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Characterization of GTA Weldments in 10Ni-8Co-2Cr-1Mo Steel

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ABSTRACT

This study of 10Ni-8Co-2Cr-1Mo steel includes evaluations of tensile, impact, hardness, fracture toughness properties, and metallographic features. Base plate and three weldments in one-inch thicknesses are examined to compare as-welded properties with those obtained after reaging, and results of welding the 10%Ni alloy with 9-4-20 wire as opposed to a matching weld wire composition. Critical crack sizes are calculated for the material.

The most desirable weld properties are obtained using the matching weld wire and a reaging cycle. However, the improvement gained through reaging is probably not sufficient to justify the additional cost for most practical applications.

PROBLEM STATUS

This report completes Tasks I and II of NASA Request C-54542B under the technical direction of Project Manager, John Misencik, Lewis Research Center.

AUTHORIZATION

NRL Problem F01-15
Project No. C-54542B

CHARACTERIZATION OF GTA WELDMENTS IN 10Ni-8Co-2Cr-1Mo STEEL

BACKGROUND

Hydrospace vehicles, rocket motor cases, and space capsules have stringent requirements for large pressure vessels functioning in severe environments. High design stresses, large size, and reliability force the design engineers to increased use of heavy sections. The higher strength materials become particularly attractive for such applications. In order that reliability not be sacrificed for weight reduction, good toughness and corrosion resistance must be maintained under the most severe environment anticipated. Weldability is another required material attribute from a practical point of view.

The Navy (NAVSEC) funded program which successfully produced the HY-80, HY-100 and HY-140 series of steels now seeks to develop an even higher strength steel to be designated HY-180/210. These steels are being developed specifically for application in sea water pressure resisting designs, but have already found other applications in military and consumer products. Advancements in strength, toughness and resistance to corrosion have led to the new 10Ni-8Co-2Cr-1Mo alloy which appears especially well adapted for the construction of large high-strength structures with thick sections (1). Most of the development effort on the Navy program since 1967 has been directed toward this promising new alloy at the 180,000 psi yield strength level.

The manufacturer claims a unique feature for the 10Ni alloy in that aging increases both yield strength and toughness (2 and 3). The strengthening mechanism was at first believed to be a "dual strengthening" effect which combined the advantages of low-carbon martensite, formed by quenching, with those of maraging. However, more recent investigations (as cited in (4)) have shown the strengthening to be due entirely to carbide precipitation during tempering. Temper brittleness is avoided through low manganese and phosphorous contents while extensive cross-rolling minimizes directional properties. Optimum mechanical properties are obtained in an ultraclean material produced through a double vacuum melting process consisting of a vacuum-induction melt followed by a vacuum-arc remelt. An exceptionally high fracture toughness for the 10Ni-8Co-2Cr-1Mo alloy has been confirmed by several investigators (i.e. (5) and (6)). These properties are still maintained after forming and hot-pressing operations (7). The alloy has also performed well in both corrosion and stress-corrosion testing (4), but more extensive evaluation programs are presently in progress.

Successful weldments in the 10%Ni alloy have only been obtained by the GTA (inert-gas-shielded tungsten-arc) process using weld wire of composition nearly matching that of the base plate. Both the conventional GTA and the hot-wire GTA processes have been used to produce acceptable welds in this alloy (4). The multipass GTA process has produced the toughest weldments, but is considered inefficient for large projects due to its relatively low deposition rate. Other weld processes are presently under study for possible adaptation to the 10Ni alloy. To be entirely acceptable for large component fabrication, the weldment should meet performance requirements in the as-welded condition not requiring post-weld heat treatment.

MATERIAL DESCRIPTION

The particular material used in this study was from heat number C-51543 produced by United States Steel Corporation for Lockheed Aircraft Corporation under invoice number 163-26439. The material had been vacuum-induction melted, vacuum-arc remelted, cold rolled into one-inch plate, double austenitized, and aged. The austenitizing consisted of an 87 minute hold at 1660°F followed by quenching in agitated cool water, a 93-minute hold at 1500°F with quenching again in agitated cool water. The plate was then aged at 950°F for five hours in an air circulating furnace. All welding and machining was performed with the plate in the aged condition.

Two weld-wire compositions were used in this study. One wire with composition nearly matching that of the base plate had been cold drawn from material of an earlier heat (No. 51361) of vacuum induction melted 10%Ni alloy. The other wire was of the HP-9-4-20 alloy from Republic Steel's heat number 60527. The second material had been melted by the consummable electrode vacuum process. Both wires were 0.062 inch in diameter and met specifications of Mil-E-19822.

Descriptions and analysis of the base plate and two weld wires are listed in Table 1. Gas analyses of base plate are shown in Table 2. All specimens for this study were cut from a single one-inch plate 45 inches by 60 inches. The plate had been cross-rolled, but the final roll direction was designated as the roll direction. Specimens with their major axis paralleled to this final roll direction are called longitudinal while those perpendicular to this direction are called transverse. All these weldments were deposited in the direction parallel to the final rolling direction.

WELDING PARAMETERS

Three panels each 13 inches by 34 inches were cut from the large one-inch-thick plate with the 34-inch dimension parallel to the final roll direction. These panels were grooved, in preparation for welding, as shown in Figure 1, with the groove running down the center of the panel along the 34-inch dimension.

All welding was by the automatic gas-tungsten-arc, GTA, process with eighth-inch tungsten electrode. (It has been popular in the past to refer to this process as the tungsten-inert gas, TIG, welding process). In all cases chill blocks were used and the plate was restrained in a horizontal position by fixtures. In general, welding was accomplished with an e.m.f. of about ten volts with a current on the order of 250 amperes. A total of about 45 passes were required to complete the weldment of the one-inch plate. More detailed welding parameters are given in Table 3.

Two of the three panels (B&C) were welded using the HP-9-4-20 weld wire and one (D) was welded with 10Ni-8-2-1 wire. One of the first panels (C) was reaged after welding while the other two (B&D) were tested in the as-welded condition.

NON-DESTRUCTIVE INSPECTION

The base plate had been ultrasonically tested for internal defects in conformance with the Lockheed Specification RV-S-0022 Class A. This inspection was performed by the manufacturer, United States Steel Corporation and the report shows that no ultrasonic discontinuity indications were detected.

After welding, the welds were inspected by the fabricator, Excelco Developments Inc. Each weldment was inspected using three nondestructive techniques; X-ray, ultrasonics, and dye penetrant. All three welds were certified to meet the acceptance requirements of both NAVSHIPS-0900-006-9010 and NAVSHIPS-0900-006-3010.

TENSILE PROPERTIES

Tensile properties were determined for the base plate and three welded panels. These properties were determined from standard ASTM 0.505-inch diameter tensile specimens as shown in Figure 2. Base plate properties are given in two directions within the plate. The so-called longitudinal specimen had its major axis parallel to the final roll direction, while the transverse specimens were perpendicular to this direction. Since the plate had been cross rolled, little directionality was expected. The data in Table 4 confirms this with an insignificant difference of only 1% in the tensile strengths and an even smaller discrepancy in yield strengths. The elongation of about 16% and reduction of area in the 68% range are exceptional for material in the 190 yield strength region.

The properties labeled "trans-weld" were obtained from specimens machined perpendicular to the weld bead with the deposited weld metal at the center of the gage length. These specimens were in a direction corresponding to the transverse base-plate specimens. The "all-weld" specimens were machined with their major axis in, and parallel to, the center of the weldment. The gage section of these specimens was almost entirely re-solidified weld metal. The trans-weld specimens failed in the weld heat-affected zone with tensile strengths only slightly below those for the base plate and deposited weld metal.

IMPACT STRENGTH

Standard Charpy impact specimens (see Figure 3) were machined from the four test panels. Both standard and pre-cracked Charpy tests were conducted at 80°F with results as presented in Table 5. Base plate specimens were machined in two plate directions as described for the tensile specimens. The welded specimens were all machined across the weld but with two different notch locations. Specimens in one group were oriented with the notch on the center line of the weld, while those in the other were notched in the heat affected zone of the weld. The pre-cracked specimens were fatigue-cracked on the multispecimen machine designed by J. M. Krafft (8) prior to testing in the normal Charpy manner.

The data shows the 9-4-20 weldments to be slightly tougher in the heat affected zone and the 10-8-2-1 weldment to be tougher in the center of the weld. Reaging after welding increases the toughness in both center of weld and heat-affected zone by amounts on the order of 20% and 35% respectively.

HARDNESS DETERMINATIONS

A through-the-thickness weld cross-section from each of the three weldments was polished and etched to show the weld structure. Microhardness measurements were spaced at 0.02-inch intervals along three traverses on each specimen. Two of the traverses were located 0.06 inch from each plate surface and the third was on the plate centerline. Figure 4 shows the etched cross-sections with hardness traverses. Average results of the hardness testing are tabulated in Table 6. Hardness profiles for the as-welded (panel B) and reaged (panel C) weldments are plotted in Figure 5. Reaging may tend to smooth out the profile somewhat, but in general the heat affected zone still remains the hardest area.

FRACTURE TOUGHNESS

With a material exhibiting a toughness to yield ratio in the range of that for the 10% nickel alloy, it is impossible to determine a K_{Ic} which would be accepted as valid by ASTM (9) standards from one-inch plate stock. Therefore the K values listed here will be designated K_a or apparent K_{Ic} values with the deficiency in size requirements noted in Table 7. Two large, 26 inch by 9 inch, specimens as shown in Figure 6 were tested in three-point bend on a 24-inch span in our 200 thousand pound closed-loop-controlled testing machine. An ASTM type clip gage (9) was used in the notch to obtain a load versus displacement plot. These pre-cracked specimens were not side-grooved and developed large plastically deformed areas at the crack tip along with the typical two-stage elastic-plastic loading curve. However the maximum, or fracture load, was beyond the capacity of our testing equipment capability. A K_Q was calculated from these curves using the secant method as recommended for loading curves of this type described as Type I in Figure 8 of (9). The average result from the two tests is shown in Table 7 of this report.

Four more conventionally sized notched-bend specimens were machined as shown in Figure 7. These specimens were side grooved to constrain the crack and reduce plastic flow. The maximum load was determined from the load deflection record and used in the ASTM formula (9) for determining the K values as recorded in Table 7.

Specimens of the type shown in Figure 7 were machined from each of the three welded panels. The pre-cracked notch was located so as to initiate the crack in either the center of the weld deposit or the heat affected zone in the base plate. The values obtained from such tests are listed in Table 7. Each value is the average of four tests. These values are recorded uncorrected for plastic flow as well as corrected by two different methods. The graphical correction is described in (10) and the scaling method in (11). Both correction methods attempt to correct for the plastic flow and lack of plane strain condition at the crack tip.

Several interesting results can be seen from Table 7. First the very close agreement between the two specimen sizes in the base plate is encouraging. The weldment of near matching composition appears slightly tougher than that from the 9-4-20 wire with no noticeable difference in the heat affected zones. This would be expected since the 10% alloy is a slightly tougher material (4) and the properties in the heat affected zone are dependent on the weld parameters and not the weld wire composition. Reaging after welding improves the fracture toughness by about 15% in the weld center and heat affected zone. The toughness in the as welded heat affected zone is only about 7% below that of the original plate.

METALLOGRAPHIC EXAMINATION

A through-the-thickness section across the weldment was polished and etched with 2% Nital for metallographic analysis of each weldment. These specimens were examined and photographed at magnifications of 2, 500, and 1000. The weld cross-sections have been shown at 2X in Figure 4 of this report.

In general, the base plate is the expected martensitic microstructure with varying amounts of retained austenite and precipitated carbides. It is a very clean microstructure, but tends to vary across the plate thickness indicating some chemical segregation or non-uniform thermal-mechanical processing. A columnar structure develops in the slower cooled regions in the weldments. Such structure is commonly formed during solidification of high-nickel-content alloys. No obvious microstructural differences exist between the 9-4-20 and 10%Ni welds. Reaging after welding tends to concentrate precipitates on the grain boundaries making them appear more distinct in the micrograph. Reaging also helps to "wash out" the weld to heat-affected-zone transition.

These observations are in general agreement with the more extensive studies cited in (12,13,14).

Figure 8 represent typical base plate microstructure near the plate surface, at quarter thickness, and center of the plate. The figure shows a fine grain martensite with evidence of carbide precipitate particles and some retained austenite. The morphology of phases present changes as you progress through the thickness of the plate.

The weld crown contains columnar grains as is typical of cast structure. These cells are particularly evident along with well-defined martensite needles after the weld was reaged. Figure 9 shows two metallographic views of the reaged weld. The basic microstructure is again predominantly martensite with some evidence of retained austenite.

The weld to heat-affected-zone transition area is shown in Figure 10, both as welded and reaged. The columnar grains of the weld are seen on the right outlined by retained austenite (white). The base plate, on the left of the view, is a martensite heavily interspersed with precipitated carbides. The region in the center appears as massive retained austenite and martensite. The division between the weld and base plate seem practically"washed out" by the reaging cycle.

The microstructure of the heat affected zone in the base plate is shown in Figure 11. The structure in this area appears as acicular martensite which converts to tempered martensite on reaging. Both structures exhibit some retained austenite and precipitated carbides.

APPLICATION OF TEST RESULTS

From the results of this evaluation one may conclude that an excellent weld can be obtained using the GTA process on one-inch 10Ni-8Co-2Cr-1Mo plate. The weld wire of matching composition gave a better weld than the other wire used in this study. Reaging after welding offers a slight improvement, but probably not enough to justify the additional production cost.

Fracture mechanics may be applied to determine a critical crack size, a_{cr}, from the equation,

$$a_{cr} = (K_{Ic}^2\ Q)/(1.2\ \pi\ \sigma^2),$$

where σ is the gross stress and Q is called the shape factor. The shape factor is obtained from,

$$Q = \phi^2 - 0.212(\sigma/\sigma_y)^2$$

where

$$\phi = \int_0^{\pi/2} \left\{ 1 - \left[(c^2 - a^2)/c^2 \right] \sin^2\theta \right\}^{1/2} d\theta$$

and σ_y is the tensile yield stress of the material. The factors a and c are dimensions of a flaw 2c long and 2a wide. For a circular, so called penny shaped, crack

$$c = a = \text{radius of flaw.}$$

The most severe condition occurs for the infinitely long crack where

$$2c = \infty \quad .$$

Semi-elliptical surface flaws are most commonly found in actual components.

The ratio a/2c may be plotted against Q for any given σ/σ_y ratio (15). Then by making assumptions concerning the flaw shape and gross stress we can choose the proper Q and thus calculate the critical crack depth, a_{cr}. Table 8 lists the critical flaw depths for both semi-circular, a/2c = 0.5, and semi-elliptical, a/2c = 0.1, type flaw. Most flaws encountered in real components would fall between these two extremes. The calculations in Table 8 were made using two different values for a/2c, σ_y and σ/σ_y with three K_{Ic} values.

In pressure vessel design it is desirable to have a critical flaw size equal to or greater than the thickness of the structure wall. This condition leads to the leak-before-failure criterion. It is also desirable to have subcritical flaws within a size range that is detectable by non-destructive means. Any of the calculated crack sizes shown in Table 8 are well within the state-of-the-art for NDT techniques.

ACKNOWLEDGEMENTS

The specimens were welded and machined by Excelco Developments, Inc., under the capable supervision of their engineer Ward Abbott.

Assistance with specimen preparation and metallographic analysis was received from Ronald Hayes, J. P. Rucker, and Jerome Hall at the U. S. Naval Weapons Laboratory, Dahlgren, Va.

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TABLE 1: DESCRIPTION AND ANALYSIS OF MATERIAL

	Base Plate	Weld Wire	Weld Wire
Material Designation	10N-8-2-1	HP-9-4-20	10N-8-2-1
Manufacturer	U.S.S.	Republic	U.S.S.
Heat Number	C51543	60527	51361
Melting Process	VIM + VAR	Vacuum Consummable Electrode	VIM
Analysis			
Carbon	0.11	0.17	0.096
Manganese	0.24	0.69	0.094
Phosphorous	0.007	0.004	0.008
Sulphur	0.006	0.006	0.005
Silicon	0.042	0.24	0.18
Copper	---	3.27	0.081
Nickel	10.03	7.38	9.98
Chromium	1.97	0.50	1.98
Molybdenum	1.00	0.98	0.96
Vanadium	0.02	----	0.092
Titanium	0.01	----	0.02
Aluminum	0.004	----	0.014
Cobalt	7.92	----	8.02
Iron	Bal.	Bal.	Bal.

TABLE 2: GAS ANALYSIS OF BASE PLATE

Gas	Parts per Million (Average of two specimens)
Oxygen	42.5
Hydrogen	1.35
Nitrogen	12.0

TABLE 3: WELDING PARAMETERS

Weldment Designation		B	C	D
Filler metal		HP-9-4-20	HP-9-4-20	10Ni-8-2-1
E.M.F.		11v.	9-10v.	10v.
Current:	Root pass	180a	180a	150a
	Fill	200-250a	200-260a	200-230a
Number of passes:	1st side	24	24	21
	2nd side	20	21	24
Gas Flow		25 C.F.H.	30 C.F.H.	25 C.F.H.
Electrode		1/8"tungsten	1/8"tungsten	1/8"tungsten
Cup size		10	8&12	10

TABLE 4: TENSILE PROPERTIES

Panel Identification	Description	Orientation	Yield Strength (0.2% offset) (ksi)	Ultimate Tensile Strength (ksi)	Young's Modulus (psi x 10^6	Reduction of Area (%)	Elongation (2" gage length) (%)
A	Base Plate	Longitudinal	192.5	203.8	28.6	69.0	16.8
		Transverse	193.0	201.8	28.8	66.9	15.8
B	Weldment 9-4-20 wire as welded	Trans-Weld	190.4	202.5	28.4	63.0	15.0
		All-Weld	197.0	209.4	28.3	54.7	18.5
C	Weldment 9-4-20 wire reaged	Trans-Weld	193.0	197.0	28.9	65.5	14.5
		All-Weld	201.0	205.0	28.6	65.0	19.5
D	Weldment 10-8-2-1 wire as welded	Trans-Weld	191.8	202.0	29.0	65.5	15.3
		All-Weld	195.5	205.4	28.6	60.4	18.0

TABLE 5: IMPACT PROPERTIES AT 80°F

Panel Identification	Description	Orientation	Standard Charpy Energy (ft.lbs.)	Pre-Cracked Charpy Energy (ft.lbs./in.^{2})
A	Base Plate	Longitudinal	71	378
		Transverse	62	355
B	Weldment 9-4-20 wire as welded	Center of weld	45	263
		Heat affected zone	69	320
C	Weldment 9-4-20 wire reaged	Center of weld	63	351
		Heat affected zone	82	373
D	Weldment 10-8-2-1 wire as welded	Center of weld	99	514
		Heat affected zone	63	347

TABLE 6: AVERAGE HARDNESS MEASUREMENTS

Panel	Location in Plate	Average DPH Number		
		Base Plate	H.A.Z.	Weld
B	Top	444	448	406
	Center	432	466	453
	Bottom	456	461	429
C	Top	428	439	423
	Center	424	457	470
	Bottom	425	443	436
D	Top	435	450	412
	Center	446	469	460
	Bottom	439	407	393
Overall Average		436	449	432

TABLE 7: FRACTURE TOUGHNESS

Plate Designation	Weld Wire	Condition	Test Location	Apparent K_a ($ksi\sqrt{in.}$) Uncorrected	Corrected (Graphical)	Corrected (Scaling)	$\frac{B\ (100)}{2.5\ (K_a/\sigma_y)^2}$
A (Base Plate) (Large Spec.)	---	Aged	Base Plate	202	-----	----	36.5
A (Base Plate) (Conventional)	---	Aged	Base Plate	208	233	223	34.4
B	9-4-20	Aged Welded	C. W.	174	188	189	51.3
			H.A.Z.	194	213	225	38.5
C	9-4-20	Aged Welded Reaged	C. W.	199	220	222	40.8
			H.A.Z.	215	243	248	32.2
D	10-8-2-1	Aged Welded	C. W.	244	296	296	25.7
			H.A.Z.	195	215	216	38.7

TABLE 8: CALCULATED CRITICAL FLAW SIZES FOR SEMI-ELLIPTICAL SURFACE FLAWS IN ONE-INCH 10Ni-8Co-2Cr-1Mo STEEL PLATE

K_{Ic} (ksi $\sqrt{in.}$)	σ_y (ksi)	σ/σ_y	A_{cr} (inches) a/2c = 0.1	A_{cr} (inches) a/2c = 0.5
200	180	1.0	0.29	0.71
		0.8	0.48	1.15*
	190	1.0	0.26	0.64
		0.8	0.43	1.03*
225	180	1.0	0.36	0.90
		0.8	0.61	1.46*
	190	1.0	0.33	0.81
		0.8	0.55	1.31*
250	180	1.0	0.45	1.11*
		0.8	0.75	1.80*
	190	1.0	0.41	1.00*
		0.8	0.67	1.61*

*Predicts leak before catastrophic failure.

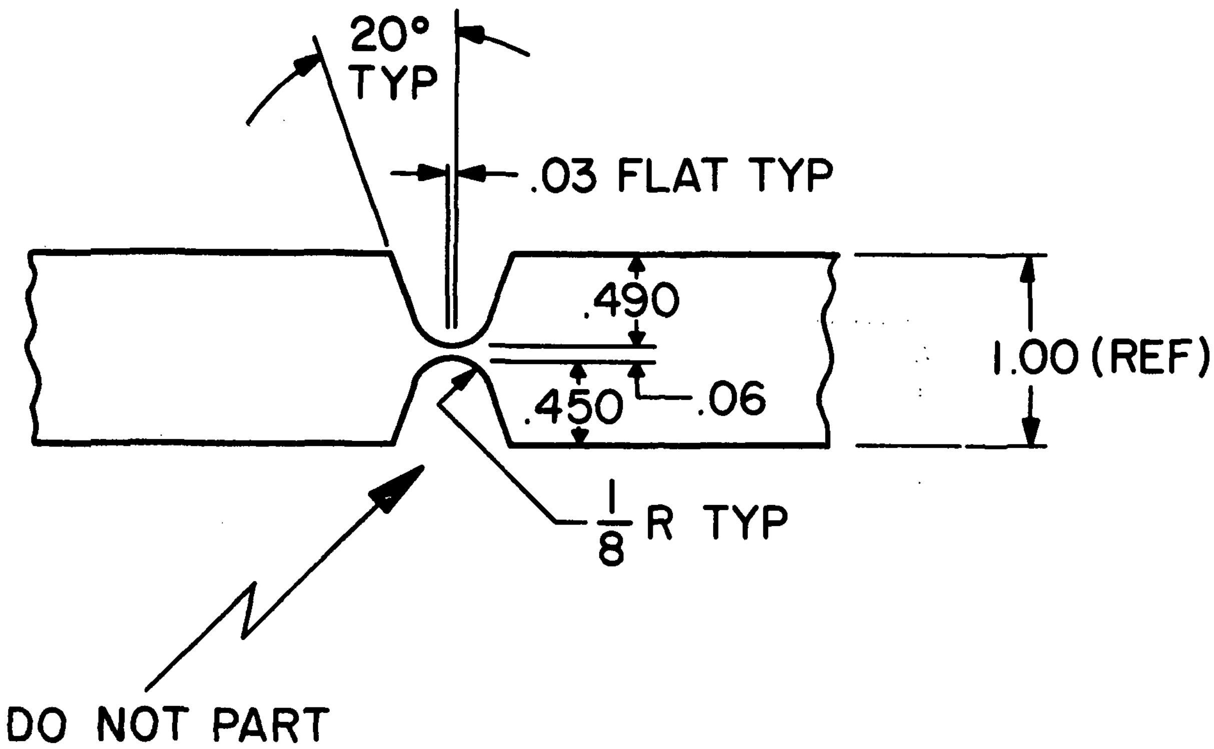


Fig. 1 - Weld preparation

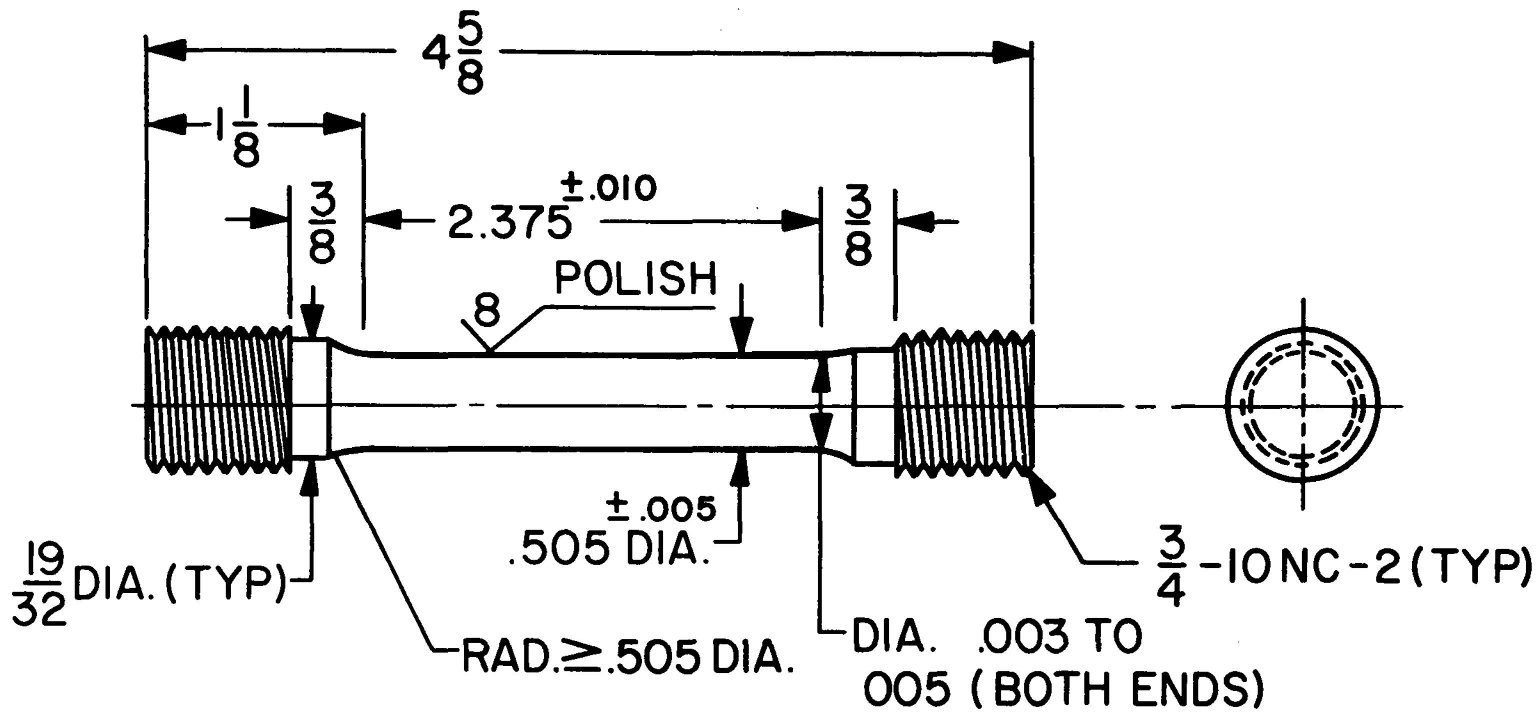


Fig. 2 - Standard tensile specimen

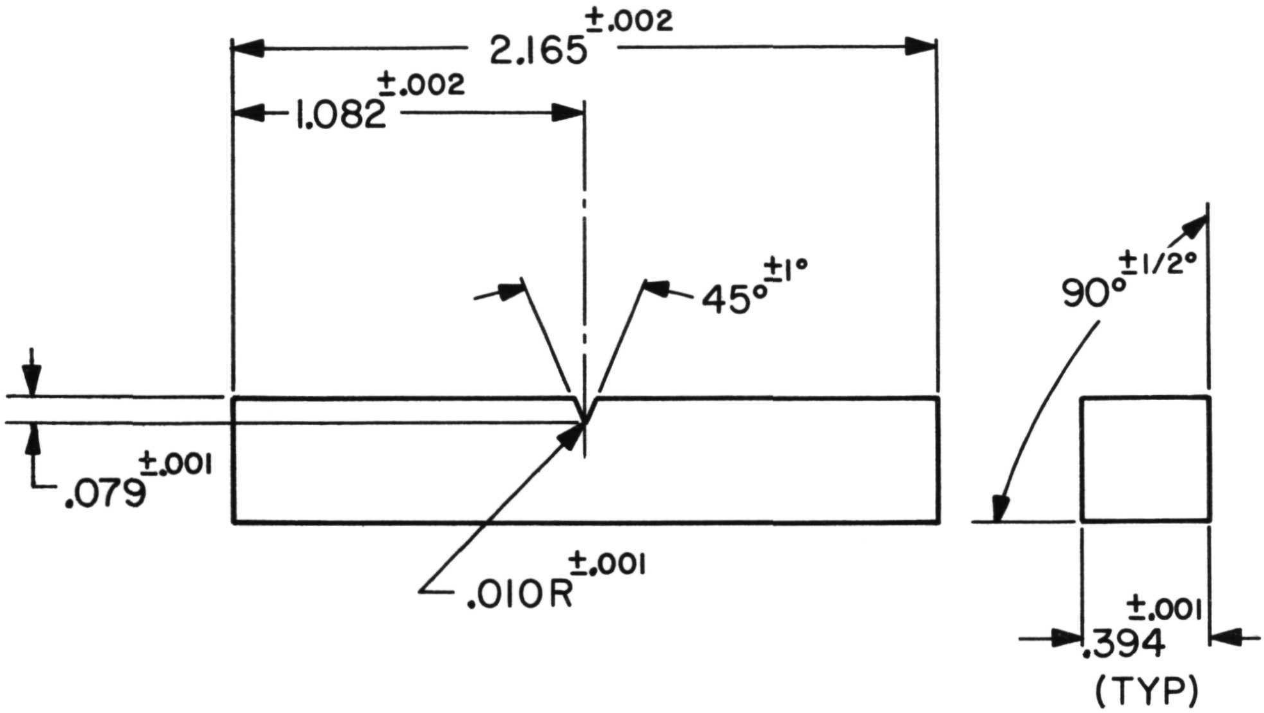


Fig. 3 Standard Charpy impact specimen

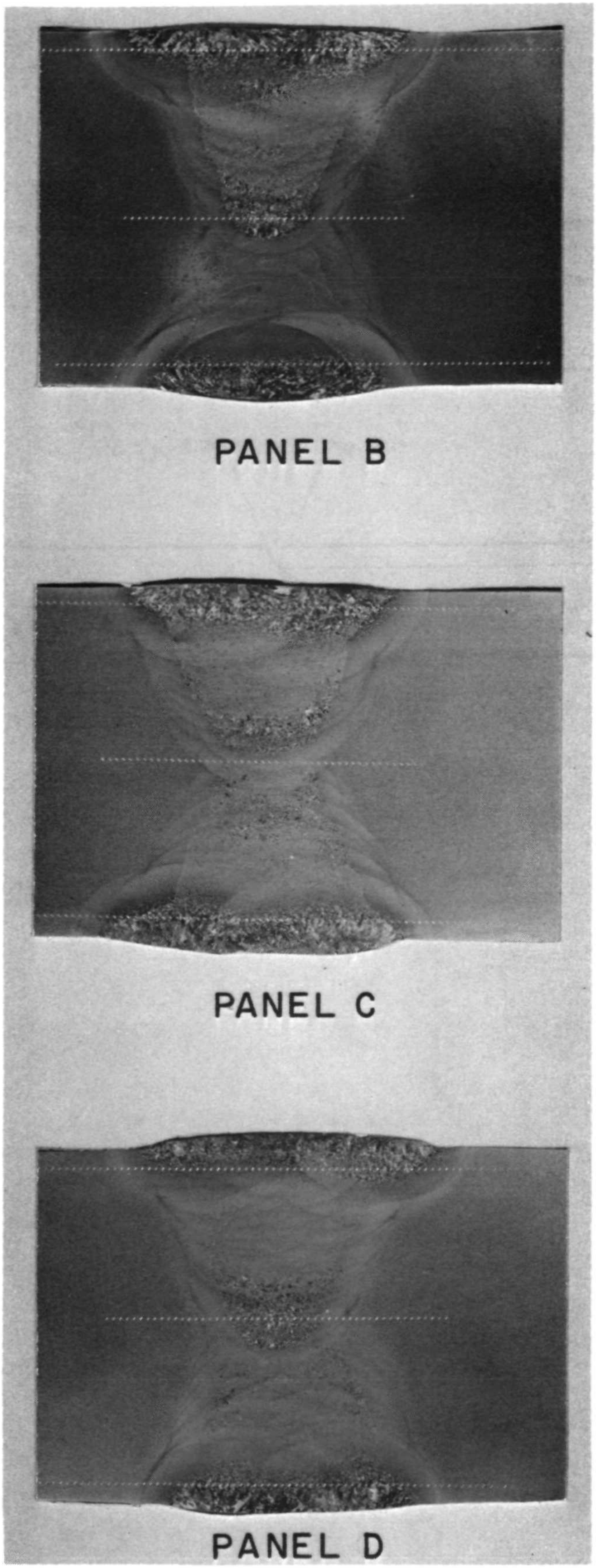


Fig. 4 - Weld cross sections (2X, 2% Nital etch)

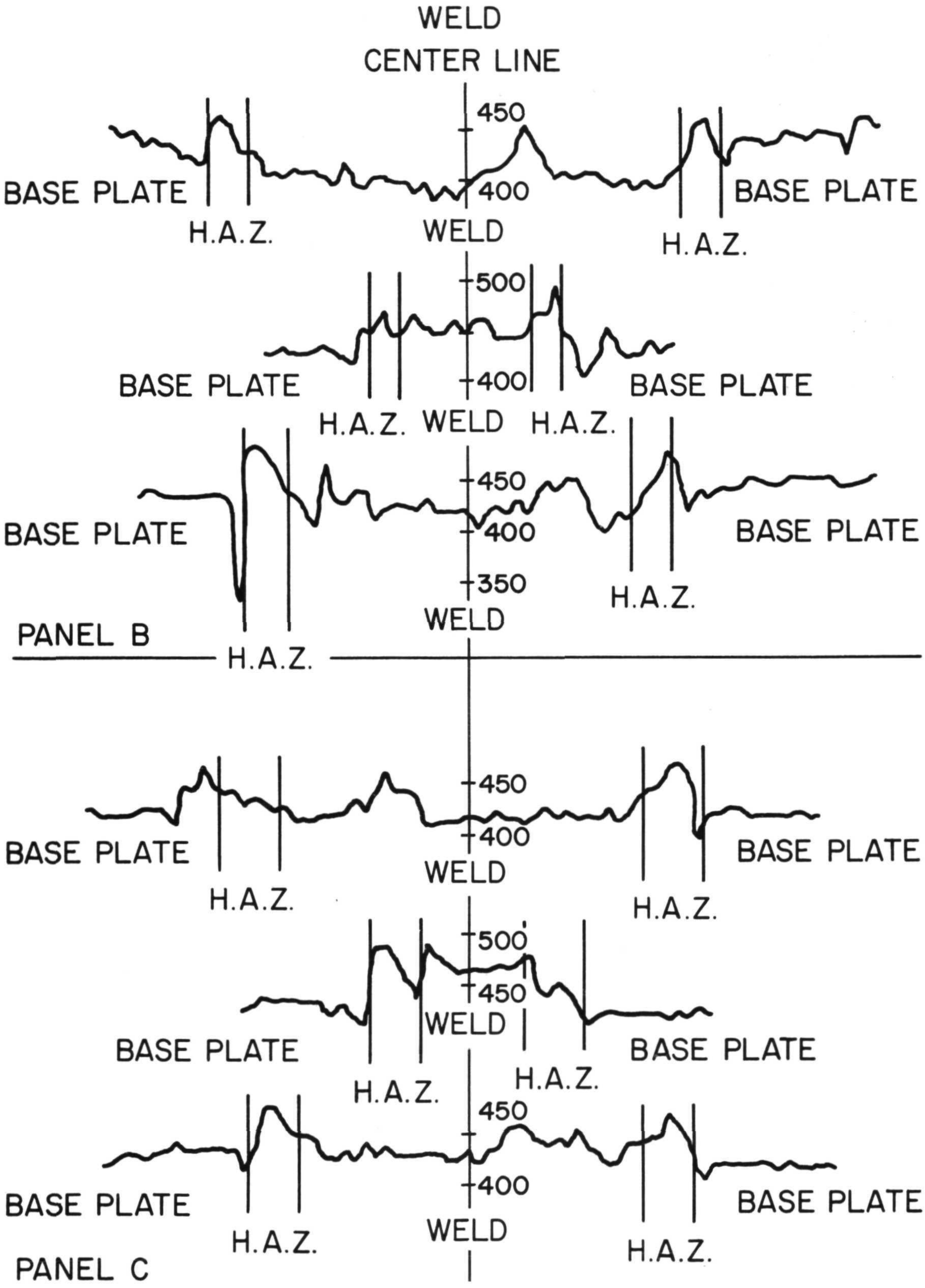


Fig. 5 - Typical hardness (DPH) profiles

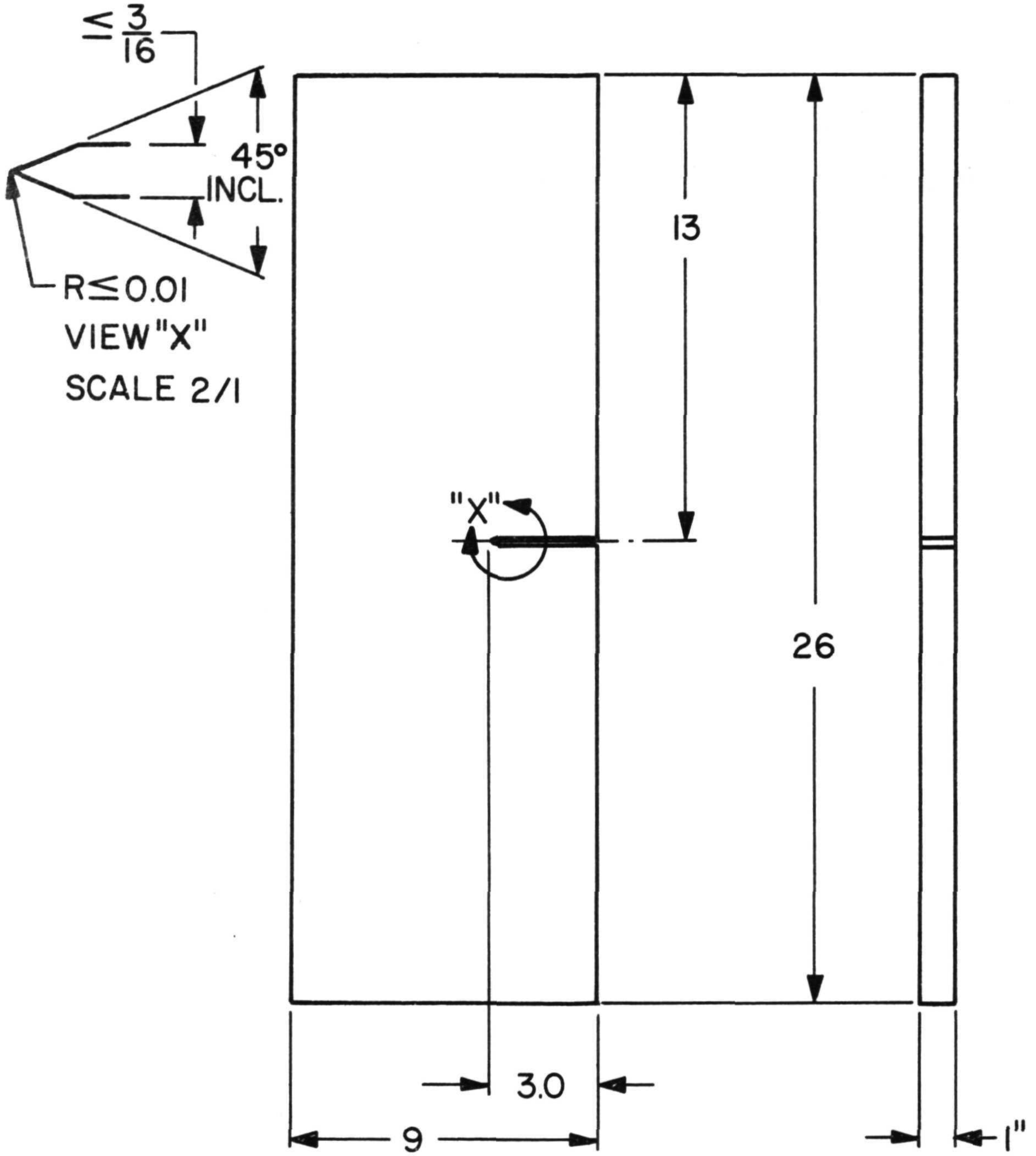


Fig. 6 - Large base-plate fracture specimen

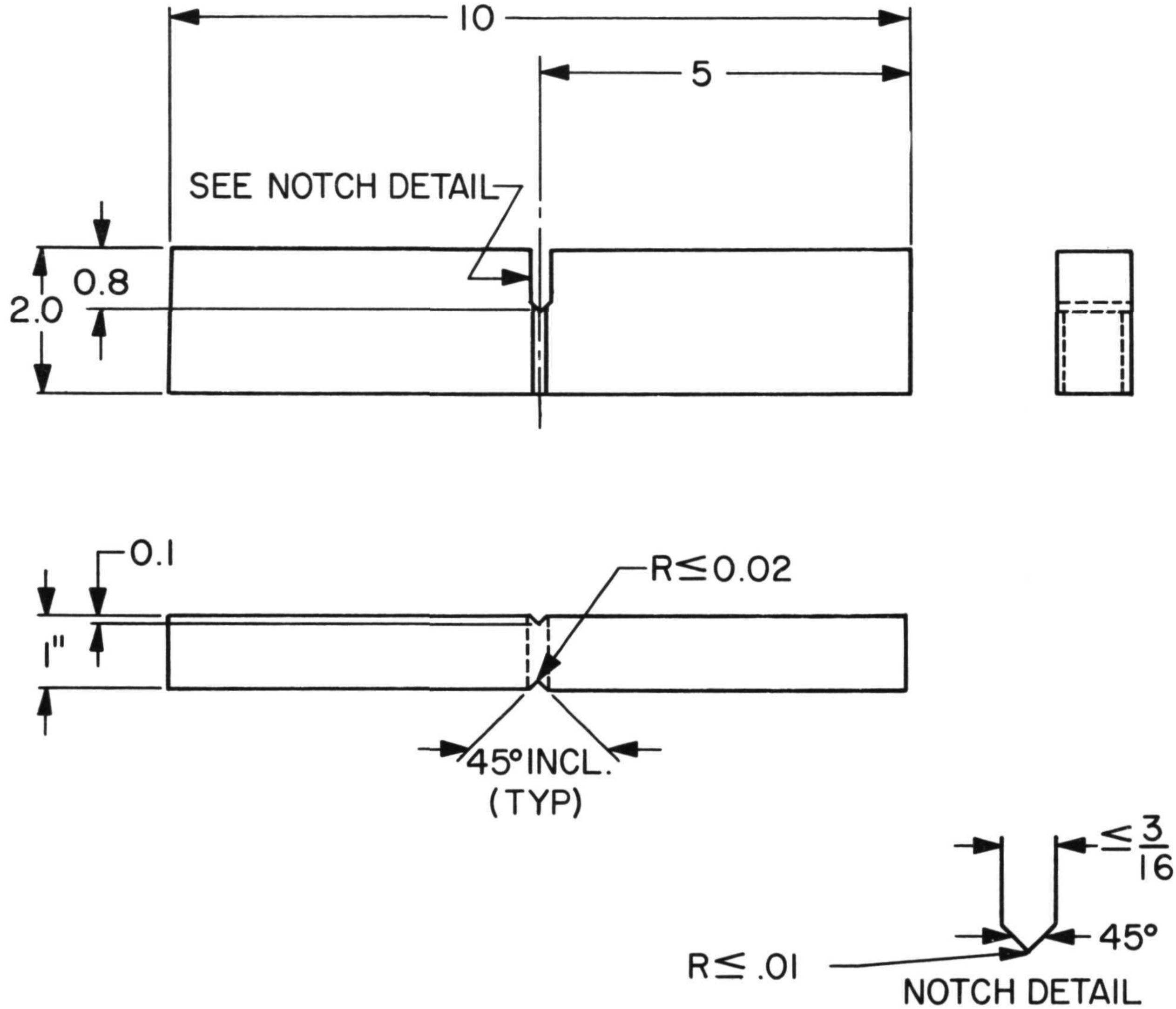
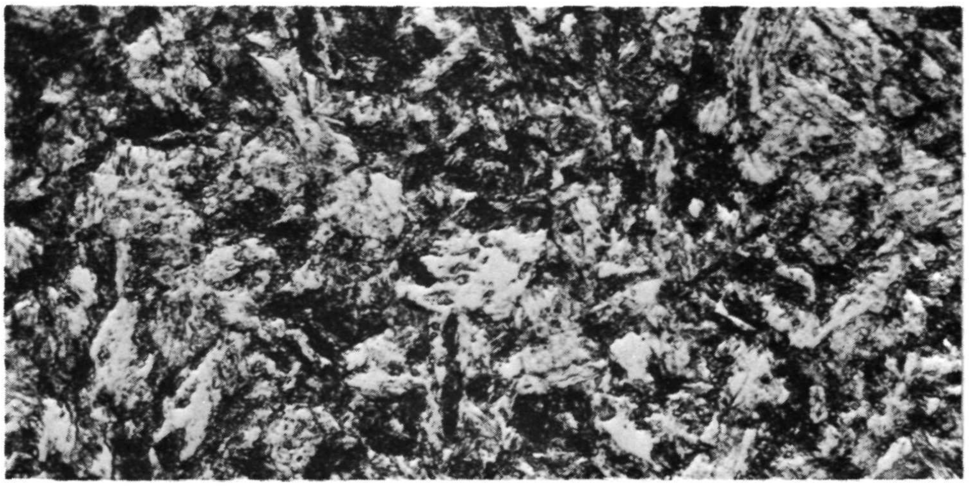
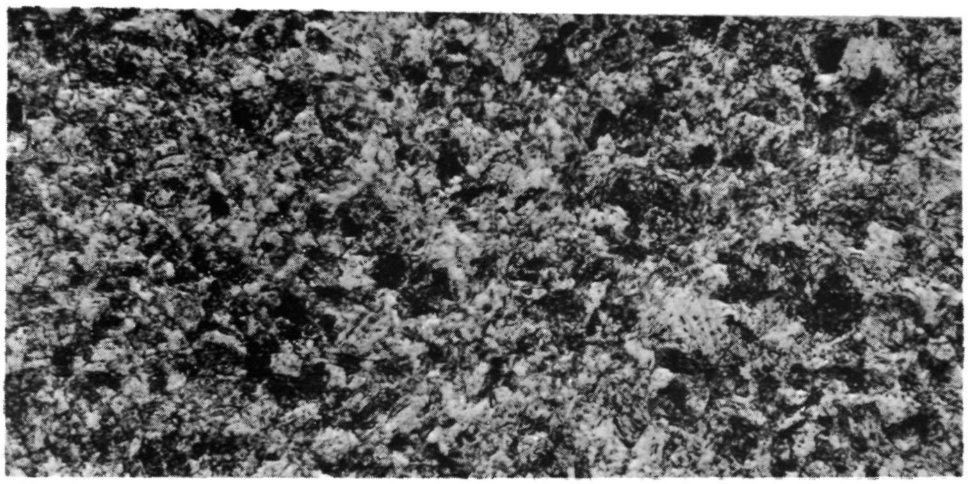


Fig. 7 - Notched-bend fracture specimen

NEAR PLATE SURFACE

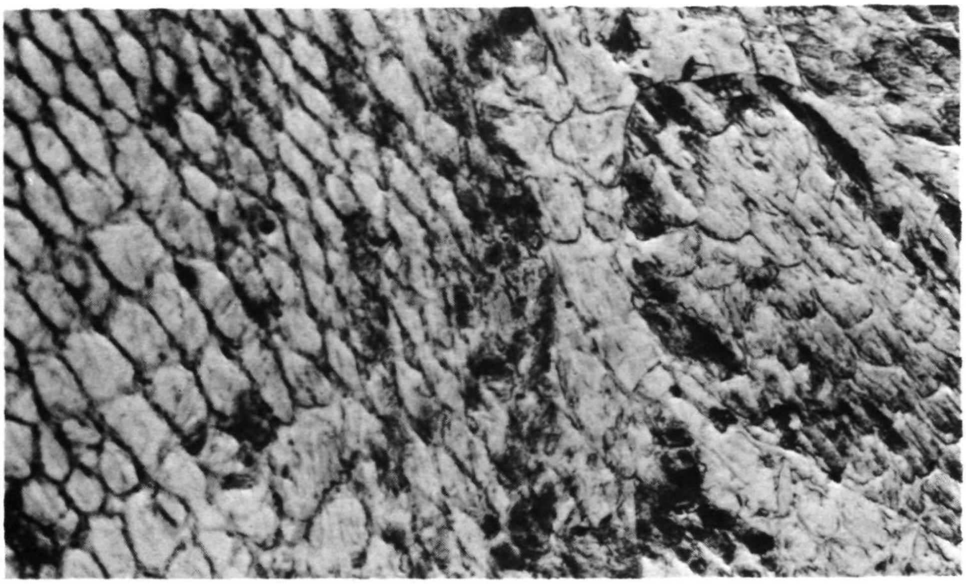




QUARTER THICKNESS

PLATE CENTER

Fig. 8 - Microstructure of 1-inch plate of 10Ni-8Co-2Cr-1Mo steel (1000X, 2% Nital etch)



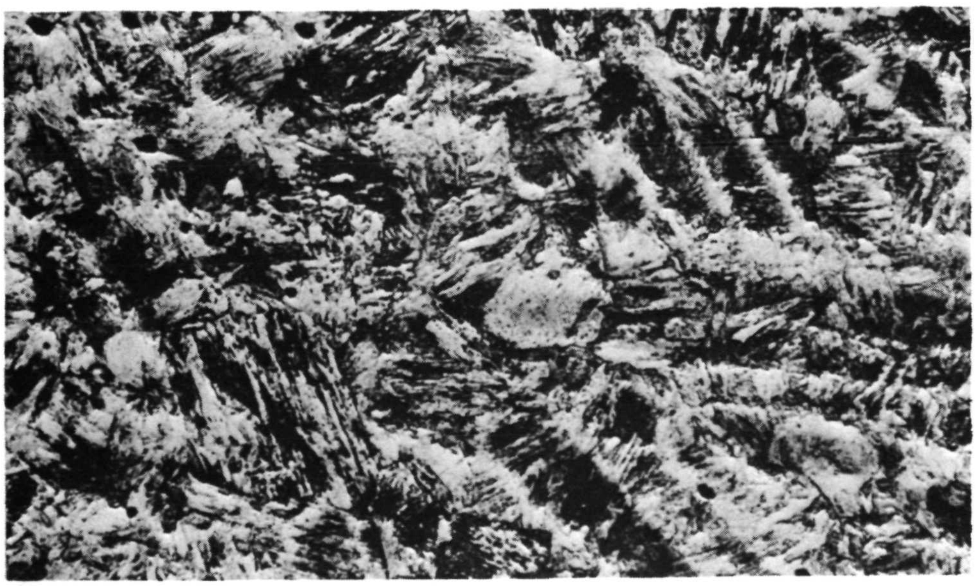
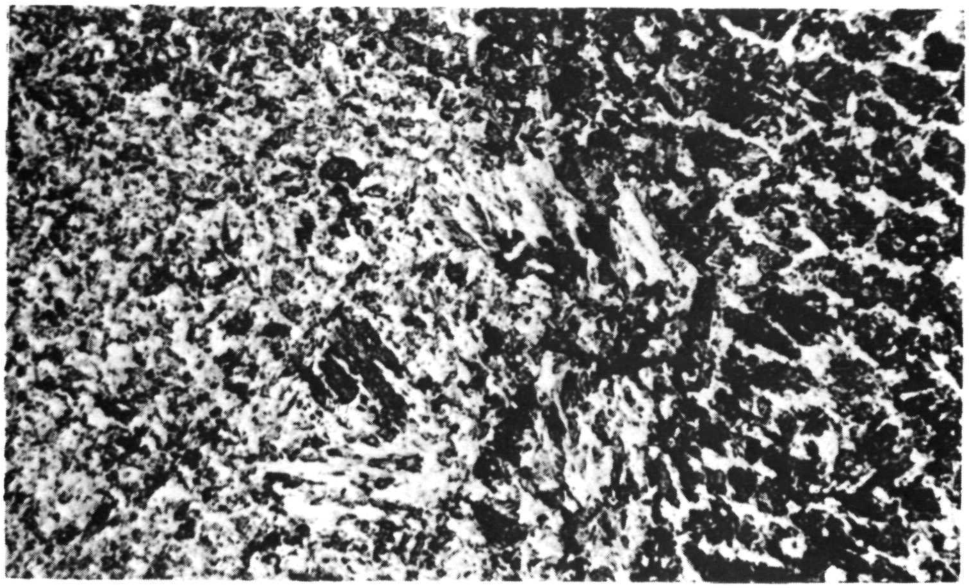
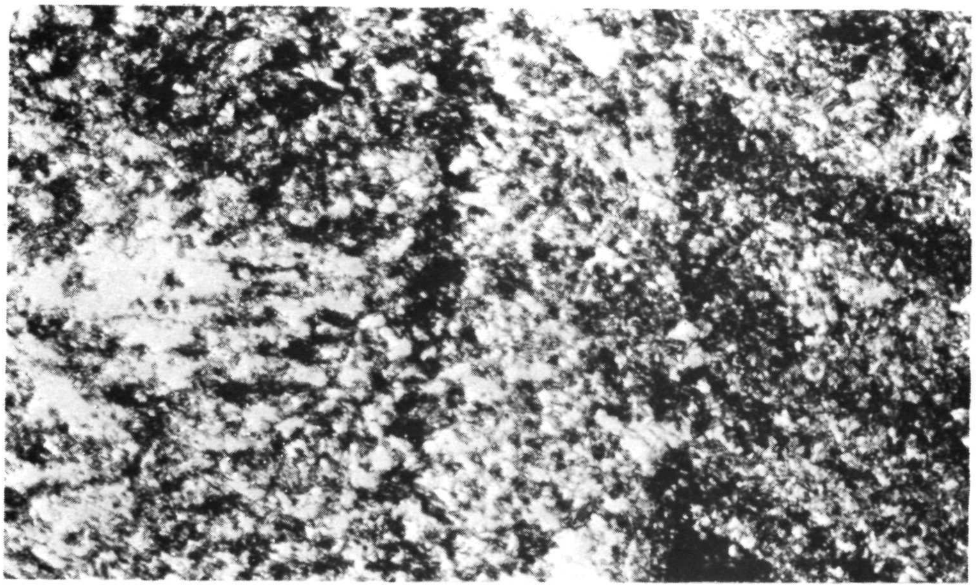


Fig. 9 - Reaged microstructures of 10%Ni weld (500X, 2% Nital etch)



A. AS WELDED



B. REAGED

Fig. 10 - Weld-to-HAZ transition (500X, 2% Nital etch)

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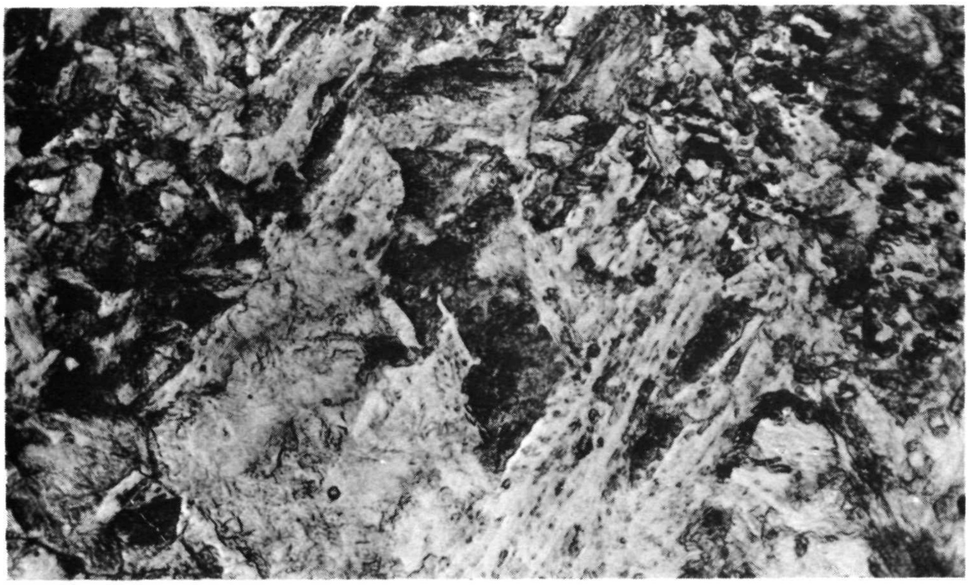
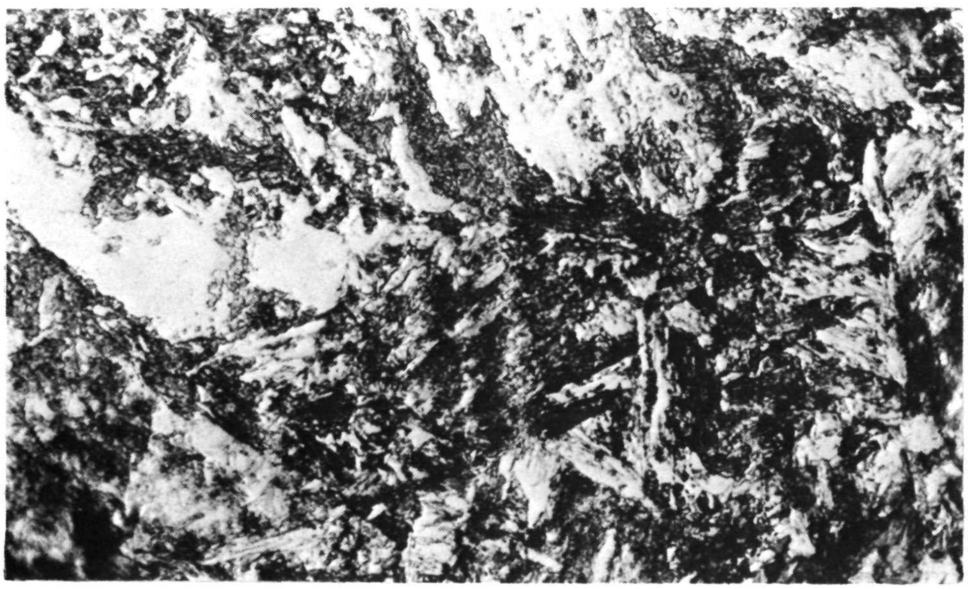


A. AS WELDED



B. REAGED

Fig. 11 - HAZ before and after reaging (1000X, 2% Nital etch)

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13. ABSTRACT

This study of 10Ni-8Co-2Cr-1Mo steel includes evaluations of tensile, impact, hardness, fracture toughness properties, and metallographic features. Base plate and three weldments in one-inch thicknesses are examined to compare as-welded properties with those obtained after reaging, and results of welding the 10%Ni alloy with 9-4-20 wire as opposed to a matching weld wire composition. Critical crack sizes are calculated for the material.

The most desirable weld properties are obtained using the matching weld wire and a reaging cycle. However, the improvement gained through reaging is probably not sufficient to justify the additional cost for most practical applications.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
10Ni-8Co-2Cr-1Mo steel						
GTA weldment						
Fracture mechanics						