

# Welding Research

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## Fracture Toughness of Pressure Vessel Steel Weldments

PVRC exploratory fracture mechanics tests of A542 and A517F weldments demonstrate that useful  $K_{Ic}$  data can be obtained and general features of the fracture toughness results are also found in conventional Charpy V-notch test data

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**ABSTRACT.** It has long been recognized that the use of welding as a fabrication method can pose some complex problems for the design engineer who must consider the heterogeneous nature of the welded joint. Within a large weldment, particularly when fabricated from a high strength steel, a gamut of microstructures exists in and around the region of the weld. Each of these microstructures has significantly different fracture characteristics and the characteristics of a particular zone or region can influence the behavior of the weldment as a whole.

The purpose of this investigation was to develop a proper technique for obtaining valid fracture toughness data on the specific regions of a weld composite (base metal, heat-affected zone, and weld metal) and to determine to what extent the conditions of heat input and thermal stress relief will be beneficial to the fracture toughness of pressure vessel weldments. The weldments tested were A517-F and A542-Class 3 steel in the form of 2 in. thick plate welded with the submerged arc process. Three-point slow-bend fracture toughness specimens as

well as conventional Charpy impact and tension test specimens were used in the program.

Valid  $K_{Ic}$  fracture toughness data were obtained for 2-inch thick steel weldments over the range of  $-200$  to  $0^\circ$  F. The balance of fracture toughness properties of the as-welded A517-F weldment were found to be good. Both the weld deposit and heat-affected zone exhibited toughness levels that were superior to the base metal. However, stress relief treatments adversely affected the A517-F weld and heat-affected zone toughness. Its effect on the base metal was negligible.

Contrasting data were obtained for the A542 weldments. In general, it was found that the base metal toughness is high and the weld metal toughness is low with the heat-affected zone falling in the intermediate range. The high temperature ( $1225^\circ$  F) stress relief treatment improved the toughness of the heat-affected zone over low temperature ( $1125^\circ$  F) treatment but its influence on the weld metal was mixed.

The  $K_{Ic}$  fracture toughness of both steels and welds was found to exhibit a strong temperature dependence, thereby giving rise to very high levels of crack toughness at temperatures approaching room temperature.

### Introduction

The use of welding and other join-

ing methods can pose some difficult problems for the engineer who is designing for a high degree of reliability and uniformity. This has become critical in recent years, since welded higher alloy steels which have higher strength and thus higher allowable stresses are increasingly employed. One of the primary reasons for failure in high strength materials is that structural components (welded or unwelded) contain flaws and discontinuities which act to trigger crack propagation—the bigger the flaw, the greater the danger of failure. The size of the flaw that will initiate catastrophic failure depends on the stress level and the fracture toughness of the material in which it is situated. Whereas relatively large flaws may have little detrimental effect in low strength materials operated at ambient temperatures, small flaws can cause unstable fracture at low operating temperatures or in high strength materials;<sup>1,2</sup> and these flaws may be difficult to detect by practical inspection techniques.

These problems are more acute in weldments, since the microstructures of practical welds are not as uniform with respect to constituents as wrought alloys. The microstructures of welds differ from those of base

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metals in that they are rapidly solidified structures. The weld metal may have several different phases, or composition variables from point to point in one phase, or variations in grain size or inclusion shape or size. These variations are often modified by subsequent weld passes made on top of earlier deposits. Furthermore, subcritical size flaws formed during welding can become critical, for a given nominal stress if residual stresses are present. Thermal treatment subsequent to welding will also contribute to the uncertainty since such treatments may reduce the toughness of the weld metal or heat-affected zone, thereby increasing the chance of fast fracture.

The ability of a pressure vessel to resist brittle fracture is of the utmost importance in design so as to ensure the safe operation of the vessel. Fracture mechanics as a design basis has only recently been applied to pressure vessels. As an approach to understanding the brittle fracture phenomenon in pressure vessel steels, fracture mechanics provides a quantitative basis on which to assess the potential of brittle fracture and to develop criteria for designing against failure during the life of a pressure vessel.

The linear-elastic fracture mechanics approach to the design against failure of structural materials is basically a stress intensity consideration in which stress intensity criteria are established for fracture instability in the presence of a crack.<sup>3,4</sup> Consequently, a basic assumption in employing this technology is that a crack or crack-like defect exists in the structure. The elastic stress field in the near vicinity of a crack tip can be described by a single term parameter designated as the stress intensity factor  $K$ .<sup>3</sup> It is a function of the flaw geometry and the nominal stress acting in the region in which the flaw resides. Therefore, if the relationship between the stress intensity factor and the pertinent external variables (applied stress and flaw size) is known

for a given structural geometry containing a particular type defect, the stress conditions in the region of the crack-tip can be established from knowledge of the applied stress and flaw size alone.

The criterion for brittle failure in the presence of a crack-like defect is that rapid failure (instability) will occur whenever the crack tip stresses exceed some critical condition. Since the crack tip stress field can be described in terms of the stress intensity factor  $K$ , a critical value of the stress intensity factor, conventionally designated by the lower case subscript  $c$ , can be used to define the critical crack tip stress conditions for failure. However,  $K_c$  is not insensitive to boundary conditions, such as plate thickness and to a lesser but significant degree, to specimen width. This dependence results from the gradual way in which the resistance to crack growth in a plate approaches a limiting value. Much of this difficulty can be removed by prescribing full constraint in the direction parallel to the crack front. For the opening mode of loading (tension stresses perpendicular to the major plane of the flaw) under brittle plane strain conditions (limited crack tip plasticity), the critical stress intensity factor for fracture instability is designated as  $K_{Ic}$ .

Metals develop a plasticized region at the crack tip, which can be defined generally as a function of the ratio  $(K/\sigma_{ys})^2$ , where  $\sigma_{ys}$  is the yield strength of the material. Except for conditions of extreme brittleness, fracture is initiated within this plastic zone. The instability event is basically related to a plastic strain limit (ductility) of the metal crystals located in the plastic zone when stored elastic energy is present.

Unstable crack movement depends on the formation of a critical plastic zone size; the larger the plastic zone size at fracture, the tougher the material. Since the critical plastic zone size is a function of  $(K_{Ic}/\sigma_{ys})^2$ , it is this ratio which properly defines fracture

conditions, and not  $K_{Ic}$  by itself.

The physical significance of plane strain condition mentioned above is that it indicates a condition of maximum triaxial constraint to plastic flow that can be imposed by the metal. This means that the plane strain plastic zone size developed at the point of fracture cannot be made smaller by increasing the depth or size of the crack. If the plastic zone size cannot be made smaller, the fracture toughness measured is the lowest possible value (singularity) for the metal. It is on this basis of singularity that  $K_{Ic}$  is considered a fundamental materials parameter.<sup>5</sup>

The accuracy of linear elastic fracture mechanics is good provided that the plastic zone at the tip of the crack is small compared with the general specimen dimensions. As the ratio of plastic zone size to specimen size increases, linear elastic fracture mechanics becomes less accurate.

Application of this approach to steels of high toughness in which large plastic zone sizes are characteristic, at least in thin sections, is therefore less certain. In actual service, many of these steels are used in section thickness up to and on occasion exceeding twelve inches. Under these conditions, plastic constraint due to thickness will produce, nominally, plane strain conditions even in high plasticity materials. Measurements of  $K_{Ic}$  in these materials would then be a potentially useful tool in fracture control, since it is a minimum level of toughness that could be expected under the most adverse stress state conditions.

Since a weldment contains a gamut of microstructures, any test which is to evaluate toughness needs to sample a wide range of these microstructures and, if possible, assign a toughness index to each. This has the value of determining which of these zones is the most critical, the "weak link," and what the relative behavior of the zone is. With this information available, the effects of welding variables and heat treatment procedures can be evaluated with the ultimate objective of producing weld joints with toughnesses that are compatible with that of the base material. Many of the weld and heat-affected zone structures are confined to narrow regions, and are sufficiently inhomogeneous that it is not certain that this can be accomplished.

Recent research programs<sup>6</sup> have produced data to show that specific areas of microstructure in a weldment have significantly different fracture characteristics and, in some cases, the characteristics of a particular zone or region can influence the behavior of

Table 1—Chemical Analysis of the Steel Weldments, %

Steel and Condition	C	Mn	P	S	Si	Cr	Ni	Mo	Al	V	Cu	B
High heat input:												
A542 weld metal	.074	1.02	.008	.014	.37	1.90	.10	1.02	.02	—	—	—
A542 base metal	.12	.47	.007	.020	.33	2.11	.20	1.11	.033	—	—	—
Low heat input:												
A542 weld metal	.085	1.00	.016	.017	.43	2.02	.09	1.08	.028	—	—	—
A542 base metal	.12	.46	.008	.020	.33	2.16	.20	1.10	.034	—	—	—
High heat input:												
A517F weld metal	.075	1.40	.007	.009	.32	.29	2.5	.59	—	.013	.40	.0005
A517F base metal	.16	.78	.011	.016	.25	.56	.88	.42	—	.036	.26	.0031
Low heat input:												
A517F weld metal	.058	1.56	.007	.009	.38	.35	2.6	.56	—	.013	.39	.0005
A517F base metal	.18	.78	.012	.018	.24	.54	.89	.43	—	.036	.26	.0030

the weldment as a whole. While such research provides valuable insight into overall fracture behavior, there is a need for complimentary data which would give quantitative measurements of the fracture toughness characteristics of many of the specific regions involved in fracture.

The objectives of this program, therefore, were to develop the test techniques for obtaining valid fracture toughness data on the weld metal and heat-affected zone regions of typical pressure vessel steels and to determine to what extent such tests could be useful in evaluating pressure vessel materials.

The fracture mechanics approach utilizing the three point loaded slow bend specimen was used in this determination of fracture toughness. The steels investigated were A542 Class 3 and A517-F, welded with the submerged arc process in the form of 2 in. thick plate. As a part of the program, the influence of welding process variables, mainly heat input, and thermal stress relief temperature were studied with respect to their influence on the plane strain fracture toughness of the three regions of the weld composite—that is, weld metal, heat-affected zone, and base metal. These results were used to compare the fracture toughness characteristics of the three zones, and to determine to what extent control of heat input and thermal stress relief can be beneficial to the fracture toughness of the materials tested.

## Experimental Program

### Materials

The two materials investigated were ASTM designations A542 Class 3 and A517-F commercially quenched and tempered steels, welded with the submerged arc process in the form of 2 in. thick plate. The chemical compositions of the weldments are shown in Table 1, and the mechanical properties (impact and tensile test data) are shown in Tables 2 and 3 respectively. In addition, some A542 Class 3 steel obtained from a previous PVRC program was used for the base metal A542 fracture toughness studies.<sup>7</sup> All of the A542 steel was cut into thick slices from heavy section production plate and heat treated to represent the thermal history of the center of a thick quenched, tempered and stress-relieved plate. The results obtained for the A542 base metal tests were compared with test data from a Westinghouse Corporation Research program<sup>8</sup> where this same plate material (with the identical heat treatment) was characterized in terms of fracture toughness.

Table 2—Tension Test Data<sup>a</sup>

Steel and condition	Temperature °F	Yield strength .2% offset, ksi	Tensile strength, ksi	Reduction of area, %	
A542 steel stress relieved at 1225° F					
Base metal	75	73.8	95.9	73.9	
	0	86.9	103.6	73.1	
	-50	89.6	107.6	74.2	
	-100	96.8	116.4	69.8	
	-150	102.9	122.2	69.5	
60 kilojoules/ in. weld metal	-200	111.8	128.9	64.3	
	75	74.5	95.0	66.5	
	0	87.6	103.6	64.6	
	-50	90.0	108.3	66.0	
	-100	95.5	115.3	61.0	
125 kilo- joules/in. weld metal	-150	102.8	122.0	62.5	
	-200	108.9	126.9	61.3	
	75	71.6	94.9	71.2	
	0	83.6	100.4	70.7	
	-50	85.9	104.4	66.4	
	-100	93.2	113.9	65.7	
	-150	98.5	117.7	64.4	
	-200	105.0	120.3	59.7	
	A542 stress relieved at 1125° F				
	Base metal	75	90.5	102.5	75.5
0		94.0	110.0	76.7	
-50		98.2	114.9	76.0	
-100		106.3	123.8	71.0	
-150		107.5	127.7	71.0	
60 kilojoules/ in. weld metal	-200	118.8	133.0	59.4	
	75	91.3	109.3	67.0	
	0	102.4	116.5	63.5	
	-50	103.8	116.5	63.1	
	-100	113.0	128.0	55.4	
	-150	117.0	133.1	58.0	
	-200	125.2	140.1	56.5	
	A517F stress relieved at 1075° F				
	Base metal	75	95.4 <sup>b</sup>	118.0	61.0
		0	106.6	120.0	60.8
-50		111.1	124.3	61.0	
-100		117.1	129.3	61.3	
-150		124.0	141.0	55.1	
70 kilojoules/ in. weld metal	-200	137.5	149.0	57.5	
	75	84.3	108.8	58.6	
	0	102.5	115.8	62.2	
	-50	105.2	119.5	61.0	
	-100	105.8	119.8	57.8	
35 kilojoules/ in. weld metal	-150	116.1	130.4	58.1	
	-200	122.7	136.3	56.0	
	75	96.5	117.2	60.6	
	0	107.9	117.7	61.6	
	-50	112.2	123.9	58.1	
	-100	116.9	128.0	57.8	
	-150	124.7	137.0	55.4	
	-200	130.7	143.6	53.9	
	A517F no stress relief				
	Base metal	75	99.2 <sup>b</sup>	119.8	58.6
0		107.9	120.0	62.2	
-50		114.1	125.6	62.4	
-100		115.1	128.8	57.5	
-150		127.0	140.3	58.0	
70 kilojoules/ in. weld metal	-200	133.9	147.2	55.6	
	75	90.4	109.8	61.8	
	0	101.3	110.2	59.4	
	-50	101.0	116.1	57.2	
	-100	107.7	122.4	55.5	
35 kilojoules/ in. weld metal	-150	128.0	142.0	55.0	
	-200	138.0	150.0	56.0	
	75	96.0	118.4	62.1	
	0	107.5	117.0	62.3	
	-50	112.8	122.8	61.0	
	-100	120.0	131.0	60.6	
	-150	127.0	140.0	57.2	
	-200	131.3	148.0	54.5	

<sup>a</sup> Extensometer was used only for the tensile tests at 75° F. <sup>b</sup> See text.

**Table 3—Charpy V-Notch Impact Test Data**

Steel and condition <sup>a</sup>	Transition temperatures, °F				Shelf energy, ft-lb
	15 ft-lb	25 ft-lb	15 mil	50% shear	
A542 steel stress relieved at 1225° F					
Base metal	-105	-85	-150	0	130
125 kj/in. weld metal	-150	-46	-50	+55	82
60 kj/in. weld metal	-90	-30	-125	+12	75
125 kj/in. HAZ	-190	-145	-200	-38	112
60 kj/in. HAZ	-104	-95	-155	-25	90
A542 steel stress relieved at 1125° F					
Base metal	-130	-100	-137	+15	115
125 kj/in. weld metal	+7	+43	-17	+50	67
60 kj/in. weld metal	-30	+7	-55	+42	60
125 kj/in. HAZ	-200	-170	-172	-40	115
60 kj/in. HAZ	-135	-95	-100	-20	112
A517F steel stress relieved at 1075° F					
Base metal	-110	-55	-127	-20	59
70 kj/in. weld metal	-65	+5	-125	+20	43
35 kj/in. weld metal	-135	-45	-200	-40	41
70 kj/in. HAZ	-163	-118	-145	-75	61
35 kj/in. HAZ	-115	-80	-145	-80	45
A517F steel—no stress relief					
Base metal	-130	-75	-150	-10	61
70 kj/in. weld metal	-150	-73	-175	-50	41
35 kj/in. weld metal	-210	-105	-200	-85	34
70 kj/in. HAZ	-175	-120	-200	-70	65
35 kj/in. HAZ	-165	-120	-185	-75	55

<sup>a</sup> kj—kilojoules; HAZ—heat-affected zone.

**Table 4—Welding Conditions**

Material	Weld process	Pre-heat, °F	Inter-pass temperature, °F	Heat input, joules/in.	Number of passes	Stress relief, °F
A542 <sup>a</sup>	Sub-arc	300	450	60,000	135	1125° F—8 hr
A542 <sup>a</sup>	Sub-arc	300	450	60,000	102	1225° F—8 hr
A542 <sup>a</sup>	Sub-arc	300	450	125,000	39	1125° F—8 hr
A542 <sup>a</sup>	Sub-arc	300	450	125,000	40	1225° F—8 hr
A517-F <sup>b</sup>	Sub-arc	200	300	35,000	64	None
A517-F <sup>b</sup>	Sub-arc	200	300	35,000	64	1075° F—2 hr
A517-F <sup>b</sup>	Sub-arc	200	300	70,000	35	None
A517-F <sup>b</sup>	Sub-arc	200	300	70,000	35	1075° F—2 hr

<sup>a</sup> Donated by Standard Oil Company of California; welded by Chicago Bridge and Iron Company.

<sup>b</sup> Donated by the United States Steel Corporation; welded by the Lukens Steel Company.

**Welding Procedure**

Both steels selected for this program were butt-welded by the submerged arc process (d.c.) in accordance with the welding parameters described in Table 4. A special vee groove preparation was used to attain a straight heat-affected zone—Fig. 1.

The A542 steel welds were made with AWS-ASTM F-61-EH14 80 flux and 2 1/4 Cr-1 Mo filler metal. A total of 4 plates were welded, two plates at each heat input—one 33 × 24 × 2 in. and one 33 × 12 × 2 in.

The A517-F steel welds were made with Linde 1092 flux and Linde 100, 5/32 in. diameter weld wire. Four plates, each 75 × 32 × 2 in., were welded.

**Experimental Variables**

Two welding process variables, low

and high heat inputs, as well as two post-weld heat treatments were used in welding each steel—Table 4.

The selection of these particular variables was based on the practical application of the steels. There was one common condition of welding and stress relief for both. The other condition for each was selected on the basis of current industrial or recommended practice.

The A542 weldments were given an 8 hr stress relief treatment because the 2 in. plates on which the welds were made had originally been sliced from 7 1/2 in. thick plates, and all original heat treatment of the plate was done in the heavy section condition. A slow cool from the stress-relief temperature (approximately 45° F/hr) to 600° F was also employed to be consistent with the heavy section treatment of the A542 plate. Charpy

V-notch, tensile, and fracture toughness tests were conducted on the weld metal, heat-affected zone, and base metal regions of the 2 in. thick weldments for each welding condition. Therefore, a total of 10 different conditions (test variables) were investigated for each material during this program.

**Test Specimen Preparation and Design**

Slow bend fracture toughness specimens were cut from the welded plates, as shown in Fig. 2, and were machined according to the ASTM Proposed Recommended Practice,<sup>9</sup> as shown in Fig. 3. All specimens were cut with their longitudinal axis parallel to the rolling direction of the plate and notched in the thickness direction of the plate—Fig. 4. Unfortunately, the specimen preparation involved a greater degree of control than would normally be necessary because the machined notches and subsequent fatigue cracks had to be placed precisely in the regions of microstructure that were to be tested. This involved macroetching each specimen after it was ground and scribing the specimen where the notch was to be machined.

Five different size slow bend fracture toughness specimens were machined for this program (1/2, 3/4, 1, 1 1/2 and 2 in. thick).

Standard Charpy V-notch impact test specimens were machined from the plates as shown in Fig. 5. The orientations of the long axis of the specimens and of the axis of the notches were the same as those used for the K<sub>1c</sub> specimens. The notches were located in the specific regions of interest (base metal, weld metal, or heat-affected zone) by macroetching the bars prior to the notching operation. Because of the limited amount of material available, the majority of the Charpy specimens were taken from the broken slow bend fracture toughness specimens. Each Charpy series consisted of from 10-20 specimens.

Tensile specimens (5/8 in. gage length—0.250 in. diameter) were machined from the plate as shown in Fig. 5. The longitudinal axis of the tensile bar is parallel to the rolling direction of the plate. Six specimens were obtained for each test condition. Obviously, tensile specimens were not obtained from the heat-affected zone region because of its limiting size and configuration. To characterize the zone, hardness traverses were made on the weldments.

**Test Methods**

*Charpy Impact Tests.* Charpy V-notch specimens were tested over a range of temperatures for the above

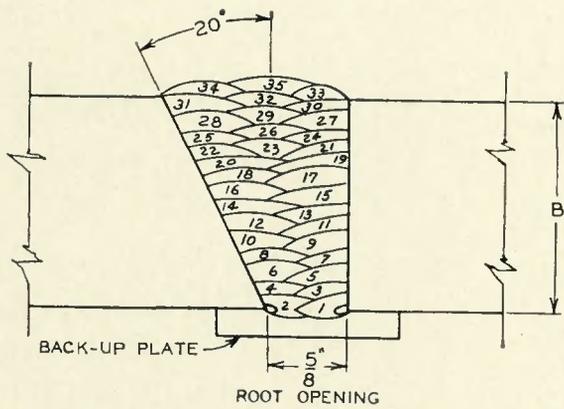


Fig. 1—A typical multipass weld using a single-vee groove preparation to attain a straight heat-affected zone—submerged arc welded A517 steel—70 kilojoules/-in. heat input

test conditions; fracture energy and lateral expansion were evaluated as a function of temperature. The results are presented in Table 3.

**Tensile Test.** Tensile specimens were tested in a 10,000 lb. capacity machine. A constant cross-head speed of 0.05 ipm was used for all specimens. Tests were performed over a range of temperature from  $-200$  to  $+75^{\circ}$  F (room temperature).

Testing below room temperature was conducted in a specially designed cryogenic chamber, utilizing liquid nitrogen circulated through a bath of methyl-butane by a coil of copper tubing. The bath was stirred constantly to maintain a uniform temperature

throughout the cooling medium. Load-extensometer records were obtained only for the room temperature tests. Since the extensometer could not be immersed in the cryogenic bath, load-time records (utilizing a constant cross-head speed) were generated for the tests below room temperature. Reliable measurements of percent elongation could not be made because of the unusually small gage length of the weld metal test specimens. The results are presented in Table 2.

**Fracture Toughness Tests.** After machining, and before testing, the slow bend fracture toughness specimens were fatigue precracked in a 3-point bending fixture at room temperature.

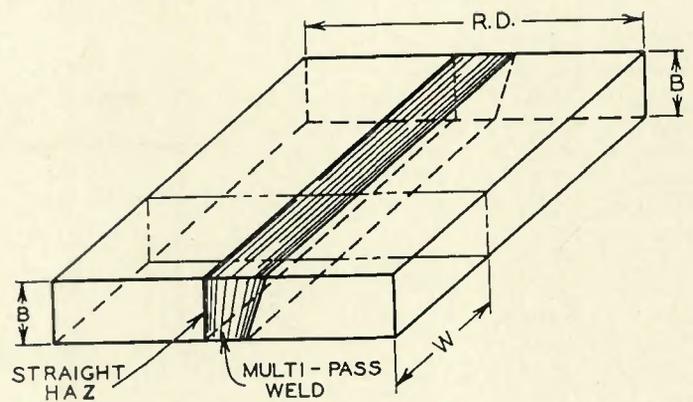


Fig. 2—Specimen location in plate weldment

perature. The ASTM E-24 Committee Recommended Practice requires that  $K_{max}$  (maximum stress intensity factor during fatigue precracking) must not exceed one-half of the  $K_{Ic}$  value determined in the subsequent test.

Initial attempts at fatigue cracking indicated that unless a successful method of precracking the specimens was found, the time required to grow the cracks would be too long to allow the testing of very many specimens. Using the following method of precracking, satisfactory fatigue cracks were grown within 1 to 2 hr of total fatiguing time.

The chevron notch configuration, shown in Fig. 6, was used in order to form a fatigue crack which did not deviate from the notch plane and yet

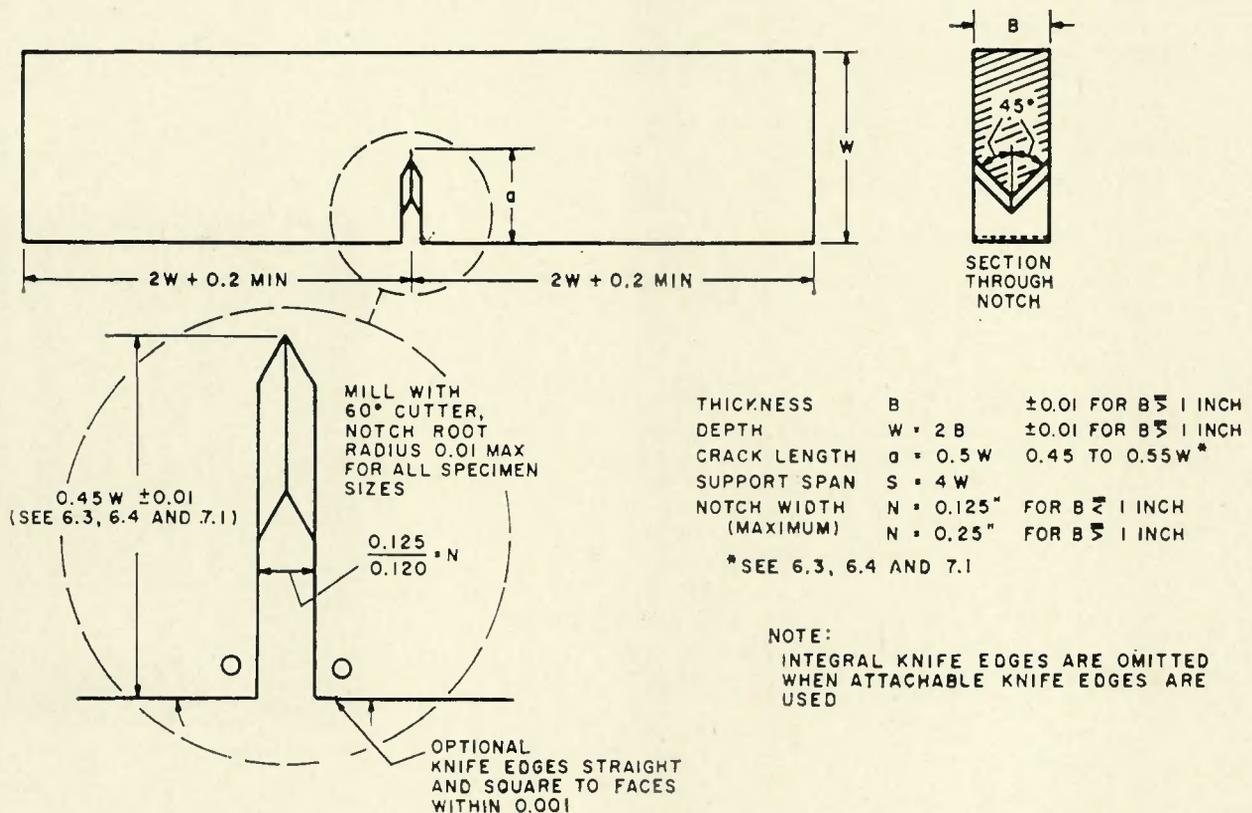


Fig. 3—Recommended standard slow bend specimens

extended substantially beyond the notch root throughout most of the specimen thickness. This substantial extension was necessary to avoid undue influence of the notch on the crack stress field. The chevron notch also expediated nucleation of the fatigue crack.<sup>4</sup>

The specimens were placed in a 10 ton high frequency fatigue testing machine, and fatigued in three-point bending at a cycling rate of 180 to 220 cycles/sec. Two stages of fatiguing were used: crack start and crack growth. The crack starting stage was to develop a growing crack (the crack was grown beyond the notch root radius). The only limitation was the capacity of the machine or the crack growth rate which could be controlled. The second step grew the crack at a slow rate. The loading was controlled to provide a crack growth rate equal to that suggested by ASTM Committee E-24. This rate was usually maintained for the last 0.10 to 0.15 in. of crack growth. In general, the crack depth after fatiguing varied from 0.45 to 0.55 times the depth of the specimen.

Fatigue cracked slow bend  $K_{Ic}$  specimens were tested in a three point bending fixture (Fig. 6) on a 120,000 lb capacity Baldwin Universal Testing Machine, at approximately a 60-120 ksi  $\sqrt{\text{in.}}$  per minute loading rate. Three point rather than four point bending was selected largely because of convenience. The deflections for a given load are larger in three point loading, requiring less magnification of strain measurements. A double

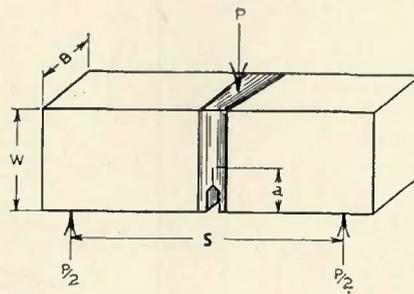


Fig. 4—Typical weld location in weld metal specimen

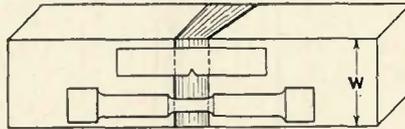


Fig. 5—Position and orientation of Charpy and tensile weld metal specimens in plate weldment

cantilever clip-in displacement gage<sup>9</sup> was used to measure crack-opening displacement during the test—Fig. 7. The gage consisted of two cantilever beams and a spacer block with four strain gages and was mounted on the specimen by means of the specially designed adjustable, attachable knife edges. This adjustable feature allows the knife edges to be used for specimens with a range of thicknesses.

The displacement output from the clip gage and the load output from the load cell were fed into an X-Y recorder to obtain a continuous (autographic) load-displacement record. The load-recording system was calibrated experimentally before each series of tests.

Figure 7 shows the overall test setup used for the slow bend fracture toughness tests. The types of load vs. displacement records obtained are shown in Fig. 8.

The  $K_{Ic}$  tests were conducted in the temperature range from  $-200$  to  $+20^\circ$  F (mid-thickness temperature measurement) according to ASTM procedures. Different test temperatures were obtained with liquid nitrogen supplied through perforated coils surrounding the specimen in a cooling chamber insulated with 2 in. thick styrofoam. Each specimen was held at temperature for 15 min before testing—Fig. 9.

#### Analysis of Data

After testing, the fracture stress intensity factor for all bend specimens was readily determined with the aid of a computer from the expression:<sup>9</sup>

$$K_Q = \frac{Y P_Q S}{B W^{3/2}} \quad (1)$$

where

$P_Q$  = load in pounds at pop-in, 5% secant offset, or maximum load

$B$  = thickness

$S$  = span length

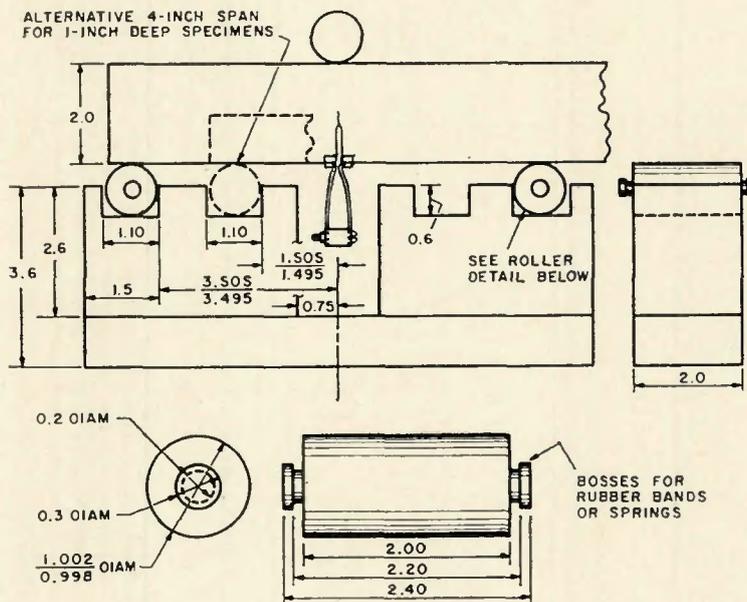
$W$  = depth

$a$  = crack length

$Y = f(a/w)$  given by the following power series (it is a calibration factor for specimen geometry):

$$\begin{aligned} f(a/w) = & [2.9 (a/w)^{1/2} - 4.6 (a/w)^{3/2} \\ & + 21.8 (a/w)^{5/2} - 37.6 (a/w)^{7/2} \\ & + 38.7 (a/w)^{9/2}] \end{aligned} \quad (2)$$

The requirements of fracture toughness testing in the fracture mechanics



#### NOTE:

FOR 1-INCH AND 2-INCH DEEP SPECIMENS;  
PROPORTION ACCORDINGLY FOR OTHER SPECIMEN SIZES

Fig. 6—Bend test fixture design

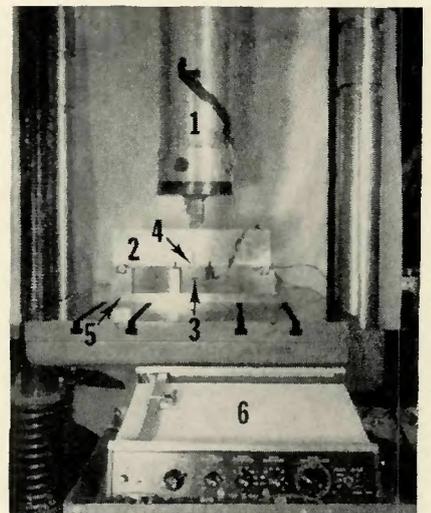


Fig. 7—Slow bend test apparatus: 1—load cell; 2—slow bend specimen; 3—clip gage; 4—attachable knife edges; 5—three point bend fixture; 6—X-Y recorder

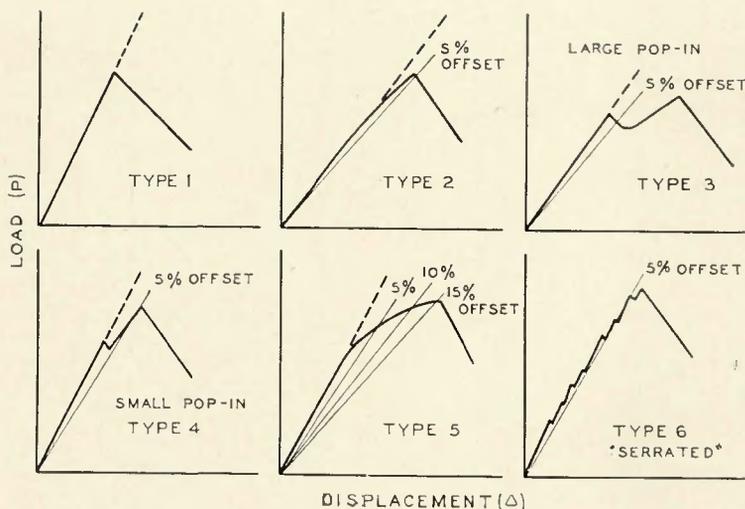


Fig. 8—Types of load-displacement records obtained

approach are unusual in that it is necessary to compare post test data with specimen pretest dimensions to determine if the fracture toughness measure ( $K_Q$ ) is the critical value for the material ( $K_{1c}$ ). Hence, validity of the test can only be determined after testing. Fracture toughness  $K_Q$  validity criteria have been proposed by the ASTM E-24 Committee.<sup>9</sup> First, that

$$a \text{ and } B \geq 2.5 \frac{K_Q^2}{\sigma_{11s}} \quad (3)$$

and second, the secant offset method be used to determine that the majority of displacement is due to crack extension. Fracture toughness,  $K_Q$  measured for specimens meeting both these criteria is considered to be the critical value  $K_{1c}$  for the material.

If the criteria are not met, the measured fracture toughness  $K_Q$  is considered to have been biased by specimen size. However, these tentative standards for  $K_{1c}$  testing are primarily intended for steels having yield strengths in excess of 200,000 psi.<sup>4</sup> Such materials do not usually have a significant plastic zone at crack instability. In fact, the standards are set up so as to preclude the formation of a significant plastic zone, and no

attempt is made in the standards to include a plasticity adjustment to the computations. The standards are an attempt to ensure valid and standardized  $K_{1c}$  testing of the materials for which they were written. The problem of standardized testing of lower strength metals is still under study by Committee E-24. There is no agreement as yet on what testing standards would be best for the lower strength metals, although suggestions have been made.<sup>10</sup>

## Experimental Results and Discussion

### Tensile Test Data

The results of the tensile tests conducted over a range of temperatures on the A542 and A517-F base metal and weld metal for the various welding conditions are presented in Table 2. The behavior over the range of temperatures investigated was representative of low alloy high strength steels.

The effect of the higher stress relief treatment on lowering the strength of the A542 weldment is readily apparent. Also, in terms of general strength level of the zones tested, the A542 low heat input, low stress relief weld metal is the strongest of the A542 weld metals or base metals tested, whereas the high heat input, high stress relief weld metal is the weakest. A similar result is observed for the A517-F weldments—that is, the low heat input, no stress relief weld is one of the stronger microstructures and the high heat input, stress relieved weld is the weakest. In general, the effect of stress relief on decreasing the general strength properties of the weldment can easily be seen. Because of their restricted size, tension tests of the heat-affected zones are not possible in the actual weldments. However, hardness traverses of the weldments, seen in Figs. 10-13 do reveal that the

heat-affected zone is the highest hardness zone in the weldment. Stress relief reduces the hardness of this zone.

It should be noted that the A517-F tension test results obtained in this investigation were slightly below the minimum yield strength specified for this grade, which is 100 ksi. Mill tests on this plate at the one-quarter thickness location produced a yield point of 141 ksi and a tensile strength of 124 ksi. Tension tests in this program were made on specimens taken in the specimen and plate center location.

### Charpy V-Notch Impact Test Data

The results of the Charpy tests are summarized in Table 3, where the effect of stress relief on the transition temperature curves is illustrated. It should always be kept in mind when viewing these data that the A542 has been given a heavy section (long time) stress relief. This was due to the fact that the 2 in. plates, on which the welds were made, had originally been sliced from 7 1/2 in. thick plates and all original heat treatment of the plate was done in the simulated heavy section condition.

The results show that on the basis of both shelf energy and transition temperatures, the weld metals are generally better in toughness for the low rather than the high heat input condition, however, the HAZ is adversely affected by low heat input. This response appears to be independent of the stress relief, with the possible exception of the high heat input A542 where the stress relief at 1225° F toughens the high heat input weld metal above the level of the low heat input weld.

A general improvement of the notch toughness for the A542 weld metal was observed after stress relief at 1225° F as compared to 1125° F, while a decrease was noted for the base metal and the high heat input (125 kilojoules/in.) heat-affected zone. The low heat input heat-affected zone remained essentially unchanged. Stress relief was found to be harmful to both the A517-F weld metal and heat-affected zone but had a negligible influence on the base-metal.

The A542 weld metal is poorer in toughness than the base metal and heat-affected zone; this difference being more pronounced for the lower stress relief condition.

The A517-F weld metal has the lowest transition temperatures when compared to the base metal and heat-affected zone for the low heat input weld in both conditions. The A517 F heat-affected zone transition temperatures were lower than the weld metal and base metal for the high heat input welds.

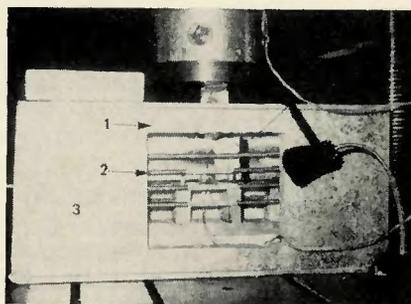


Fig. 9—Cooling chamber for slow bend test apparatus: 1—Styrofoam lining; 2—cooling coils (carry liquid nitrogen); 3—cooling chamber

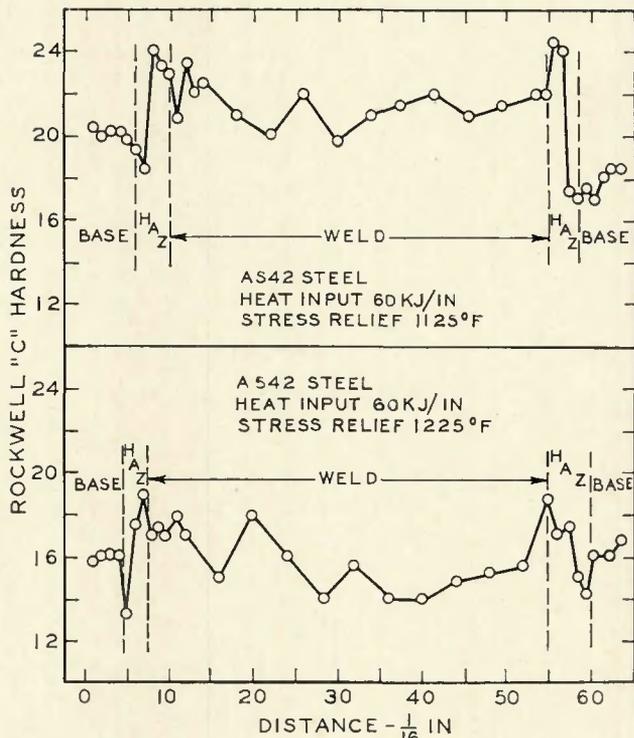


Fig. 10—Hardness traverses across low heat input A542 weldments

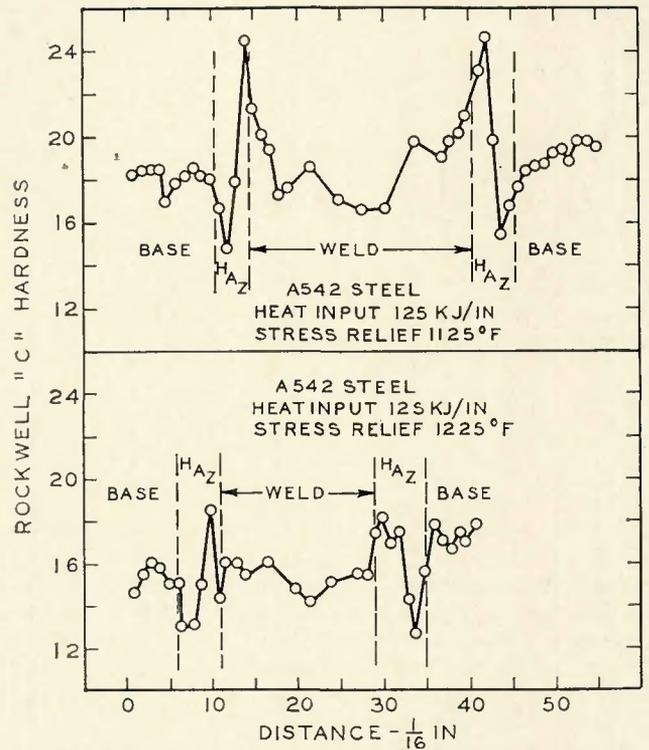


Fig. 11—Hardness traverses across high heat input A542 weldments

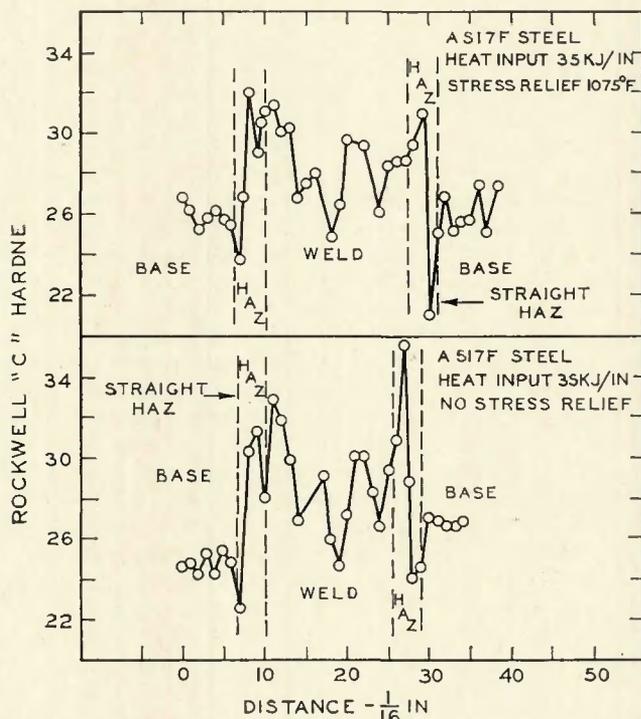


Fig. 12—Hardness traverses across low heat input A517F weldments

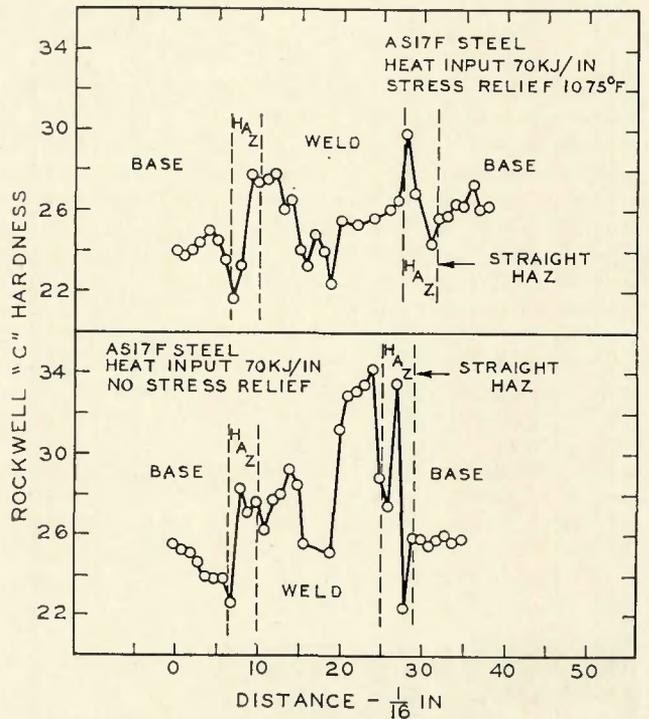


Fig. 13—Hardness traverses across high heat input A517F weldments

#### Fracture Toughness Test Data

The results of the fracture toughness tests on heavy section A542 steel weldments are presented in Fig. 14-16. The data are summarized in Fig. 17. In general, it may be seen that the estimated base metal toughness of the steel is high and the weld metal toughness is low, with the heat-

affected zone falling in the intermediate position. Figure 14 shows  $K_{1c}$  data for A542 Class 3 steel obtained by Lehigh University and the Westinghouse Corporation for the same heavy section heat of steel identically heat treated. The results seem to indicate that plane strain  $K_{1c}$  transition may exist for this steel. As may be seen,

both sets of data agree well with each other at the lower temperatures (up to  $-250^{\circ}\text{F}$ ). The specimens tested at  $0^{\circ}\text{F}$  appeared to be about the limit of usefulness for the largest specimen tested since one of the two showed only a slight pop-in behavior and both specimens did not meet the required ASTM validity criteria with respect to

specimen size.

Figures 15 and 16 show several interesting contrasts. They indicate that the weld metal toughness is generally poorer than that of the base metal, and that stress relief temperature does not have a significant influence on weld metal toughness. The high heat input weld metal is improved slightly by a higher stress relief temperature. In contrast, the heat-affected zone is influenced by stress relief temperature in a mixed manner. It is much improved in toughness at temperatures below  $-75^{\circ}\text{F}$  when the  $1225^{\circ}\text{F}$  stress relief temperature is used for the high heat input. However, the toughness decreases when the higher stress relief temperature is used for the low heat input.

At low temperatures (below  $-100^{\circ}\text{F}$ ) the heat-affected zone appears to be superior to the base metal for all welding conditions except the high heat input, low stress relief condition. Low heat input, heat-affected zones were better in toughness than their high heat input counterparts. This also applies to the weld metal down to  $-115^{\circ}\text{F}$ ; however, at lower test temperatures the high heat input weld metal toughness was superior. On the basis of these data, however, it is apparent that for the A542 steel, the matching composition weld metal does not match the estimated toughness of the base metal in the temperature range tested, and is inferior to the heat-affected zone in toughness in many cases.

The conventional Charpy V-notch test data for this steel generally reflects the fracture toughness test results in the sense that the weld metal is low in toughness compared to the base metal and heat-affected zone. Beyond this general level of agreement, however, differences exist. For example, the improvement in Charpy test toughness observed in the weld metal after stress relief at  $1225^{\circ}\text{F}$  as compared to  $1125^{\circ}\text{F}$  was not clearly seen in the fracture toughness results,

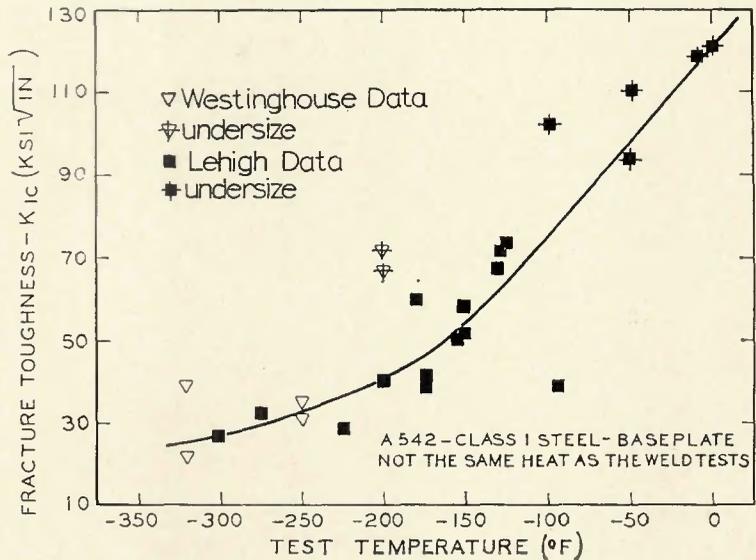


Fig. 14—Plain strain fracture toughness transition behavior as a function of temperature for A542 base metal

nor was the superiority of the heat-affected zone compared to the base metal.

It appears that tests in the heat affected zone for A542 are in some cases valid by ASTM Committee E-24 tentative specifications but may be invalid for other reasons—that is, the load-displacement curves meet the specifications for defining  $K_{1c}$ , but the specimen sizes are below the thickness requirements designated by eq (1). The weld metal specimens often show classical pop-in behavior; however, the heat-affected zones have not frequently shown such behavior.

The heat-affected zone specimens present another difficulty in testing because of the limited size of the zone. Moreover, in the A542 specimens this zone, which is relatively tough, is adjacent to the low toughness weld metal. As a result, if the heat-affected zone is not perfectly straight and the fatigue crack front penetrates a portion of the weld metal, the fracture initiates in the weld metal and the measured fracture toughness is charac-

teristic of the weld metal not the heat-affected zone. Several "mixed" fracture data points of this type are seen in Fig. 15 and 16, and in Figs. 23 and 25.

The fracture toughness data developed for A517-F steel welded at two heat inputs and tested both with and without stress relief are presented in Fig. 21-23. The data are summarized in Fig. 24. On the first examination of these data, several points are evident. First, the weld metal and heat affected zone are superior in toughness to the base metal. Second, it is also clear that both weld metal and heat-affected zone toughness for this steel are reduced by stress relief treatments. This is particularly true of the low heat input welds. However, it was not true of the base metal—Fig. 21. Third, the weld metal and heat-affected zone data show a fair range of scatter, particularly in the unstress relieved condition. This last affect is due primarily to the difficulty encountered in growing satisfactory fatigue cracks in the weld

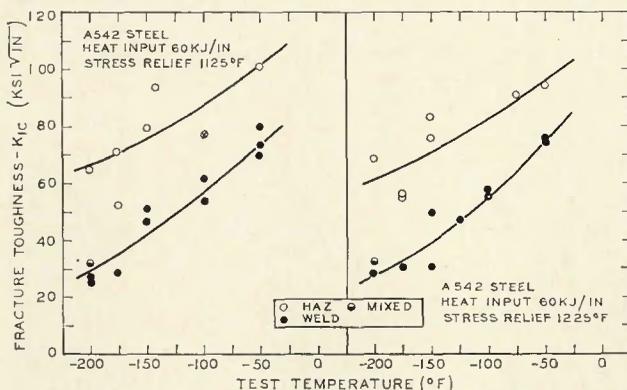


Fig. 15—The effect of temperature on the plain strain fracture toughness of A542 weldments with different stress reliefs

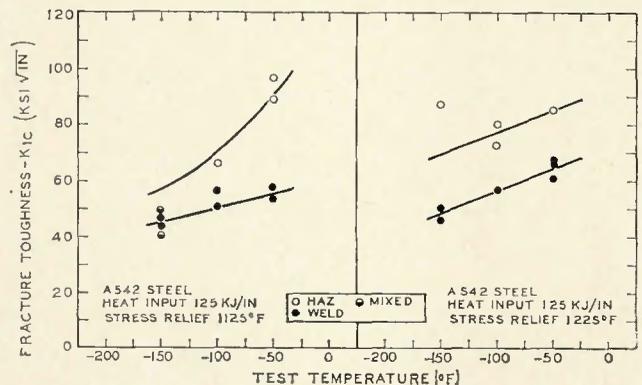


Fig. 16—The effect of temperature on the plain strain fracture toughness of A542 weldments with different stress reliefs

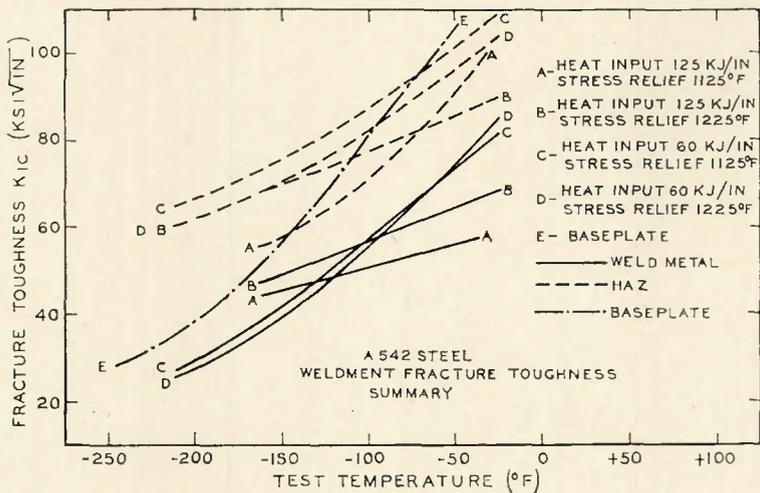


Fig. 17—A542 steel-weldment fracture toughness summary

metal and heat-affected zone. Cracks grown in the weld metal, for example, have irregular crack fronts where the fatigue crack was apparently arrested locally by microstructural features. Stress relief appeared to produce more uniform crack growth.

A comparison of the conventional impact test data (Table 3) for this steel with the summary seen in Fig. 24 indicates that, as with the A542 steel, many but not all of the general features of the fracture toughness results are found in the conventional test results. For example, the good toughness of the low heat input, unstress relieved weld metal is revealed in both tests, as is the lower toughness of the base metal. Stress relief is revealed to be harmful to both weld

metal and heat-affected zone structures. On the other hand, the unstress relieved heat-affected zones appear to be similar in toughness to the weld metal, which was not recorded in the fracture toughness tests.

It is possible to make a comparison of the two steels tested at 60 and 70 kilojoules/in. heat input and 1075 and 1125° F stress relief from the data of this study and this comparison is made in Fig. 25. In examining Fig. 25, it should be noted that 1075° F is a high stress relief condition for A517-F but 1125 is low for many applications of A542. In neither case will the best toughness of the two weldments be revealed.

The outstanding difference in the toughness behavior of the steel seen in

Fig. 25 is the relative positions of the weld metal and base metal. The A542 weld metal is the lowest in toughness of any of the structures tested, whereas the A517-F weld metal is the highest. In comparison the A517-F base metal is low while the A542 is high. Above -150° F the heat-affected zones of the two steels are intermediate in toughness. Because of these differences the overall behavior of the A517-F weldments should be different from that of the A542 weldments. The A542 base metal will be generally superior to both the weld metal and heat-affected zone in toughness and the weld metal should be the "weak link." In the A517-F, because of the good toughness of the weld metal, the base metal appears to be the region of lowest fracture toughness in the weldment.

Results similar to those obtained here with fracture toughness tests were reported in a previous study<sup>11</sup> using a variety of conventional tests. For example, Charpy impact tests on as welded and stress relieved weldments of 2 in. thick A517-F steel produced weld metal toughness somewhat better than the base metal and the levels similar to those reported here. The adverse effect of stress relief on the weld metal toughness was also noted. These results were confirmed by both drop weight and explosion bulge tests. In the explosion bulge tests, an FTE temperature of -60° F was reported for the weldment, with cracking occurring in the base metal.

The various types of load-displace-

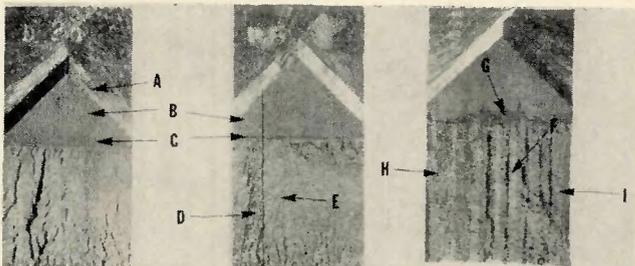


Fig. 18—Fracture surfaces corresponding to type 1 and type 2 load vs. displacement records: Left—type 1 (specimen A); center—type 1 (specimen B); right—type 2 (specimen C). See Appendix

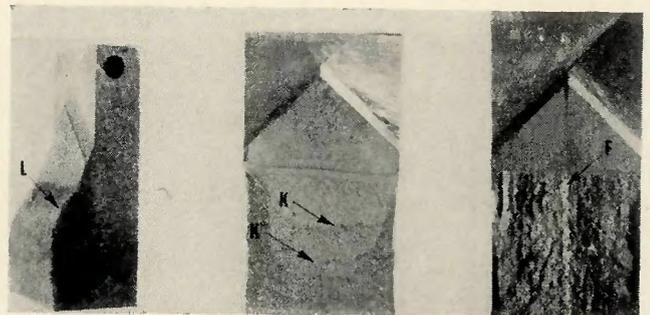


Fig. 19—Fracture surfaces corresponding to type 3 and type 4 load vs. displacement records: Left—type 3 (specimen A); center—type 3 (specimen B); right—type 4 (specimen C). See Appendix



Fig. 20 (right)—Fracture surfaces corresponding to type 5 and type 6 load vs. displacement records: Left—type 5 (specimen C); center—type 5 (specimen B); right—type 6 (specimen A). See Appendix

ment records obtained in this investigation were classified into six types, as shown schematically in Fig. 8. The load-displacement records ranged from ideal Linear Elastic Fracture Mechanics (LEFM) behavior (type 1—no deviation from linearity prior to complete fracture) to behavior evidencing considerable plastic deformation (type 5—“roundhouse” load-displacement records).

Typical specimen fracture surfaces for a type 1 curve are shown in Fig. 18. Notice that the fracture surfaces are macroscopically flat and exhibit little or no shear lips. Specimen B should have been a heat-affected zone test but it shows a mixed fracture of weld plus heat-affected zone (predominant). This is due to the narrow and non-linear heat affected zone. The type 1 record is essentially linear to maximum load at which point there is an unstable crack extension with no ensuing crack arrest (the specimen fails). This indicates the specimen was sufficiently thick and exhibits almost ideal LEFM behavior.  $K_{Ic}$  values for specimens which gave this type of curve are valid by the ASTM Committee E-24 requirements. Approximately 50% of all load-displacement records were linear for the specimens

tested.

A type 2 fracture surface is also

shown in Fig. 18. The deviation from linearity is equal to or less than a

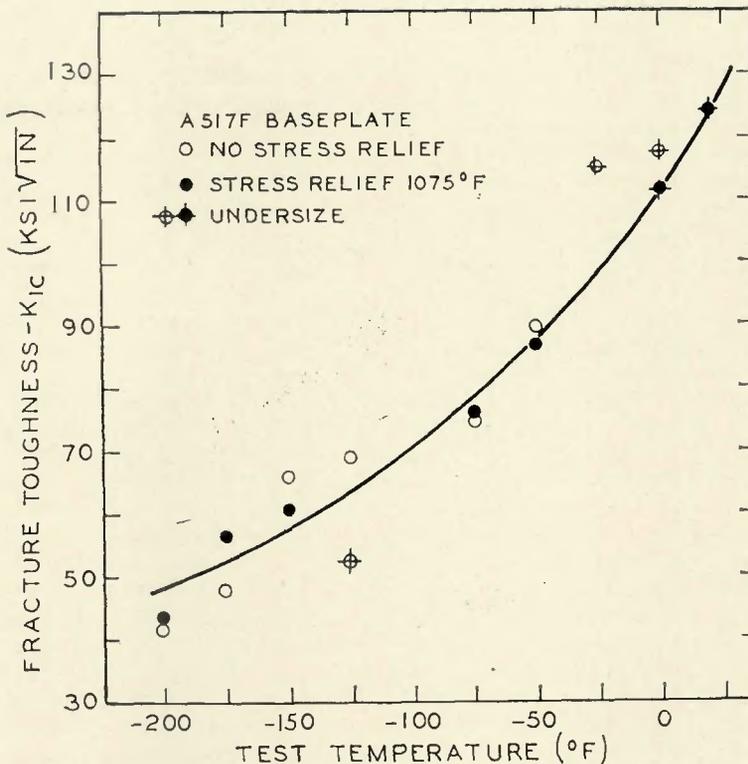


Fig. 21—Plain strain fracture toughness transition behavior as a function of temperature for A517F base metal

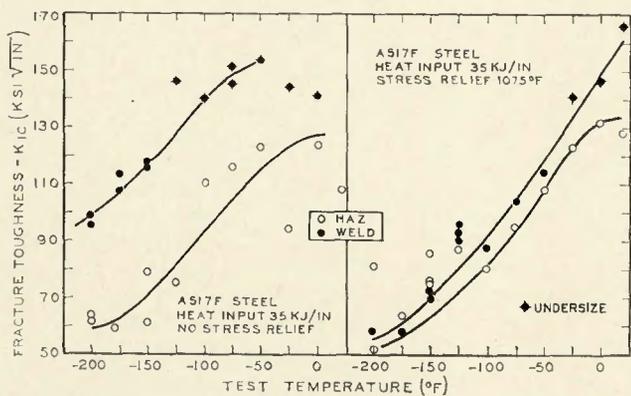


Fig. 22—The effect of stress relief on the plain strain fracture toughness transition behavior of A517F weldments

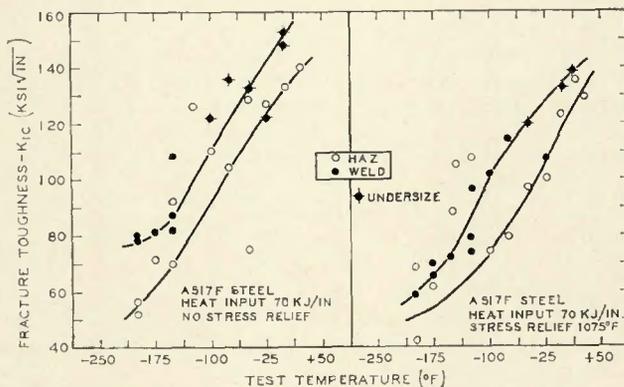


Fig. 23—The effect of stress relief on the plain strain fracture toughness transition behavior of A517F weldments

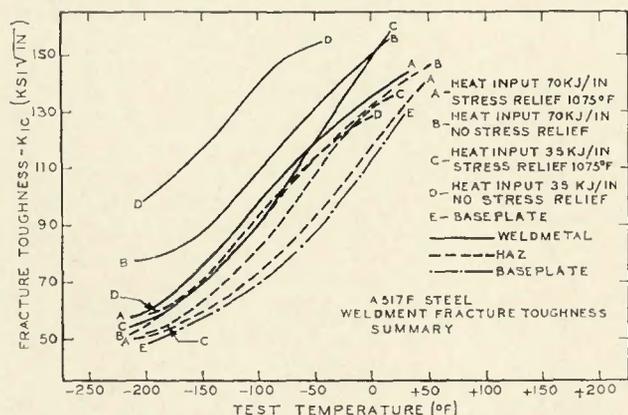


Fig. 24—A517F steel-weldment fracture toughness summary

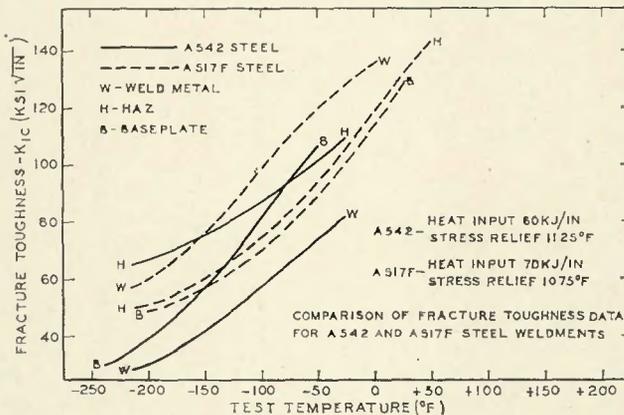


Fig. 25—Comparison of fracture toughness data for A542 and A517F steel weldments

secant intercept of 5% less than the slope of the initial straight line portion of the curve. Note that the individual weld passes are clearly evident in this fracture.

Types 3 and 4 fracture surfaces are shown in Fig. 19. Both load-displacement records exhibit pop-in behavior (an abrupt change in slope greater than 35%); however, type 3 is much more pronounced—that is, a considerable amount of unstable crack extension occurs before the crack is arrested. The fracture appearance of specimens A and B in Fig. 19 are quite similar for the following reason. Namely, the A517-F HAZ specimens do not readily fatigue crack in this zone when unstress-relieved, but rather the crack curves out into the baseplate (poorer toughness) region. This produces mixed mode fractures, especially for the low heat input (35 kilojoules/in.) because of the narrow HAZ. Similar difficulties occur when the heat-affected zone is matched with poorer weld metal, as is apparently the case of the stress relieved weld metal for A517-F and for the A542 steel.

A "serrated" (type 6) load displacement curve was obtained in several tests at temperatures below  $-125^{\circ}$  F. In this type one or more distinct pop-ins are observed well below the maximum load and are separated by portions of the curve showing no crack extension. If the material structure is strongly laminated or contains large particles of a randomly dispersed second phase (both likely to be found in weldments), isolated bursts of crack extension of appreciable magnitude may occur at loads substantially less than the maximum.<sup>4</sup> Behavior of this type may indicate considerable variability in the fracture properties of the specimen. Thus, an identical specimen taken from another location might rupture completely at a load near that corresponding to the first pop-in of record type 6. Rather than use the first pop-in load to calculate  $K_{1c}$ , a 5% secant offset was used to determine the load. The specimen geometry and the load displacement curves satisfy the validity criteria; however, the method of determining  $K_{1c}$  (evaluating the records) is questionable.

The final type of test record obtained (type 5) is illustrated in Fig. 25. The non-linearity of these curves ranges anywhere from slightly greater than 5% secant offset, to 15% secant offset, to a general yielding condition ("roundhouse").

It is readily apparent from this study that for both the A517-F and A542 weldments, the toughness is increasing rapidly with increasing tem-

perature. While the weld metal and heat-affected zone  $K_{1c}$  data do not extend to temperatures of practical interest for A542, the results are significant in indicating that in some cases very high toughness prevails at ambient temperatures. For A517-F, which is qualified for use down to  $-50^{\circ}$  F, the tests do provide data showing high toughness in service temperature ranges. Additional tests of weldments using larger test specimens would provide a better definition of the temperature dependence of  $K_{1c}$  for the weldments at higher temperatures than were attained in this program. One important aspect of this investigation that should be emphasized is the temperature dependence of  $K_{1c}$ .

If over some narrow temperature range, a significant change is observed in the slope of the  $K_{1c}$  temperature curve, then this change may be identified as a significant transition in the fracture behavior in which the crack toughness increases rapidly with increasing temperature providing appropriate specimen dimensions are used to maintain plane strain behavior.

Barsom and Rolfe<sup>12</sup> have recently shown that the "knee" of the  $K_{1c}$  curve for A517-F steel, that occurs between  $-125$  and  $-100^{\circ}$  F is a fracture transition that occurs in a valid plane-strain stress state. This transition temperature behavior in the  $K_{1c}$  test and also in the Charpy tests on A517-F steel reflects predominantly a transitional change in the microscopic mode of fracture from quasi-cleavage at cryogenic temperatures to tear dimples at room temperature. Thus it is apparent that certain steels do exhibit a metallurgical transition in  $K_{1c}$  that is independent of a nominal stress-state change. This behavior was noticed for both the A517-F and A542 steel tested in this program.

## Conclusions

The results of this investigation may be summarized as follows:

1. Linear elastic fracture mechanics can be used to analyze the fracture behavior and to evaluate the material characteristics of weldments of low alloy, high yield strength, quenched and tempered pressure vessel steels.  $K_{1c}$  values ranging from 26.2 to 166.5 ksi  $\sqrt{\text{in.}}$  over the temperature range of  $-200$  to  $0^{\circ}$  F were obtained for the two steels investigated. Although some difficulties were encountered in performing the tests, the toughness values obtained are considered to be useful in indicating the general level of toughness in various microstructural portions of the weldments. It is apparent that relatively large section sizes are required to pro-

vide valid  $K_{1c}$  tests at temperatures of general practical interest.

2. It appears that high yield strength steels such as these characteristically exhibit a rapid rise in fracture toughness with increasing temperature. The  $K_{1c}$  fracture toughness of the A542 Class 3 and A517-F steels was found to exhibit a strong temperature dependence, thereby giving rise to very high levels of crack toughness at temperatures approaching room temperature.

3. The properties of the A517-F weldments were found to be good when compared to the base metal. Both the weld deposits and heat-affected zone exhibited toughness levels that were superior to the base metal. The weld metal appears to be the toughest portion of the microstructure. Stress relief treatments were found to adversely affect the A517-F weld metal and heat-affected zone toughness. This is particularly true of the low heat input welds, but was not true of the base metal.

4. For the A542-Class 3 steel, it was found that the base metal toughness of the steel is high and the weld metal toughness is low, with the heat-affected zone falling in the intermediate range. A higher stress relieving temperature ( $1225^{\circ}$  F as compared to  $1125^{\circ}$  F) was helpful from the toughness standpoint for the heat-affected zone, but its influence on the weld metal was mixed.

5. A comparison of the conventional impact test data for both steels with their respective fracture toughness summaries indicates that many but not all of the general features of the fracture toughness results are found in the conventional test results.

## Acknowledgements

The authors gratefully acknowledge the financial support of the Pressure Vessel Research Committee of the Welding Research Council. The technical guidance of the Thermal and Mechanical Treatments Subcommittee of the Fabrication Division, PVRC, was at all times most helpful. The authors wish to express their appreciation to the United States Steel Corporation and the Standard Oil Company of California for donating the test plates, and to the Chicago Bridge and Iron Company and the Lukens Steel Company for welding the test plates used in the present investigation. They also gratefully acknowledge the Chevron Research Company which contributed to the financial support of this investigation.

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#### Appendix: Prominent Features on Fracture Surfaces (Fig. 18, 19, 25)

- A—Chevron notch-milled with 60 deg cutter.
- B—Fatigue crack—"fast" growth rate.
- C—Fatigue crack—"slow" growth rate.
- D—Weld metal section of mixed fracture (weld metal + heat-affected zone).

E—Heat affected zone section of mixed fracture (weld metal + heat-affected zone.)

F—Individual weld passes are apparent.

G—Oil and dirt stain on fatigue crack surface.

H—Fracture surface appearance—smooth (flat).

I—Fracture surface appearance—rough (fibrous).

K—First pop-in (heat-affected zone).

K°—Second pop-in (heat-affected zone).

L—Bowed or curved fracture surface.

R—Macroscopic delaminates on fatigue surface.

S—Non-uniform fatigue crack front (region where crack growth is suppressed).

T—Non-uniform fatigue crack front (region where crack growth is favorable).

U—Crack growth initially occurred perpendicular to the thickness plane.

## ... Calling All Authors ...

All authors interested in presenting papers at the AWS 52nd Annual Meeting which will be held in San Francisco, California, during April 26-30, 1971, will find that "An Invitation to Authors" and "Author's Application Form" appear as a detachable insert in this issue of the WELDING JOURNAL.

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