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THE EFFECTS OF BASE METAL NOTCH ORIENTATION AND ACUITY AND WELD--ETC(U)
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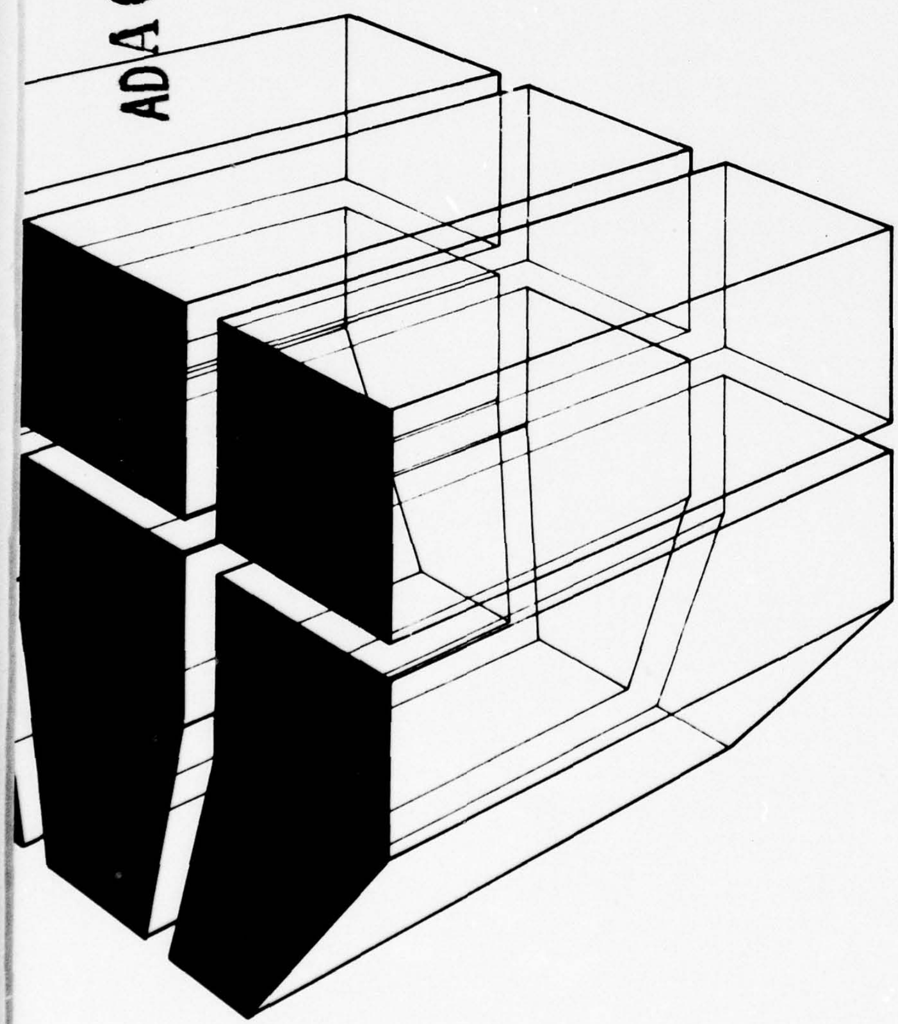
February 1977

THE EFFECTS OF BASE METAL NOTCH ORIENTATION AND ACUITY AND WELD POROSITY ON THE DYNAMIC TEAR TOUGHNESS OF A514F STEEL

by
E. P. Cox



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The effects of weld porosity on the dynamic tear properties of A514F steel butt welds were assessed in a program which conducted dynamic tear tests in six areas of experimentation: (1) the base plate steel in the longitudinal and transverse orientations; (2) sound weld metal; (3) weld metal containing clustered porosity; (4) weld metal containing linear porosity; (5) stress-relieved weld metal; and (6) base metal in the longitudinal and transverse directions having fatigue precracked notches.

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The upper shelf dynamic tear toughness of the base plate was observed to be much greater for specimens with the notch oriented perpendicular to the final rolling direction than for the specimens with the notch parallel to the final rolling direction. Specimens which had notches precracked in fatigue and oriented parallel to the rolling direction had the same toughness-temperature behavior as specimens that were machine-notched in the same orientation. The toughness values of the fatigue precracked specimens whose notches were perpendicular to the rolling direction were greater than for the same orientation specimens with machined notches. The fatigue precracked specimens had higher temperature ductile-to-brittle transitions than the machine-notched specimens.

Weld specimens had upper shelf toughness values which were less than the toughness values of base plate specimens that were notched perpendicular to their rolling direction; however, these values were greater than the toughness values of base plate specimens notched parallel to the rolling direction. Both the clustered porosity and the linear porosity specimens had toughness values somewhat lower than the sound weld specimens. Stress relief heat treatment had little effect on the toughness of sound welds.

FOREWORD

This investigation was performed for the Directorate of Military Construction, Office of the Chief of Engineers (OCE) under Project 4A078012A0K1, "Applications Engineering," Task 02, "Engineering Criteria for Design and Construction," Work Unit 102, "Engineering Criteria for Welds." The applicable QCR number is 1.06.004. The OCE Technical Monitor was Mr. I. A. Schwartz.

The investigation was performed by the Metallurgy Branch (MSM), Materials and Science Division (MS), U. S. Army Construction Engineering Research Laboratory (CERL). CERL personnel directly involved with this study were Mr. E. P. Cox, Mr. F. H. Kisters, and Ms. R. E. Hannan.

Dr. A. Kumar is Chief of MSM, and Dr. G. R. Williamson is Chief of MS. COL J. E. Hays is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director.

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THE EFFECTS OF BASE METAL NOTCH ORIENTATION AND ACUITY AND WELD POROSITY ON THE DYNAMIC TEAR TOUGHNESS OF A514F STEEL

1 INTRODUCTION

Background

Many of the Corps of Engineers' metallic structures are fabricated by welding, and preventing brittle fracture of these structures is very important. Discontinuities and defects are sometimes introduced into the weld during fabrication and, when detected, are usually removed to insure the structural integrity of the joint. However, not all discontinuities are detected nor are they always eliminated during service. Of particular interest are porosity defects–both uniformly distributed and clustered. Little experimental research has been conducted on the effects of porosity on the toughness and ductile-to-brittle transition temperature (DBTT) of high-strength, low-alloy (HSLA) steels.

When the effects of porosity on weldment mechanical properties were reviewed by Pense and Stout, [1] results indicated that scattered porosity had no effect on tensile strength unless it was "excessive." No indication was given about the amount of porosity that was considered to be excessive or about the quantities of porosity in the welds. In a more recent investigation on the effects of uniformly distributed porosity on the tensile strength of aluminum alloy weldments, Lawrence and Munse[2] noted that visible porosity was often accompanied by significant amounts of invisible microporosity. Their results indicated that the tensile strength and ductility gradually decreased in proportion to the amount of total porosity present on the fracture surface.

Lundin[3] has recently completed a literature review about the effects of weld discontinuities on mechanical properties. The section concerning porosity in ferritic steels indicated that many researchers have found that scattered, unaligned, and unclustered porosity in amounts less than 7 percent had an insignificant influence on yield strength, tensile strength, slow bend ductility, and reduction in area. Internal porosity was observed to be less harmful than surface or near-surface porosity, while aligned or clustered porosity was found to be a severe stress concentrator.

Clustered porosity in A514F butt weld specimens pulled in tension has been investigated by Honig and Carlson.[4] Their research indicated that clustered porosity severely reduced ductility when present in amounts of 1 percent of the theoretical cross-sectional area or more and that the tensile strength decreased 8 percent for porosity levels greater than 6 percent. The slight reduction in strength indicated that porosity in certain amounts can be tolerated under static loading but, because of the drastic loss of ductility, it is unacceptable for use in limit load designed structures. Similar tests on A514F weldments were conducted by Lawrence, Radziminski, and Kruzic.[5] No reduction in tensile strength was noted for amounts of clustered porosity of less than 4 percent; however, 1 percent porosity caused the strain at fracture to decrease from 20 to 9 percent.

Very little research has been conducted on the impact toughness (a characteristic property of a material to resist fracture under an impact load) of welds containing porosity. One such investigation was conducted by Green, Hamad, and McCauley[6] on AISI 1020 steel. Their work on submerged arc welds showed a decrease in impact energy proportional to the percentage of porosity on the fracture surface. Similar results were found for GMA welds for porosity levels up to 3 percent. The results of Charpy V-notch impact tests on A514F steel conducted by Bradley and McCauley[7] showed no decrease in impact energy for porosity levels as high as 5 percent on the cross

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[1] A. W. Pence and R. D. Stout, "Influence of Weld Defects on the Mechanical Properties of Aluminum Alloy Weldments," *Welding Research Council Bulletin*, No. 152 (July 1970).

[2] F. V. Lawrence, Jr., and W. H. Munse, "Effects of Porosity on the Tensile Properties of 5083 and 6061 Aluminum Alloy Weldments," *Welding Research Council Bulletin*, No. 181 (February 1973).

[3] C. D. Lundin, "The Significance of Weld Discontinuities: A Review of Current Literature," *Welding Research Council Bulletin* (in publication).

[4] E. M. Honig, Jr., and K. W. Carlson, "Tensile Properties of A514 Steel Butt Joints Containing Cluster Porosity," *Welding Journal*, Vol 55 (4) (1976), Res. Supp. 103s-107s.

[5] F. V. Lawrence, Jr., J. B. Radziminski, and R. W. Kruzic, *The Effect of Porosity on the Static Tensile Behavior of High Strength Structural Steel Weldments*, Technical Report UILU-ENG-71-2024 (University of Illinois, 1971).

[6] W. L. Green, M. F. Hamad, and R. B. McCauley, "The Effects of Porosity on Mild Steel Welds," *Welding Journal*, Vol 37 (7) (1959), Res. Supp. 209s-306s.

[7] J. W. Bradley and R. B. McCauley, "The Effects of Porosity in Quenched and Tempered Steel," *Welding Journal*, Vol 43 (9) (1964), Res. Supp. 408s-414s.

section. Submerged arc welds were unaffected to 5 percent cross section porosity, but a rapid decrease in impact energy occurred for greater amounts of porosity.

The general consensus of sources investigated in Lundin's literature review[8] is that porosity in amounts less than 5 percent has little effect on Charpy V-notch toughness and, in greater amounts, the impact behavior is a function of the percentage of the area occupied by the porosity.

Tests were conducted by Schwartz, Lange, and Martin[9] on A514F steel of various thicknesses, locations within the plate's thickness, and specimen orientations. A514F base metal impact toughness was measured using 5/8 in. (1.6 cm) dynamic tear (DT) specimens tested in the temperature range between -190°C (-310°F) and +100°C (+212°F). Both plate thickness and specimen orientation were found to affect the impact toughness and DBTT.

The effect of notch acuity on DT toughness of A514F steel was studied in research done by Herberling and Selby[10] on the effect of test variables. Fatigue precracked specimens were observed to exhibit a more abrupt transition from upper shelf to lower shelf toughness (narrower DBTT range); it was also found that the upper shelf energy of precracked specimens was slightly below that of the machine-notched or -pressed notch specimens. Fatigue precracked specimens also exhibited a 20°F (-5.5°C) increase in the DBTT. Herberling and Selby also performed some DT tests on welded specimens in the heat affected zone (HAZ). The HAZ had a much lower toughness than the base metal and the toughness decreased proportionally with temperature, i.e., no abrupt toughness transition was seen.

Objective

Various types of weld defects such as cracks, porosity, and lack of penetration have been shown to cause premature brittle fracture in structural steel weldments. The purpose of this investigation was to evaluate the effects of clustered and uniform porosity on the impact toughness of A514F steel weldments. Nondestructive tests were used to examine and quantify the presence of the porosity. Tests were also conducted to determine base plate orientation and notch acuity effects.

This investigation provides a partial basis for evaluating inspection criteria relating allowable defect parameters to given levels of weldment mechanical properties performance.

Approach

This investigation was comprised of four sub-studies aimed at understanding the effects of specimen variables on dynamic tear testing.

1. The first part of the investigation generated DT data on a set of base plate specimens machine-notched perpendicular to the rolling direction (RW) and a set notched parallel to the rolling direction (WR). This series of tests was conducted to establish the change in toughness within the temperature range of -190°C to +100°C (-310°F to +212°F) and to find the extent to which notch orientation influences toughness.

2. A series of tests was conducted on base metal specimens having the same orientations, but whose notches consisted of sharp fatigue cracks. The current literature is unclear regarding a standard specimen notching technique and whether notch acuity is a pertinent variable affecting shelf toughness and DBTT.

3. Sound weld specimens were fabricated to establish a control data base of DT energy values.

4. Welds containing controlled amounts of clustered porosity or uniformly distributed (continuous) porosity were fabricated. These specimens were tested over the same temperature range as the base plate. Specimens containing clustered porosity were prepared and machine-notched so that the cluster was located at the notch root. Linear porosity specimens had the porosity aligned along the notch in the fracture path. All welds were inspected by x-ray radiography prior to machining to determine their adequacy for subsequent testing. The fracture surfaces were visually examined after testing.

Mode of Technology Transfer

The information in this report is part of a long-term research effort designed to improve Corps of Engineers guide specifications concerned with the accept/reject levels of weld defects.

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[8] C. D. Lundin, "The Significance of Weld Discontinuities: A Review of Current Literature," *Welding Research Council Bulletin 222*, (December 1976).

[9] I. A. Schwartz, E. A. Lange, and M. L. Martin, *Notch Toughness Properties of Pressure Vessel Steels*, Technical Report 67-021 (Office of the Chief of Engineers, 1967).

[10] T. Q. Herberling and G. E. Selby, "Drop Weight Tear Test–Effect of Variables on Test Results," *Impact Testing of Metals*, ASTM STP 466 (1970), pp 224-240.

Table 1

Chemical Composition of Base Metal and Welding Electrode

	Base Metal*	Welding Electrode**
Manufacturer	U.S. Steel Corporation	Air Reduction Co., Inc.
Designation	T-1	Airco AX110
Plate Thickness	3/4 in. (1.91 cm)	1/16 in. (0.16 cm) bare wire
Electrode Type	– –	– –
Element	**Chemical Composition, %**	
C	0.15	0.084
Mn	0.89	1.54
P	0.009	0.008
S	0.027	0.008
Si	0.27	0.45
Ni	0.90	2.43
Cr	0.52	0.049
Mo	0.42	0.48
V	0.06	0.008
Al	– –	0.0075
Ti	– –	0.004
Zr	– –	– –
B	0.0015	– –
Cu	0.21	– –

* Data from independent analysis
** Data supplied by manufacturer

Table 2

Tensile Properties of Base Metal and Weld

Properties	Base Metal*	Weld**
Tensile Strength, ksi	120.8	140.0
Yield Strength, ksi	113.1	126.3
Elongation at Fracture, %	36.0 in 2.0 in. (5.08 cm)	50 + in 3/4 in. (1.91 cm)
Reduction in Area, %	66.4	– –

* Properties of base metal provided by manufacturer.
** Average of three specimens taken from weld metal (from F. V. Lawrence, Jr., E. P. Cox, and E. M. Honig, Jr., *Influence of Heat Input and Lack of Penetration Length on the Static Tensile Behavior of High Strength Structural Steel Weldments*, Technical Report M-135/ADA012730 (Construction Engineering Research Laborabory, June 1975).

2 PROCEDURE

Materials

The base metal used in this study was ASTM A514 grade F steel (U. S. Steel T-1), an extra-high-strength, low-alloy structural steel suitable for weld fabrication. Since this is a quenched and tempered steel, its microstructure is comprised of tempered martensite and tempered bainite. The welding electrode used was Airco AX110, 1/16 in. (0.16 cm) bare wire electrode. Tables 1 and 2 give the chemical compositions and mechanical properties of the base and weld metals.

Specimen Fabrication

Base plate specimens were fabricated from the center thickness of 3/4 in. (1.91 cm) thick plate. Specimens were machined in accordance with MIL-STD-1601 (SHIPS).[11] Figure 1 shows the machine-notched

[11] MIL-STD-1601, *Military Standard Method for 5/8-Inch Dynamic Tear Testing of Metallic Materials*, Naval Ship Systems Command, FSC 95GP (Department of the Navy, 8 May 1973).

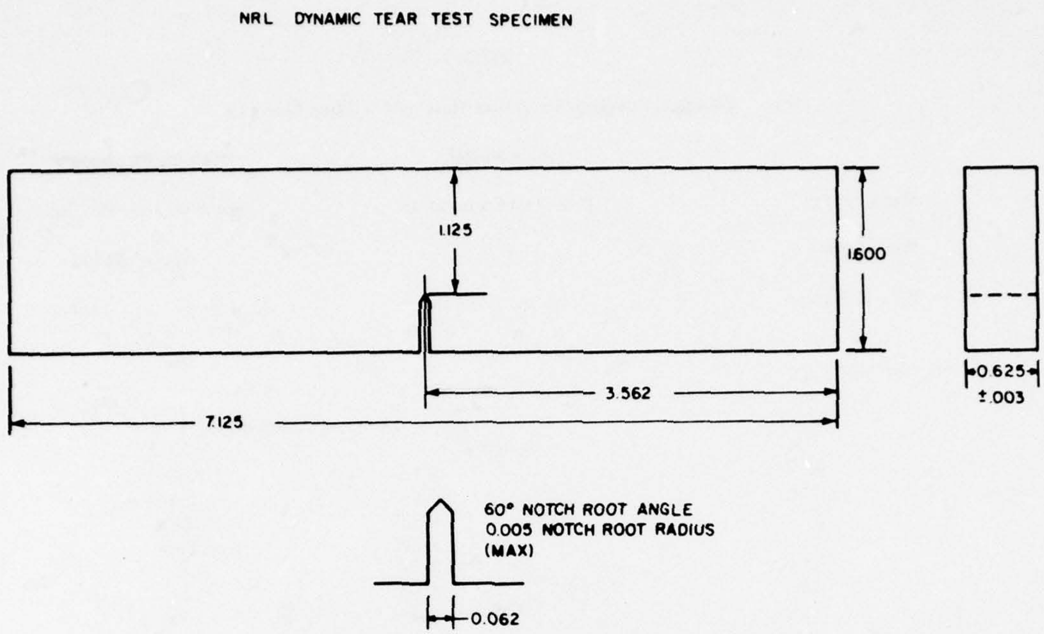


Figure 1. Standard 5/8 in. (1.59 cm) dynamic tear specimen as specified in MIL-STD-1601 (SHIPS). (All dimensions are in inches; metric conversion factor: 1 in. = 2.54 cm.)

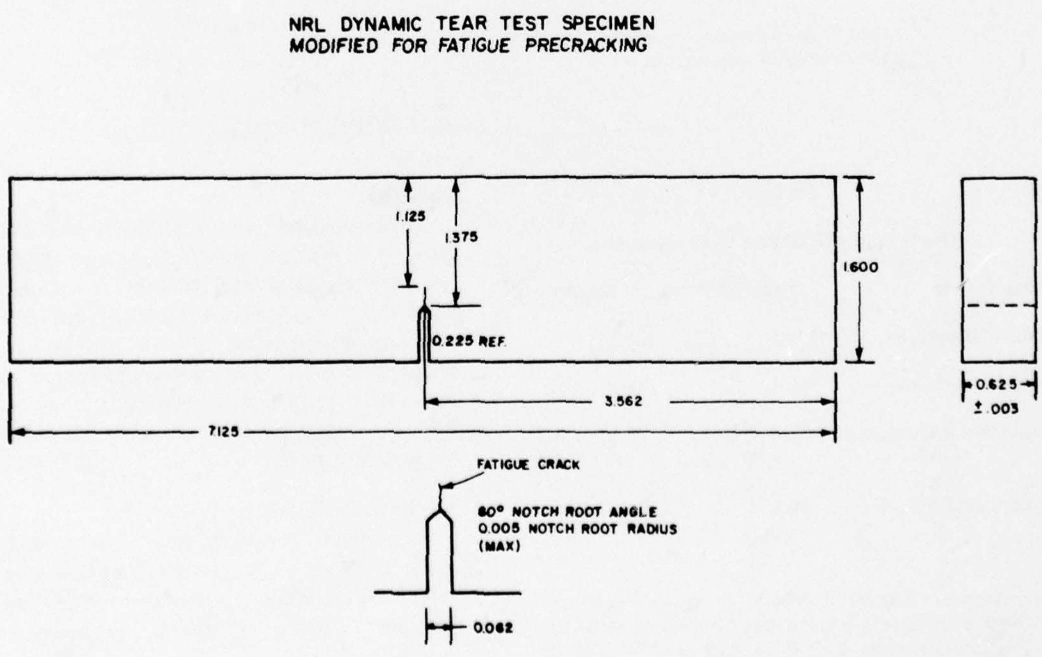


Figure 2. Fatigue precracked specimen having the same notch length as the standard specimen. (All dimensions are in inches; metric conversion factor: 1 in. = 2.54 cm.)

specimen dimensions. The specimen faces were surface-ground to provide a smooth surface and to insure their parallelity and perpendicularity. Several specimens were machined according to the modified specimen shown in Figure 2. These specimens had shorter notches which were extended by fatigue into a sharp notch. Fatigue precracking of the specimens was accomplished by cyclic loading, using a zero-to-tension (R=0) loading scheme. The stress intensity was maintained below 10 ksi $\sqrt{in.}$ (11 MPa$\sqrt{m}$), and the fatigue cracks were extended to the same length as the notches in the machine-notched specimens. The notch orientations were the same for both the machine-notched and the fatigue-precracked specimens; i.e., the notches were aligned parallel (WR direction) and perpendicular (RW direction) to the rolling direction. Figure 3 shows the specimen orientations.

Welded specimens were fabricated from large specimen blanks remaining from a previous study. The specimen blanks were saw-cut in half, and 60° double V-bevels without root faces (lands) were machined. The specimen blanks were butted together and preheated to 200°F (93.3°C). Welding was done by gas metal arc (GMA) process; Table 3 gives the welding parameters used. Clustered porosity was induced into the weld metal by momentarily interrupting the shielding gas on the first pass and then using sound weld cover passes. Linear porosity specimens were fabricated similarly. Figure 4a shows the specimen joint design, and Figure 4b shows the specimen orientation in the parent plate. After welding, the specimen blanks were x-ray radiographed to insure that the welds were suitable for testing and to locate weld porosity for specimen layout and machining.

SCHEMATIC OF SPECIMEN ORIENTATION

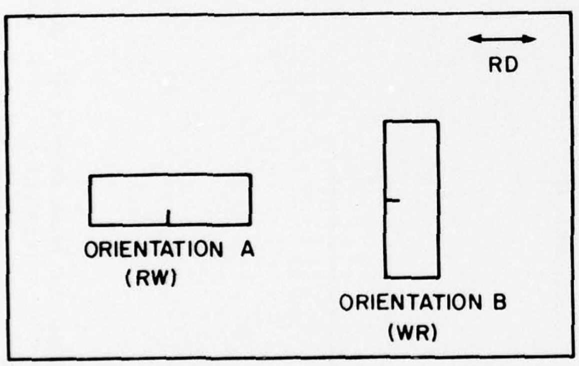


Figure 3. Specimen orientations in base plate. RD is the rolling direction.

Dynamic Tear Testing

The DT specimens were fractured by impact loading in a Southwest Research Institute 2000 ft-lb (2710 J) capacity, double pendulum dynamic tear machine. The specimens were fractured at temperatures ranging between -190°C (-310°F) and +100°C (+212°F). The DT specimens had thermocouples spot-welded close to the notch and connected to a digital volt meter; temperature was monitored by direct readout of the thermocouple. To obtain the desired test temperature, the specimens were either warmed from liquid nitrogen temperature or cooled from an elevated temperature. Figure 5 shows the location of the thermocouple on a specimen prepared for testing.

After testing, the specimen halves were warmed to room temperature in a double chamber bath, with acetone in one chamber and surrounding warm water in the other. This prevented condensation of water and, therefore, corrosion on the fracture surfaces of specimens tested below room temperature. The fracture surfaces were then dried, sprayed with a clear lacquer, marked, and taped together. Fracture surfaces were examined after testing was completed, and all surface irregularities were noted. Each series of specimens was then assembled and photographed.

Table 3

Welding Parameters

	Voltage, V	Current, amps	Travel Speed, in./min (cm/min)	Interpass and Preheat Temp, °F (°C)	Heat Input, kJ/in. (kJ/cm)	Shielding, Gas Comp, %
First Pass	20	330	10 (25.4)	200 (93)	39.6 (15.6)	98 Ar-$2O_2$
Second Pass	20	330	15 (37.5)	200 (93)	26.4 (10.4)	98 Ar-$2O_2$

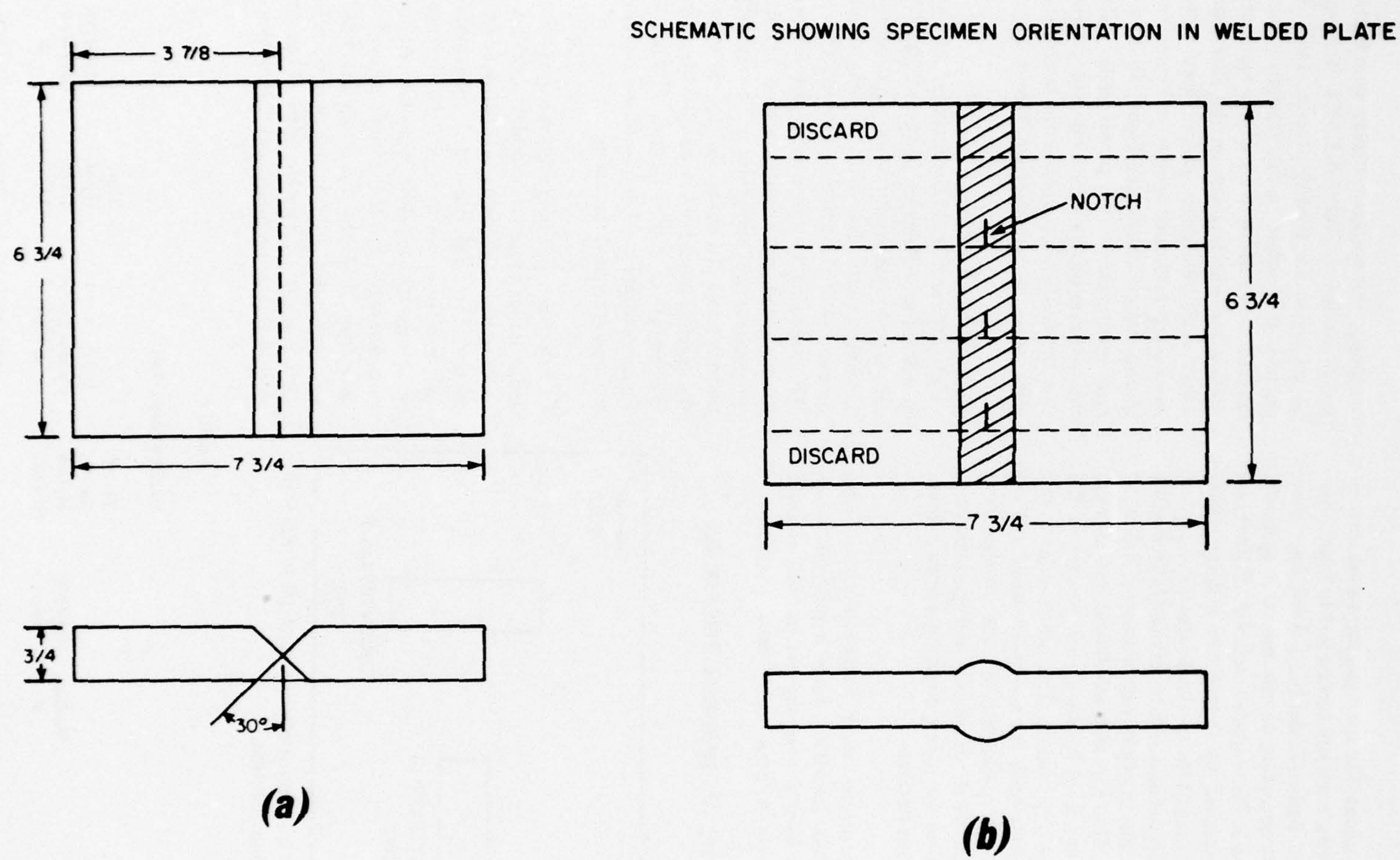


Figure 4. Weld specimen preparation blank showing (a) V-groove preparation and (b) specimen orientation. (All dimensions are in inches; metric conversion factor: 1 in. = 2.54 cm.)

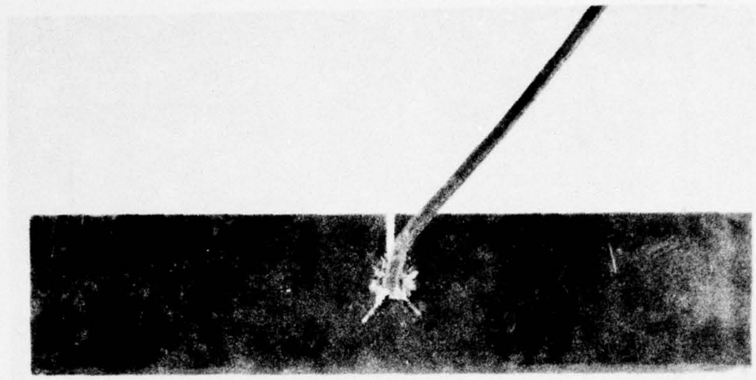


Figure 5. Dynamic tear specimen with iron-constantan thermocouple spot welded across the notch root.

Table 4

Test Results of Machine-Notched Base Plate Specimens; WR Orientation

	Temperature °C	Temperature °F	Fracture Energy ft-lb	Fracture Energy J
A1	- 190	- 310	53	72
A2	- 190	- 310	54	73
A3	- 190	- 310	49	66
A8	- 190	- 310	50	68
A9	- 140	- 220	73	99
A10	- 140	- 220	49	66
A11	- 90	- 130	82	111
A12	- 90	- 130	87	118
A15	- 60	- 76	109	148
A16	- 60	- 76	158	214
A13	- 40	- 40	187	254
A14	- 40	- 40	199	270
A4	+ 30	+ 86	194	263
A5	+ 30	+ 86	206	279
A6	+ 30	+ 86	196	266
A7	+ 30	+ 86	209	283
A17	+100	+212	210	285
A18	+100	+212	195	264

3 RESULTS AND DISCUSSION

Dynamic Tear Testing of Base Metal

Base metal (A514F steel) specimens were impact-tested at various temperatures to obtain data on the energy absorbed in fracturing the DT specimen (henceforth referred to as the fracture energy [FE] or DT energy).

Many structural steels and welds exhibit an abrupt change in fracture energy as the test temperature is decreased below room temperature. The temperature spread over which a rapid change from a relatively high fracture energy (upper shelf energy) to a much-reduced fracture energy (lower shelf energy) occurs is known as the ductile-to-brittle transition temperature (DBTT) range. The DBTT in steels is very sensitive to specimen dimensions, loading rate, microstructure, and notch acuity. Charpy V-notch specimens can be used to locate the DBTT in very high-strength, low-toughness steels but often do not adequately describe the toughness change occurring in lower-strength structural steels. Charpy impact tests on thick plate steels sometimes give results unrepresentative of the plate, hence indicating the necessity for larger specimens.

The 5/8 in. (1.59 cm) dynamic tear specimen has been found to give adequate data on heavy section structural steels. The DBTT is well defined in this test, and there are empirical correlations relating DT fracture energy to fracture toughness.[12, 13] Fracture toughness is the vehicle for relating material properties to useful design parameters.

[12] T. W. Crooker and L. A. Cooley, *Fracture Toughness of Thick Steel Sections (Correlations Between 5/8-in. and 1-in. Dynamic Tear Test Energies for Steels Under Conditions of Fully Plastic Fracture)*, Report of NRL Progress (Naval Research Laboratory, June 1969).

[13] W. S. Pellini, *Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe Design for Structural Steels*, NRL Report (Naval Research Laboratory, 3 April 1968) (also *Welding Research Council Bulletin* 130, May 1968).

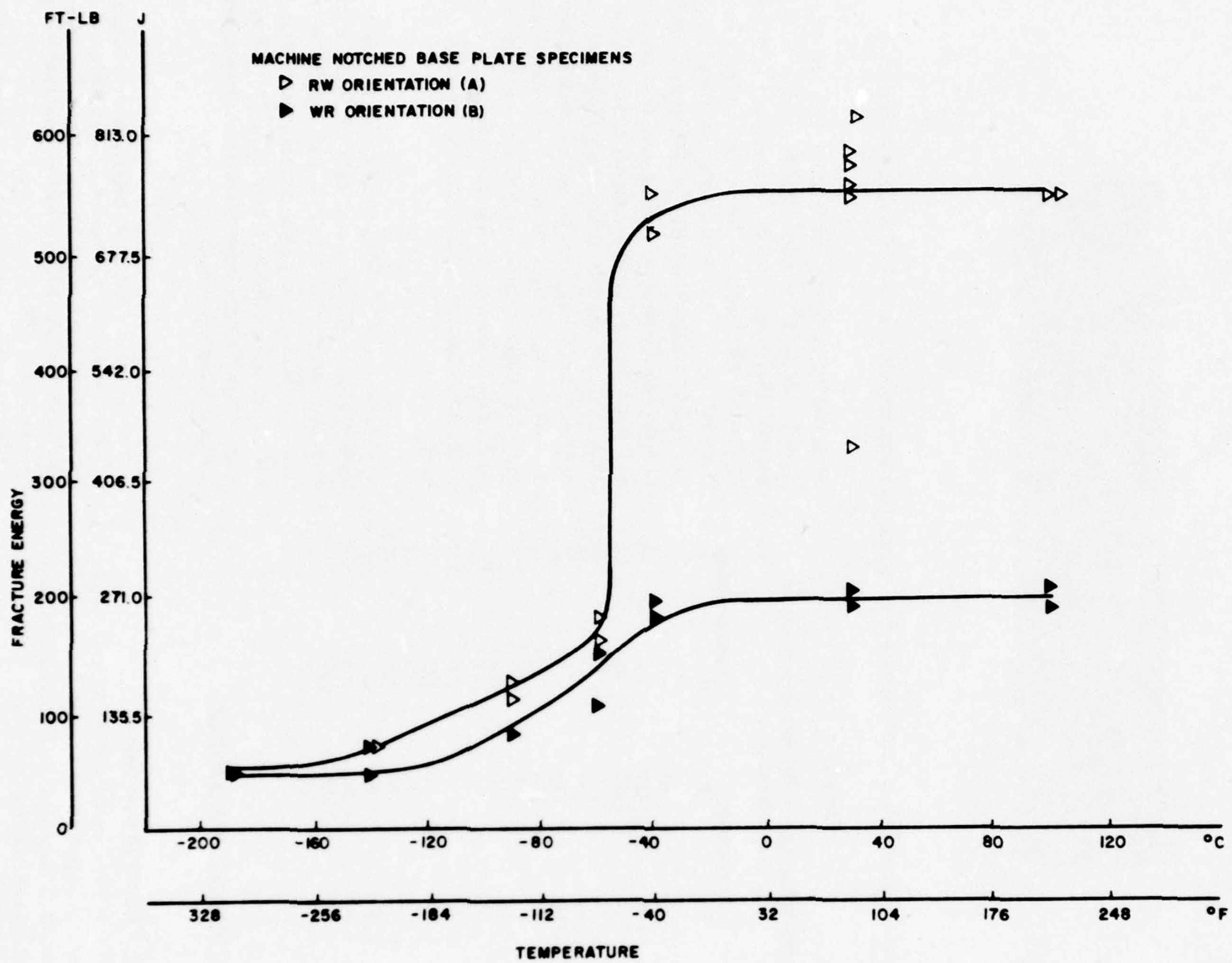


Figure 6. Fracture energy vs. temperature for machine-notched base plate specimens tested in the RW and WR orientations.

Table 4 provides data for machine-notched base plate DT specimens tested in the WR orientations; Figure 6 is a graph showing the testing results. It can be seen that the upper shelf fracture energy (FE) is approximately 200 ft-lb (271 J) and the lower shelf FE is approximately 50 ft-lb (67.8 J). The DBTT range lies between -90°C (-130°F) and -40°C (-40°F). Figure 7 shows the fracture surfaces of this series of specimens. The fractures are flat with no lateral contraction at test temperatures below -90°C (-130°C). At -60°C (-76°F), some lateral contraction can be seen in the fracture surface, although the surface is essentially flat. At -40°C (-40°F) and above, greater amounts of lateral contraction are observed, and the fracture surfaces contain greater amounts of shear failure.

Table 5 contains the data obtained for the machine-notched base plate specimens tested in the RW orientation. These data are plotted in Figure 6. The upper shelf fracture energy for this series of specimens is 550 ft-lb (745 J), which is more than twice the amount of FE observed in the WR orientation. At temperatures below -40°C (-40°F), the FE decreased rapidly to ~175 ft-lb (235 J) at -60°C (-76°F). The FE then gradually decreased to 50 ft-lb (68 J) at -190°C (-310°F). Figure 8 shows the RW orientation fracture surfaces. The fracture surfaces are similar for both orientations, but the RW specimens exhibited much more lateral contraction at room temperature and above. Specimens tested at -40°C (-40°F) and above exhibited large amounts of lateral contraction. The plastic deformation associated with the lateral contraction consumed a large amount of energy—an amount equal to or greater than the energy required to form two new fracture surfaces. Consequently, specimens which exhibited extensive lateral contraction had high DT energies. Laminations could be seen on both the RW and WR sets of fracture surfaces. These laminations reduced ductility and provided a preferred fracture path which reduced the fracture energy. Orientation of the laminations affected the amount of lateral contraction observed in the specimens.

The effects of notch acuity (or sharpness) on upper shelf fracture energy and DBTT were studied by comparing specimens whose notches had been sharpened by fatigue precracking with specimens having machined notches. A fatigue crack propagated at low stress intensity (ΔK) will produce a very sharp crack. The specimens used in this portion of the investigation had the same dimensions and orientations as the machine-notched base-plate specimens. The crack length in the fatigue precracked specimens was the same as the length of the notch in the machine-notched specimens. Both tests were conducted in the same temperature range, using the same thermocouple temperature-measuring technique. Tables 6 and 7 provide data obtained from the fatigue precracked specimens.

Table 5

Test Results of Machine-Notched Base Plate Specimens; RW Orientation

Specimen	Temperature °C	°F	Fracture Energy ft-lb	J	Remarks
B3	-190	-310	50	68	
B4	-190	-310	54	73	
B7	-190	-310	47	64	
B8	-190	-310	59	80	
B9	-140	-220	71	96	
B10	-140	-220	74	100	
B11	- 90	-130	114	155	
B12	- 90	-130	132	179	
B15	- 60	- 76	184	250	
B16	- 60	- 76	167	226	
B13	- 40	- 40	552	749	
B14	- 40	- 40	522	708	Laminations on fracture surface
B1	+ 30	+ 86	582	789	
B2	+ 30	+ 86	628	852	Laminations on fracture surface
B5	+ 30	+ 86	557	755	
B6	+ 30	+ 86	585	793	Laminations on fracture surface
B17	+100	+212	557	755	
B18	+100	+212	546	740	Laminations on fracture surface

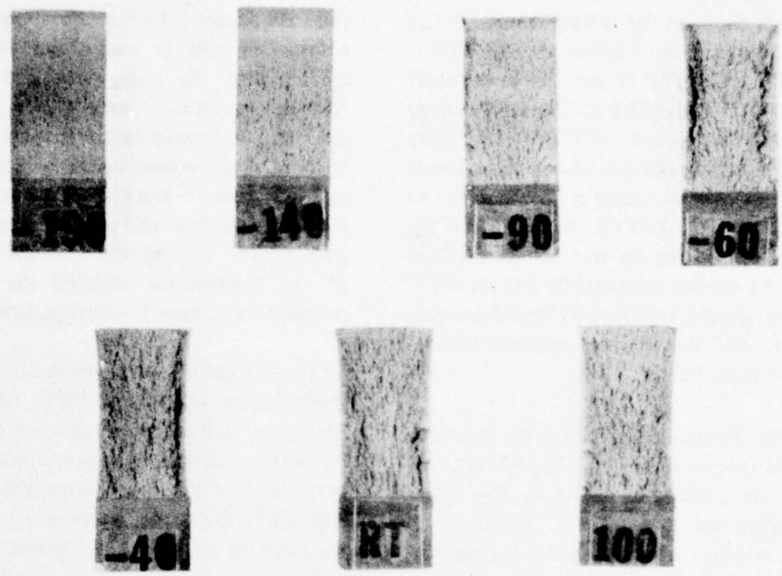


Figure 7. Fracture surfaces of machine-notched base plate specimens tested at the temperatures indicated (°C); WR orientation. (Note the large amount of lateral contraction for specimens tested above -40°C [-40°F].)

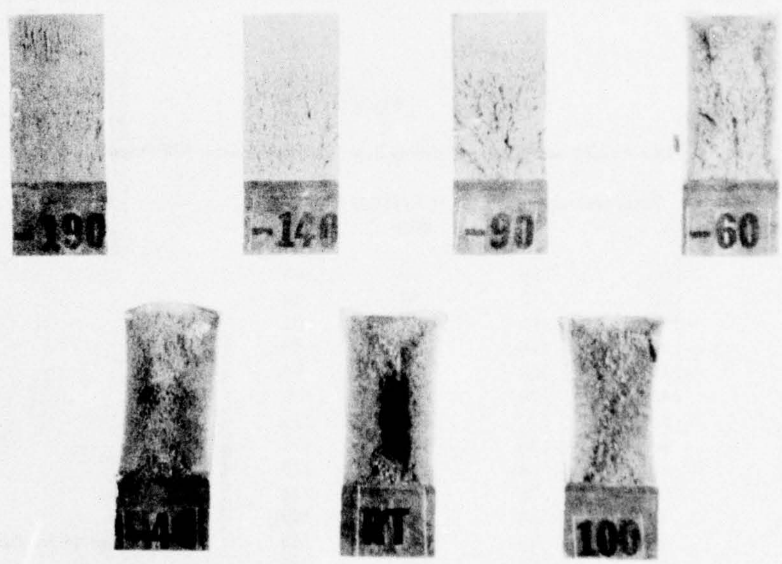


Figure 8. Fracture surfaces of machine-notched base plate specimens tested at the temperatures indicated (°C); RW orientation.

Figure 9 is a plot of the fracture energies vs. temperature for the specimens tested in the WR and RW orientations, respectively. The upper shelf FE of the precracked WR specimens was much higher than the upper shelf FE observed in the machine-notched WR specimens (Figure 6). This was unexpected, since fatigue-cracked notches generally produce FE's equal to or less than those observed in machine-notched specimens. Figure 10 shows the fracture surfaces of these specimens.

The results for the fatigue precracked specimens are as expected. The upper shelf FE of the fatigue precracked specimens was somewhat higher than the machine-notched specimens (600 ft-lb compared to 560 ft-lb [813 to 759 J]), but within the normal scatter. With decreasing temperature, the precracked specimens experienced an approximate 20°C (68°F) upward shift in the DBTT with respect to the machined specimens. There was a decrease in FE between the fatigue-precracked and machine-notched specimens of almost 250 ft-lb (136 J) at -40°C (-40°F). Figure 11 shows fracture surfaces of the RW orientation specimens. The fracture surfaces were very similar to those obtained for machine-notched specimens. The fatigue crack region is easily seen in the figure. Close examination of the fracture surfaces showed that little lateral contraction occurred in specimens tested at -60°C (-76°F) and below. The amount of lateral contraction also appears to be reduced somewhat.

Figure 19 (p 29) is a summary plot of all data obtained in this investigation.

Dynamic Tear Testing of Weld Metal

Dynamic tear tests were conducted on welded specimens with (1) sound welds, (2) welds containing localized clustered porosity, and (3) welds having linear porosity extending along the weld length. In all specimens the fracture occurred completely through the weld metal. Duplicate specimens were fabricated and tested to provide an indication of the scatter in toughness of similarly welded joints. Table 8 contains the data for sound weld specimens, and Figure 12 plots their fracture energy vs. temperature. The upper shelf toughness of the sound weld specimens ranged between

Table 6

Test Results of Fatigue Precracked Base Plate Specimens; WR Orientation

Specimen	Temperature °C	Temperature °F	Fracture Energy ft-lb	Fracture Energy J	Remarks
PCA10	- 190	- 310	47	64	
PCA3	- 140	- 220	51	69	
PCA7	- 90	- 130	70	95	
PCA9	- 60	- 76	87	118	
PCA8	- 40	- 40	292	396	Laminations on fracture surface
PCA6	+ 30	+ 86	474	643	Laminations on fracture surface
PCA1	+100	+212	575	780	
PCA2	+100	+212	543	736	

Table 7

Test Results of Fatigue Precracked Base Plate Specimens; RW Orientation

Specimen	Temperature °C	Temperature °F	Fracture Energy ft-lb	Fracture Energy J	Remarks
PCB4	- 190	-310	56	76	
PCB1	- 140	- 220	60	81	
PCB2	- 90	- 130	72	98	
PCB9	- 60	- 76	102	138	
PCB10	- 40	- 40	202	274	Laminations on fracture surface
PCB6	- 40	- 40	273	370	Laminations on fracture surface
PCB7	+ 30	+ 86	581	788	Laminations on fracture surface
PCB8	+100	+212	602	816	Laminations on fracture surface

Table 8

Test Results of Sound Weld Specimens

Specimen[a]	Temperature °C	°F	Fracture Energy ft-lb	J	Remarks[b]
WB3	- 190	- 310	57	77	Small LOF
WB7	- 190	- 310	59	80	Small LOF
WB6	- 140	- 220	72	98	Small LOF
WB9	- 140	- 220	62	84	Small LOF
WB8	- 90	- 130	86	117	Narrow, full-length LOF
WB10	- 90	- 130	78	106	Full-length LOF
WB12	- 60	- 76	188	255	Small LOF
WB13	- 60	- 76	163	221	Small LOF
WB15	- 40	- 40	256	347	
WB4	+ 30	+ 86	430	583	
WB11	+ 30	+ 86	359	487	Narrow, full-length LOF
WB1	+100	+212	689	934	
WB5	+100	+212	446	605	
WB14	+100	+212	415	563	
W#54	- 190	- 310	52	71	Small LOF
W#15	- 190	- 310	52	71	
W#46	- 190	- 310	59	80	
W#37	- 140	- 220	80	108	
W#28	- 90	- 130	112	152	Full-length LOF
W#59	- 60	- 76	172	233	
W#210	- 40	- 40	423	574	
W#412	- 40	- 40	429	582	
W#21	+ 30	+ 86	442	599	Full-length LOF
W#52	+ 30	+ 86	377	511	
W#33	+ 30	+ 86	520	705	
W#413	+100	+212	356	486	
W#111	+100	+212	370	502	

[a] Duplicate weld specimens were tested

[b] Lack of fusion (LOF)

360 and 540 ft-lb (485 to 732 J). The scatter in the upper shelf fracture energy results from normal toughness variations generally found in welds and from the presence of minor weld discontinuities. The weld specimen's upper shelf toughness was midway between the machine-notched base plate upper shelf toughness for the RW and WR orientations (Figure 6). The DBTT range of the welded specimens was broader than that observed for the base plate specimens; the upper knee of the energy-temperature curve was elevated by approximately 22°C (40°F), and a gradual reduction in FE was observed between 30°C (86°F) and -90°C (-130°F). At low testing temperatures, below -90°C (-130°F), the FE was the same as for the base metal, i.e., ~50 ft-lb (68 J).

Figure 13 shows fracture surfaces of typical sound weld specimens. The fracture surfaces tended to be flat for specimens tested at -60°C (-76°F) and below; at all temperatures, the fracture surfaces of the welded specimens were flatter than those observed on the base plate specimens. Very little lateral contraction was seen in the welded specimens even at 100°C (212°F). The specimen shown in Figure 13, which was tested at -90°C (-130°F), has nearly full-length lack of fusion discontinuity. The discontinuity had no observable effect on the weld's FE.

Clustered porosity was a weld discontinuity of particular interest in this research. Duplicate specimens (series C and D) containing clustered porosity were fabricated like the sound weld specimens except that the shielding gas was momentarily interrupted. The specimen blanks were x-ray radiographed and the radiographs were used to lay out the specimens for machining. The clustered porosity was intended to be located at the base of the machined notch and used as the crack starter. The porosity would then be the major influence on the crack initiation toughness. Unfortunately, it was not possible to always locate the cluster

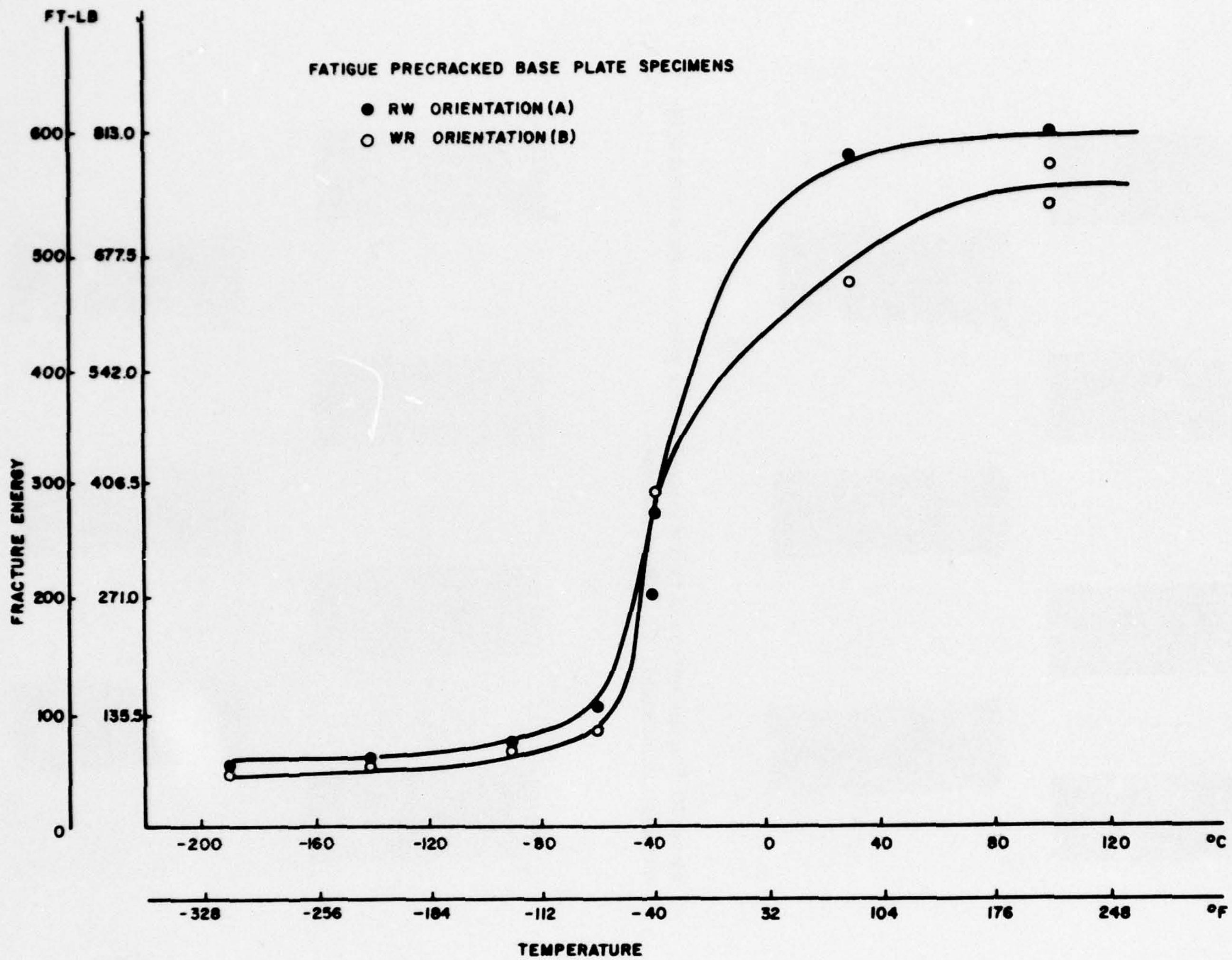


Figure 9. Fracture energy vs. temperature for fatigue precracked base plate specimens tested in the RW and WR orientations.

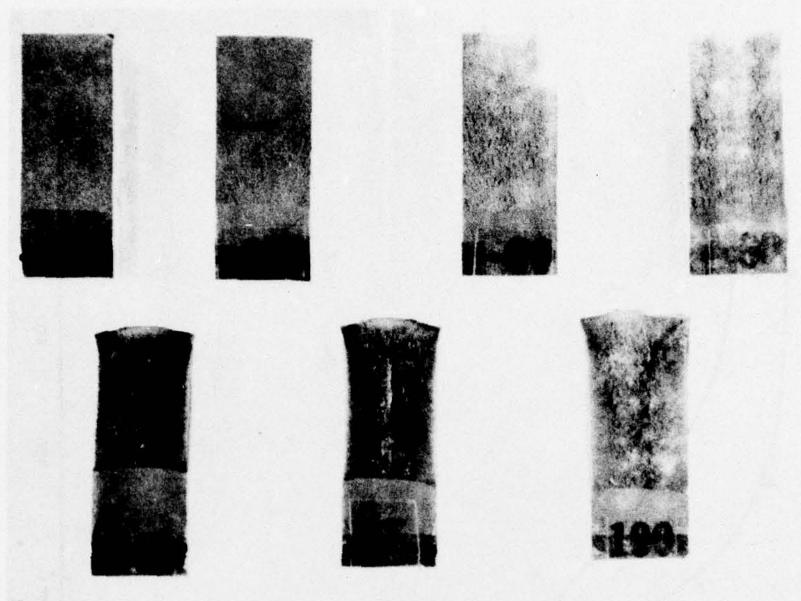


Figure 10. Fracture surfaces of fatigue precracked base plate specimens tested at the temperatures indicated (°C); (WR orientation).

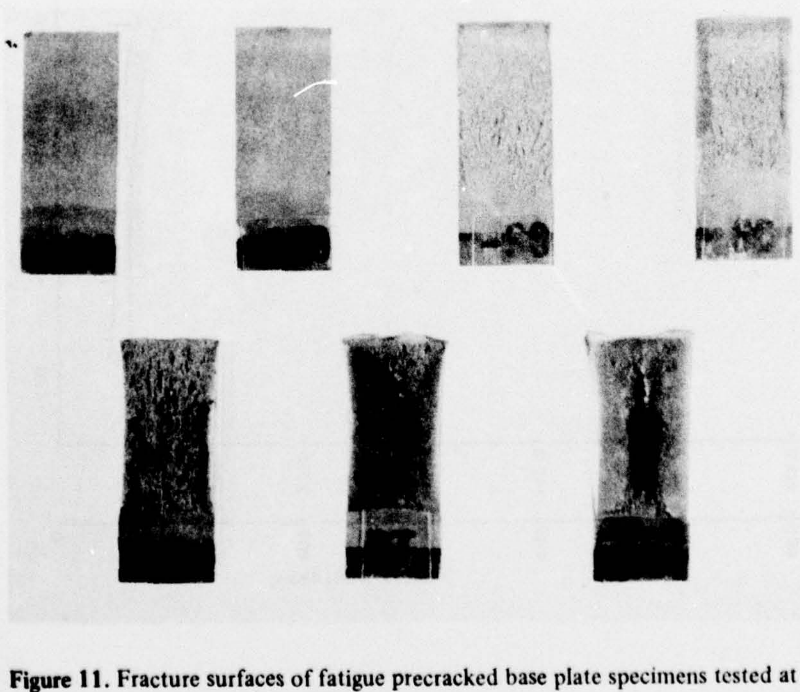


Figure 11. Fracture surfaces of fatigue precracked base plate specimens tested at the temperatures indicated (°C); (RW orientation).

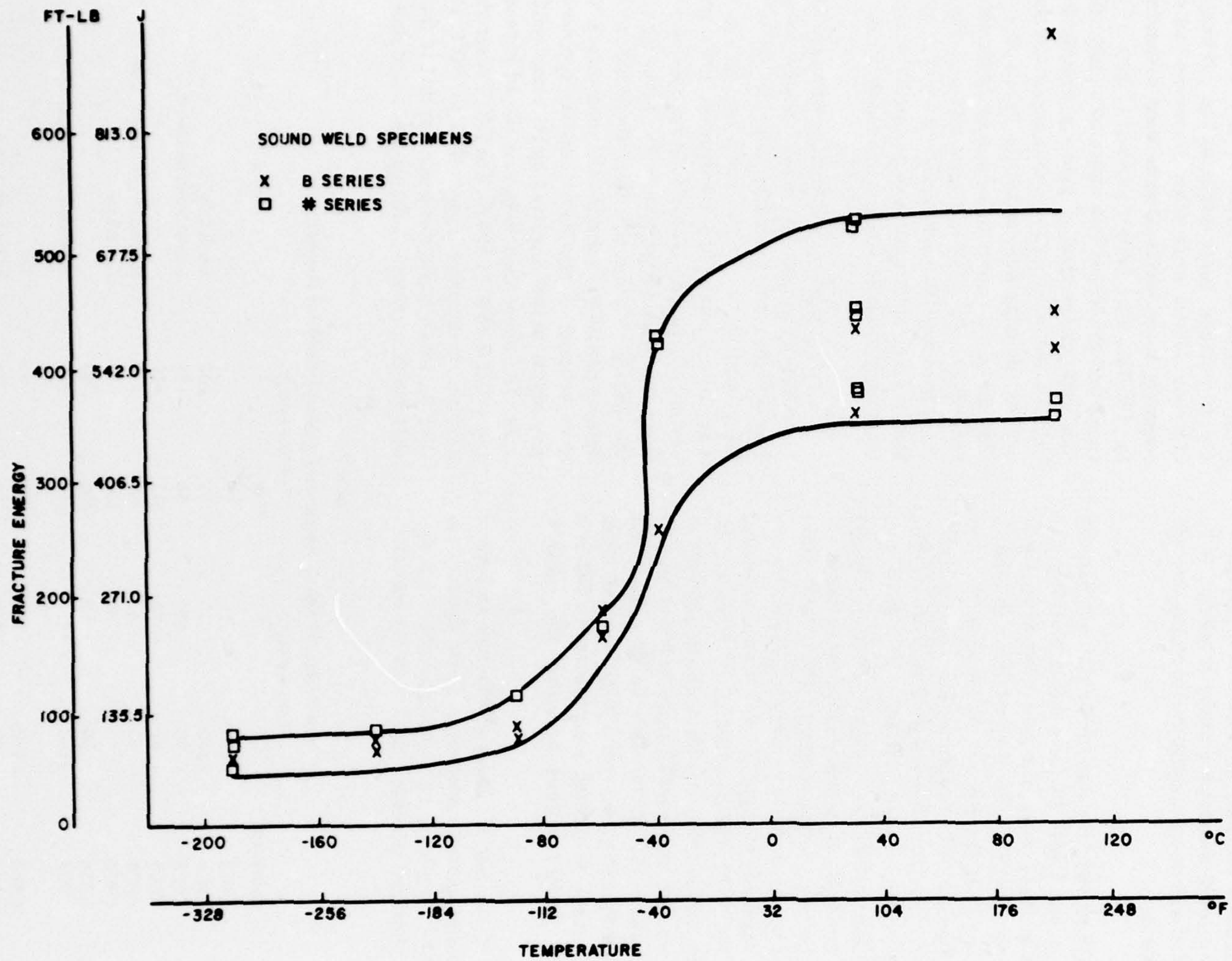


Figure 12. Fracture energy vs. temperature for sound weld specimens.

accurately at the notch tip, and some specimens had a large amount of porosity while others had little. These two factors would account in part for the scatter in fracture energy obtained in these sets of specimens. The presence of observable porosity is believed to be evidence of widespread invisible microporosity throughout the weld.

Table 9 provides the data for the clustered porosity specimens, and Figure 14 plots this information as a function of temperature. The data shown in this figure indicate an upper shelf FE of about 340 ft-lb (460 J). This is less than the RW orientation base plate but greater than the WR orientation. The upper shelf FE was slightly less than the sound weld specimens (Figure 12) and ranged between 310 and 360 ft-lb (418 to 475 J). The scatter was as expected and due to the varying amounts of porosity and the presence of small, secondary discontinuities. The DBTT range exhibited by the clustered porosity specimens was very gradual, beginning at about 0°C (32°F) and extending to -90°C (-130°F). The extended DBTT range was the most deleterious effect of the clustered porosity in welds. This shift in the DBTT range to higher temperatures reduces the fracture-safe design, which was established by using base metal properties, and could be instrumental in causing a component to fail in a northern climate's normal operating temperatures.

Figures 15a and 15b show the fracture surfaces of the clustered porosity specimens. These figures were the result of duplicate tests conducted on welds containing clustered porosity. Both sets of specimens exhibited generally flat fractures over the entire temperature range, and very little lateral contraction occurred even at 100°C (212°F). The clusters were not always located at the notch tip and often varied in size. In addition, some specimens had full-length lack of fusion defects while other specimens had macroscopically sound welds. Despite these discontinuities, the FE data were fairly consistent (Figure 14), indicating that cluster size had only a secondary effect on toughness. The method of inducing porosity into the weld resulted in the presence of microporosity throughout the adjoining weld metal; the interruption of the shielding gas is known to be a cause of localized embrittlement. The embrittlement was probably more deleterious than the mechanical presence of the porosity and, of equal importance, is an occurrence which sometimes happens during GMA welding in the field.

The clustered porosity specimens were used to assess the effects of porosity on crack initiation toughness. This was further extended by using the ability of the DT specimens to evaluate crack propagation toughness. In this part of the investigation, linear porosity was introduced into the welds in the specimen blanks along the crack propagation path. Table 10 contains the data for the linear porosity specimens, and these data are plotted in Figure 16. The toughness vs. temperature behavior of the linear porosity specimens was very similar to that displayed by the sound weld specimens. The upper shelf toughness ranged between 370 and 440 ft-lb (500 to 594 J). The DBTT range occurred over the temperature range of 0 to -90°C (32° to -130°F), which is about the same as that of the sound weld metal specimens, although somewhat more grad-

Table 9

Test Results of Welded Specimens Containing Clustered Porosity

Specimen[a]	Temperature °C	Temperature °F	Fracture Energy ft-lb	Fracture Energy J	Remarks[b]
CPC2	-190	-310	57	77	
CPC1	-140	-220	80	108	Small LOF
CPC3	-90	-130	88	119	Sound weld, no cluster
CPC5	-60	-76	235	319	
CPC6	-40	-40	386	523	No cluster, full-length LOF
CPC4	-40	-40	203	275	Small LOF
CPC8	+30	+86	356	483	
CPC7	+100	+212	314	426	No cluster, full-length LOF
CPD6	-140	-220	63	85	
CPD4	-90	-130	68	92	Full-length LOF
CPD2	-60	-76	216	293	Full-length LOF
CPD1	-40	-40	238	323	Full-length LOF
CPD3	+30	+86	304	412	Small LOF
CPD5	+100	+212	357	484	

[a] Duplicate specimens tested

[b] Lack of fusion (LOF)

ual. The scatter in the data is a result of the small number of specimens tested and the variation in the amount of porosity on the fracture surfaces. The upper shelf FE of the linear porosity specimens was greater than that observed in the specimens containing clustered porosity at the notch tip, and the DBTT range was shifted slightly to lower temperatures. This may have been caused by a combination of two factors. The first was that the porosity leads to more rapid heat loss in the weld, and hence a finer microstructure; the second was that the linear porosity provided a pathway for hydrogen, nitrogen, and other gases. Therefore, less gas was absorbed into the weld metal, and, consequently, the embrittlement caused by a loss of shield gas was reduced. The FE's of the linear porosity specimens were still greater than the WR orientation base metal.

Table 10

Test Results of Welded Specimens Containing Full-Length Linear Porosity

Specimen	Temperature °C	°F	Fracture Energy ft-lb	J	Remarks[a]
COE6	- 190	- 310	52	75	Full-length LOF
COE8	- 140	- 220	59	80	Small LOF
COE1	- 140	- 220	60	81	Full-length LOF
COE2	- 90	- 130	93	126	Narrow, full-length LOF
COE4	- 60	- 76	277	376	Full-length LOF
COE9	- 60	- 76	229	311	
COE7	- 40	- 40	271	367	
COE10	- 40	- 40	284	385	Small LOF
COE5	+ 30	+ 86	436	591	Small LOF
COE11	+100	+212	381	517	Small LOF

[a] Lack of fusion (LOF)

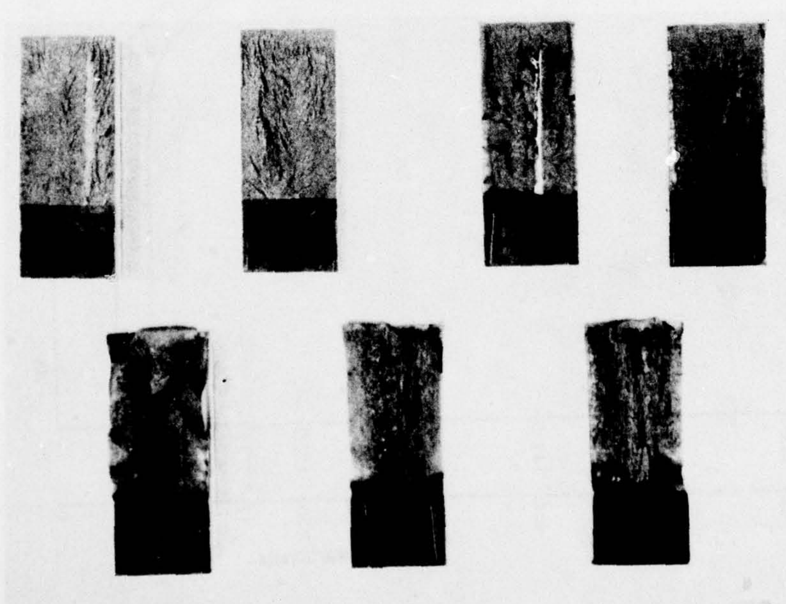


Figure 13. Fracture surfaces of typical sound weld specimens tested at the temperatures indicated (°C). (All fractures are through the weld metal.)

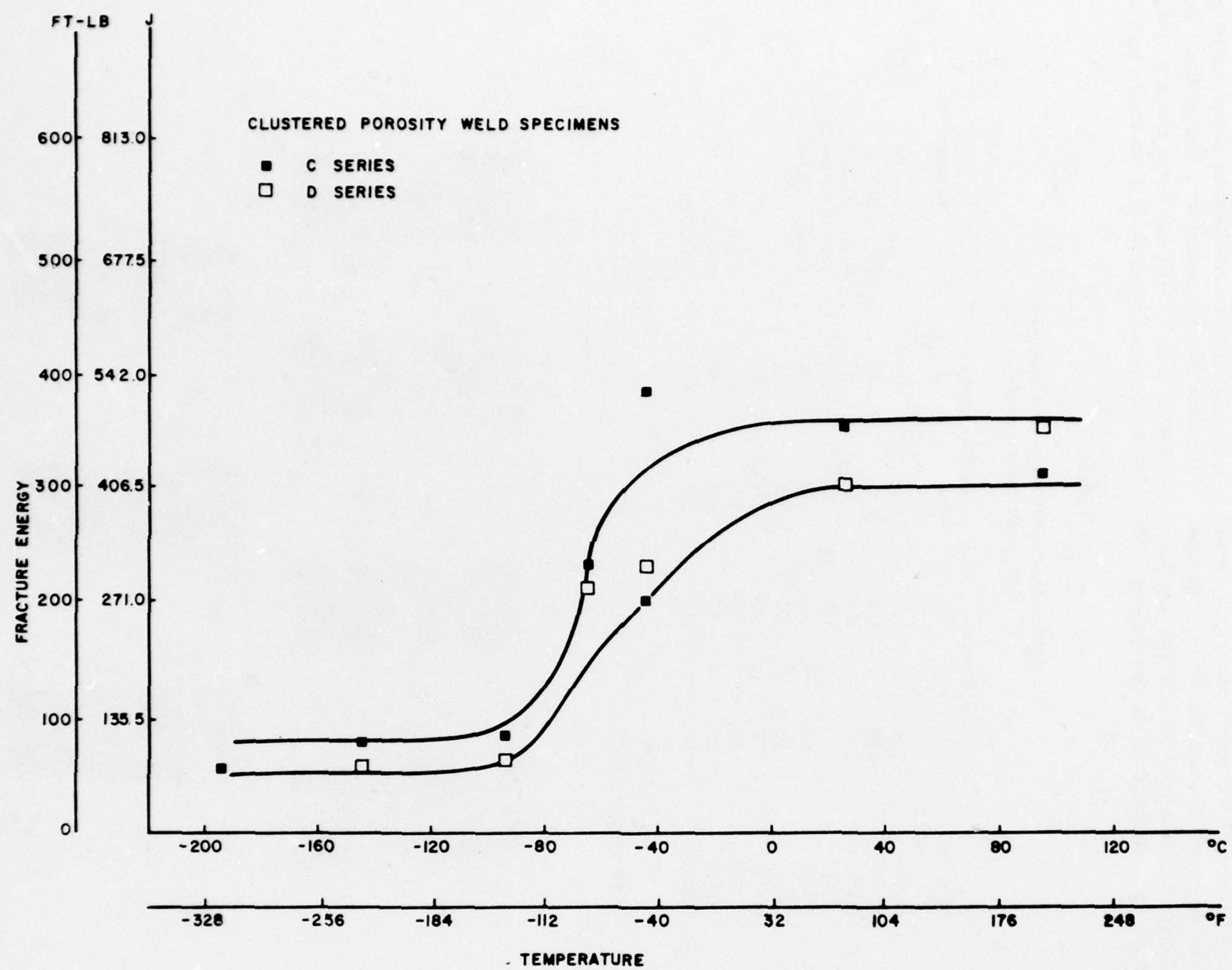
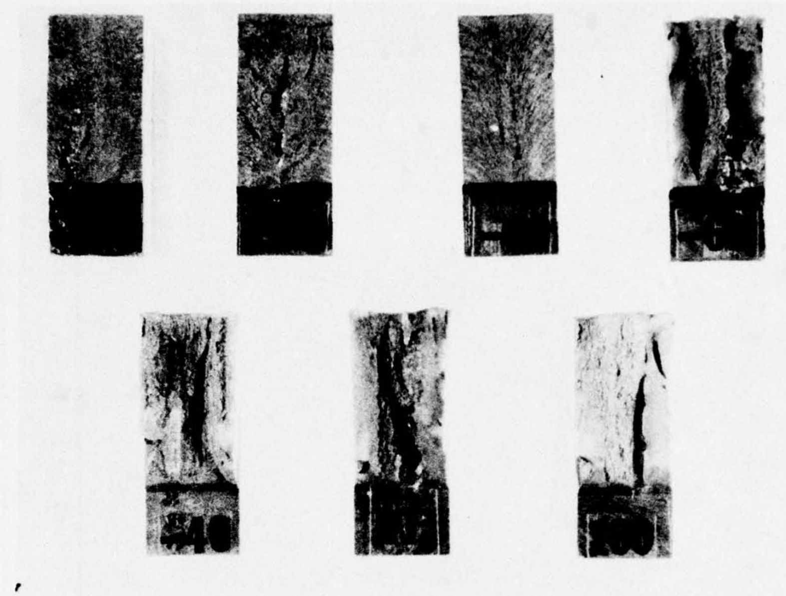


Figure 14. Fracture energy vs. temperature for weld specimens containing clustered porosity.



(a)

(b)

Figure 15. Fracture surfaces of weld specimens containing clustered porosity tested at the temperatures indicated (°C). Series C is shown in (a), and Series D is shown in (b). (All fractures are through the weld metal.)

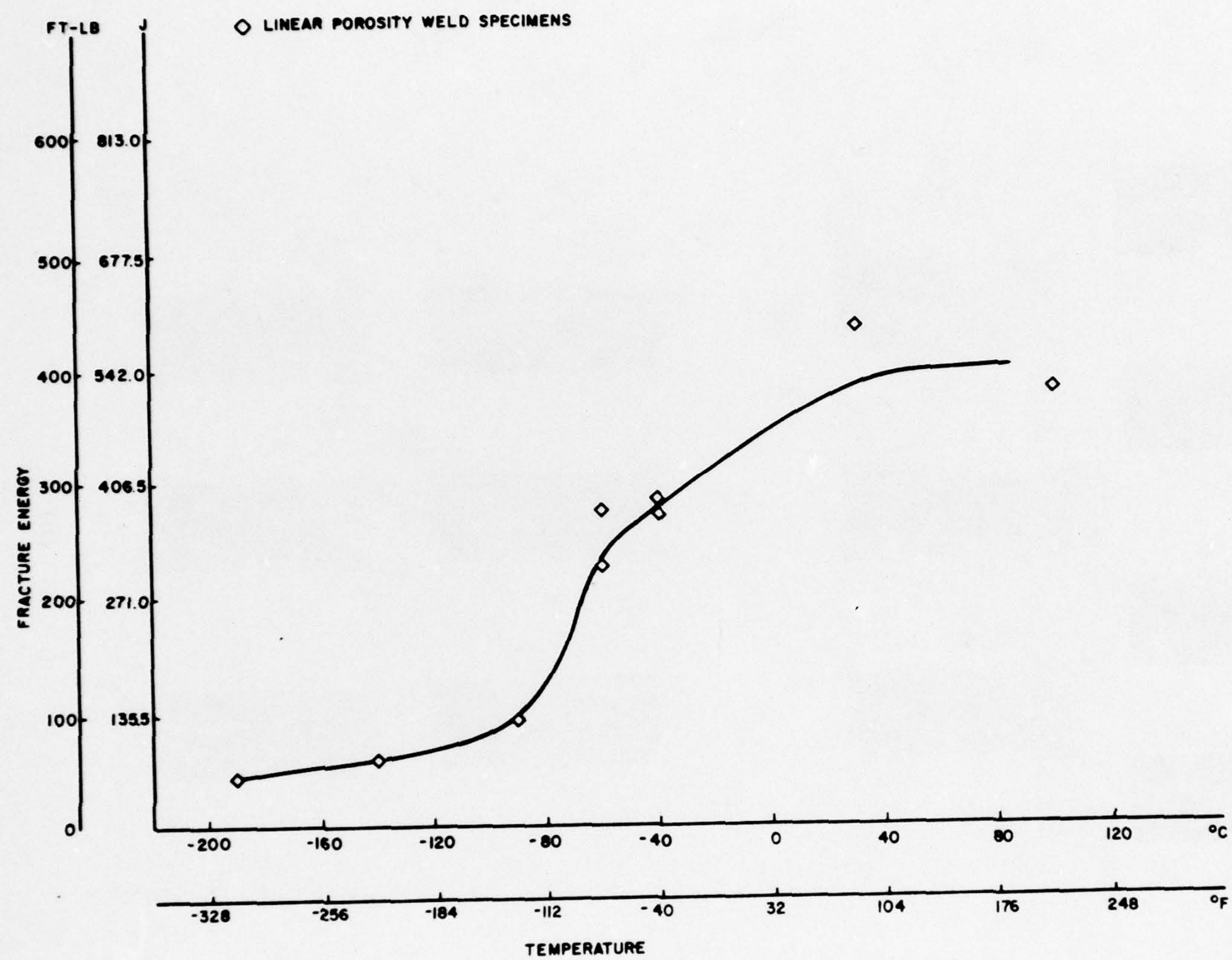


Figure 16. Fracture energy vs. temperature for weld specimens containing linear porosity along the fracture path.

Figure 17 shows the fracture surfaces of the specimens containing linear porosity. As seen in this figure, the amount of porosity on the fracture surfaces varied from specimen to specimen, and the location varied from close to the center to being completely along one side. The size of the pores was fairly uniform in all specimens. Some specimens also lacked fusion in small amounts along the length of the fracture. This was believed to have had very little effect on the fracture energy. The fracture surfaces are flat for test temperatures of -60°C (-76°F) and below. The lateral contraction that was seen occurred in specimens whose porosity was located along one side only.

Two specimens were tested at room temperature and at liquid nitrogen temperature to see if post-weld heat treatment affected the upper and lower shelf fracture energies. The specimens were post-weld heat-treated at 538°C (1000°F) for 1 hour. The testing was conducted at -190°C (-310°F) and 30°C (86°F) (see Table 11). Figure 18 is a plot of fracture energy vs. temperature. It can be inferred from the data of these two specimens that post-weld heat treatment at 538°C (1000°F) has apparently only a minor effect on the upper and lower shelf toughnesses. The lower shelf toughness was the same as all the other sound weld specimens tested, but the upper shelf was slightly reduced. Figure 19 is a composite graph of all the specimens tested.

Table 11

Test Results of Stress-Relieved Sound Weld Specimens

	Temperature		Fracture Energy	
	°C	°F	ft-lb	J
SR1	- 190	- 310	53	74
SR2	+ 30	+ 86	339	445

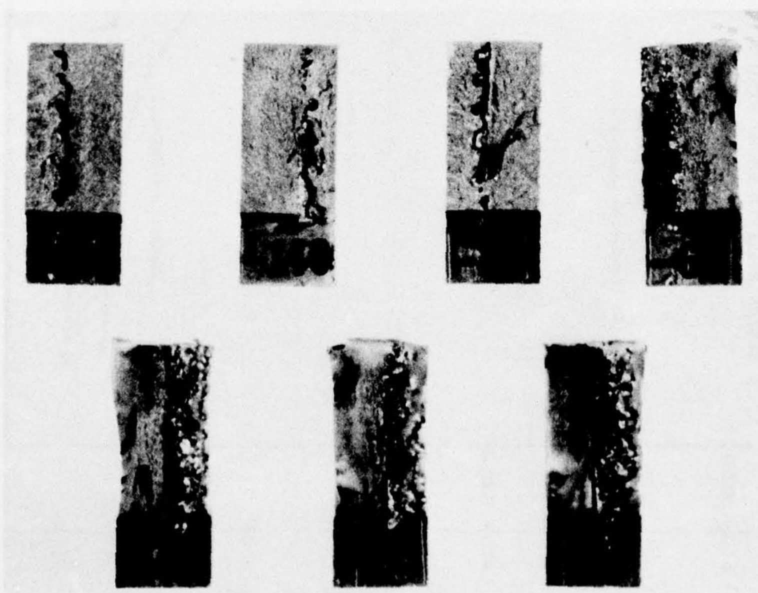


Figure 17. Fracture surfaces of weld specimens containing linear porosity (tested at the temperatures indicated [°C]). (All fractures are through the weld metal.)

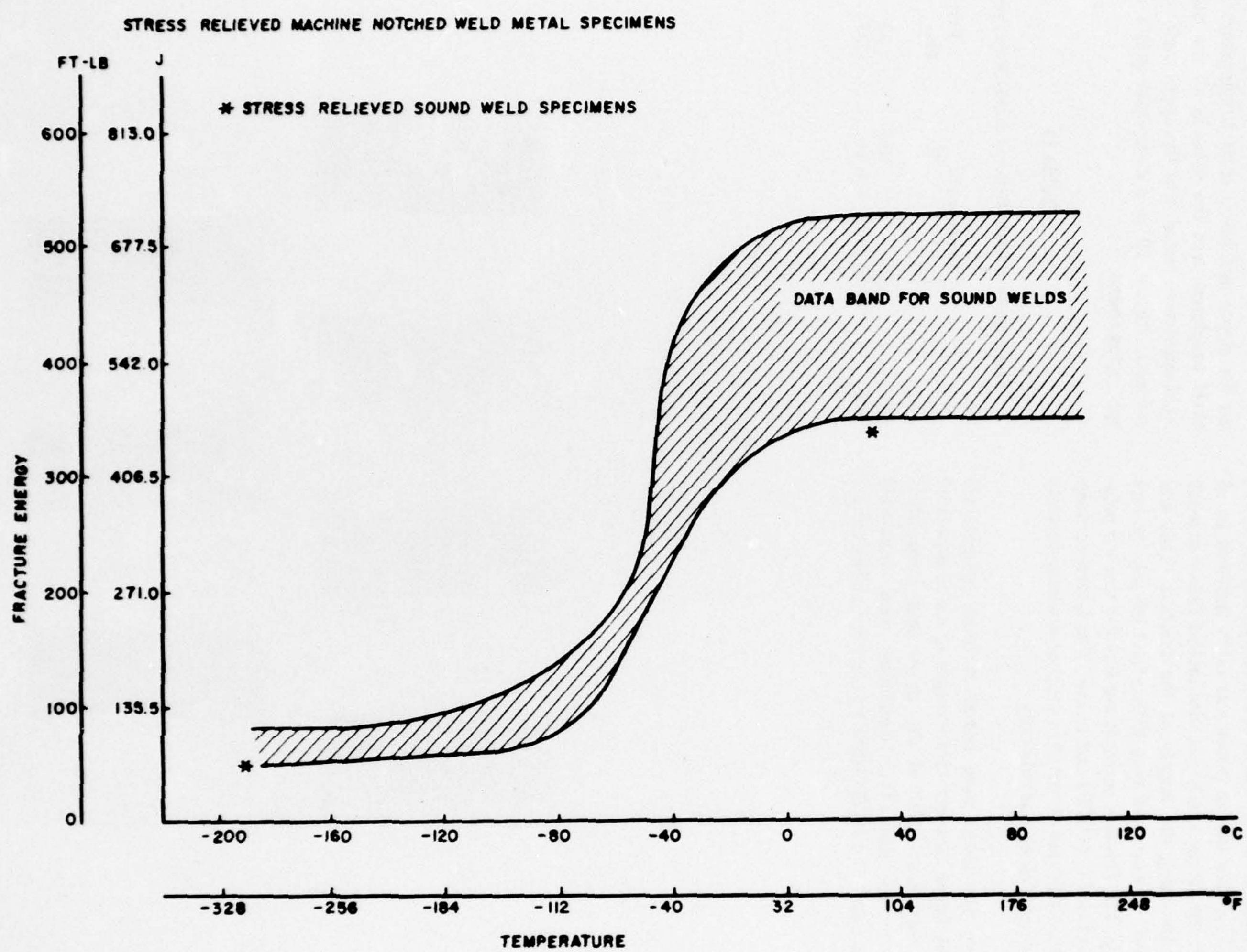


Figure 18. Fracture energy vs. temperature of stress-relieved weld specimens (°C).

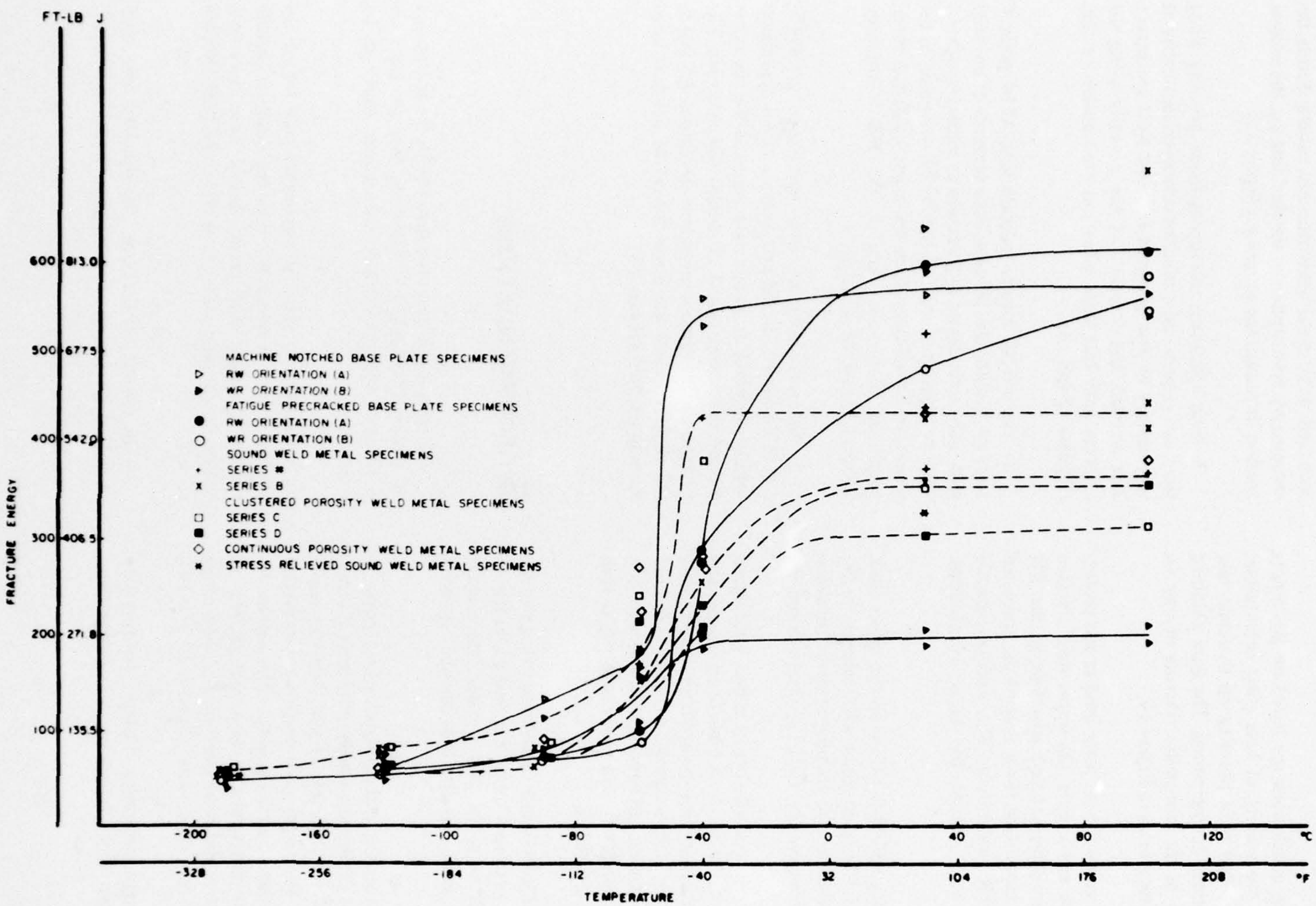


Figure 19. Composite curves of fracture energy vs. temperature for all data obtained in this investigation (°C). (Note the relative magnitudes of the upper shelf energies and the temperatures of the ductile-to-brittle transitions.)

4 CONCLUSIONS

The following conclusions are based on the results of research on the effects of base plate orientation, notch sharpness, and weld porosity on dynamic tear toughness at various temperatures. The data obtained are summarized in the composite fracture energy vs. temperature curves shown in Figure 19.

1. The A514 grade F base plate used in this investigation was highly anisotropic; the upper shelf fracture energy of the machine-notched specimen in the RW orientation was more than twice that of the specimen tested in the WR orientation. The ductile-to-brittle transition was very abrupt for both orientations. (Figure 6).

2. Notch acuity had little effect on the upper shelf toughness in the RW orientation with respect to the base plate but increased the ductile-to-brittle transition temperature approximately 20°C. (Figures 6 and 9).

3. The upper shelf toughness of sound weld specimens fell between the two base plate orientations. The RW orientation obtained for the machine-notched base plate had an upper shelf toughness of ~550 ft-lb (745 J), sound weld metal ranged between 360 and 400 ft-lb (465 to 540 J), and WR base plate was ~200 ft-lb (270 J). (Figures 6 and 12).

4. The ductile-to-brittle transition temperature range of sound weld specimens was shifted to higher temperatures and extended over a wider temperature range than that shown by the base metal (Figures 6 and 12).

5. Welded specimens containing clustered porosity at the notch root exhibited a mean upper shelf fracture energy of about 60 ft-lb (80 J) less than the sound weld specimens. The upper shelf toughness was greater than the WR orientation base plate. The ductile-to-brittle transition temperature range was shifted to higher temperatures and extended over a broader range than the sound weld specimens. (Figures 12 and 14).

6. The specimens containing clustered porosity had the lowest upper shelf toughness and the highest ductile-to-brittle transition temperature range of all the weld specimens. The cause of these is attributed to localized weld metal embrittlement caused during the momentary interruption of the shielding gas, the process used to introduce the porosity. (Figure 19)

7. Weld specimens containing linear porosity along the fracture path had a toughness-temperature behavior very similar to that observed in sound weld specimens. The amount and location of the porosity along the fracture path had little effect on the fracture energy. (Figures 12 and 14)

8. The overall results indicate that A514 grade F steel weldments can tolerate large amounts of porosity with only a moderate degradation in impact toughness with no significant shift in the DBTT compared to the sound weld specimens. Even the worst welds had better toughness than base plate in the WR orientation. (Figures 12, 14, 16, and 19)

9. Stress-relieving of two specimens at 538°C (1000°F) for 1 hour did not produce any results significantly different from the data reported for the other welded specimens tested at similar temperatures. The upper shelf toughness specimens developed FE which fell slightly below the lower bound of the data band for sound welds. (Figure 18)

5 RECOMMENDATIONS

1. Dynamic tear test requirements for the acceptance of a material should be written so that the tests are conducted with the notch orientations likely to be found in service.

2. Structural steels and weldments used for critical applications at temperatures near the ductile-to-brittle transition temperature range should have tests conducted in the weld metal, base plate, and heat affected zone.

3. In critical applications, the dynamic tear tests should be conducted using fatigue precracked notches.

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