56	0.79	130
E-17	0.42	58	0.79	133
E-19	0.46	-	0.54	111
E-14	0.47	56	0.73	123
E-38	0.48	60	0.80	100
E-175	0.50	63	0.85	138
E-150	0.50	64	0.81	134
E-212	0.50	59	0.85	-
E-6	0.52	57	0.72	123
E-9	0.52	58	0.70	136
E-109	0.55	60	0.64	119
E-136	0.58	65	0.73	133
E-169	0.58	78	0.72	134
E-154	0.61	74	0.01	94
E-132	0.61	68	0.62	129
E-115	0.61	64	0.64	135
E-33	0.62	75	0.43	113
E-3	0.63	-	0.58	129
E-16	0.65	-	0.63	133
E-123	0.67	67	0.21	109
E-13	0.67	-	0.56	138
E-8	0.68	-	0.15	108

tests (~0.75 for ABS-B and ~0.61 for E vs. 0.48 and 0.42 respectively). The cause of this difference was shown to be the surface condition of the bars: the axially tested bars had a newly machined surface after prestraining, whereas the reverse-bend bars were with as-rolled surfaces. Comparative reverse-bend tests

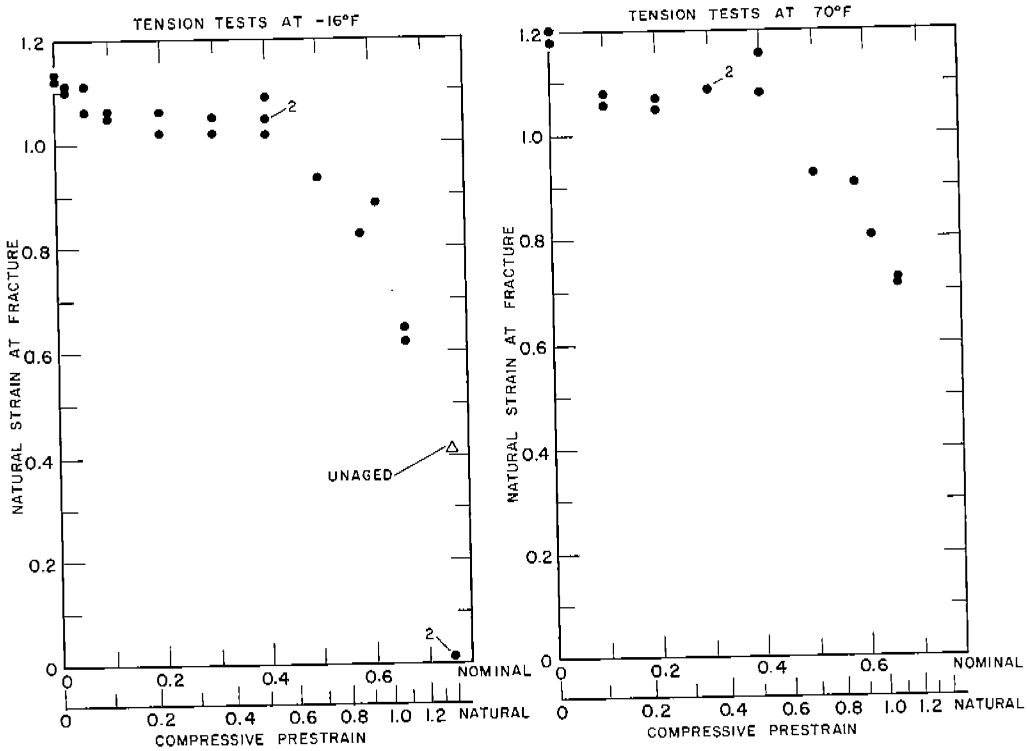


Fig. 2. Bars of ABS-B Steel Compressed at 70°F and Aged.

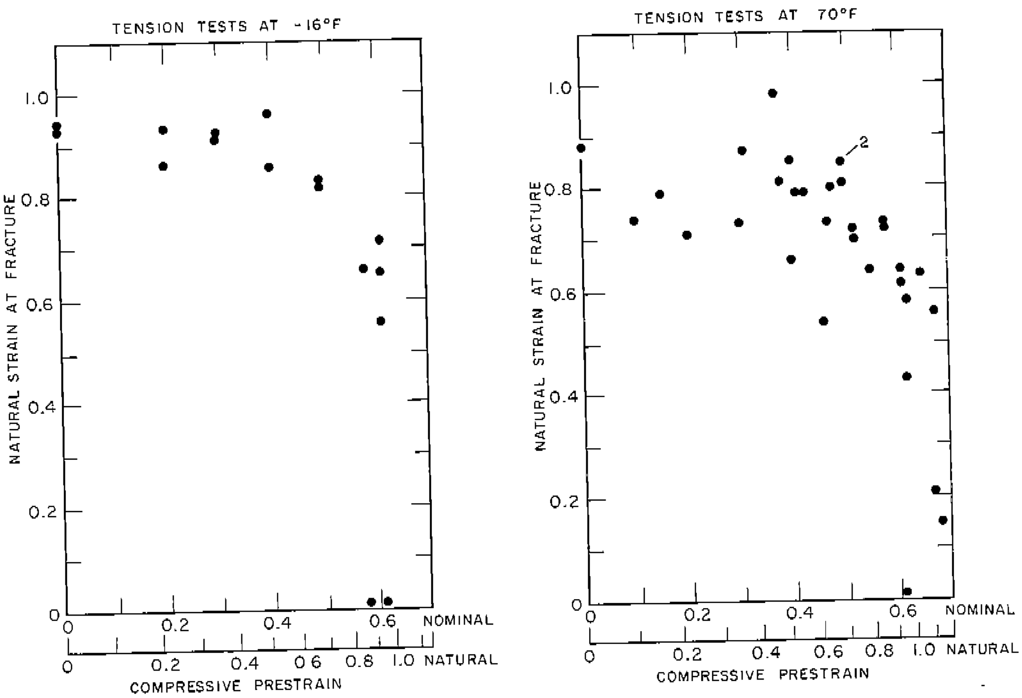


Fig. 3. Bars of Project E-Steel Compressed at 70°F and Aged.

TABLE VI ABS-B STEEL

BARS AXIALLY COMPRESSED AT 70°F TESTED IN TENSION AT -16°F

Bar B-Steel	Prestrain	0.1% Offset Stress ksi	Fracture		Tension During Aging ksi *
			Nat. Strain	True Strain ksi	
115	0.50	44.3	1.029	171	Unaged
116	0.50	70.1	0.932	155	0
117	0.50	72.7	0.993	168	15/15
118	0.50	74.7	1.022	174	27/30
119	0.50	73.6	0.924	159	27/40
120	0.50	74.3	1.024	174	27/50
121	0.50	81.9	1.022	174	27/60
122	0.50	87.9	1.024	173	27/70
131	0.58	44.9	1.015	189	Unaged
132	0.58	71.1	0.824	153	0
133	0.58	75.4	0.862	167	15/15
134	0.58	74.8	0.824	150	27/30
135	0.58	76.4	0.852	158	27/40
136	0.58	76.7	1.029	189	27/50
137	0.58	87.0	0.894	177	27/60
138	0.58	93.2	0.858	162	27/70
147	0.61	49.9	0.841	155	Unaged
148	0.61	71.7	0.892	164	0
149	0.61	74.9	0.799	159	15/15
150	0.61	75.1	0.837	157	27/30
151	0.61	75.3	0.746	147	27/40
152	0.61	83.2	0.881	171	27/50
153	0.61	84.8	0.815	159	27/60
154	0.61	93.6	0.802	158	27/70
185	0.66	40.2	0.642	128	Unaged
186	0.66	42.5	0.770	145	Unaged
169	0.66	65.0	0.647	135	0
170	0.66	65.2	0.615	132	0
171	0.66	68.6	0.837	154	15/15
172	0.66	65.8	0.723	141	15/15
173	0.66	67.6	0.615	134	27/30
174	0.66	70.0	0.621	133	27/30
175	0.66	69.9	0.647	138	27/40
176	0.66	71.4	0.747	149	27/40
177	0.66	71.9	0.742	148	27/50
178	0.66	69.6	0.723	143	27/50
179	0.66	75.5	0.593	134	27/60
180	0.66	72.6	0.587	135	27/60
181	0.66	84.6	0.693	144	27/70
182	0.66	85.4	0.682	142	27/70

* First number for stress during first 1/2 hour when temperature rises, second number the stress at aging temperature.

indicated that machining of the surfaces before straining caused an increase in the exhaustion limit by about 0.06 in ABS-C steel (11). Machining after prestraining raised the exhaustion limit still further, by a total of about 0.15, as will be separately reported (12); b) The difference between exhaustion limits of ABS-B and E-steel is much larger in axial tests (~0.75 for ABS-B vs. ~0.61 for E) than in bend tests (~0.48 vs. ~0.42, ref. 1). The differences are even larger when judged by the natural or logarithmic compressive strains at the exhaustion limit: -1.39 vs. -0.91, giving a difference of 0.48 in axial tests and -0.65 vs. -0.54 with a difference of 0.11 in bending. It

TABLE VII ABS-B STEEL

BARS AXIALLY COMPRESSED AT 70°F TESTED IN TENSION AT 70°F

Bar B-Steel	Prestrain	0.1% Offset Stress ksi	Fracture		Tension During Aging ksi *
			Nat. Strain	True Stress	
107	0.50	41.7	1.026	168	Unaged
108	0.50	65.9	0.924	155	0
109	0.50	67.7	1.015	165	15/15
110	0.50	69.3	0.947	153	27/30
111	0.50	70.0	0.985	164	27/40
112	0.50	77.3	0.974	151	27/50
113	0.50	81.3	0.963	150	27/60
114	0.50	86.7	0.955	152	27/70
123	0.58	40.1	0.965	133	Unaged
124	0.58	67.8	0.904	160	0
125	0.58	70.6	0.910	156	15/15
126	0.58	66.5	0.928	159	27/30
127	0.58	73.1	0.920	159	27/40
128	0.58	73.0	0.841	153	27/50
129	0.58	80.0	0.916	157	27/60
130	0.58	85.8	0.850	154	27/70
139	0.61	41.5	0.940	161	Unaged
140	0.61	67.0	0.802	149	0
141	0.61	74.4	0.867	157	15/15
142	0.61	74.6	0.783	149	27/30
143	0.61	75.4	0.808	151	27/40
144	0.61	79.1	0.760	144	27/50
145	0.61	84.3	0.850	157	27/60
146	0.61	85.0	0.763	145	27/70
183	0.66	39.1	9.824	144	Unaged
184	0.66	41.2	0.705	132	Unaged
155	0.66	63.0	0.723	135	0
156	0.66	63.1	0.715	138	0
157	0.66	65.4	0.756	143	15/15
158	0.66	67.8	0.730	138	15/15
159	0.66	66.3	0.693	139	27/30
160	0.66	66.2	0.634	126	27/30
161	0.66	65.7	0.711	129	27/40
162	0.66	69.3	0.711	137	27/40
163	0.66	69.2	0.640	130	27/50
164	0.66	70.4	0.770	142	27/50
165	0.66	75.4	0.730	140	27/60
166	0.66	70.6	0.705	133	27/60
167	0.66	77.0	0.644	128	27/70
168	0.66	77.5	0.718	136	27/70

* First number for stress during first 1/2 hour when temperature rises, second number the stress at aging temperature.

may also be observed that at axial prestrains lower than 0.40 ABS-B steel has a much larger total ductility than E-steel (~1.10 vs. ~0.75). Two series of tests were made to check these differences. An attempt was first made to cause additional embrittlement to ABS-B steel compressed between 0.50 and 0.66, by aging under tension of various intensities, as had previously been done with E-steel (4). The results, including specimens aged without tension and unaged, are given in Tables VI and VII. Aging under tension obviously did not cause any significant decrease of ductility. It was then thought that the improved ma-

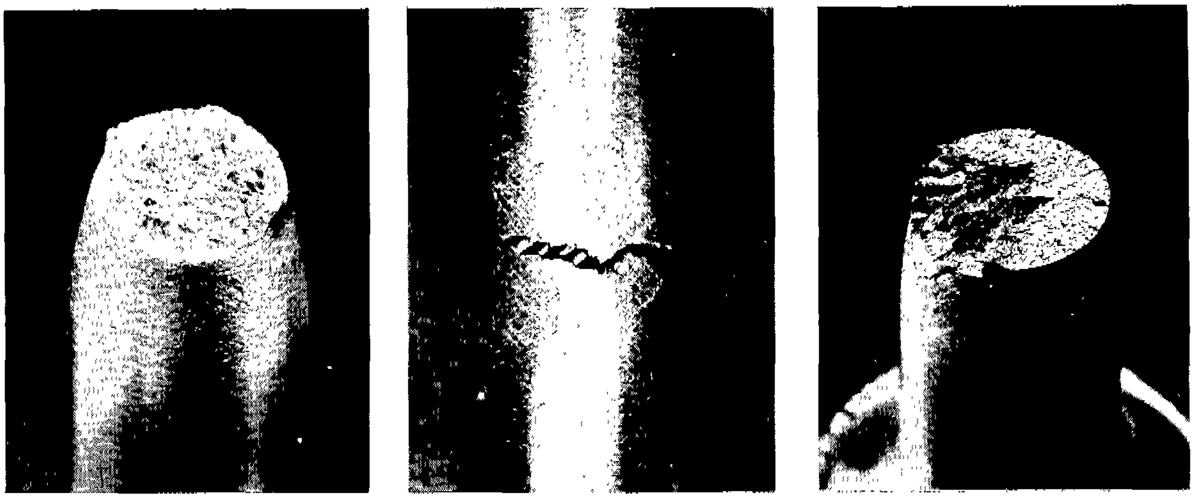
TABLE VIII ABS-B STEEL

BARS AXIALLY COMPRESSED AT 70°F TESTED IN TENSION AT -16°F WITH HELICAL GROOVE

Bar B-Steel	Prestrain	Depth 10^{-3} in.	0.1% Offset Stress ksi	Fracture		Tension During Aging ksi
				Nat. Strain	True Stress ksi	
187	0.66	6	41.9	0.476	113	2 hrs 165°C
188	0.66	1	66.2	0.563	129	2 hrs 165°C
189	0.66	6	42.0	0.361	102	27/30
190	0.66	1	70.1	0.658	140	27/30
191	0.66	6	41.1	0.223	92	27/50
192	0.66	1	72.6	0.601	131	27/50
193	0.66	6	41.9	0.228	88	27/70
194	0.66	1	85.2	0.593	133	27/70
195	0.66	6	43.5	0.344	102	2 hrs 165°C
196	0.66	1	64.8	0.698	144	2 hrs 165°C
197	0.66	6	43.3	0.431	115	27/30
198	0.66	1	68.4	0.657	139	27/30
199	0.66	6	41.6	0.658	136	27/50
200	0.66	1	70.7	0.608	135	27/50
201	0.66	6	43.8	0.476	115	27/70
202	0.66	1	83.3	0.604	138	27/70

chining of the bars might have eliminated small grooves and scratches and led to the greater apparent ductility. The influence of machining imperfections was easily checked with bars compressed by 0.66, smoothly machined and deliberately damaged by machining a helicoidal groove of about $\frac{1}{4}$in. pitch all along the cylindrical part of the tension specimen. The depth of the groove was either 0.001 or 0.006 in., both larger than any possible irregularity of the earlier specimens. Various aging procedures were applied as shown in Table VIII. The 0.001 in. deep groove did not appear to cause any reduction of ductility (compare Tables II and VIII). The 0.006 in. deep groove caused only a partial reduction of the ductility, by amounts varying between zero (bar 199, Table VIII) and $\frac{2}{3}$ (bars 191 and 193). No bar, however deep its groove, broke in a definitely brittle manner. The lowest strain at fracture was about 0.23 in two out of 8 tests with 0.006 grooves. The other 6 bars gave strains between 0.34 and 0.66. It may be concluded that the lower ductility and exhaustion limit of E-steel found in earlier tests were not caused by machining irregularities. The higher ductility of ABS-B appears as real.

In other respects the ABS-B bars behaved in the same manner as the E-steel



E-132 $\epsilon_0 = 0.61$ $\epsilon_f = 0.62$ $\epsilon_0 = 0.75$ B-403 $\epsilon_f = 0.41$

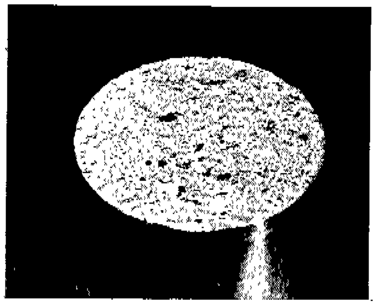
Fig. 4. Ductile Fractures of Highly Prestrained Bars.

bars. Figure 4 shows two ductile fractures at high prestrain. Fig. 5 shows four brittle fractures, one of E-steel and three of ABS-B steel, all at very high prestrains. The more pronounced flakes on the fracture surface of ABS-B bars may be due to their higher prestrain (0.75 vs. 0.66 for E-steel, corresponding to 1.39 and 1.08 in natural strain). Pin hole defects with 45° yield zones in the shape of the letter X were also observed in ABS-B steel bars just as necking began (4). In many instances they were the surface traces of interior fractured surfaces.

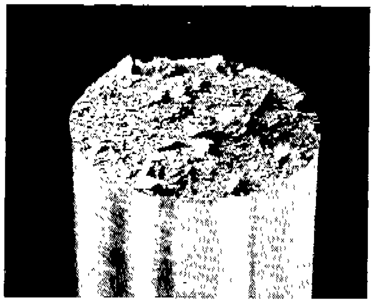
6. CIRCUMFERENTIALLY GROOVED BARS AFTER UNIFORM COMPRESSION

Grooved bar tests were made with ABS-B and for comparison with Project E-steel axially compressed and aged as described in paragraph 5.

The bars had a square cross-section of 0.75 in. side (the parent plate thickness) at light prestrains, or 1.00 in. side after heavy prestrain. The grooves had a 0.375 in. root diameter and 0.003 or 0.010 or 0.030 in. notch radius. The bar-to-root diameter ratio on the basis of equivalent round cross-sections are 2.27 and 3.00. These are not far from the experimental value given

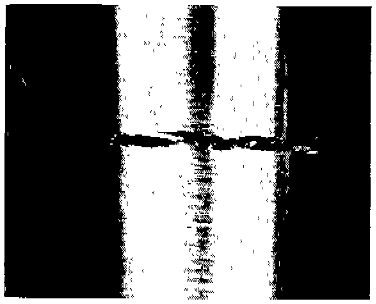


E-143 $\epsilon_0 = 0.61$ $\epsilon_f = 0.01$

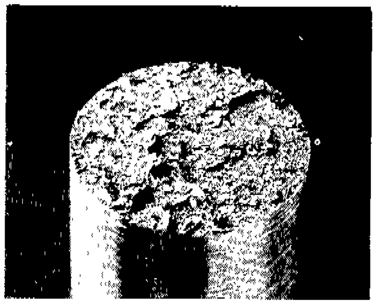


B-400 $\epsilon_0 = 0.75$ Fillet

B-404 $\epsilon_0 = 0.75$ $\epsilon_f = 0.01$



B-405 $\epsilon_0 = 0.75$ $\epsilon_f = 0.01$



B-405

Fig. 5. Brittle Fractures of Highly Prestained Bars.

in paragraph 4 or from an approximate value of 3 given by McClintock (9). The tests confirm that the bars were sufficiently wide, since the theoretical flow limit was reached and exceeded by the unstrained and lightly prestrained bars (up to about 0.10). The more brittle bars must have a less developed region of yielding, so there can be no question that the bar-to-root ratio is sufficient. The bar-to-root area ratio is 5.1 or 9, so that no yielding in the bar proper can occur even at the highest load.

The high stress concentration at the sharp groove could easily cause additional local straining during fabrication. This had to be avoided at all costs if the effects of the initial compression were to remain unmodified. Accordingly machining was done with extreme care, especially when difficulties were encountered at the higher prestrains and sharper notches (0.003 and 0.010 in. radius). The following technique was evolved after many trials in the lathe and by grinding. The bars were first machined to a 0.75 or 1.00 in. square cross-section and the ends were threaded, but a cylindrical shank was left on one side for holding when cutting the groove. Knife edges for holding the extensometer

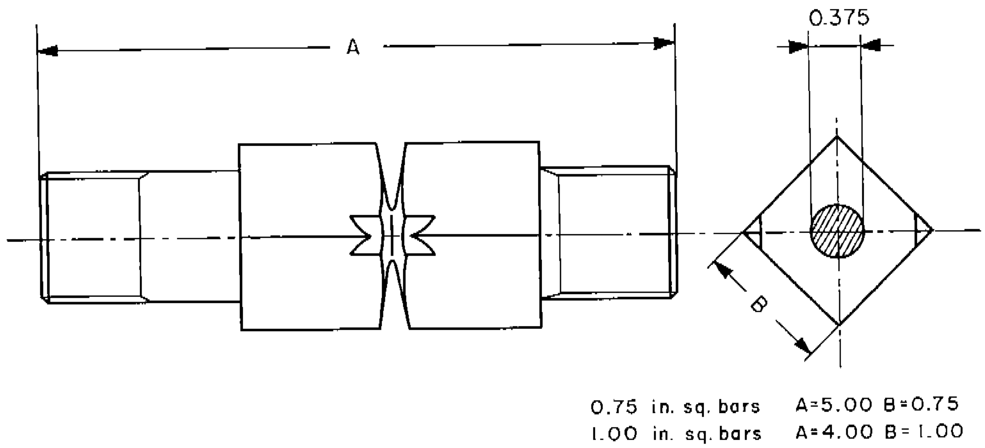


Fig. 6. Notched Specimen

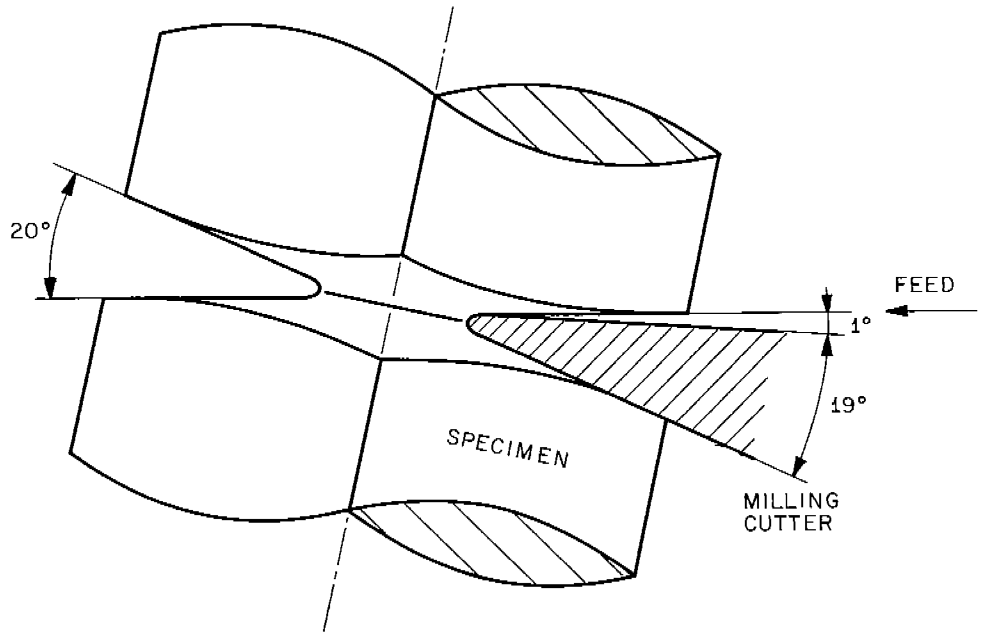


Fig. 7. Detail of Notch During Machining

were then machined on diagonally opposite edges (Fig. 6). The groove was machined last by milling, with the specimen held on one end only on an indexing head fitted with a motor so as to rotate at about 1/15 rpm (Fig. 7 and 8). Several 19° milling cutters, with tip radii of 0.030, 0.010, and 0.003 in. were specially ground, and were used consecutively because direct use of the sharpest

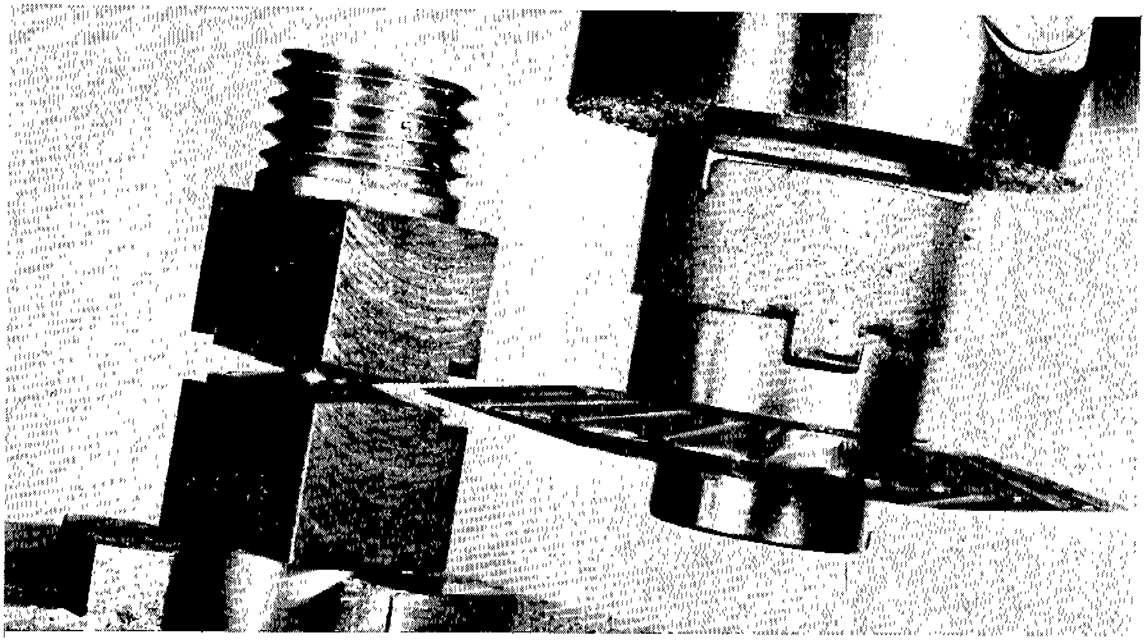


Fig. 8. Machining of Grooves.

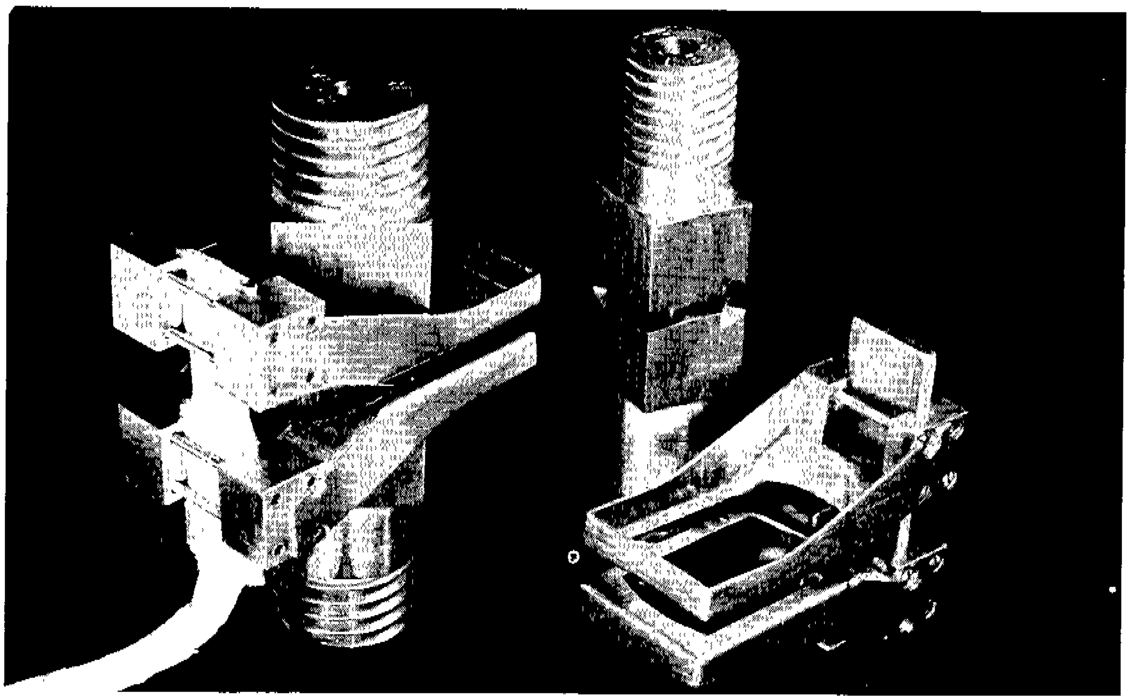


Fig. 9. Extensometer Mounted on Grooved 1 in. Square Bar (Left) Arms for 3/4 in. Square Bar are Shown on Dummy Spring Blade (Right).

cutter would quickly damage it. The mid-plane of the cutter was inclined by $\frac{1^\circ}{2}$ to the normal bar cross-section and feeding was at an angle of 10° to it so that cutting occurred over the whole contact area on the side toward the supported end of the specimen, but only at the cutter tip on the unsupported side above the groove, with a 1° relief (Fig. 7). This minimized both the total force acting on the unsupported side and its distance from the specimen axis, hence greatly reduced the bending moment and the danger of local straining at the grooved section. The groove of each specimen was checked in an optical comparator for concentricity, smoothness and root radius.

The elongation at the shoulders of the groove was measured by a special spring extensometer consisting of a thin elastic bar with full strain gage bridge, ending on both sides in interchangeable arms fitting between the knife edges at the shoulders of the groove (Fig. 9). Two pairs of arms were used, one for each of the two bar sizes (0.75 and 1.00 in. square). The extensometer could be adjusted to a size slightly larger than the gap between knife edges and was fitted in place after some elastic compression so that it could follow the elongation up to fracture and then spring back undamaged to its normal size. Its total range exceeded 0.080 in., with a departure from linearity by 10^{-4} in. and a sensitivity better than 5×10^{-5} in. when used with the X-Y recorder. The largest measured elongation was about 0.040 in. (unstrained ABS-B steel), but in most cases it was less than 0.010 in. Autographic load-deformation diagrams were made on the X-Y recorder.

The load-extension curves were remarkably linear and reversible up to very high loads. Repeated tests showed that deviations from linearity represented permanent deformations. With an elastic stress concentration factor of about 8 for the sharpest groove (0.003 in.) and about 3 for the least sharp (0.030 in.) as found for corresponding hyperbolic grooves (13), some plastic straining should start at a load equal to 1/8th or 1/3rd the yield strength load $A\sigma_{0.1}$ (where A

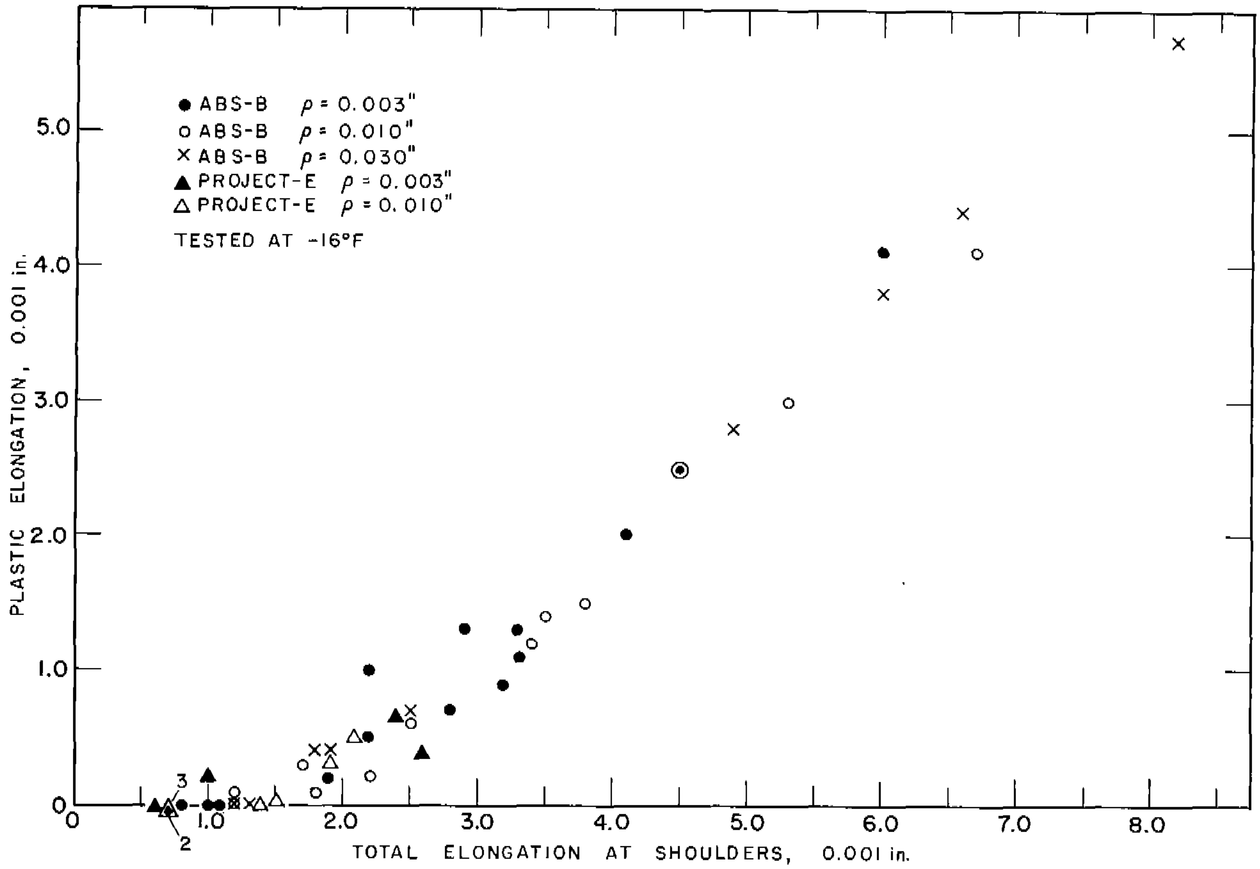


Fig. 10. Plastic vs Total Elongation at the Shoulders of All Notched Bars at -16°F

is the net section and $\sigma_{0.1}$ the 0.1% yield strength). These loads are small fractions ($\frac{1}{22}$ or $\frac{1}{7}$) of the flow limit. It must be concluded that the plastic strains must have been highly localized, because no departure from linearity or permanent extension on unloading could be detected even at much higher loads, at least equal to $\frac{1}{2}$ the flow limit and frequently much higher.

The permanent or plastic component of the elongation at the shoulders at fracture could be easily found from the total by subtracting the elastic elongation. The plastic elongation is plotted against the total in figure 10. It is clear that the elastic deformation was very small. In fact it was very close to 0.0015 in. for all tests with ABS-B or E-steel.

The total and the plastic elongation at fracture, the average net fracture

TABLE IX ABS-B STEEL

TENSION TESTS AT -16°F OF PRESTRAINED, AGED AND GROOVED BARS NOTCH RADIUS 0.003 in.

Bar	Prestrain	Root Dia. in.	Cross-section in.	Elong. at fracture 0.001 in.		Av. Stress ksi	
				Total	Plastic	At fract.	Flow limit
B-227	0	0.3770	3/4x3/4	16.5	15.2	103	100
B-228	0	0.3730	"	16.4	14.8	102	100
B-229	0.055	0.3760	"	2.2	0.5	106	115
B-230	0.055	0.3750	"	6.0	4.1	146	115
B-203	0.10	0.3770	"	2.9	1.3	132	138
B-204	0.10	0.3755	"	4.5	2.5	134	138
B-205	0.20	0.3660	"	3.3	1.3	138	157
B-206	0.20	0.3750	"	4.1	2.0	150	157
B-207	0.30	0.3755	"	2.2	0.5	127	170
B-208	0.30	0.3704	"	3.3	1.1	146	170
B-209	0.40	0.3765	"	2.8	0.7	144	177
B-210	0.40	0.3780	"	3.2	0.9	150	177
B-211	0.50	0.3765	1.0x1.0	1.0	0	63	188
B-212	0.50	0.3760	"	1.8	0.2	107	188
B-213	0.60	0.3745	"	0.8	0	57	192
B-214	0.60	0.3770	"	1.1	0	74	192

TABLE X ABS-B STEEL

TENSION TESTS AT -16°F OF PRESTRAINED, AGED AND GROOVED BARS NOTCH RADIUS 0.010 in.

Bar	Prestrain	Root Dia. in.	Cross-section in.	Elong. at fracture 0.001 in.		Av. Stress ksi	
				Total	Plastic	At fract.	Flow limit
B-000	0	0.3750	3/4x3/4	35.2	33.2	96	100
B-275	0	0.3733	"	37.4	35.6	110	100
B-276	0	0.3757	"	37.0	35.0	108	100
B-279	0.02	0.3696	"	25.7	23.7	127	108
B-280	0.02	0.3755	"	14.7	12.8	122	108
B-283	0.05	0.3770	"	6.0*	4.1	119*	115
				11.0	9.0	129	
B-215	0.10	0.3745	"	4.5	2.4	136	138
B-216	0.10	0.3750	"	5.3	3.0	139	138
B-217	0.20	0.3755	"	6.7	4.1	179	157
B-218	0.20	0.3755	"	3.8	1.5	144	157
B-219	0.30	0.3747	"	3.4	1.2	148	170
B-220	0.30	0.3750	"	2.5	0.6	132	170
B-221	0.40	0.3740	"	3.5	1.4	155	177
B-222	0.40	0.3742	"	1.7	0.3	109	177
B-223	0.50	0.3743	1.0x1.0	1.8	0.1	92	188
B-224	0.50	0.3765	"	1.4*	0	81*	188
				2.2	0.2	117	
B-225	0.60	0.3746	"	1.2	0.1	65	192
B-226	0.60	0.3753	"	1.2	0	72	192

* *First Crack.*

stress and the flow limit stress based on the 0.1% offset yield stress at the same compression ratio (2.68 $\sigma_{0.1}$) for grooved bars of notch radii 0.003, 0.010 and 0.030 are given for ABS-B bars in Tables IX to XI and for E-steel in Tables XII to XIV. The results are also shown in the graphs of figures 11 to 13 for ABS-B steel and 15, 16 for E steel. The collected results are shown in figure 14 for ABS-B steel and figure 17 for E-steel. These figures also show the smoothed curves of the flow limit stress at the corresponding prestrains. Total strains

TABLE XI ABS-B STEEL

TENSION TESTS AT -16°F OF PRESTRAINED, AGED AND GROOVED BARS NOTCH RADIUS 0.030 in.

Bar	Prestrain	Root Dia. in.	Cross-section in.	Elong. at fracture 0.001 in.		Av. Stress ksi	
				Total	Plastic	At fract.	Flow limit
B-277	0	0.3668	3/4x3/4	> 38.0	> 36.0	117	100
B-278	0	0.3760	"	56.0	54.4	106	100
B-281	0.02	0.3785	"	> 34.0	> 32.2	122	108
B-282	0.02	0.3732	"	21.2	19.4	113	108
B-285	0.05	0.3770	"	22.0	20.0	127	115
B-286	0.05	0.3757	"	17.1	15.1	125	115
B-287	0.10	0.3578	"	9.6	7.5	144	138
B-288	0.10	0.3759	"	16.8	14.6	145	138
B-289	0.20	0.3731	"	4.9	2.8	146	157
B-290	0.20	0.3771	"	4.2*	2.0*	142*	157
				5.9	3.5	148	-
B-291	0.30	0.3737	"	3.2*	1.2*	138*	170
				9.7	7.3	170	-
B-292	0.30	0.3768	"	3.1*	1.2*	137*	170
				6.6	4.3	162	-
B-293	0.40	0.3773	"	2.5	0.7	131	177
B-294	0.40	0.3755	"	2.5*	6.4*	130*	177
				8.2	5.7	175	-
B-295	0.50	0.3792	1.0x1.0	1.9	0.4	114	188
B-296	0.50	0.3789	"	1.8	0.4	107	188
B-297	0.60	0.3769	"	1.3	0	81	192
B-298	0.60	0.3769	"	1.2	0	78	192

** Value at arrested crack.*

TABLE XII PROJECT E-STEEL

TENSION TESTS AT -16 F OF PRESTRAINED, AGED AND GROOVED BARS NOTCH RADIUS 0.003 in.

Bar	Prestrain	Root Dia. in.	Cross-section in.	Elong. at fracture 0.001 in.		Av. Stress ksi	
				Total	Plastic	At fract.	Flow limit
E-325	0	0.3800	3/4x3/4	14.5	13.0	96	110
E-327	0.10	0.3755	"	2.8	1.0	116	113
E-328	0.10	0.3790	"	3.8	2.0	136	113
E-333	0.20	0.3810	"	2.0	0.6	112	151
E-334	0.20	0.3650	"	1.8	0.4	108	151
E-306	0.30	0.3740	"	2.4	0.7	132	166
E-307	0.30	0.3755	"	2.0	0.4	118	166
E-310	0.50	0.3755	1.0x1.0	0.7	0	49	177
E-311	0.50	0.3740	"	1.0	0	66	177
E-314	0.61	0.3755	"	0.6	0	46	186
E-315	0.61	0.3760	"	0.7	0	58	186
E-308*	0.30	0.3630	3/4x3/4	1.8	0.4	103	147*
E-309*	0.30	0.3780	"	3.2	1.2	137	147*
E-312*	0.50	0.3755	1.0x1.0	1.8	0.1	94	166*
E-313*	0.50	0.3765	"	1.0	0	57	166*
E-316*	0.61	0.3515	"	1.0	0	52	185*
E-317*	0.61	0.3760	"	0.7	0	49	185*

** Tested 72°F.*

have been plotted in all figures. The corresponding plastic strain may be found exactly in the corresponding tables, or approximately by raising the ordinate axis by about 0.0015 in.

The scatter is no worse than usual in fracture tests and allows recognition of some significant trends. At prestrains between 0 and 0.10 the average fracture stress of ABS-B steel specimens equals or exceeds the flow limit stress based on the corresponding 0.1% offset yield stress, which proves that the grooves

TABLE XIII PROJECT E-STEEL

TENSION TESTS AT -16°F OF PRESTRAINED, AGED AND GROOVED BARS NOTCH RADIUS 0.010 in.

Bar	Prestrain	Root Dia. in.	Cross-section in.	Elong. at fracture 0.001 in.		Av. Stress ksi	
				Total	Plastic	At fract.	Flow limit
E-329	0.10	0.3780	3/4x3/4	2.8	1.4	115	113
E-330	0.10	0.3750	"	5.4	3.6	137	113
E-335	0.20	0.3780	"	2.9	1.1	128	151
E-336	0.20	0.3750	"	3.0	1.2	137	151
E-292	0.30	0.3767	"	1.9	0.4	109	166
E-293	0.30	0.3764	"	2.1	0.5	113	166
E-296	0.50	0.3758	1.0x1.0	0.7	0	99	177
E-297	0.50	0.3722	"	0.6	0	72	177
E-300	0.61	0.3738	"	1.5	0	78	186
E-301	0.61	0.3766	"	1.4	0	77	186
E-000*	0	0.3750	3/4x3/4	34.2	32.0	99	96*
E-294*	0.30	0.3455	"	2.6	0.7	123	147*
E-295*	0.30	0.3781	"	3.5	1.6	133	147*
E-298*	0.50	0.3769	1.0x1.0	1.7	0.3	100	166*
E-299*	0.50	0.3766	"	1.8	0.7	106	166*
E-302*	0.61	0.3798	"	1.0	0	70	185*
E-303*	0.61	0.3762	"	1.1	0	75	185*

* *Tested at 72°F.*

TABLE XIV PROJECT E-STEEL

TENSION TESTS AT -16°F OF PRESTRAINED, AGED AND GROOVED BARS NOTCH RADIUS 0.030 in.

Bar	Prestrain	Root Dia. in.	Cross-section in.	Elong. at fracture 0.001 in.		Av. Stress ksi	
				Total	Plastic	At fract.	Flow limit
E-326	0	0.3765	3/4x3/4	35.8	34.4	108	110
E-331	0.10	0.3760	"	5.8	3.9	133	113
E-332	0.10	0.3755	"	8.0	5.8	139	113
E-337	0.20	0.3745	"	5.1+	3.2+	143+	151
E-338	0.20	0.3730	"	5.1+	3.2+	150+	151
				7.8	5.8	-	-

+ *First Crack.*

were deep enough, even in the 0.75 in. square bars, to permit the application of the infinite depth flow limit. The fracture stress changes little at prestrains between 0.10 and 0.40 even though the 0.1% offset yield stress and the flow limit continue to increase. As a consequence the fracture stress is lower than the flow limit at prestrains of 0.20 or more. Beyond a prestrain of 0.40 the fracture stress decreases rapidly. At 0.60 prestrain it is about equal to the corresponding 0.1% yield strength. On may conclude on the basis of the fracture stress that ABS-B steel is certainly embrittled by compressive prestrains larger than about 0.15 to 0.20, but the transition from ductility to brittleness is gradual. "Embrittlement" here means the reduction of the ductility below that needed in the grooved bars at a load equal to the flow limit based on the 0.1% offset yield strength at the same compression. As explained in paragraph 4 the flow limit based on $\sigma_{0.1}$ is not a necessary condition. The ductility may

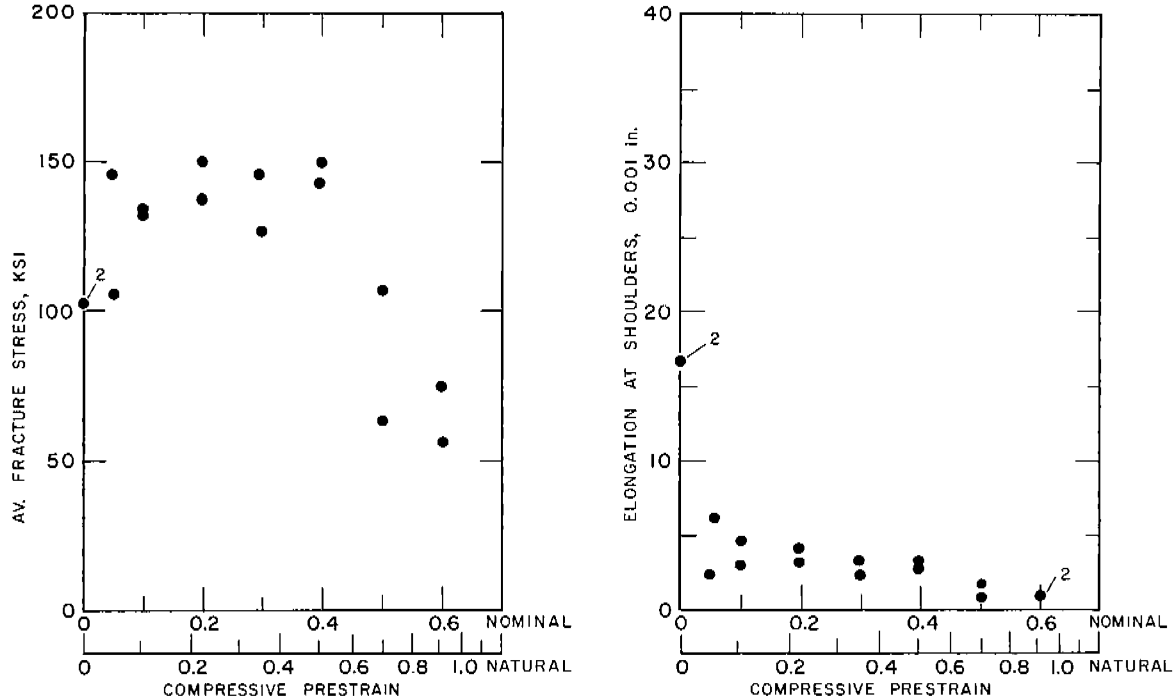


Fig. 11. Tension Tests of Notched ABS-B Steel Bars at $-16^{\circ}F$ Notch Radius ρ = 0.003 in.

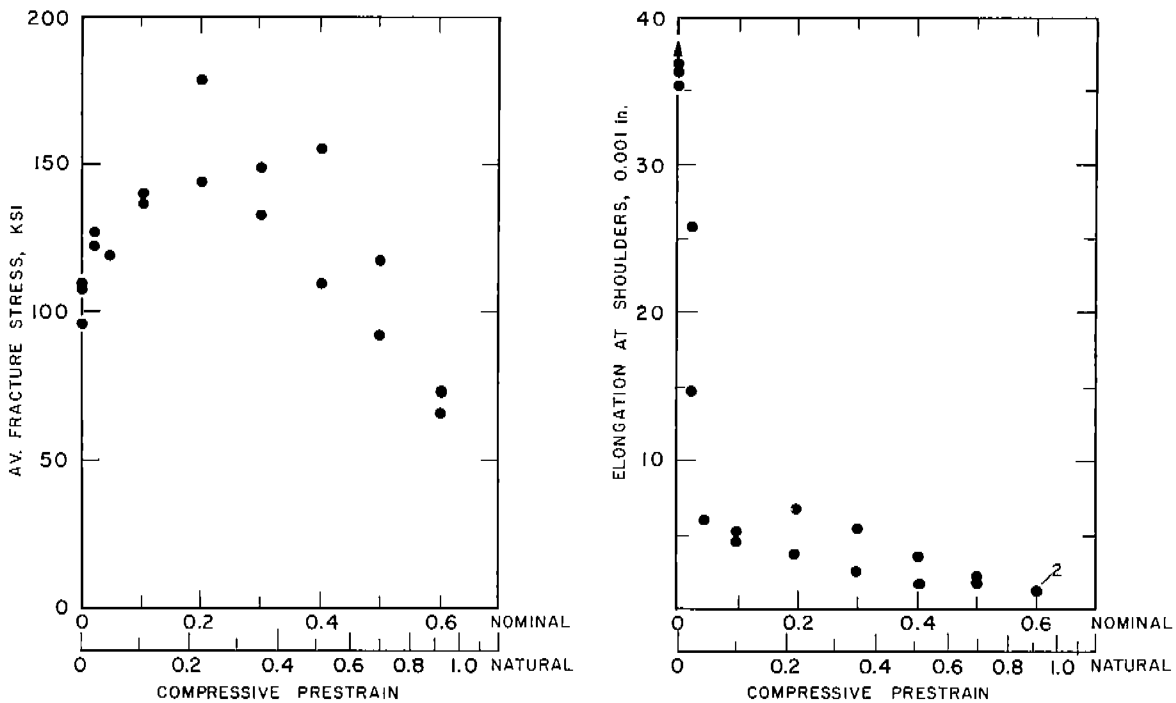


Fig. 12. Tension Tests of Notched ABS-B Steel Bars at $-16^{\circ}F$ Notch Radius ρ = 0.010 in.

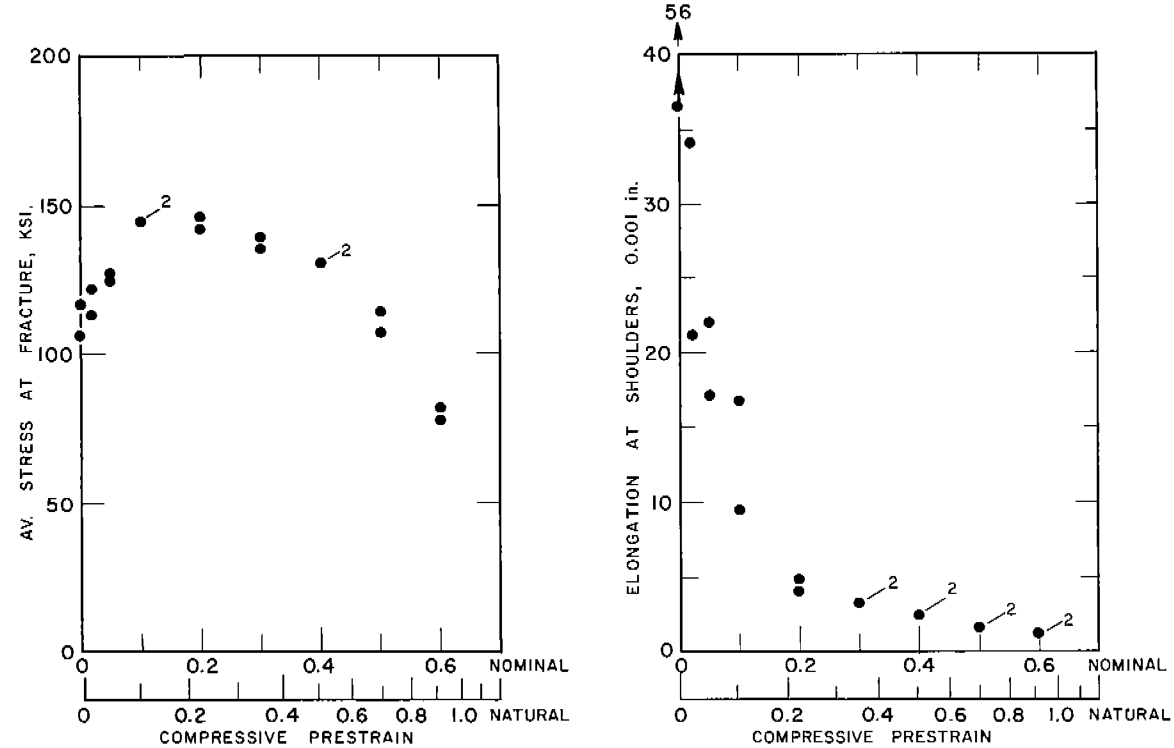


Fig. 13. Tension Tests of Notched ABS-B Steel Bars at -16°F Notch Radius ρ = 0.030 in.

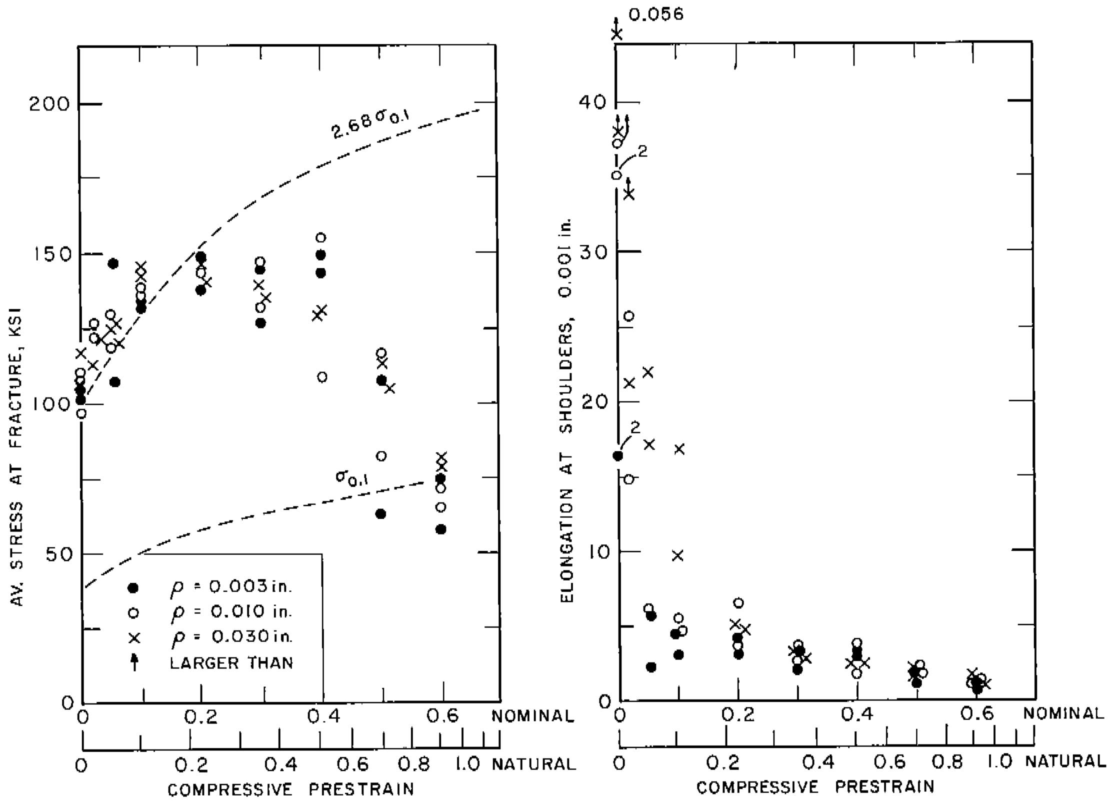


Fig. 14. Collected Results of Notched Bar Tests of ABS-B Steel Aged and Tested at -16°F

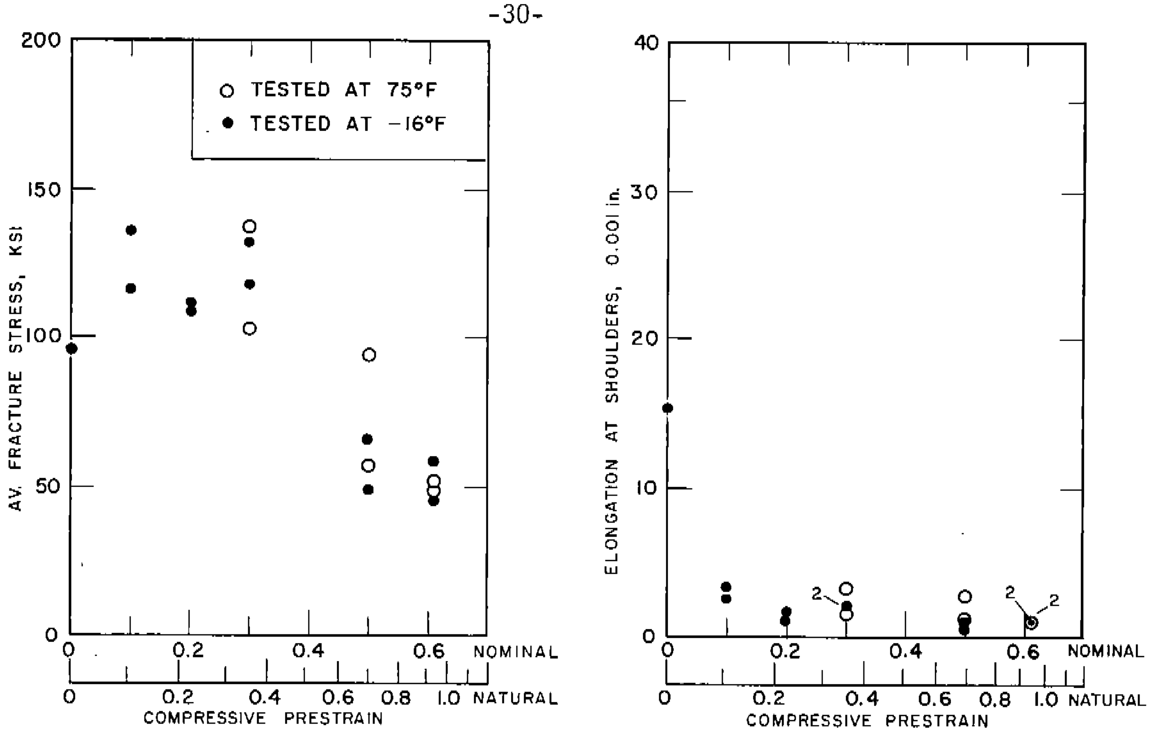


Fig. 15. Tension Tests of Notched E-Steel Bars at 75° and -16°F Notch Radius ρ = 0.003 in.

be "insufficient" without necessarily causing fracture at a stress lower than $2.68\ \sigma_{0.1}$. As will be seen later, deformation measurements do show that "embrittlement" occurs at prestrains lower than 0.15. The prestrain limit of 0.15 to 0.20 causing definite embrittlement of notched bars of ABS-B steel is much lower than the exhaustion limit of 0.48 found in reversed bending and of 0.75 in axial compression-tension. The results with E-steel follow a very similar trend.

The results are surprising in one respect: the average fracture stress appears to be independent of the notch radius, or at least not to vary significantly for notch radii between 0.003 and 0.030 in. The bars of ABS-B steel with the largest notch radius (0.030 in.) seem to give less scatter. Their strength is highest at prestrains between 0.10 and 0.20 (Fig. 14), appears to drop faster than for the other radii up to a prestrain of 0.4, but to be higher again at prestrains of 0.50 and 0.60. The differences are too small in comparison with the scatter to give any certainty and to warrant explanations based on severity

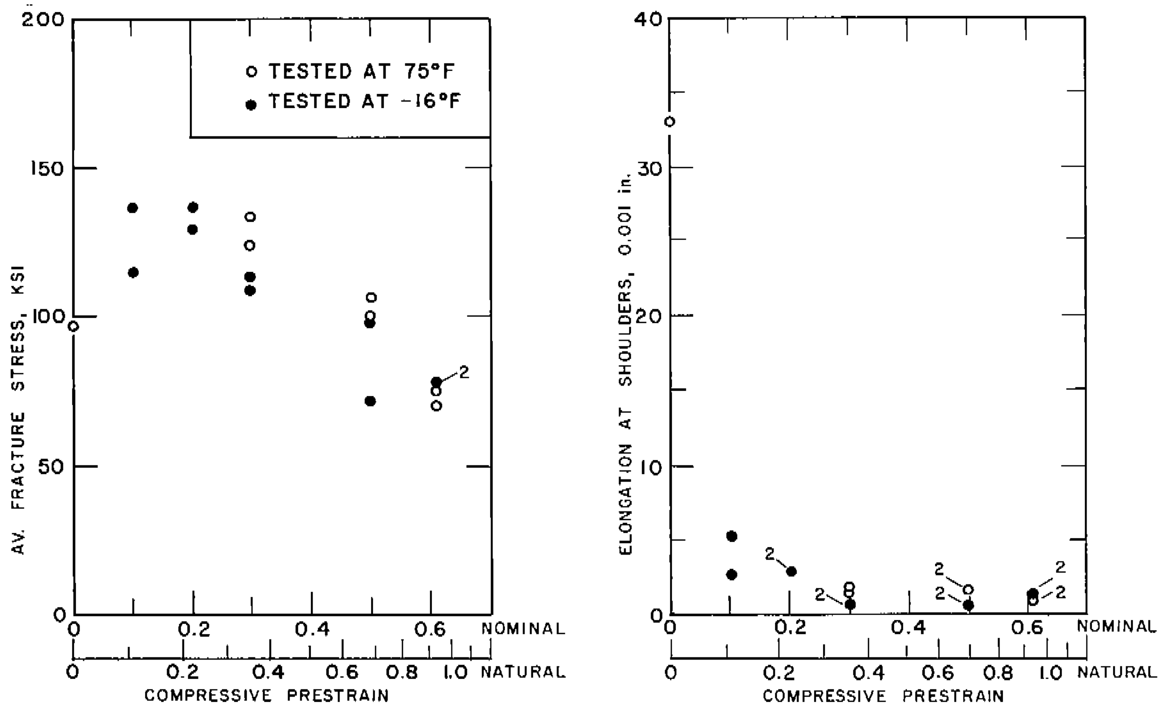


Fig. 16. Tension Tests of Notched E-Steel Bars at 75° and -16°F Notch Radius ρ = 0.010 in.

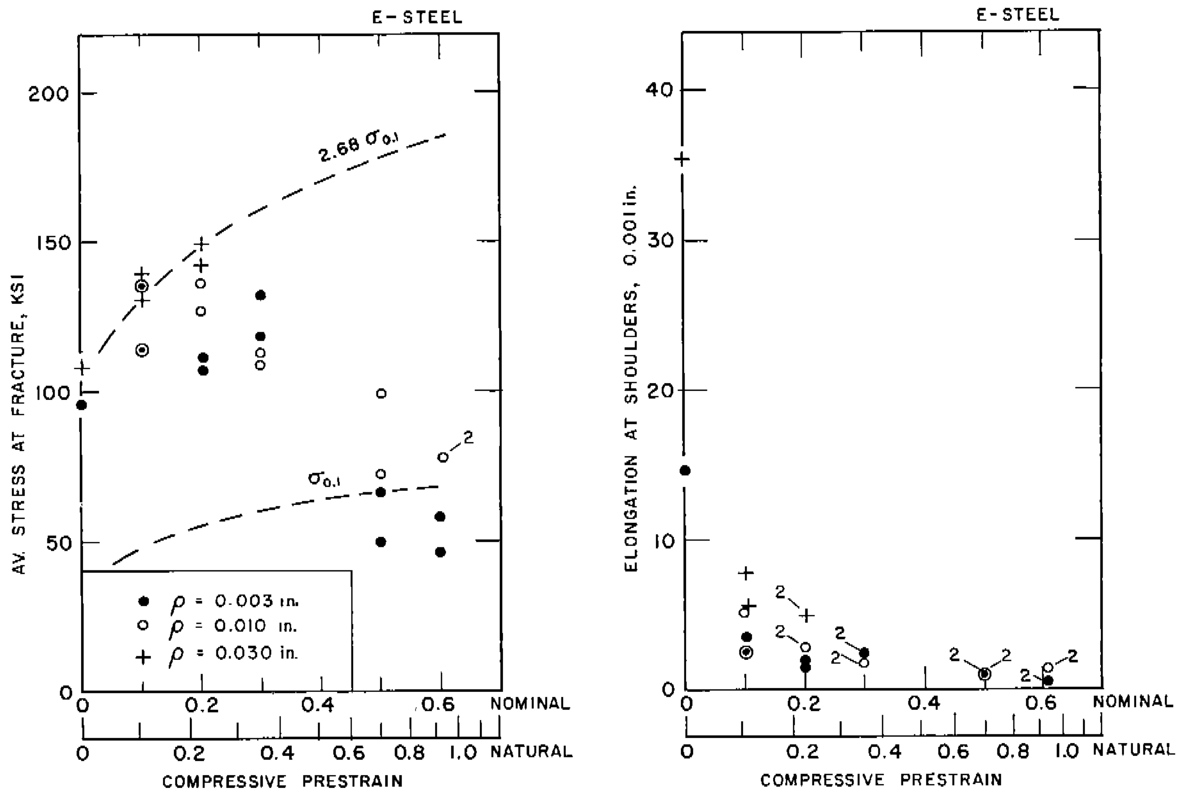


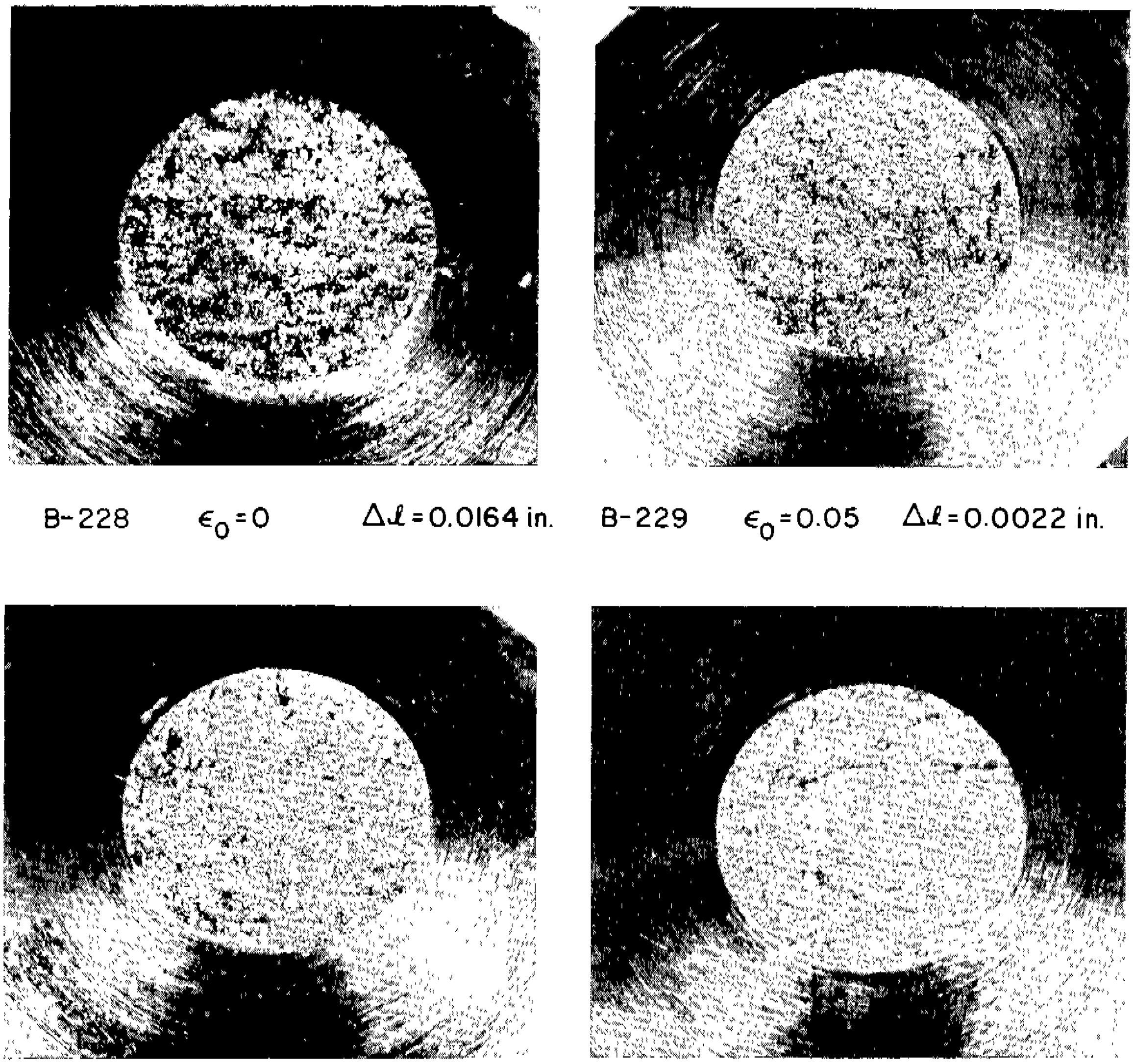
Fig. 17. Collected Results of Notched Bar Tests of Project E-Steel Aged and Tested at -16°F

of strains and triaxiality. Bars of E-steel of 0.030 in. notch radius were tested only up to prestrains of 0.20, because of exhaustion of the material, but this covers the most interesting region. The results showed a generally similar trend as with ABS-B steel, except that the strength of bars with 0.030 in. notches is definitely on the increase at prestrains of 0.20.

The picture is somewhat different when judged by the elongation at the shoulders (right graph of figures 11-17). As shown by the collected results of ABS-B steel (Fig. 14, right) the elongation depends strongly on notch radius at prestrains below 0.2 where the 0.003 in. notch elongation is less than half that of the 0.030 in., but is independent of radius at prestrains above 0.2. The drop of ductility occurs at smaller prestrains than observed by the fracture stress and varying with the notch radius. For 0.030 in. notches the elongation decreased from over 0.040 in. at zero prestrains to about 0.005 in. at 0.20 prestrain, then much more slowly to 0.001 in. at 0.60 prestrain. With bars of 0.010 and 0.003 in. radius the elongations at zero prestrain were respectively 0.035 in. or more and 0.016 in.; they dropped quickly to about 0.005 in. at a prestrain of only 0.05; and then very slowly decreased to about 0.001 in. at 0.60 prestrain, just like the bars of 0.030 in. radius. Transition from ductile to brittle behavior is very fast and appears to occur at compressive prestrains as small as 0.05 (i.e. 5%), which is even smaller than the value found by the fracture stress and of course much smaller than the exhaustion limits in axial and bend tests. A similar behavior was observed with bars of E-steel, but with consistently smaller strains than ABS-B steel. The greatest difference appears with a notch radius of 0.030 in. at zero and 0.10 prestrain (compare figures 14 and 17), where the elongations vary with notch radius. At higher prestrains all notch radii as well as both steels show only small differences.

The magnitude of the stress at fracture is of considerable interest. An average stress of over 100,000 psi was reached in unstrained notched bars, whose yield stress in simple tension before prestraining was about 36 000 psi. With prestrains of 0.2 to 0.4 the average stress at fracture of the notched bars reached 150 000 psi. The true stress at the notch root must have been much higher, but its value is not known. All that can be said is that because of local yielding the true stress must be less than the corresponding elastic stress, hence for the sharpest notch (0.003 in.) with a factor of stress concentration of 8, the true stress must have been less than 1 200 000 psi. A better estimate can be based on the following observation. At prestrains of 0.2 to 0.4, even at 0.6, both the fracture stress and the elongation at the shoulders are about the same for all three notch radii (0.003; 0.010; 0.030 in.). Equal elongations, however, should cause plastic straining varying nearly inversely with the arc length or with the radius at the notch roots. This in turn means a strong stress reduction where the factor of stress concentration is high and small reduction where it is low, or a stress leveling process. Although it is not known whether actual equalization occurs, this process suggests the adoption of a fixed stress criterion of fracture, as has been frequently suggested and has been calculated for notched bars by Hendrickson, Wood and Clark (14). Then the fracture stress in all bars should be the same as in the one of least sharpness (0.030 in. radius), whose elastic factor of stress concentration is 2.7, hence its true fracture stress should be less than about 400 000 psi. Of course all stresses are macroscopic local stresses due to the notch, and not microscopic stresses caused by smaller flaws, inclusions or dislocations. The microscopic stresses could be much higher.

The flow level stress reached at low prestrains independently of notch radius (Fig. 14, 17, left), is of course due to the large available ductility which allows the development of triaxiality and strain hardening. The dependence of elongation on notch radius at the same low prestrains may be seen as the re-



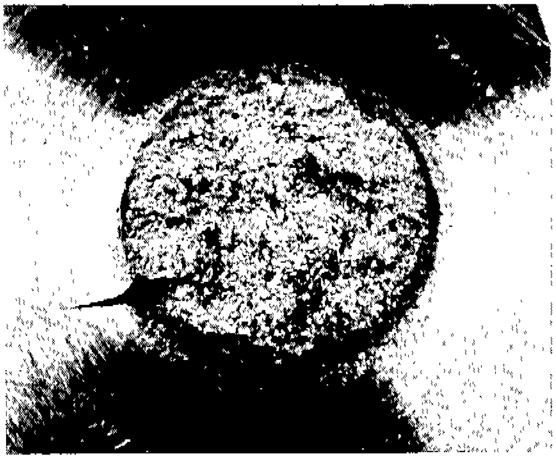
B-228 $\epsilon_0 = 0$ $\Delta\ell = 0.0164$ in. B-229 $\epsilon_0 = 0.05$ $\Delta\ell = 0.0022$ in.

B-203 $\epsilon_0 = 0.10$ $\Delta\ell = 0.0029$ in. B-211 $\epsilon_0 = 0.50$ $\Delta\ell = 0.0010$ in.

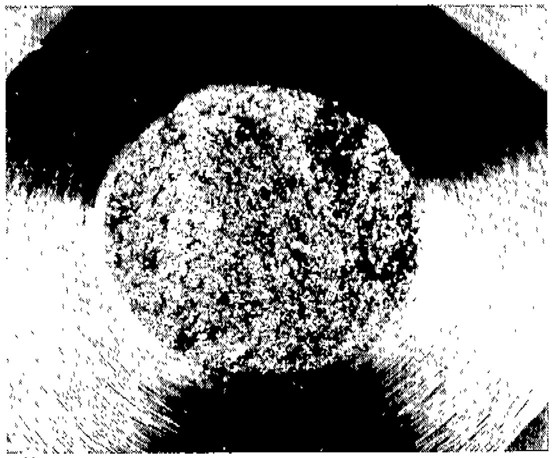
Fig. 18. Fractures of Grooved Bars of ABS-B Steel. Radius $\rho = 0.003$ *in.*

sult of local strain hardening over too small an area to affect the average stress, but raising the local stress to the fracture level. Strain and hence stress increase faster at the sharper notches which fail at lower elongation than the blunter notches, but all develop about the same average fracture stress.

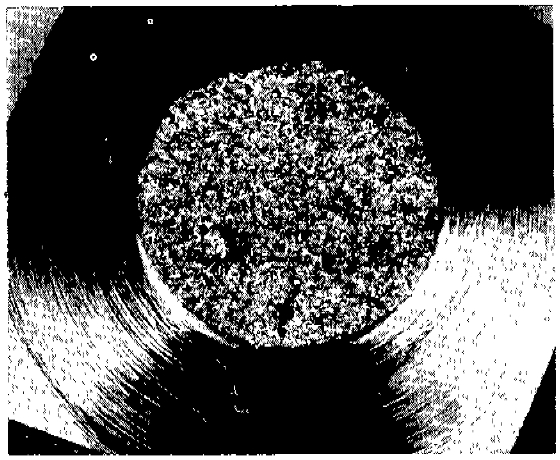
According to this discussion fracture may initiate at the interior of the most ductile bars, but at the perimeter of the most brittle. Little can be said about the probable fracture origin in bars of intermediate ductility, except to indicate a likely origin at sites just inside the perimeter where longitudinal



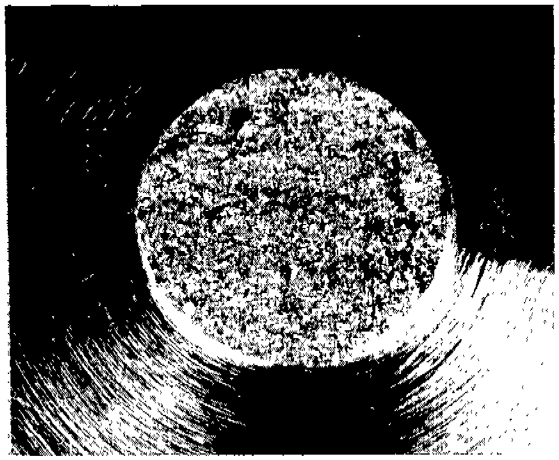
B-276 $\epsilon_0 = 0$ $\Delta \ell = 0.0370$ in.



B-283 $\epsilon_0 = 0.05$ $\Delta \ell = 0.0060$ in.



B-221 $\epsilon_0 = 0.40$ $\Delta \ell = 0.0014$ in.



B-223 $\epsilon_0 = 0.50$ $\Delta \ell = 0.0018$ in.

Fig. 19. Fractures of Grooved Bars of ABS-B Steel. Radius $\rho = 0.010$ *ir*

straining though smaller than at the surface is still strong and triaxiality though still increasing inwards is substantial. A shallow but distinct cup-and-cone fracture indicative of an internal fracture origin was visible in unstrained bars of 0.030 in. notch radius (Fig. 20, bar B-278), less so of 0.010 in. radius (Fig. 19, bar B-276 showing also an almost radial crack), and not at all in bars of 0.003 in. radius (Fig. 18, bar B-228) or in prestrained bars of any notch radius (Figs. 18-20). Signs of yielding were apparent at the neck up to about 0.10 prestrain for a notch radius of 0.030 (Fig. 20, bars B-278, B-286,

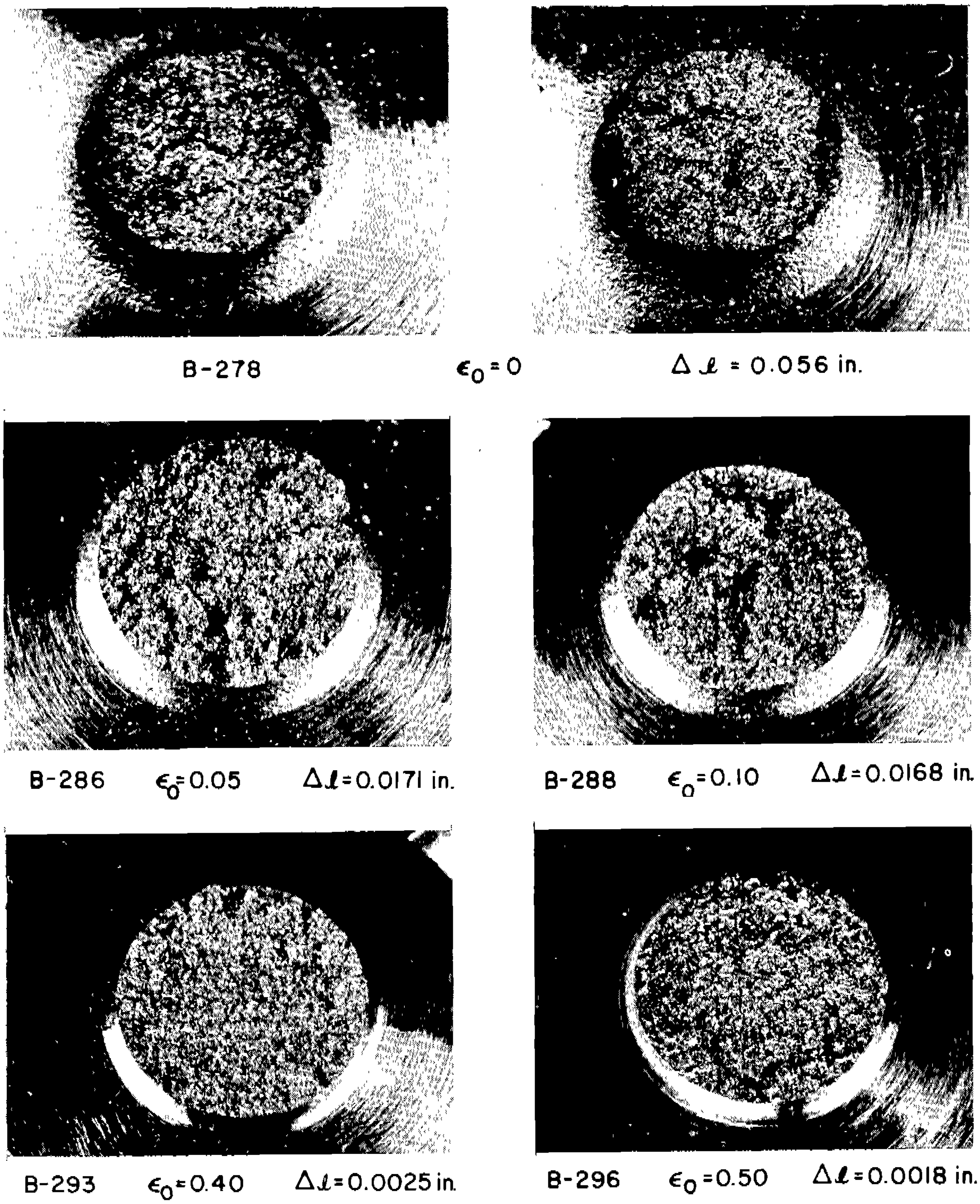


Fig. 20. Fractures of Grooved ABS-B Steel Bars. Radius $\rho = 0.030$ in.

B-288); up to about 0.05 for a notch radius of 0.10 (Fig. 19, bars B-276, B-283) and only in unstrained bars for a notch radius of 0.003 (Fig. 18, bar B-228). These are the only visible changes of fracture appearance occurring between prestrains of 0 and 0.05 or 0.10, where the rapid drop of elongation was found. The rough and irregular fracture surfaces of notched bars with light and medium prestrains may indicate the existence of several interior arrested fractures. The surface irregularity decreased with increasing prestrain, especially with the 0.003 in. notches which produces very flat fracture surfaces. Some platelets slightly raised in the flattest surfaces in roughly the same direction (Fig. 18, B-211; Fig. 19, B-223), similar to those of unnotched highly prestrained bars (Fig. 5), may indicate a unique direction of fracture propagation, hence an initiation at the groove perimeter. Unfortunately no systematic radial streaks or chevron patterns facilitate the recognition of the region of fracture initiation.

7. CONCLUSIONS

The most striking result obtained is the severe and rapid reduction of ductility of deeply grooved bars by prior uniform compressive prestrain as low as 0.05. Certainly the demands on ductility are far greater in notched than in smooth bars, but the decrease of the embrittling prestrain from about 0.75 for smooth bars (ABS-B steel) to 0.05 for grooved was unexpectedly large, especially as the ductility (i.e. the fracture strain) of smooth bars remained high and appreciably unchanged up to prestrains of 0.40 or 0.50. These results reemphasize the importance of the history of strain (including the straining to fracture) and of the state of stress at fracture; they also show the importance of the local conditions at the notch when examining the ductility of the material. The distance between the two extremes of smooth bar and deep sharp groove may be filled by any number of configurations of intermediate severity because of blunter grooves or of basically different types of straining (e.g. plane strain, or plane stress or intermediate states) and different local demands on ductility. The same material, partially embrittled by prestraining or by other processes used in production or manufacturing, may show tremendous differences in ductility when tested in various shapes. This shows how incomplete and probably dangerous could be the assessment of steel toughness by a specific test, even more so by a test of undamaged steel. There is no a-priori way of classifying notch severity in basically different configurations nor a certainty that all materials will fare correspondingly well or badly under the different conditions so as to be classified in the same order by all tests. In the absence of more fundamental methods of assessment, such as by required and existing (reduced) ductility, the results of specific toughness tests have an undeniable usefulness, but only for conditions very similar to those of the test. Their application to strongly different situations may be quite misleading.

When judged by the stress criterion of fracture, transition from ductility to brittleness is very gradual. The intersection of fracture stress and flow limit curves is not clear and becomes even more unprecise because the flow limit is an idealization and may vary within a small range according to the accepted yield strength in simple tension. With a flow limit based on the 0.5% offset yield strength all bars would have probably been found brittle, even more so if it were based on the ultimate fracture strength. The fracture-to-flow-stress criterion is valuable not for the transition range which it cannot clearly determine, but for differentiating between more extreme cases of fractures without recourse to deformation measurements, which in service fractures are practically never known.

The rapid transition of elongation at fracture in notched bars as a function of prior prestrain gives a far clearer picture of the prestrain embrittlement than the change of fracture load. The test consisting of prestraining, notching and measuring the elongation at fracture reproduces the essential processes operative in service failures, which to an important extent are due to a suitable history of strain and temperature reducing the deformability at the region of a notch or crack. The dependence of the elongation at fracture of notched bars on the history and amount of prestrain should give a realistic measure of the resistance of steel to embrittlement and fracture.

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13. ABSTRACT

Earlier studies of reduction of ductility by prestraining have been extended to include behavior under severe notch constraint of uniformly prestrained and aged ABS-B and Project E-Steel. Tension bars with deep circumferential grooves of 20° angle and 0.030 or 0.010 or 0.003 in. notch radius were used. The depth of the grooves was sufficient to enable the more ductile bars to reach and exceed the theoretical flow limit for infinite depth based on the 0.1% offset yield stress $\sigma_{0.1}$. Both load and elongation at the groove shoulders were measured. The average fracture stress increased with increasing prestrain at first at about the same rate as the $\sigma_{0.1}$ stress and the corresponding flow limit and then at a slower rate, so that at a prestrain of 0.20 it was clearly below the corresponding flow limit. From there on the fracture stress gradually decreased till at 0.60 prestrain it was close to the 0.1% offset yield stress of unnotched bars. According to the criterion of average fracture stress, the transition from ductile to brittle behavior under the conditions at the notch was very gradual and occurred at prestrains close to 0.20. On the contrary the elongation at the shoulders, which is a direct measure of ductility, showed an abrupt drop at prestrains as low as 0.05, which is a tremendous reduction from the prestrain of 0.75 needed to embrittle smooth bars of ABS-B steel subjected to tension, and of 0.48 when subjected to bending. The conditions of fracture at a notch in a strain hardening material are discussed in relation with the obtained results.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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