Anisotropy and Weldability

Decohesion-cracking planes parallel to plate surfaces occur most commonly in corner and tee joints when welded under conditions of high restraint, and the solution to this problem includes material improvement, weldment redesign, and welding procedure modification

BY J. HEUSCHKEL

SYNOPSIS. Some otherwise weldable steels are subject to through-thickness tension decohesion cracking under static nonload conditions during or soon after welding. The cracking occurs at temperatures below about 450° F. Geometrical arrangements of indicidual parts, specified by the designs in corner and tee joints, result in transmission of welding stresses in the through-thickness direction. The cracking is maximized when using welding conditions that result in high levels of internal tensile stress.

These decohesion cracks are associated with highly anisotropic plates having low tensile ductility, low fracture strength, and low impact energy in the through-thickness direction. Unwelded plates, evaluated with smooth-bar tensile specimens, provided elongation at rupture values of from 0.03 to 6.0%. Charpy V-notch energy values of from 3 to 10 ft-lb were obtained at ambient temperatures. Ductility values were not improved by heating to commonly used preheat temperatures.

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Incident steels included ASTM A-36, A-284A, A-302B, A-441, A-514H and A-517F. Nonincident ASTM A-533 and HY-80, HY-100, HY-130, and HY-180 steels were evaluated for background reference.

Flat, planar type inclusions were present in the lower quality plates. Rupture in tensile specimens occurred as local extensions of these opened inclusions. The through-thickness ductility of these plates was inversely related to plate cleanliness and was independent of tensile proportional limit.

Introduction

An isotropic material, by definition, is one which has the same properties in all directions. An anisotropic material is one which is not isotropic. Such a material has unequal properties in at least two directions. Anisotropy is the quality of being anisotropic.

Three-directional properties were obtained for ten grades of steels commonly used in industry. Particular attention was given to the tensile strengths and weaknesses, tensile ductility and brittleness, and impact toughness and brittleness in the through-plate thickness, or short-transverse, direction.

Many hot-rolled, normalized, annealed, and quenched-and-tempered structural and pressure vessel steels are three-dimensionally anisotropic to some degree. Some are anisotropic to such an extent that their weldability is degraded in the through-thickness direction. When the steel through-thickness ductility and tensile fracture strengths are sufficiently low, and the applied tensile strains and stresses are sufficiently high, grossly anisotropic materials separate by decohesion—that is, they crack in multiple planes which are parallel to the original plate rolling surfaces.

The stresses which cause these separations accumulate during cool-down under restraint. Consequential cracking occurs during or shortly after welding, or during subsequent heat treatment. Such cracks occur in the base metal, either in or at some distance from the weld heat-affected zone. The multiple planes of decohesion commonly follow and extend from lamellae and inclusion bound-

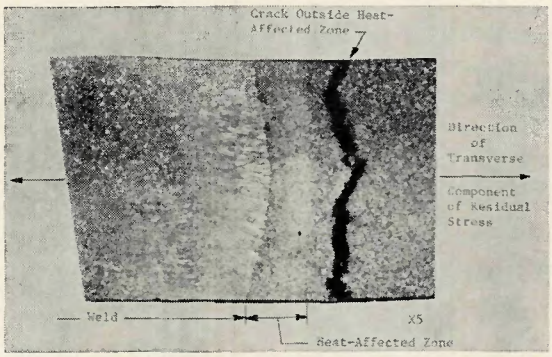

Fig. 1—Section of core drilling from cracked A-284A carbon steel weldment (see Fig. 5-1). X5 (reduced 66% on reproduction)

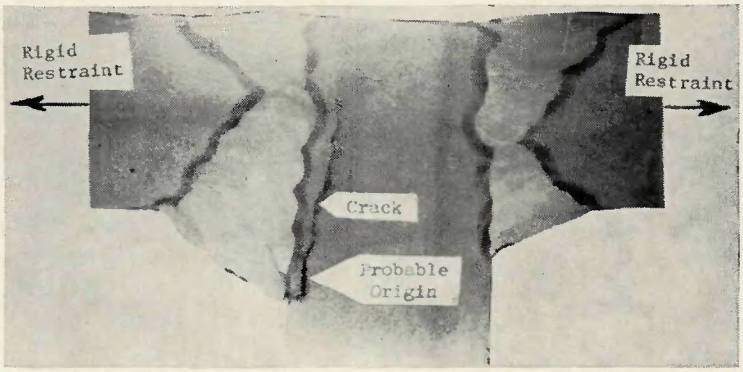

Fig. 2—Section across restrained joint in carbon steel. X1 (reduced 35% on reproduction)

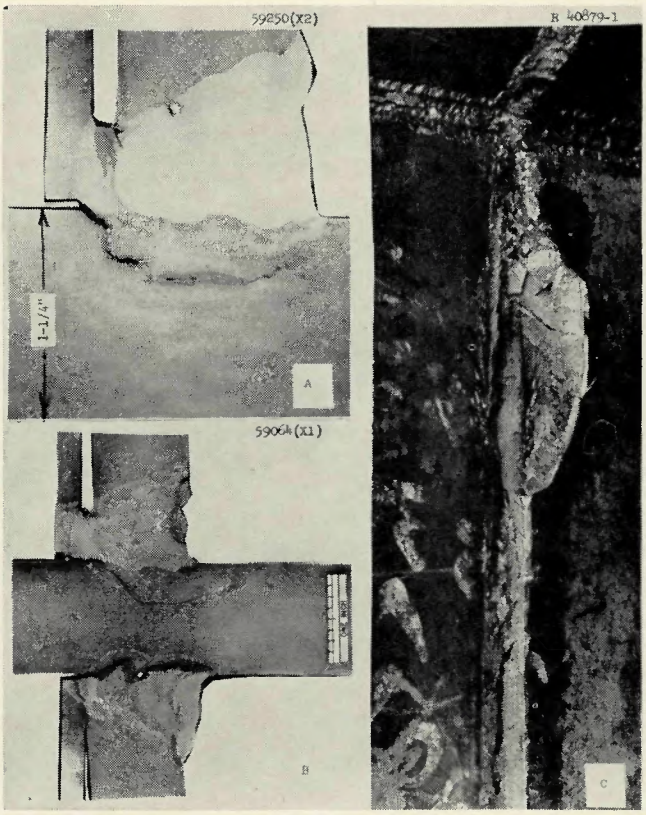

Fig. 3—Consequences of combined effect of joint design with sharp notches, high restraint, and low plate ductility in through-thickness direction. (A-514H steel)

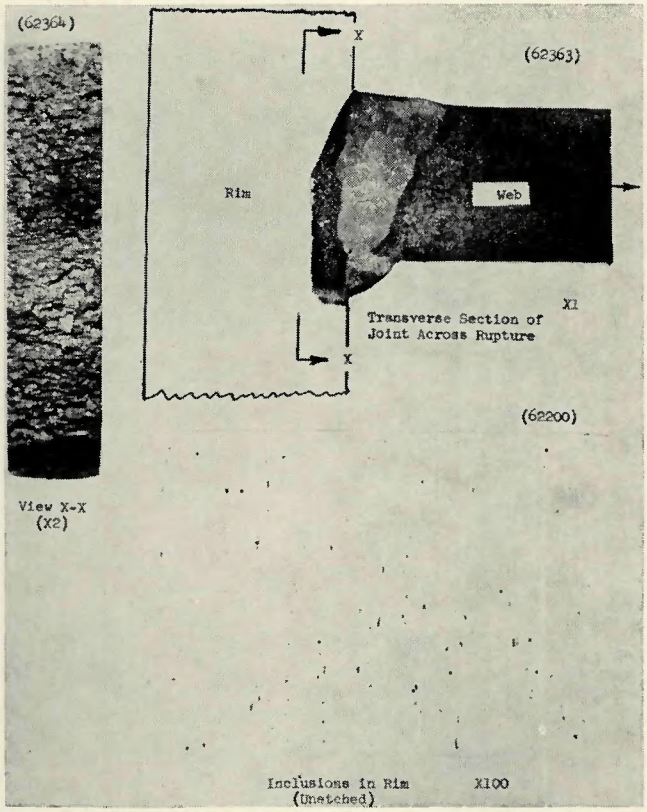

Fig. 4—Shop floor rupture during fabrication. (A-441 Steel = MnV, 50,000 psi Y.S.)

aries and are referred to as "lamellar tearing" by some investigators.[1-17] This phenomenon is most prevalent in corner and tee joints.

Investigations of several incident weldments demonstrated that unwelded portions of the affected steel plates exhibited exceptionally low tensile ductility and fracture strength and impact toughnesses in the through thickness direction. In these incidents the cracking commonly occurred outside of the weld heat-affected zones. The several planes of propagation were parallel to the rolled plate surfaces.

Illustrative Incidents

Plate decohesion is experienced in unalloyed carbon steels (Figs. 1 and 2); in alloyed, austenitized, quenched-and-tempered steels, (Fig. 3); and in hot-rolled, alloyed steels, (Fig. 4). Plate thicknesses involved in the four cited example incidents ranged from 1 to 6 inches. In each incident, the designs and welding procedures used provided conditions which resulted in high (but unmeasured) residual stresses in the plate through-thickness directions—Fig. 5. Such decohesion has been observed in plates as thin as $^1/_2$ in.

Other production incidents could be cited. In all observed cases, the decohesion occurred in welded tee or corner joints which were subject to relatively high through-thickness tensile strains and stresses imposed by structural restraints.

The four cited examples include welds made with the manual covered-electrode, the semiautomatic gas-shielded, and the submerged arc processes.

The through-thickness elongation obtained from smooth-bar tensile specimens representative of the incident plates was low, i. e., from 0.03 to 6.0%.

Materials Investigated

The materials studied can be classified into two groups:

1. Those taken directly from, or being representative of, steels in self-ruptured weldments.
2. Higher quality, high-strength alloy steels which have minimum susceptibility to decohesion cracking.

The first group includes unalloyed hot-rolled carbon steels (A-36, A-284A), hot-rolled alloy steel (A-441), hot-rolled and annealed alloy steel (A-302B), and quenched-and-tempered alloy steels (A-514H and A-517F). The second group was studied to obtain a better understanding of the total problem. It included A-533, HY-80, HY-100, HY-130, and HY-180 steels.

The first group was established and identified by the realities of industrial experience. The second group includes those more recently developed steels which are intended for use in complex weldments under adverse conditions.

The compositions of the individual plates, by check analyses, are listed in Table 1. The tensile, impact and inclusion characteristics of these steels are shown in Figs. 7 to 39, inclusive.

Measuring and Evaluating Anisotropy

Test Specimens

Standard 0.357 in. diam. smooth-bar tensile specimens, having a total overall length of 2.25 in., and standard Charpy V-notch impact specimens having a total length of 2.0 in. are adequate to obtain the necessary information on through-thickness mechanical properties of plates. For thicknesses less than 2.25 in., it is necessary to either deposit weld pads on one or both plate surfaces, in the region to be tested, or to weld extension bars to the test plates, much as shown in the lower left view of Fig. 3, except that unrestrained welding conditions are used.

The tensile specimen is a standard button-head type having a cross-section area of 0.100 sq. in.—Fig. 6. It is satisfactory for use in all orientations, for all strength levels, at all test

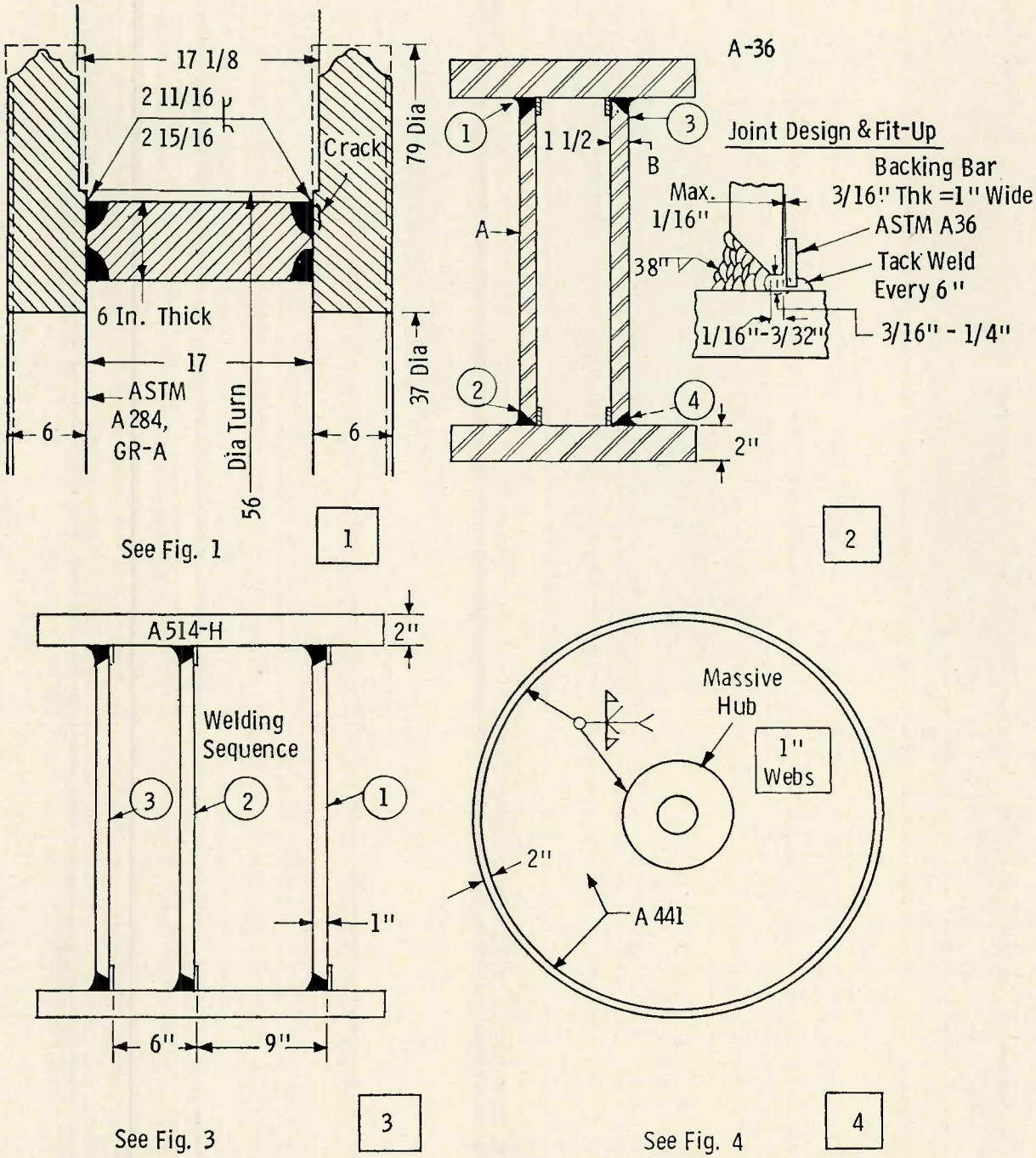

Fig. 5—Four incident weld designs. All resulted in high residual stresses in through-thickness direction

temperatures of interest (−200 to +2200° F), and may be used for short or long-time tests. All tensile specimens were tested at a constant strain rate of 750% per hour.

Tensile Properties

For 1:1 cross-rolled plates, the properties obtained from specimens having their axes in the conventional longitudinal and transverse directions are usually nearly identical. When lesser cross-rolling is used the results are reflected in joint performance.[16] As the degree of cross-rolling decreases, the differences in ductility and fracture strength for the two directions increase.

The significant differences in tensile characteristics occur in the through-thickness direction, as shown by the stress-strain curves in Fig. 7. In the through-thickness direction, the maximum load resisted is usually reached at a lesser amount of strain (uniform elongation). This appears to be true whether or not the nominal ultimate strength of the material (maximum resisted load divided by original cross-section area) is reduced, indicating that the material in the through-thickness direction is less able to withstand cold strain.

In extreme cases, rupture may occur at, or even prior to, reaching the nominal longitudinal yield strength of the material—Fig. 7. A few of the extreme cases approached the strength-ductility conditions of laminated plate. However, obtaining low levels of ductility and true stress at fracture in prewelded plate in the through-thickness direction does not require the presence of plate laminations. Such poor results may be obtained in plates which are sound, as determined both macrographically and by the use of ultrasonic inspection techniques.

The degradation in through-thickness tensile properties can result from any one of three or more causes, or a combination of causes. The most common of these is the existence of

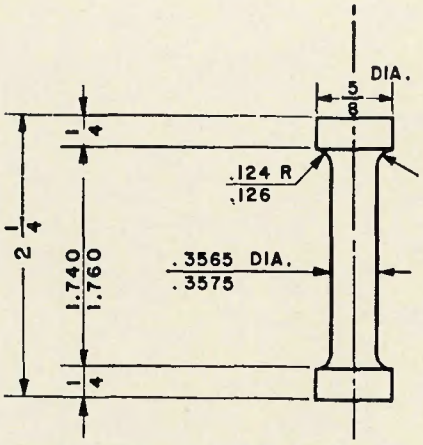

Fig. 6—Threadless, tensile specimen. Notes: (1) radii must be tangent to both surfaces with no undercut; (2) specimen axis must be on straight line through end centers within 0.0005 in.; all dimensions in inches

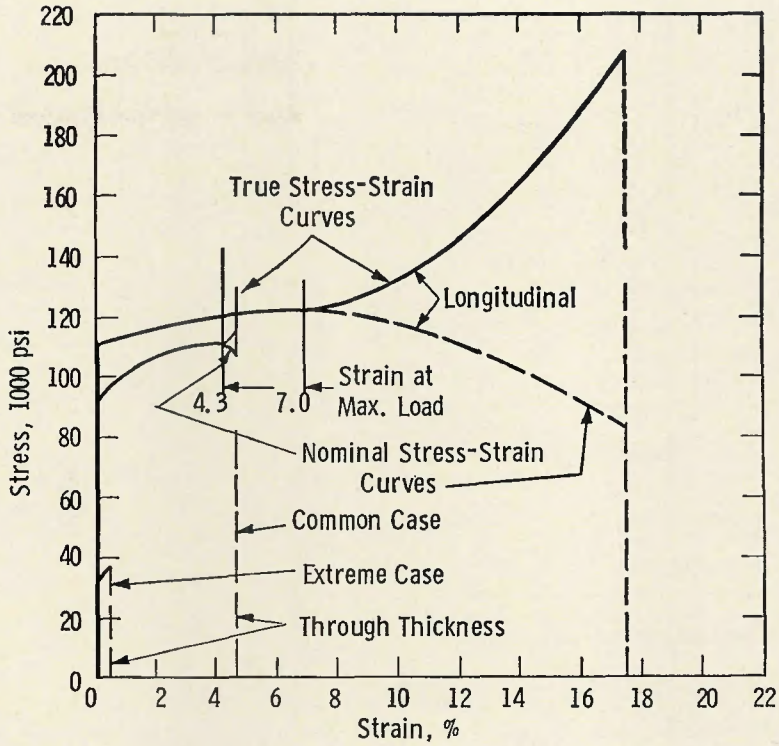

Fig. 7 (right)—Typical tensile stress-strain curves for A514-H steel (1 in.thick)

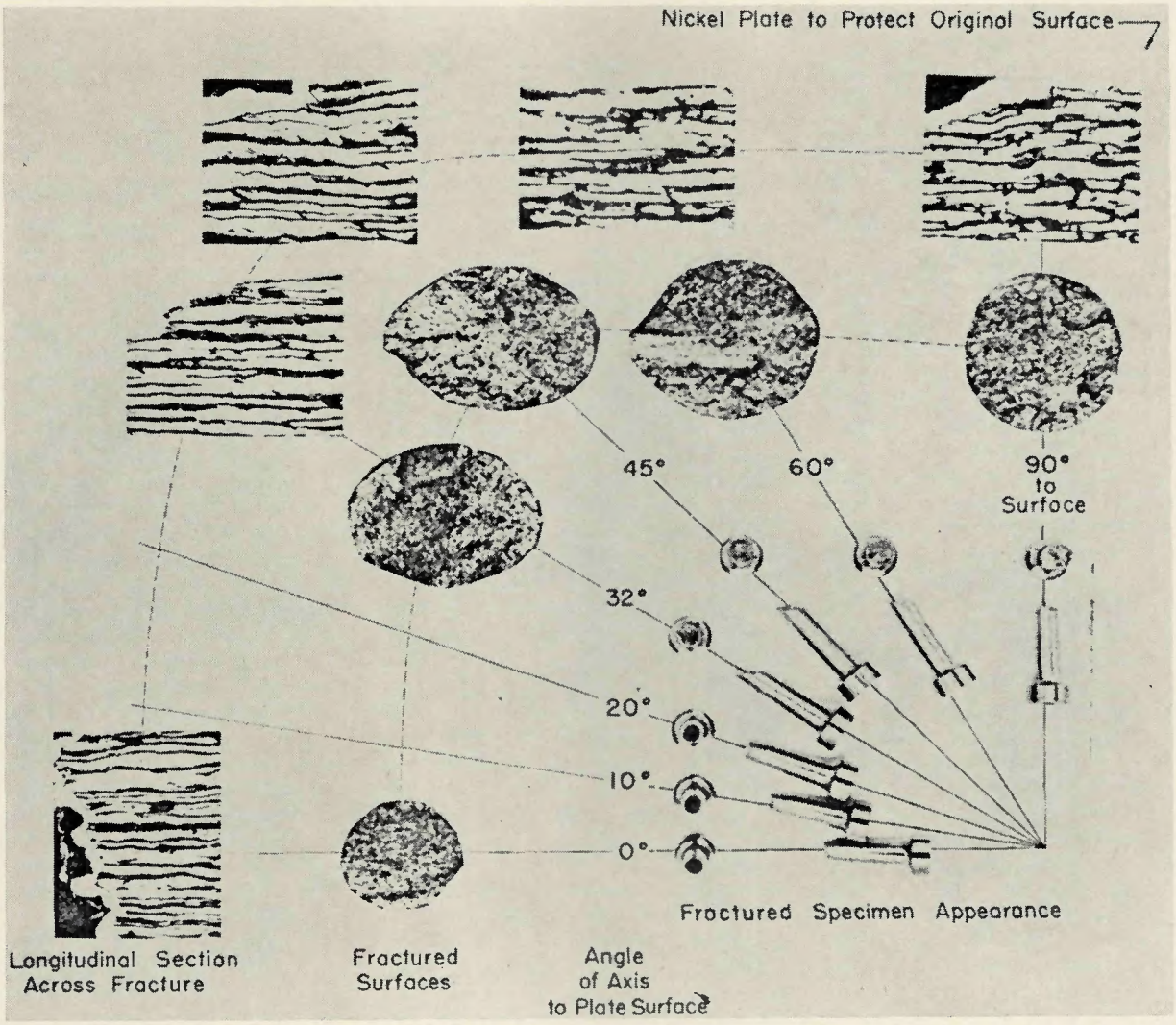

Fig. 8—Orientation dependence of tensile characteristics for banded plate in A-302B steel 3¼ in. thick

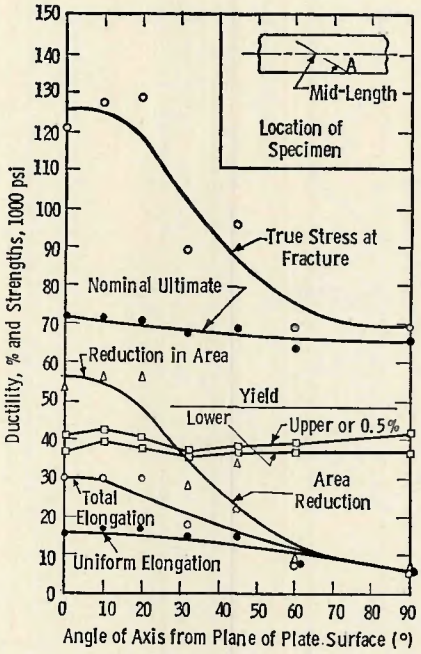

Fig. 9—Relations between angular disposition of tensile specimen and obtained properties—+80° F; A302B

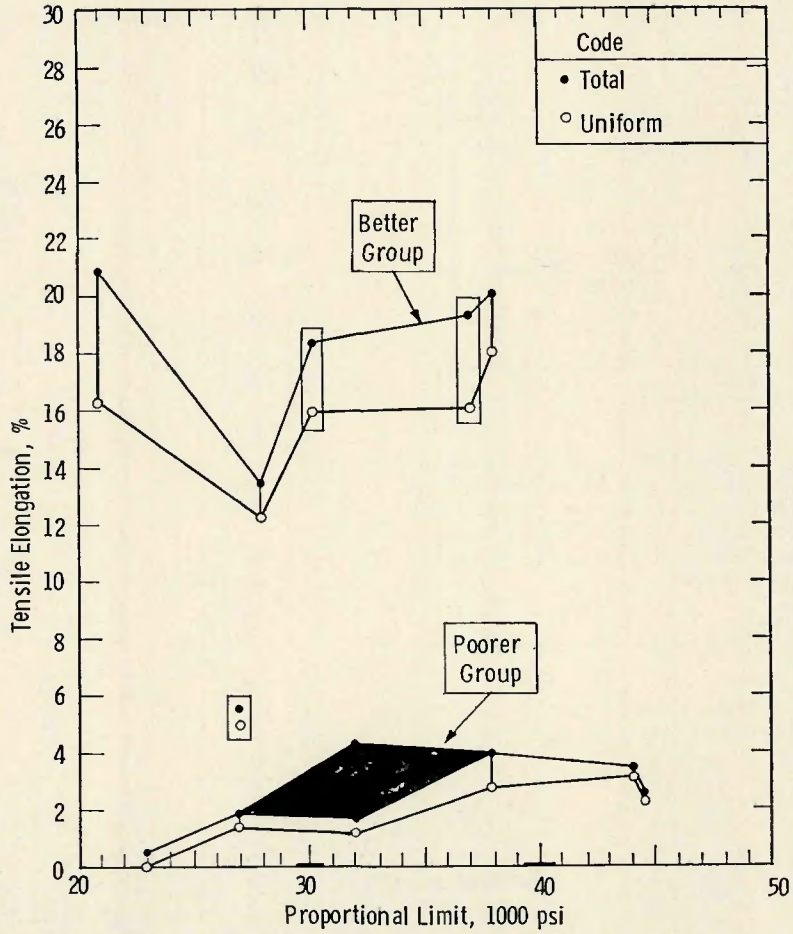

Fig. 10—Through-thickness elongations are independent of strength for carbon steels A-36 and A-284A

extensive platelet type inclusions—Fig. 4. The presence of banding in the plate microstructure is a second cause for deficiencies in through-thickness ductility and fracture strengths—Fig. 8. The fracture appearance, ductility, and strength vary continuously as the axes of the specimens change orientations from the longitudinal to the through-thickness directions—Figs. 8 and 9. In this instance the yield and ultimate strengths were not significantly influenced by the banded structure. A third factor is the presence of a softer and weaker mid-plate region. This condition can exist in hot-rolled and in quenched-and-tempered steels which were not fully transformed during the quench operation.

The through-thickness tensile elongation for steels in general, and carbon steels in particular, is not directly related to their elastic or plastic strengths. For any level of proportional limit strength between 21,000 and 45,000 psi in carbon steels, the through-thickness uniform elongation and the through-thickness total elongation values may be either poor or good, depending upon factors other than those which cause variations in steel strengths—Fig. 10.

The same conclusion is reached for carbon steels by using either area reduction or total elongation as a criterion of ductility—Fig. 11. The area reduction is approximately 1.0 to 2.0 times that of the elongation. With detail exceptions, this range in the relationship is descriptive of all three plate orientations.

The longitudinal and transverse ductility of the carbon steel plates is conspicuously superior to those obtained in the through-thickness direction, where as low as 1% elongation and 2% area reduction values were obtained in two incident cases. Most of the incident cases investigated were found to have total elongation values of less than 6% and area reduction values of less than 15% in the through-thickness direction.

The same general interrelation between area reduction and total elongation was observed for a series of incident austenitized, quenched-and-tempered A-514H and A-517F alloy steels (Fig. 12) except that the ratio of the two values was higher. Both ductility values, in the longitudinal and transverse directions, were as much as one order of magnitude (ten times) higher than those obtained in the through-thickness direction. Some of the specimens, taken from incident plates such as Fig. 3, exhibited total elongation values less than 1%, and area reduction values less than 5%.

Seven other alloy steels, with two exceptions, had the same general interrelation between area reduction and elongation—Fig. 13. The longitudinal and transverse values, in general, were from good to excellent, considering the strength levels; but once again, those values were significantly higher than the corresponding values obtained in the through-thickness direction. The Mn-V alloy steel, used in the Fig. 4 incident, had a through-thickness elongation of less than five percent and an area reduction of less than eight percent.

The two alloys having conspicuously good through-thickness ductility are the HY-80 and HY-180 steels—Fig. 13. For those two cases the through-thickness ductility was the same, or nearly the same, as obtained from the respective longitudinal and transverse orientations. The specimens in the HY-180 steel, when orientated in the through-thickness direction, resulted in full cup-cone type ductile fractures. This was an exceptionally clean steel made from electric furnace plus vacuum-arc remelted ingots. Also, as a consequence of control of original materials used in the melt, it contained low S and Si (Table 1) both of which are common components of nonmetallic inclusions.[18]

True stress at fracture, as obtained from a smooth-bar tensile specimen, is more closely related to area reduction than to total elongation. However, because weldment decohesion rupture

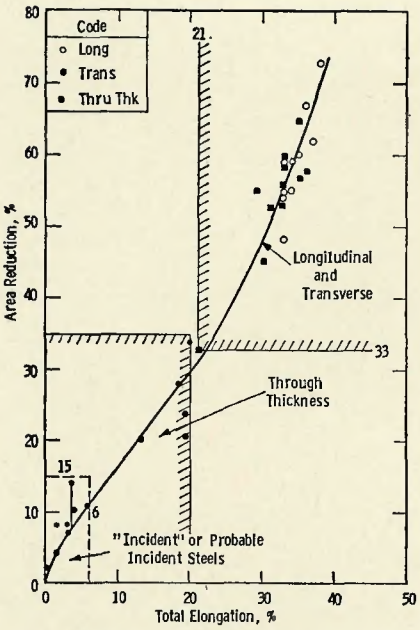

Fig. 11—Elongation-area reduction relations for A-36 and A-284A carbon steels

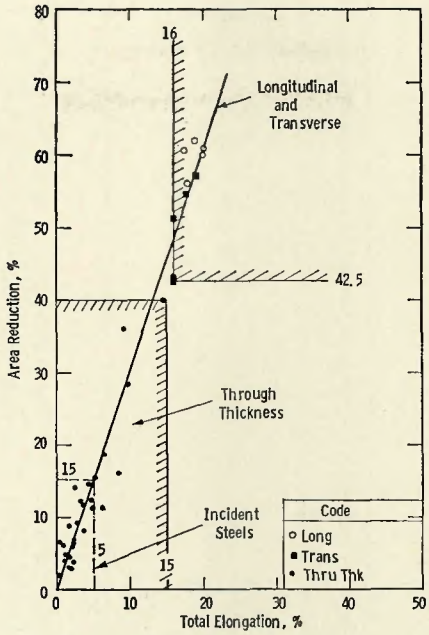

Fig. 12—Elongation-area reduction relations for A-514H and A-517F alloy steels

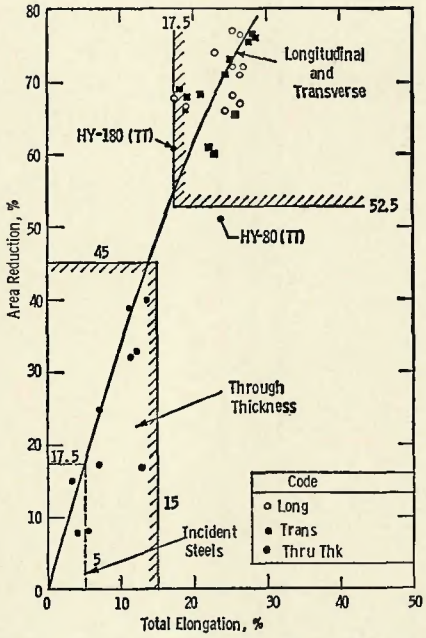

Fig. 13—Elongation-area reduction relations for A-302B, A-441, A-533, and HY-80, -100, -130, and -180 steels

is more closely related to elongation capabilities than to area reduction, the dependence of fracture strength on elongation was examined. For carbon steels, fracture strength as indicated in Fig. 14 was always highest when the elongation values were highest—that is, for the longitudinal and transverse directions. In the through-thickness direction the true stress at fracture* values were lowest as the total elongation values decreased. The minimum value, slightly less than 30,000 psi, was obtained from an incident steel specimen having less than 1% total elongation at rupture. It is, therefore, concluded that the observed weldment decohesion failures, which occur during shop fabrication, result from a combination of high applied shrinkage stresses and the coexistence of low fracture strength and low tensile elongation in the plate materials. Since there was no evidence of oxidization on the incident fractures, it was concluded that the cracks occurred at temperatures of about 450° F and lower.

The tensile elongation and true stress at fracture data for all of the reported steels are summarized, for all three orientations, in Fig. 15. In every steel the best relations between fracture strength and elongation are obtained for the longitudinal and transverse directions, and the poorest relations are obtained for the through-thickness direction. All of the steels investigated are somewhat anisotropic. For any given elongation value the fracture strengths are higher for the higher yield strength, cleaner steels. High fracture strengths are not obtained with unalloyed carbon steels. The one HY-180 steel investigated had outstandingly good ductility and fracture strength in the through-thickness direction.

*Full load of fracture divided by final cross-section area.

Thickness Dependence

Other investigators have noted that the incidence of "lamellar tearing" increases as plate thickness decreases.[3, 8] The reported tensile data tend to verify this observation for decohesion rupture, although the trends are not dramatic. Over the 1 to 6 in. thick range of incident carbon steel cases the downward trend of fracture strength with decreasing plate thickness appears to be real—Fig. 16. Steels taken from commercial lots representative of those causing difficulties during shop fabrication showed similar trends. The thickness trend for impact values, a criterion which probably relates to the ease of propagation of a locally initiated decohesion, is not conclusive although it appears to be contrary—that is, the impact values tend to decrease slightly as plate thickness increases. For both criteria, the same grades of steels can have good or poor fracture strengths and impact energy absorbing capabilities.

The true stress at fracture values also decreased with plate thickness in A-514H steels from 4 to 0.75 in. thick —Fig. 17 (upper graph). The total elongation values for this series exhibited considerable scatter—Fig. 17 (lower graph). In general, the trend for best obtained elongation values in the through-thickness direction indicates less available ductility in the thinner plates.

Temperature Dependence

Temperature dependence of fracture strength and ductility is both similar and dissimilar in the through-thickness direction as compared to that observed in the conventional longitudinal and transverse direction tests.

The largest incremental drop in proportional limit occurs for carbon steels when the temperature is raised from normal ambient (+75° F) to +200° F. Within this 125° increment those values reduced as much as 50% —Fig. 18. Further heating, up to as high as 1050° F, has a lesser unit effect upon the proportional limit. The ductility of incident carbon steels in the through-thickness direction did not improve by increasing the temperature up to 1050° F. However, heating to 1200° F, and above, significantly increased the ductility in the through-thickness direction.

Temperature dependence data from a series of A-514H alloy steels were similar to those described for the carbon steels, except that heating to 200° F produced little reduction in elastic and plastic strengths. It is necessary to heat such steels to approximately 1200° F, which is above their tempering temperature, before the elastic strengths are reduced by 50%. Once again, the ductility was not improved by heating to any temperature up to and including 1050° F. Over the −60 to +1050° F range the average total elongation was less than three percent—Fig. 19.

Data from 4 in. thick plates of the same alloy composition provided similar results except that the average

Table 1—Check Analyses of Steels Included in Investigation

	ASTM code	Test mark	Element, wt-% C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Co	Ti	As	Sb	Sn	Pb	Zn	N	O	Al Sol	Al Al_2O_3
	A-36	7BR[a]	0.24	1.11	.009	.024	.17	.02	.01	.05	<.005	.005	.006	<.003	.0030	.0002	.0008	<.001	.0018	.0050	.0020	.023	.0005
	A-36	1396[a]	0.21	1.01	.008	.015	.23	—	—	—	—	—	—	—	—	—	—	—	—	.005	.0180	.012	.001
Uu-	A-284A	EPG[a]	0.14	0.51	.018	—	.18	.18	.17	.062	.022	—	—	—	—	—	—	—	—	.0120	—	—	—
alloyed		1512B	0.273	0.72	.005	0.020	.23	.087	.004	.21	—	.001	—	—	.0060	.0015	.0017	—	—	.0064	.0027	.011	.0009
carbon		1512D	0.273	0.75	.009	0.022	.25	.16	.15	.11	—	.0009	—	—	.0110	.0028	.0066	—	—	.0058	.0096	.011	.0011
steels		1512E	0.258	0.64	.009	0.022	.19	.15	.14	.13	—	.001	—	—	.0110	.0024	.0060	—	—	.0052	.0131	.002	.0008
	Mod	1512G	0.296	0.79	.010	0.023	.30	.030	.020	.032	—	.003	—	—	.0058	.0007	.0009	—	—	.0077	.0043	.004	.0011
	A-215	1514[a]	0.259	0.78	.004	0.028	.25	.15	.09	.040	—	.002	—	—	.0062	.0023	.0042	—	—	.0038	.0270	.004	.0008
		1488	0.290	0.85	.010	0.011	.25	—	—	—	—	.021	—	—	—	—	—	—	—	.0102	.0270	.008	.0007
		1489	0.204	0.60	.010	0.019	.086	.020	.08	.075	—	.002	—	—	.0052	.0007	<.0005	—	—	.0050	.0097	.007	.0002
		1490	0.128	1.08	.007	0.020	.24	.14	.07	.078	—	.003	—	—	.0098	.0024	.0062	—	—	.0074	.0013	.019	.0009
	A-302B	SW A 302-B	0.32	1.49	.013	.017	.26	.13	2.77	0.05	.57	.005	.009	<.003	.0150	.0025	.0201	.001	.0007	.0109	.0022	.019	.0006
	—	(S) HY-80(2)	0.17	.23	.007	.015	.23	.05	2.51	1.25	.35	.005	.02	<.003	.0042	.0002	.0063	<.001	.0012	.0056	.0016	.026	.0003
	—	(SW) HY80-(1)	0.23	.24	.009	.013	.23	.21	2.74	1.65	.41	.005	.01	<.003	.0081	.0002	.0144	<.001	.0014	.0113	.0023	.030	.0003
	A-533	1412	.21	1.30	.020	.019	.19	.17	0.60	0.14	.54	.0040	.015	<.001	.0117	.0029	.0111	<.0001	.0007	.0057	.0017	.028	<.0003
	A 441	1413W	.15	1.09	.012	.017	.24	.13	1.10	0.056	.20	.039	.009	.0016	.0028	.0013	.0078	.0005	.0003	.013	—	.013	.0003
	A 441	1413R[a]	.15	1.17	.006	.015	.25	.16	1.04	0.060	.21	.042	.010	<.001	.0022	.0007	.0080	.0090	.0005	.018	—	.013	<.0003
Alloyed	—	(S) HY-100	—	0.34	.008	.016	.21	.16	3.31	1.63	.48	.01	.02	<.003	.0111	.0039	.0163	.001	<.0003	—	—	.038	<.0003
steels	—	(217) HY-80	.14	0.31	.025	.016	.19	.034	3.02	1.34	.50	.0044	.020	<.001	.0039	.0007	.0090	<.0001	.0005	.0043	—	.012	.0008
	—	(241) HY-100	.14	0.27	.013	.015	<.03	.035	3.00	1.34	.50	.0043	.020	<.001	.0028	.0007	.0061	<.0001	.0005	.0044	.0031	.008	.0010
		BL 2	.24	1.06	.008	.018	.26	.03	.53	.57	.24	.05	.02	.009	.0063	.0004	.0073	<.001	.0019	.0027	.0013	.033	.0004
	A514H	BL 3	.21	.91	.012	.020	.23	.26	.80	.51	.47	.06	.01	.017	.0045	.0006	.0103	.001	.0032	.0016	.0017	.029	.0006
		BL 4	.20	.74	.009	.013	.18	.29	.81	.50	.43	.04	.02	.009	.0026	.0009	.0094	<.001	<.0003	.0020	.0016	.022	.0005
	—	(S)HY-130	—	.85	.007	.0032	.21	.12	4.96	0.57	0.47	.05	.03	.003	.0051	.0007	.0130	.001	.0032	.0052	.0019	.008	.0010
	—	(S)HY-180	.21	.30	.002	.0043	.004	.11	12.5	0.62	1.06	.10	4.15	<.003	.0051	.0009	.0155	.006	<.0003	.0016	.0008	.0059	<.0003
	—	1496HY-180	.20	.25	.007	.0032	<.005	.13	9.11	0.82	1.20	.11	3.20	<.001	.0078	.0013	.0131	<.0001	<.0003	.0022	.0005	.008	<.0003

[a] Incident plate.

obtained total elongation value of 11.7% was superior to those for the lesser plate thicknesses.

The 0.2% yield strength of a clean HY-180 quenched-and-tempered steel, through thickness, decreased 22% when heated to 900° F—Fig. 20. Above that temperature all strength values decrease rapidly as the tempering temperature of the steel is reached and exceeded. Above 1050° F all ductility values increase. A through-thickness elongation value of 128% was obtained at 1800° F.

Time Dependence

The time-temperature dependence of the strength and ductility of any welded steel has basic significance, particularly when the weldment is subject to stress-relief-annealing operations or is intended for elevated temperature service. It is known from experience that some steels can be satisfactorily welded under restrained conditions without cracking, but that they may crack during some phase of the stress-relief-annealing operations.

This aspect of the problem was studied by making double-tee welded joints in the laboratory using 2 in. thick plates for the test portion. The conditions were such that the residual stresses in the through-thickness portion of the specimen, the volume of interest, were not of significant magnitude. One inch wide strips were saw cut across these joints, and 0.505 in. diameter standard threaded-end tensile specimens were prepared from those strips. The 2 in. gage length was in the through-thickness direction of the test plate. The specimens were then individually loaded in stress-rupture machines at room temperature to predetermined stress levels at and below the room temperature yield strength of the plate. Each specimen was then heated while under static load to a predetermined simulated stress-relief-annealing temperature within the 900 to 1150° F range. Time-strain curves were obtained for each specimen. This procedure was intended to simulate conditions existing in a highly restrained weldment which had been allowed to cool to shop temperature after welding and was then stress-relief annealed. During the welding and postwelding period, various parts of weldments develop different stress levels, up to the yield strength of the material.

Failures in those test specimens were observed to occur either in, near, or out as much as 0.5 in. away from the weld heat-affected zone—Figs. 21 and 22. In one specimen (Fig. 22), wherein failure occurred 0.5 in. from the weld bond, cracking and incipient failure were also observed in the heat-affected zone of the through-thickness direction plate; furthermore, a crack of lesser magnitude was observed in the heat-affected zone of the longitudinally orientated plate.

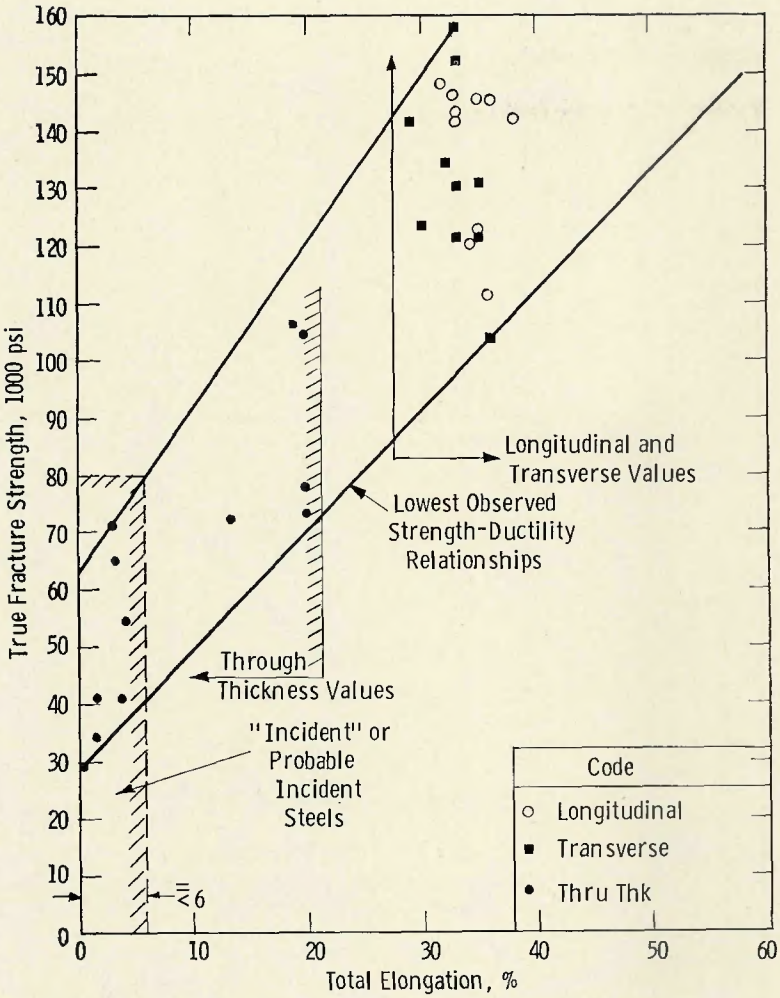

Fig. 14—Relations between elongation and fracture strength for A-36 and A-284A carbon steels

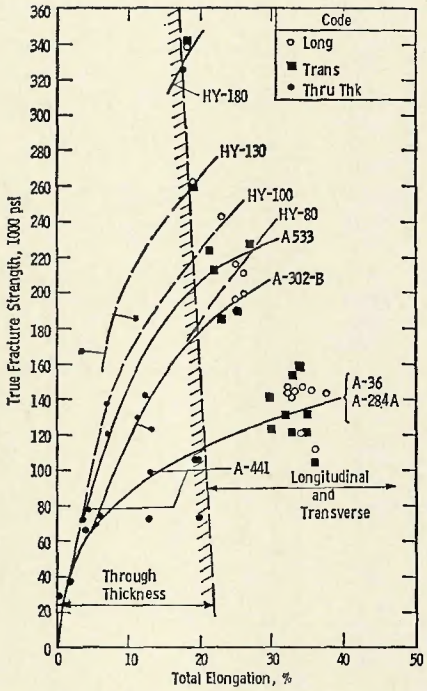

Fig. 15—Relations between total elongation and fracture strength for carbon and alloy steels

These test specimens duplicated observed shop experiences for A-514H steel in which cracking had occurred during stress-relief annealing both in and distant from the weld heat-affected zones—Fig. 22. The obtained data show that, when the pre-applied stress was at the 100,000 psi yield strength level, these specimens (by time projection) failed in approximately 1 minute at 900° F. By deduction, therefore, had the welding procedure used resulted in a residual stress of approximately the full yield strength of the plate material, such a weldment would have been expected to crack even under low temperature stress-relief annealing. It is apparent that the cracking occurs on the heating portion of the heat treating operation. By deduction, it is concluded from these tests that rapid rates of heating are the most harmful.

The response to variation in levels of temperature (Fig. 23) was similar to that obtained for conventional directions to the extent that as the temperature increased there was a decreasing capability to withstand a particular stress level for a specified period of time. One specimen, when preloaded to 40,000 psi, approximately 40% of the room temperature yield strength of this material, broke on heating at 1150° F.

Similar tests were made from one lot of A-533 steel, having a nominal room temperature yield strength of 90,000 psi. When it was stressed above 60,000 psi, it could not be heated above 1000° F without rupture in the through-thickness direction at times of less than 30 minutes—Fig. 24.

Impact Toughness

A decohesion crack, once initiated, could be expected to propagate most rapidly under tensile stress when the energy required for propagation was minimal. To obtain some insight on this matter, standard Charpy V-notch impact specimens were made in all three orientations from many of the steels investigated.

No precise relation was found between tensile elongation and impact energy values. The general relation is that the steels exhibiting the most ductility in the tensile specimens have the highest impact energy absorbing capabilities. For the carbon steels this differential was not always significantly large—Fig. 25.

Incident carbon steel impact specimens in the through-thickness direction exhibited minimum temperature dependence because the values obtained were low at all test temperaures—that is, the transition temperature was above +200° F (Fig. 26).

The impact energy values were determined for an A-514H steel which cracked in the field in the through-thickness direction—Fig. 3. A series of 36 Charpy specimens were prepared across an uncracked double-tee welded joint with the notch being progressively shifted across the joint at increments of distance averaging 0.125 in.

All specimens in this series were tested at +10° F—Fig. 27. The average absorbed energy values for the web plate material involved in the incident, for the longitudinal direction, was 31.6 ft-lb. The heat-affected-zone values of that plate averaged 27.7 ft-lb. The average energy values of the weld metal, joining the web to the rib plate, was 53.8 ft-lb. As the notch was moved into the rib plate, a companion to the one which failed, and where the plate was now being tested in the through-thickness direction, the energy values dropped to an average of 6.2 ft-lb, the lowest individual value being 3.0 ft-lb at the plate center. The average value for the second web plate, which was orientated in the transverse direction,

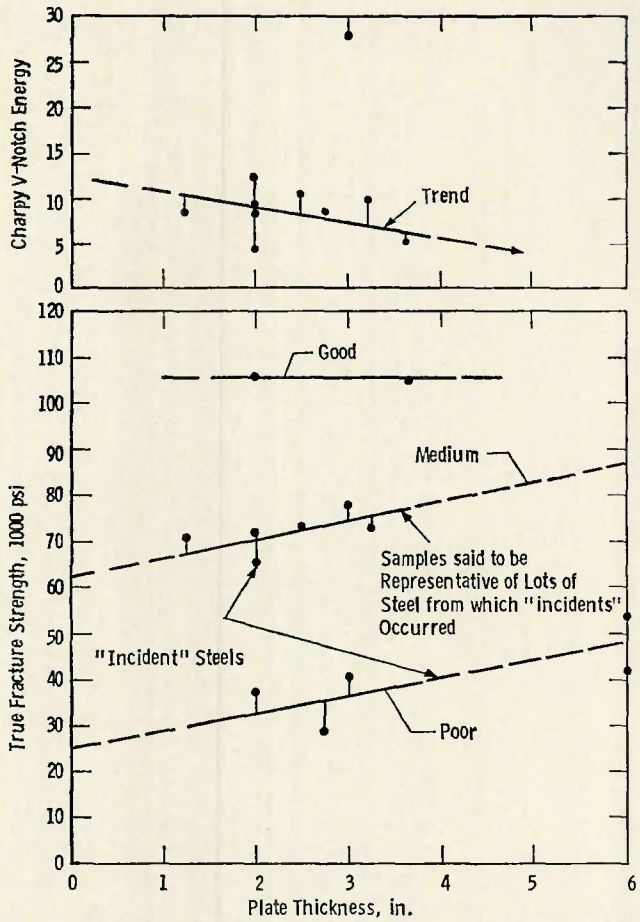

Fig. 16—Relation between plate thickness, fracture strength and impact energy in through-thickness direction for carbon steels

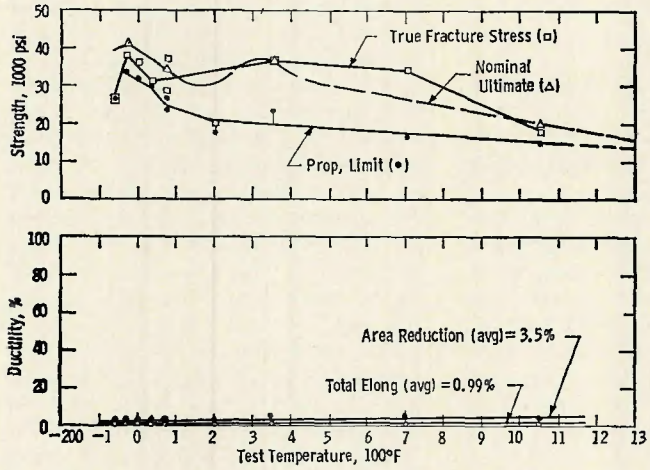

Fig. 18—Temperature dependence of tensile properties for incident A-36 carbon steel

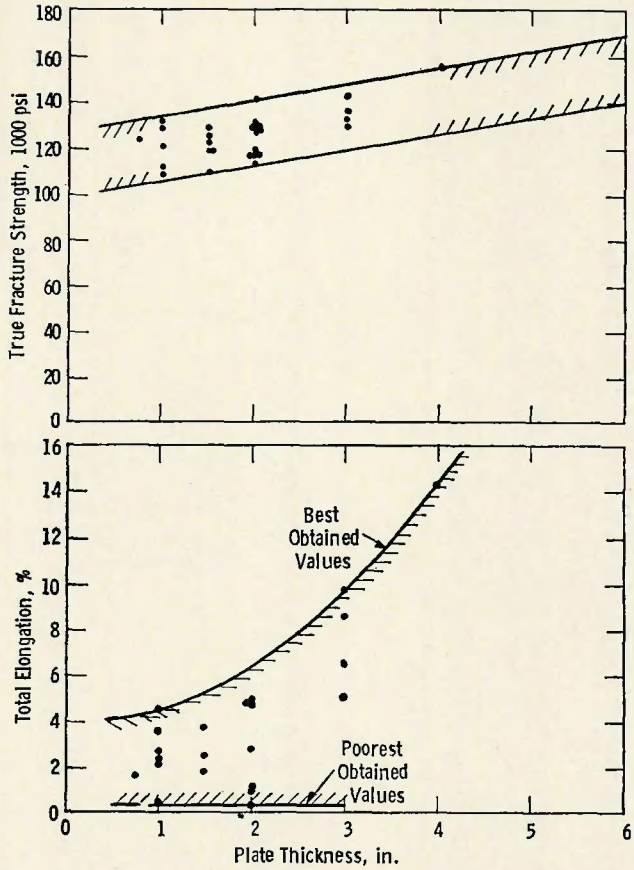

Fig. 17—Relations between plate thickness, elongation and fracture strength through-thickness (A-514H)

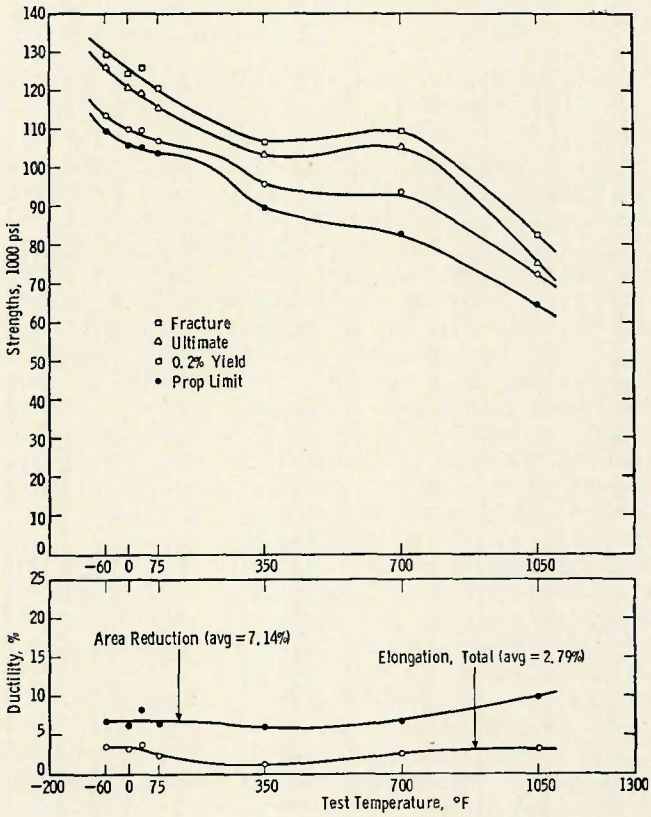

Fig. 19 (right)—Average temperature dependence of tensile properties for A-514H steel (through thickness)

was 22.0 ft-lb.

This sequence of tests helps explain the rapidity and ease with which the Fig. 3 field failure occurred. Also, it clearly shows the anisotropy of these plates with respect to impact properties.

The temperature dependence of the impact energy values, for the same plate material and for the weld metal, is shown in Fig. 28. The weld metal toughness is significantly higher

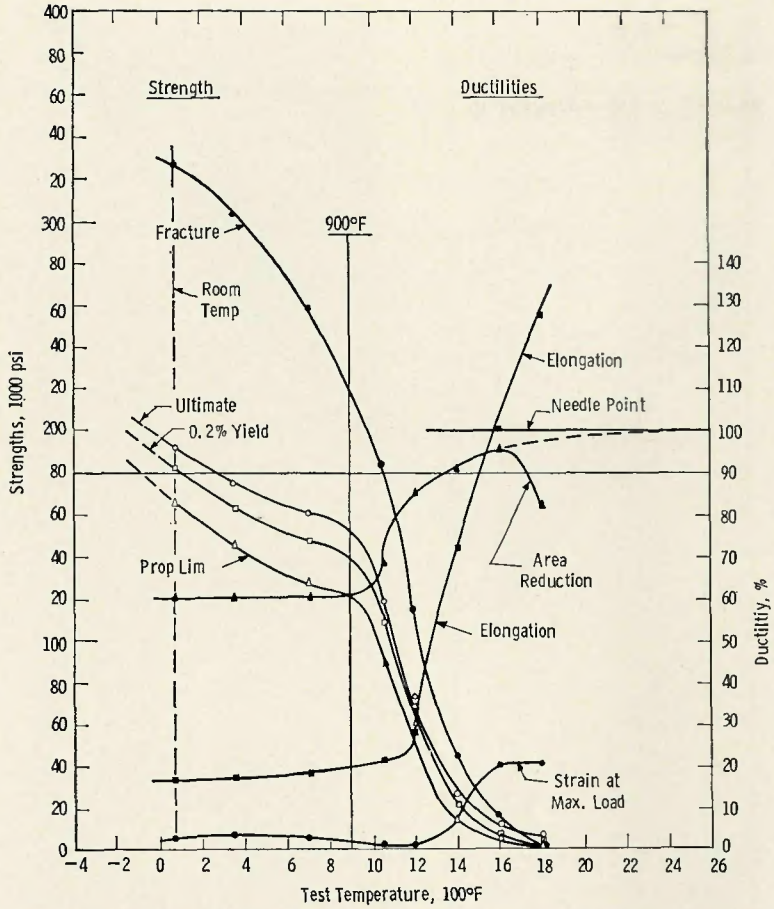

Fig. 20—Through-thickness strength and ductility dependence upon temperature for clean austentized, quenched and tempered steel (Republic's 9Ni-4Co-0.20C steel)

Fig. 21—Surfaces of stress-rupture through-thickness test specimens

(about 4:1) than that for the plate in the through-thickness direction, across the entire temperature range tested, +200 to −150° F.

Another +10° F study was made of the variation in impact properties of A-514H steel across a welded tee-joint. The stem of the tee was 2 in. thick. Again, the lowest energy value (6 ft-lb) was obtained at mid-thickness of the plate—Fig. 29. The average value for the through-thickness impact values for the two-inch plate was 8.5 ft-lb. The average value in the transverse direction of the web plate was 22.6 ft-lb. The weld metal was much tougher than the plate material in either orientation, the average being 72.4 ft-lb.

The through-thickness plate toughness need not always be low. For example, the impact characteristics of HY-80 steels (Fig. 30) do show that this material is also anisotropic. The through-thickness energy values were lower across the entire test temperature range compared with the longitudinal and transverse directions. The through-thickness energy values were in excess of 70 ft-lb for all test temperatures between −60 and +200° F and were above 50 ft-lb for all test temperatures above −120° F.

Summary of Anisotropy Data

The relations between through-thickness total elongation and conventional direction proportional limit values for the steels investigated are summarized in Fig. 31. Specimens taken from incident steels are identified on this graph. Most incident steels exhibit through-thickness elongation values of less than 6%, at room temperature. Best through-thickness elongation values were obtained for the HY-80 and HY-180 steels—that is, two of the nonincident steels.

A similar summary of the impact energy values is shown in Fig. 32. Specimens taken from incident steels exhibited through-thickness energy values of 10 ft-lb, or less, at room temperature. Thus, both the tensile elongation and the impact energy through-thickness values were low for all observed incident steels. Best through-thickness impact values were obtained for the HY-80, HY-100, HY-130, and HY-180 steels—that is, for the cleaner nonincident steels.

Through-thickness tensile strengths, relative to the corresponding longitudinal values, are shown in Fig. 33. Except for some of the carbon steels and the extreme cases of the A-514H steels, the through-thickness proportional limits, yield strengths, and ultimate strengths were within 5% of the values obtained in the longitudinal direction. The ratio of the fracture strength in the through-thickness direction to the corresponding value in the longitudinal direction was a maximum in the HY-180 steel. For the other steels, that ratio decreased in a nonuniform manner as the proportional limit of the steel in the conventional directions decreased, and was a minimum for some of the carbon steel plates. Conversely, the relative fracture strength increased progressively as the strength and quality of the steel increased. The use of the fracture strength as a criterion for anisotropy is therefore more meaningful than the use of the proportional limit, yield strength, or ultimate strength values.

A similar summary of the ratios of the through-thickness to longitudinal ductility values (Fig. 34) shows that the ductility relationships are roughly similar to those for the fracture strength. These ratios were highest for the HY-80, A-533, and HY-180 steels.

The corresponding impact value ratios (Fig. 35) show that the least relative degradation for the through-thickness direction was observed in the HY-180 steel. Maximum degradation occurred for the A-36, A-533, and A-514H steels. For any given strength level the "HY" series steels are superior to those produced for more routine commercial applications.

While none of the steels is isotropic in all respects, the A-302B, HY-80, HY-100, and HY-180 values approximate the desired levels of elongation and impact values in the through-thickness direction. Also, for the A-302B, HY-80, and HY-180 steels, the through-thickness fracture strength increases in direct proportion to the longitudinal yield strength, the ratio being 1.72:1. Some of the carbon steels, and the A-514H and A-517F alloy steel grades, exhibited maximum anisotropic characteristics. These steels have been common offenders with respect to through-thickness decohesion weldment cracking. The A-441 grade has also exhibited deficiencies in this respect. Adequate values

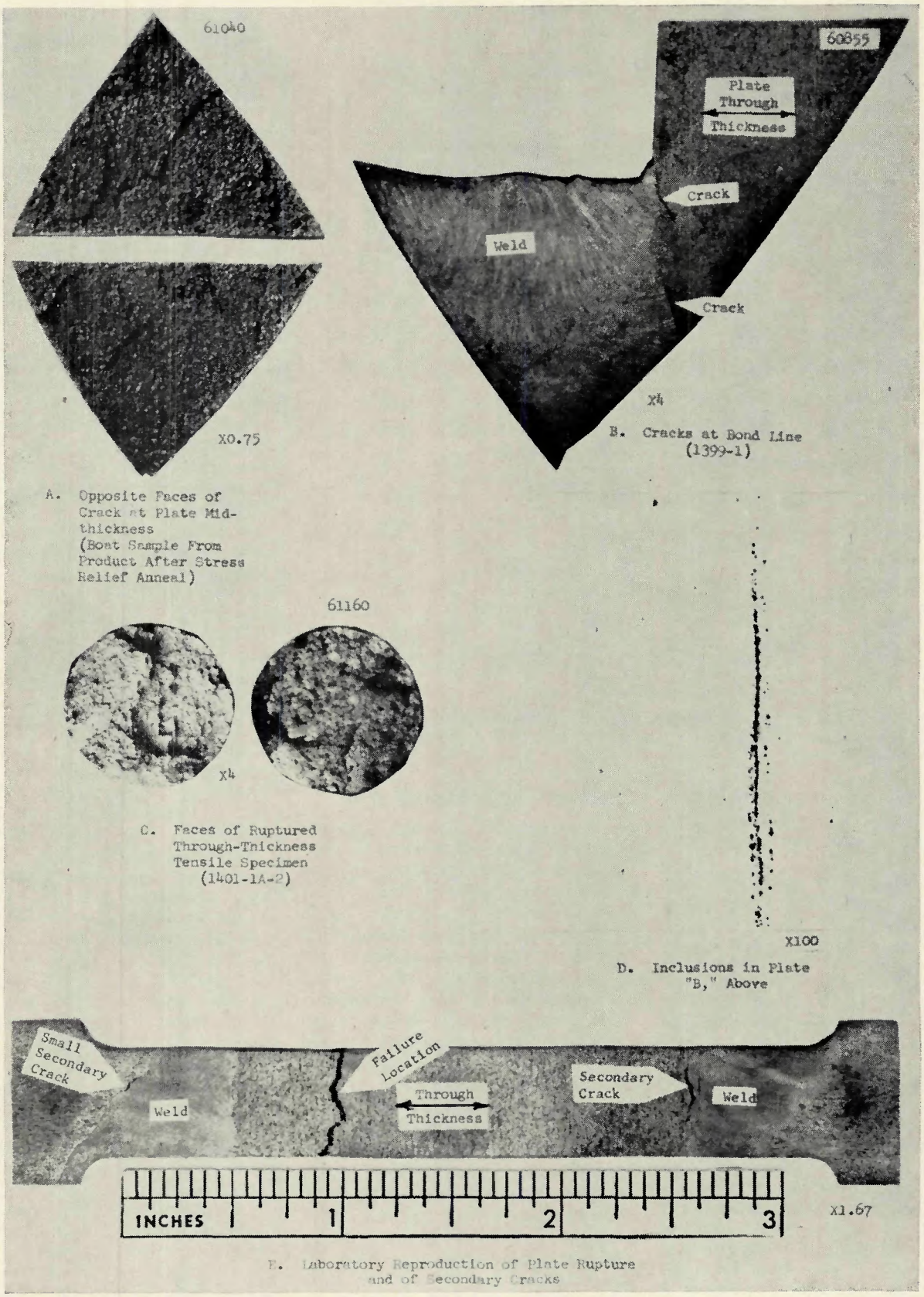

Fig. 22—Local through-thickness rupture in A-514H steel and laboratory reproduction of crack

for that steel are not shown because, for the incident investigated, it was not possible to obtain longitudinal and transverse direction samples.

Inclusions

Inclusions observed in the several steels are shown in Figs. 36 to 39, arranged in ascending order of steel strength.

The A-36 carbon steel (Fig. 36) cracked extensively when used in the design of Fig. 5-2, wherein the residu-

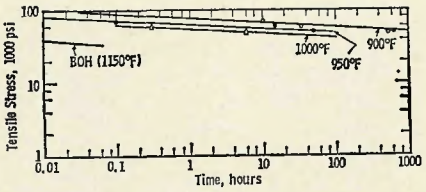

Fig. 23—Stress-rupture curves for A-514H steel in through-thickness direction

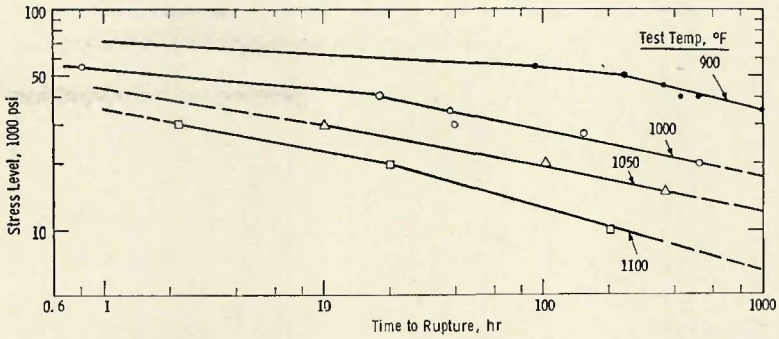

Fig. 24 (right)—Stress-rupture curves for A-533 steel in through-thickness direction

al stresses were imposed in the through-thickness direction of the flange material through a single-bevel joint with backing strap. Extensive local inclusions were observed in this plate, as shown on the lower right of Fig. 36. The steel microstructure is otherwise normal. The evidence that such decohesion initiated with the planar inclusions is shown in Fig. 37.

A series of alloy steel inclusion contents, which contributed to decohesion, and a fracture of an impact specimen in one of these materials, are shown in Figs. 36, 38 and 39. Both initiation and propagation of the impact fracture shown in Fig. 38 tended to follow inclusion platelets.

The HY-180 steel was the only one in the series which contained essentially no inclusions—Fig. 39 (upper right). This electric furnace plus vacuum-arc remelted steel was made with low silicon and sulfur contents—Table 1. It exhibited superior through-thickness tensile and impact characteristics—Figs. 13, 15, and 35.

Identification of compositon of individual inclusions is not included in this paper. These have been identified by other investigators as manganese-sulfides, silicates, and oxides. Charts for classification of those inclusions have been in existence for many years.[18]

These data provide at least circumstantial evidence that one solution to the elimination of decohesion through-thickness type rupture in restrained weldments is to eliminate, or at least grossly minimize, the sizes and amounts of local inclusion concentrations in the steels.

Discussion

Wherever possible, in tee and corner joints, the designs should provide for maximum component flexibility. Use of backing strap, with built-in notches, should be avoided. Beveled

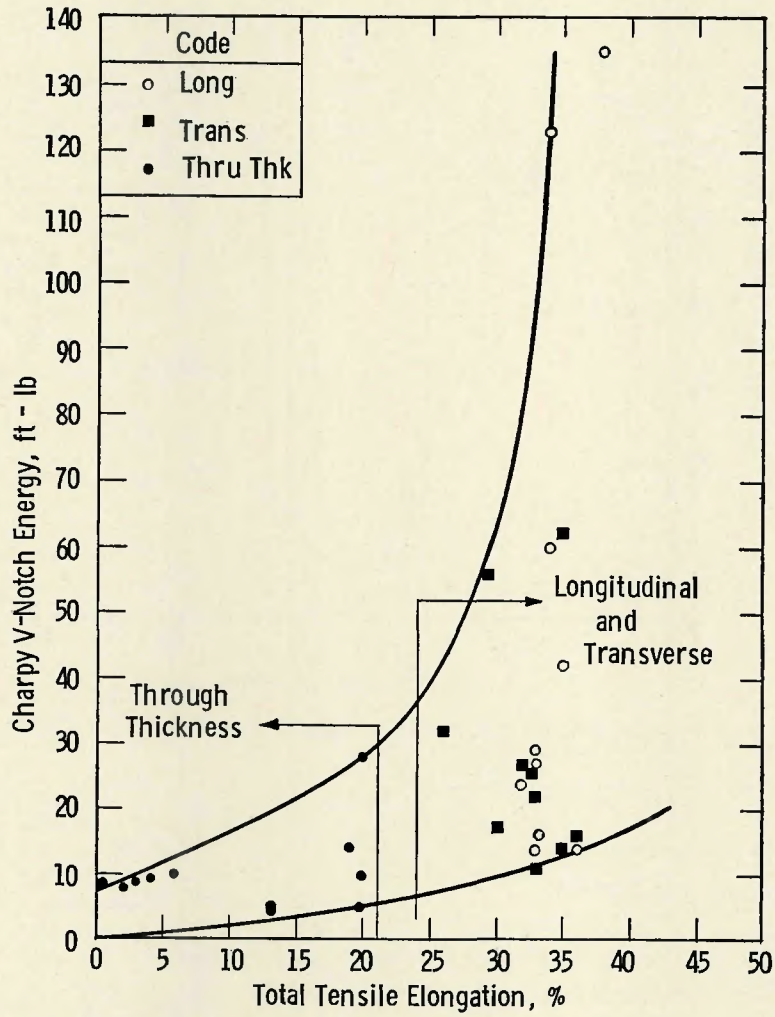

Fig. 25—Relation between total tensile elongation and impact energy in through-thickness direction for carbon steels

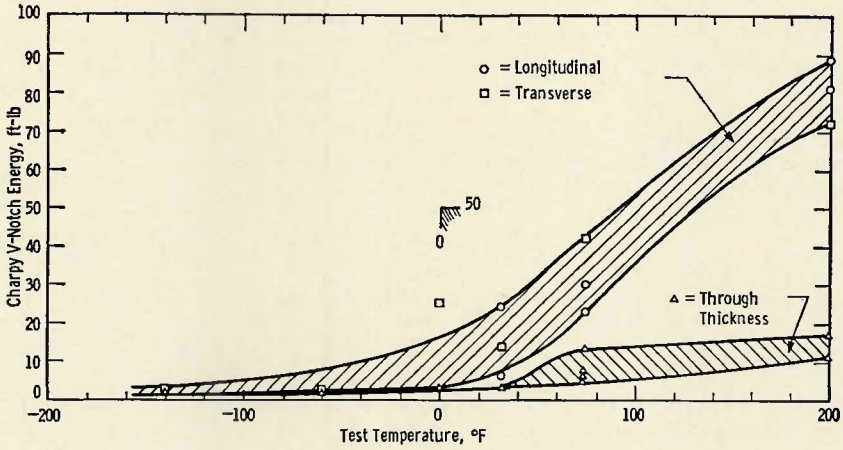

Fig. 26 (right)—Influence of temperature and orientation on Charpy V-notch energy values (A-36 steel)

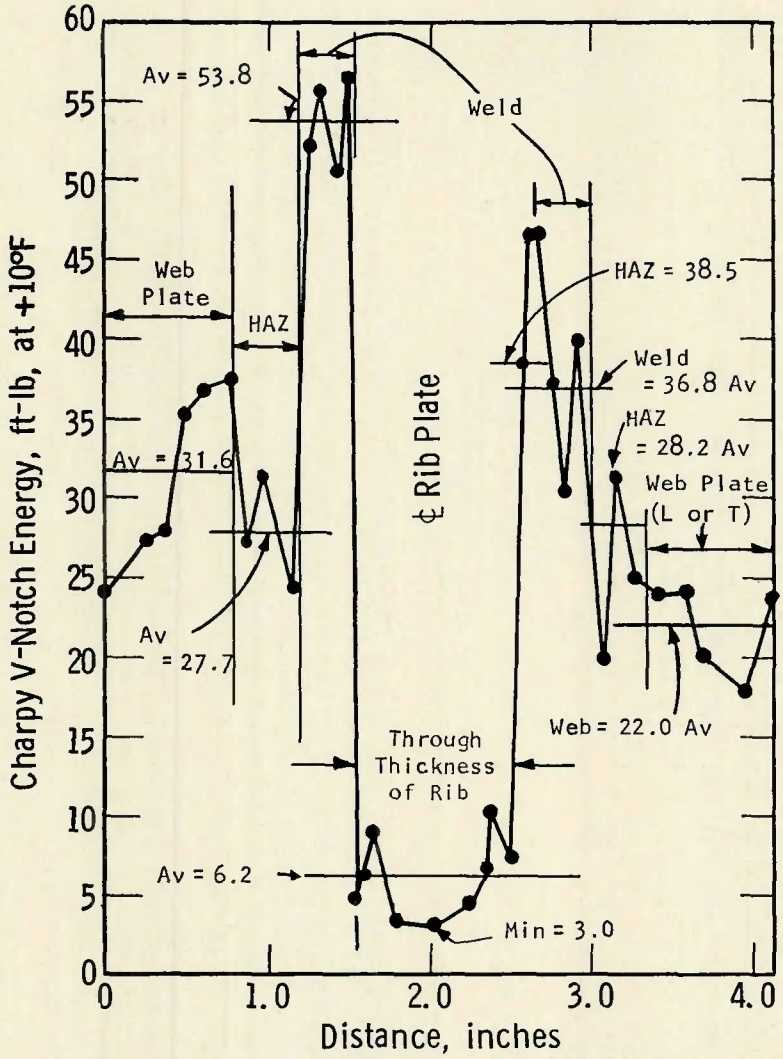

Fig. 27—Charpy V-notch impact energy traverse across web-to-rib-to-web joint (at +10° F) A-514H steel

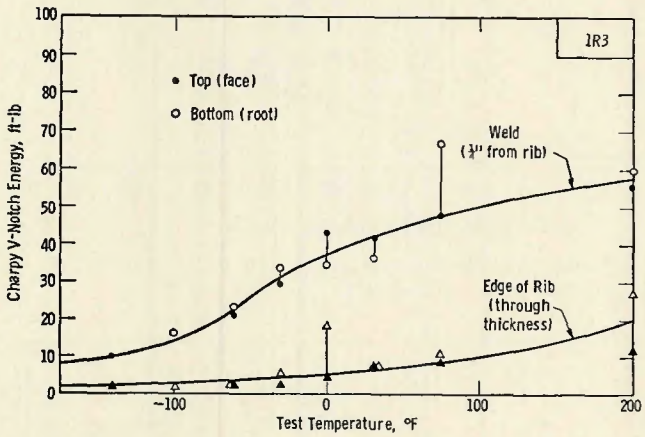

Fig. 28—Charpy V-notch impact energy values in weld and through-thickness rib plate metals as influenced by test temperature (A-514H steel)

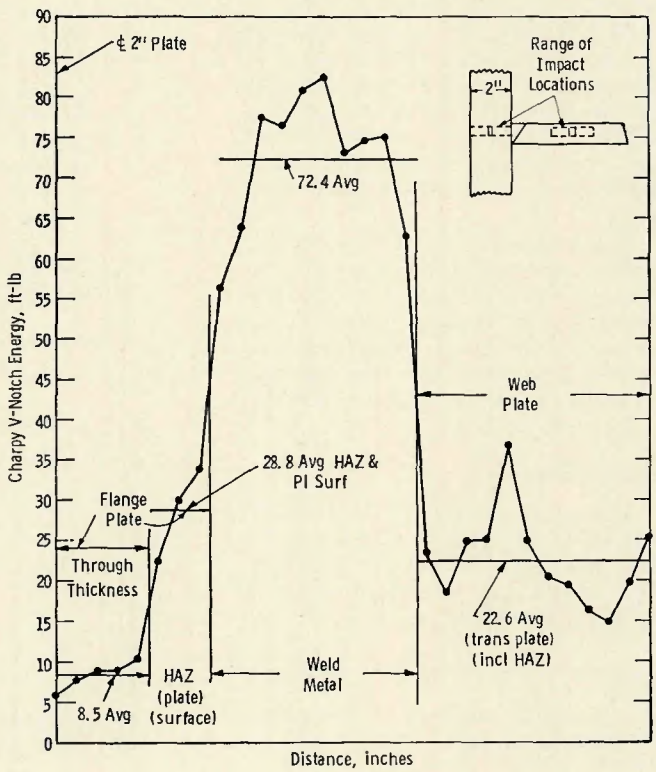

Fig. 29 (right)—Charpy V-notch impact energy traverse across flange-to-web joint in A-514H steel (at +10° F)

grooves should be held to a minimum volume to reduce shrinkage stresses as much as possible. Where feasible, bevels should be in the through-thickness member. Weld sizes should be held to a minimum, consistent with the strengths required. Even these corrective procedures have been found to be inadequate for highly anistropic materials.

Full-scale tensile test specimens of transverse joints taken from uncracked portions of the Fig. 3 rejected weldment developed approximately one-third of the yield strength of the longitudinal load transmitting members before failure occurred in a manner similar to that shown in macrographic sections A and B of Fig. 3.

One technique for improving the strength of such joints is to specify buttering (or surfacing) for the surfaces of the through-thickness plates prior to welding the load transmitting members, with the cladding extending out to provide a base for the fillet welds. With this procedure it was demonstrated, by tests, that the full strength of the load transmitting members could be developed without failure in the through-thickness members. This conclusion was reached from joints made by both the manual covered-electrode and the submerged arc welding processes.

Comparable tests were made on simulated salvage type joints using base materials similar to those shown in Fig. 3, except that the backing straps were gouged out and the cladding welds on the surfaces of the through-thickness plates were made

continuously. Again, these joints were stronger than the original butt-strapped ones used in the Fig. 3 design, although they did exhibit a strength deterioration of approximately 10% below those without the retained backing strap. The failures on these salvage type joints started from the root of the notch at the backing straps.

The practical problem with tee and corner joints, as presented to the welding engineer, is that steel procurement specifications do not include any through-thickness property quality requirements. The possibilities for the existence of poor through-thickness properties as described in this paper are not always recognized by the purchasers, designers, or fabricators. Moreover, these deficiencies cannot always be detected by the prewelding nondestructive inspection techniques being employed.

Conclusions

Decohesion cracking planes parallel to plate surfaces occur most commonly in corner and tee joints when welded under conditions of high restraint.

The threefold solution to this problem includes material improvement, weldment redesign, and modification of welding procedures.

Decohesion cracking, often called "lamellar tearing" occurs in, or at a distance from the weld heat-affected zone.

The cracks usually occur at temperatures below 450° F, i.e., below the temperature of rapid oxidation.

All observed incidents involved use of steel plates having low magnitudes of ductility, fracture strength, and impact toughness in the through-thickness direction.

All observed incidents involved the presence of nonmetallic inclusions or banding.

The cracks were extensions of the platelet type inclusions.

A maximum susceptibility condition exists when a smooth-bar tensile specimen breaks in the through-thickness direction prior to reaching the strain and strength levels corresponding to the nominal longitudinal direction yield strength.

A second susceptible potential for tensile decohesion exists when unwelded steels, loaded in their through-thickness direction, do not have the capability to withstand low strain-rate tension in a smooth-bar specimen up to the level of strain corresponding to that where necking begins, i.e., they break prior to developing the normal ultimate strength.

A third potential susceptibility to decohesion rupture is where design-material-procedure conditions permit completion of a successful weldment,

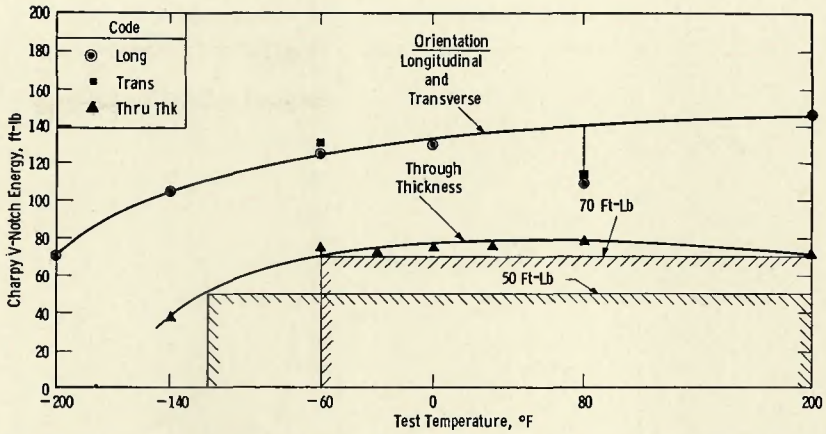

Fig. 30—Temperature dependence of impact energy values for HY-80 steel in all three directions

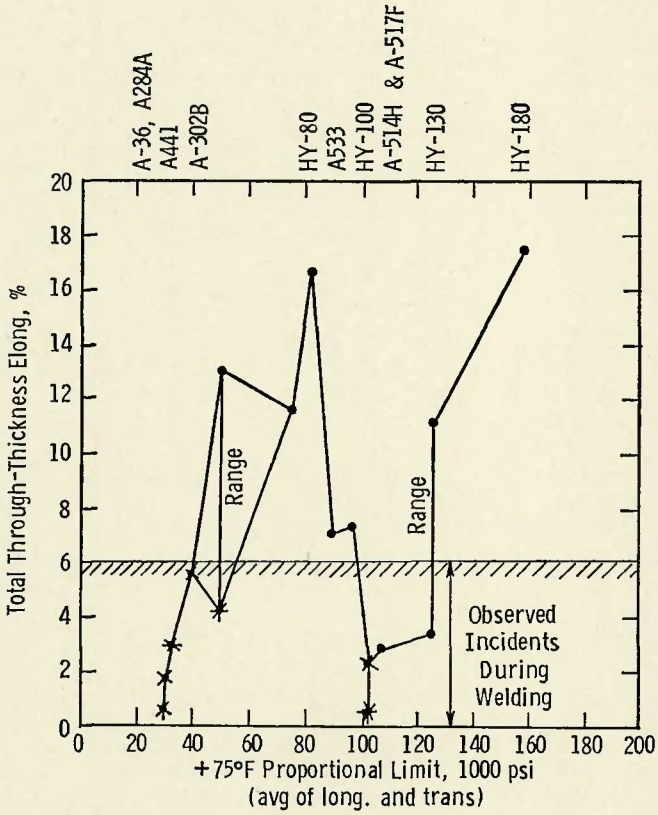

Fig. 31—Variations in through-thickness ductility (elongation) values at +75° F for various steels

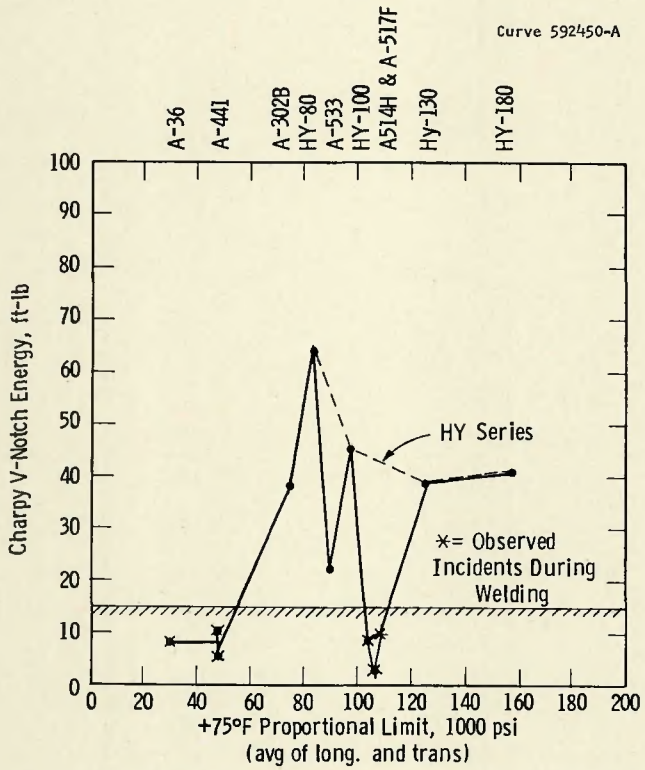

Fig. 32—Variations in through-thickness impact values at +75° F for various steels

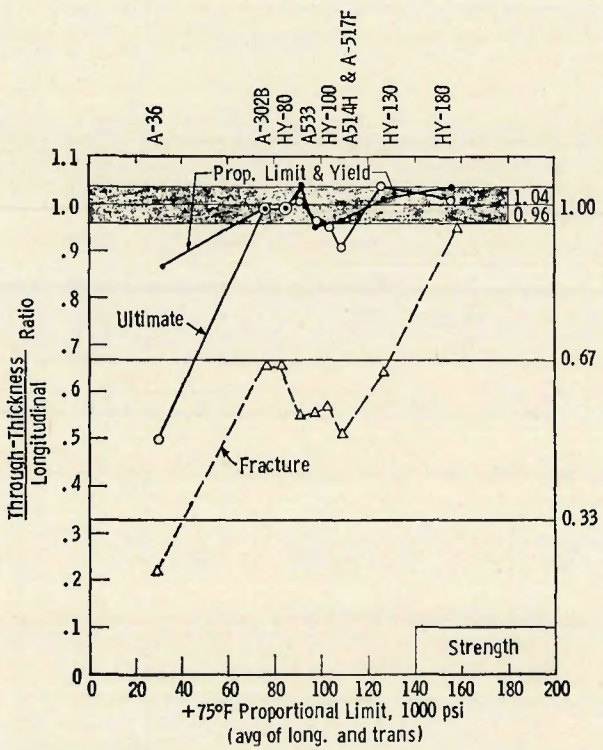

Fig. 33—Variations in ratios of through-thickness to in-plane strength values at +75° F for various steels

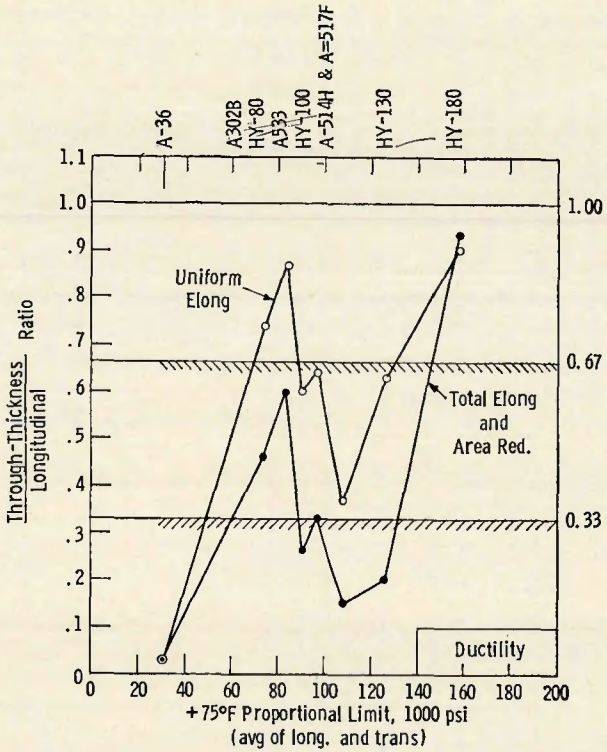

Fig. 34—Variations in ratios of through-thickness to in-plane ductility values at +75° F for various steels

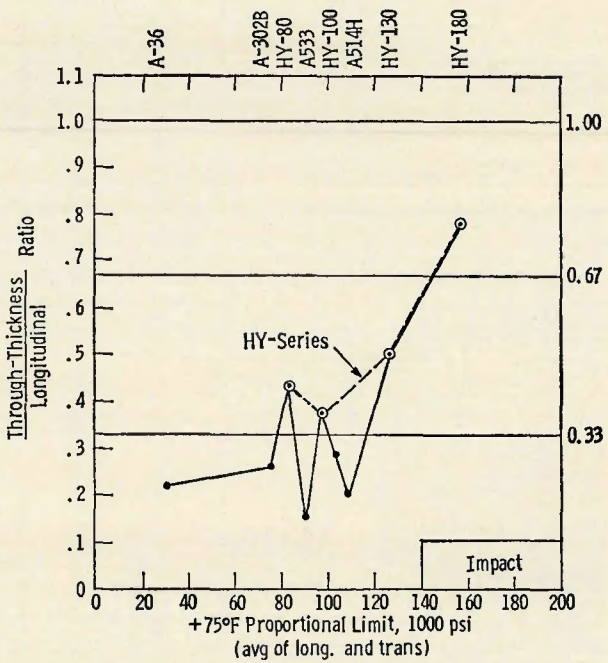

Fig. 35—Variations in ratios of through-thickness to in-plane impact values at +75° F for various steels

which then fails during subsequent heat treatment because rupture occurs before strain relaxation.

Cracks may occur during or following welding, and are commonly audible to the unaided ear.

Minimum weldment susceptibility to decohesion cracking occurs in clean, ductile, tough steels and where the designs and welding procedures involve minimum rigidity and lowest residual stresses.

Steel procurement to a foolproof through-thickness quality specification, including through-thickness tensile testing, is difficult at the present time.

The procurement of time-stress-temperature stress-rupture data provides an insight to the conditions under which a highly restrained weldment would be expected to rupture on-heating, provided the level of residual stress is known.

The smooth-bar, 0.357 in. diam. × 2.25 in. long tension specimen is the most useful and simplest means for predetermining susceptibility to decohesion cracking during restrained weldment manufacture. Any total elongation value of less than about 6% or area reduction of about 15% indicates the existence of a suspect material. However, for carbon steels somewhat higher, minimum ductility values may be required.

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P. T. Ehrhardt, W. R. Kuba, G. R. McGraw, Jr., and R. J. Wurdack, of Metals Joining Research, rough cut and laid out the necessary coupons, made the detail sketches and lay-outs of the individual impact, tensile, and macrographic specimens required, identified those specimens, and followed them through the saw and machine shop operations until they were ready for testing.

Impact and tensile testing was done by W. H. Pryle and R. R. Hovan of Research Mechanics.

Check analyses were made under the supervision of F. P. Byrne and J. Penkrot, Technology Development & Evaluation Laboratories.

Macrographic and micrographic examinations were made under the supervision of R. M. Slepian, Metallography Laboratory.

Typing was done by H. B. Radovich.

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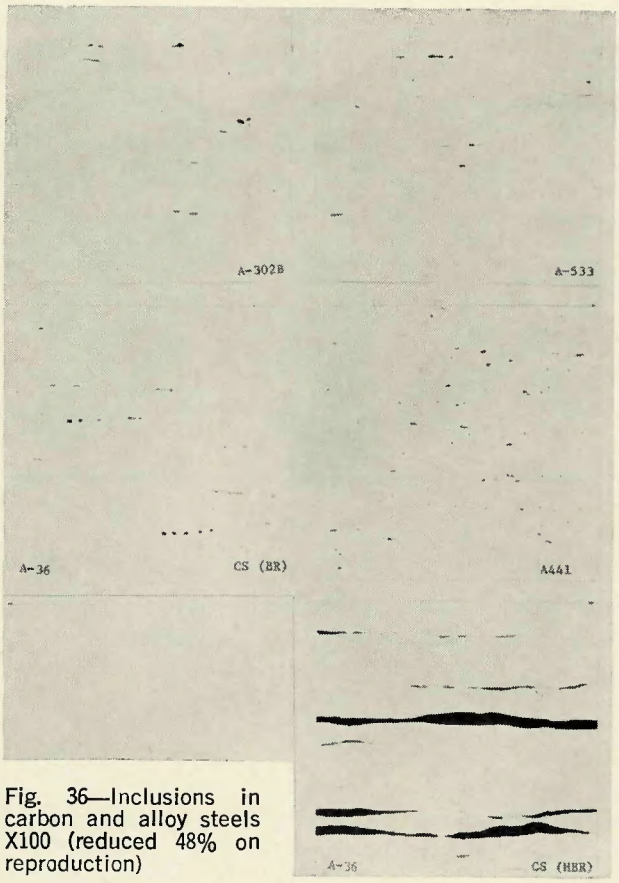

Fig. 36—Inclusions in carbon and alloy steels X100 (reduced 48% on reproduction)

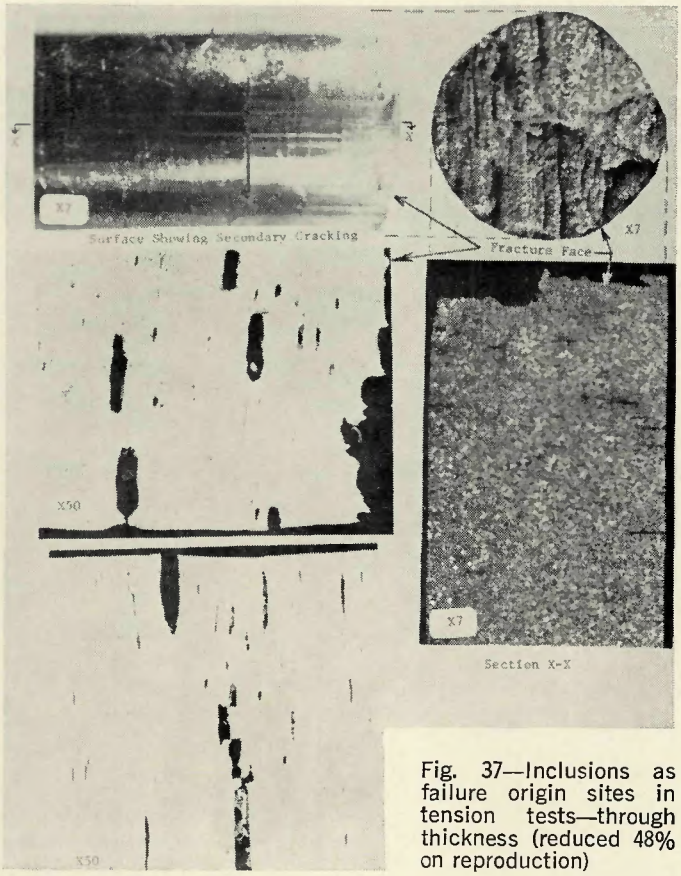

Fig. 37—Inclusions as failure origin sites in tension tests—through thickness (reduced 48% on reproduction)

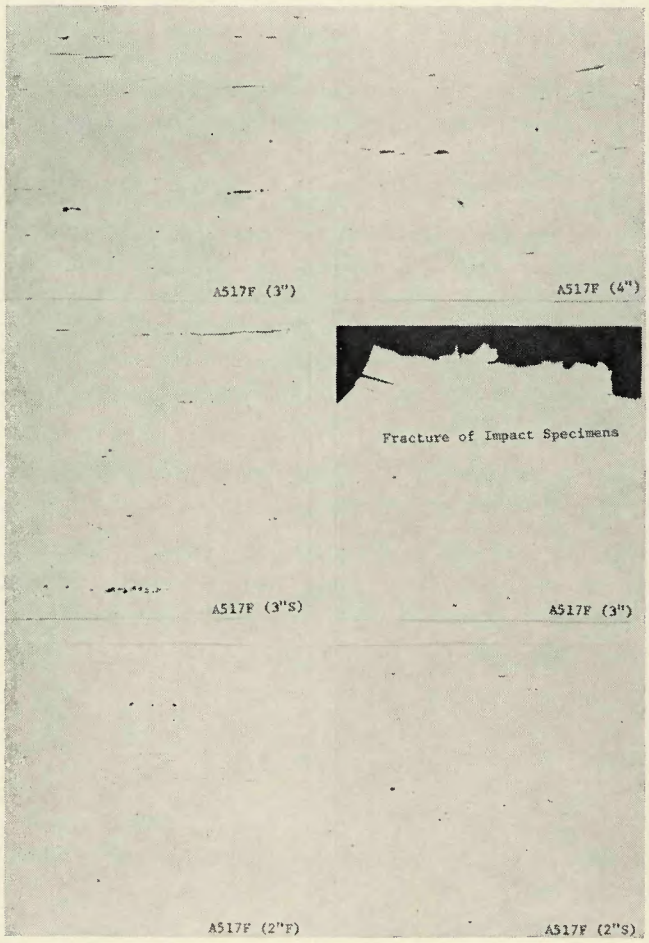

Fig. 38—Inclusions in A-517F steel. X100 (reduced 45% on reproduction)

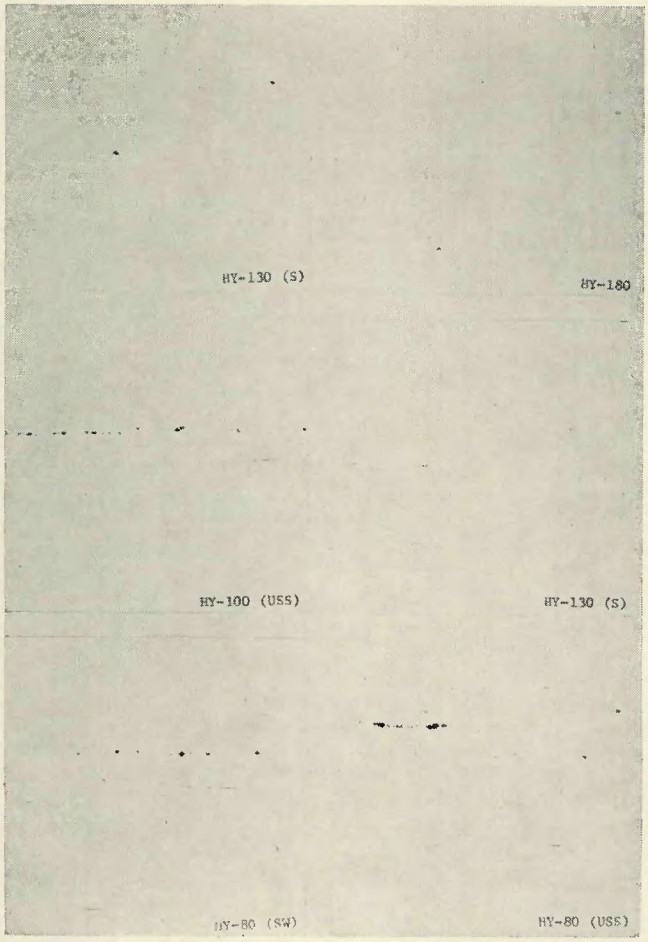

Fig. 39—Inclusions in "HY" series steels. X100 (reduced 45% on reproduction)

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PVRC Interpretive Report of Pressure Vessel Research Section 3 — Fabrication and Environmental Considerations

by A. P. Bunk

This is the third section of an interpretive report sponsored by the Pressure Vessel Research Committee summarizing research on pressure vessels.

Section 1, Design Considerations (*WRC Bulletin 95*), covered the improvements in analytical design procedures and the significance of calculated stresses. Section 2, Materials Considerations (*WRC Bulletin 101*), compared for steel the factors, by means of safety indexes, which insure against the various stress-dependent modes of steel pressure-vessel failures. Section 3 covers the effects of fabrication operations and environmental conditions on pressure vessel behavior.

Fabrication operations are related to pressure vessel behavior in several ways: (1) Forming operations may lead to undesirable effects such as strain aging with a loss in toughness and ductility; the Bauschinger effect with a loss in yield strength; and stress-corrosion cracking with a potential loss in the pressure vessel; (2) Welding operations may lead to undesirable effects such as slow cooling rates in the heat-affected zone resulting in the loss of toughness and may produce high tensile residual stress which not only may aid stress-corrosion cracking, but also may cause stress-rupture cracking during postweld heat treatment of some low-alloy steels.

Environmental conditions may produce undesirable effects such as temper embrittlement, stress-corrosion cracking, and hydrogen embrittlement.

The intent of this section, therefore, is to summarize the pertinent information relating fabrication operations and environmental conditions to pressure vessel behavior. For this purpose the author has drawn heavily on data from PVRC-sponsored investigations.

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