

A Fundamental Difficulty in Charpy V-Notch Testing Narrow Zones in Welds

The "cross weld Charpy test" is proposed to offset discrepancies that occur with conventional Charpy V-notch testing when highly brittle weld metal (with a sufficiently high yield strength exceeding that of the base metal) provides CVN data showing base metal toughness

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ABSTRACT. Dangerously misleading results obtained by conventional Charpy V-notch (CVN) testing of narrow zones in electron beam welds in an X-70 fine grained micro-alloyed steel are reported. In one case these results suggested a 50% fracture appearance transition temperature (FATT) of -37 C (-38 F) in the weld metal when a more careful investigation using a specially devised test determined the FATT was actually $+90$ C (162 F) higher at $+50$ C (122 F).

It is proposed that this discrepancy arose because the yield strength of the weld metal was much higher than the yield strength of the base metal. Consequently, general yielding began in the base metal and exceeded the fracture strain of the base metal before brittle fracture initiated in the weld metal. Under these conditions, it is suggested that highly brittle weld metal can yield CVN data showing base metal toughness providing the weld metal yield strength is sufficiently high. In order to detect such misleading results, a simple economical test called the "cross weld Charpy test" is proposed. It is described, and experimental data supporting its effectiveness are presented.

In another case, where bimodal CVN data was obtained, it is shown that the high energy mode corresponds to the base metal CVN data and the lower energy mode to the cross weld Charpy test data for weld

metal. This result suggests the cross weld Charpy test does actually measure CVN FATT in EB weld metal. The relevance of these results to the CVN testing of HAZ microstructures in general is discussed.

Introduction

In plain carbon steel structures, it has long been recognized that brittle fractures almost never propagate along the heat-affected zone (HAZ) of welds; consequently little effort was made to measure the toughness of the HAZ. However, with the increasing use of medium and high strength steel and the development of high heat welding processes, the toughness of the HAZ was questioned¹⁻³ and a number of papers were published on the subject¹⁻⁷. Although McGeady,⁴ Dolby,⁶ and Gross² mention that notch toughness testing the HAZ is difficult because the fracture path will not usually follow or stay in the zone being tested, none explain the nature of the errors that can result or present any experimental data to substantiate

their views.

In the fusion zone, adequate toughness has been readily attained by controlling composition and cooling rates for plain carbon steel and medium strength HSLA (high-strength, low-alloy) steel with well established arc welding procedures. However, for the recently developed electron beam and laser welding processes which promise higher welding speeds and better weld properties, the toughness of the fusion zone is not well documented. In particular the possibility that the narrow fusion zones typical of these processes may introduce difficulties in toughness testing has not been explored.

The purpose of this paper is to present data proving that conventional Charpy-V notch (CVN) testing of narrow zones in electron beam (EB) welds can produce dangerously misleading results and to describe a simple economical technique for measuring the true ductile brittle transition temperature of narrow zones in welds.

Experimental

The steel used in this study was a controlled rolled line pipe steel. Its chemical composition is listed in Table 1. Welding parameters for the heat inputs tested are shown in Table 2. No preheat or filler metal was used. All

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welds were bead on plate single pass full penetration EB welds in 10 mm (0.4 in.) thick plate. A circular beam oscillation was used with the higher heat input welds to maintain a planar weld nugget.

Conventional CVN tests were carried out according to ASTM E23-66. In the 35 kJ/in. (1.4 kJ/mm) weld CVN tests were made with the five notch locations listed in Table 3 and shown in Fig 1. In the 5 kJ/in. (0.2 kJ/mm) and 8 kJ/in. (0.32 kJ/mm) weld, the HAZ was too narrow to permit accurate location of the notch; therefore, CVN tests in these welds were limited to specimens with notches in the fusion zone. To accurately position notches in the weld zones, the CVN specimens were polished and microetched before notching, and the notch positions checked with a microscope prior to testing. Absorbed energy and lateral contraction were measured. Also fracture appearance (per cent shear) was estimated with a binocular microscope and checked with a SEM for all specimens.

In addition to CVN tests in which the weld plane is parallel to the fracture plane (Fig. 2A) a new test called the cross weld Charpy test (CWCT) was devised (Fig. 2B). The CWCT uses a conventional Charpy-V notch specimen except that the weld plane is perpendicular to the fracture plane to force the fracture to pass through all zones of the weld. The fracture appearance of the various weld zones as measured with a binocular microscope and a SEM is plotted vs. test temperature to establish a transition temperature. A 6 kJ/in. (0.24 kJ/mm) weld which is 0.06 in. (1.5 mm) wide was positioned on the specimen mid-plane (Fig. 2B) with the notch in base metal. For both CVN and CWCT tests only longitudinal specimens of two thirds size were used.

The microstructure was studied by optical microscopy, scanning electron microscopy (SEM), thin foil and replica transmission electron microscopy. Microhardness was measured. Heating and cooling rates were measured and calculated. The detailed metallurgical results will be published separately.

Table 1—Chemical Analysis of the Steel (Ipsco X70) Used, %

| | | | |
|----|------|----|-------|
| C | 0.04 | Nb | 0.05 |
| Mn | 1.66 | P | 0.011 |
| Mo | 0.20 | S | 0.013 |

Results

Table 3 shows the results of CVN tests on a 35 kJ/in. (1.4 kJ/mm) weld with notches accurately placed at various distances from the weld center line (Fig. 1). The planar nature of the EB weld was expected to encourage the fracture path to follow a plane of constant microstructure. Figure 3 shows brittle fracture in the fusion zone and grain coarsened HAZ exactly as expected, and the ductile fracture in the grain refined HAZ. The microhardness traverse across the weld (Fig. 4) implies a significant loss of strength in the grain coarsened and grain refined HAZ.

On decreasing the weld energy to 5 kJ/in. (0.2 kJ/mm) the hardness of the weld increased to a maximum of 350 VPN compared to the base metal hardness of 210 VPN (Fig. 5). Conventional CVN test results for energy absorbed, fracture appearance and lateral contraction are shown in Figs. 6-8. A careful study of the fracture path revealed the disturbing fact that no tough fractures were ever observed in the weld metal for this weld at any temperature (Fig. 9). Above the CVN FATT all fractures occurred in base metal by a plastic hinge mechanism (e.g., Figs. 9 and 10). Below the CVN FATT all fractures were brittle and traveled in the weld metal (Figs. 9 and

10).

At -3 and 21 C (27 and 70 F) the CWCT results shown in Figs. 11 and 12 show a completely brittle fracture in the fusion zone comprised entirely of cleavage facets. At +50 C (122 F) Fig. 13 shows equal areas of cleavage fracture and ductile dimpling in the fusion zone indicating a "FATT" for the fusion zone in the CWCT.

In an 8 kJ/in. (0.32 kJ/mm) weld, two distinct curves can be fitted to the data points for CVN tests for longitudinal specimens (Figs. 14 and 15). The upper curve corresponds to base metal toughness and the fracture path of all such data points did indeed travel through the base metal or grain refined HAZ by a plastic hinge failure mechanism. The fracture path for all data points on the lower curve traveled through the fusion zone or coarse grained HAZ. A microhardness traverse (Fig. 16) revealed the weld metal (VPN 275) was much harder than the base metal (VPN 210), but no HAZ softening was observed.

Discussion

McGeedy⁴ ascribed the difficulties in fracture toughness testing the HAZ in a conventional weld to its undulated curved shape slanted to the plate surface which reduces the fracture force and increases the area of fracture surface. These factors make it difficult to maintain plane strain conditions in the HAZ. In work reported here, the HAZ zone is highly planar and perpendicular to the plate surface which avoids this difficulty entirely.

McGeedy also pointed out that the HAZ is relatively narrow but did not explain what difficulties the narrowness posed. It is suggested that the difficulties are accurately placing the notch in the HAZ and in restricting the plastic zone at the crack tip to the HAZ being tested. The first difficulty is one of technique and is easily overcome by checking the notch position with a microscope on a polished and etched specimen prior to testing.

Restricting the plastic zone at the crack tip to a particular HAZ microstructure or a narrow fusion zone is a

Table 2—Welding Parameters for Different Levels of Heat Input

| Heat input, kJ/in. (kJ/mm) | Voltage, KV | Current, MA | Speed, ipm (cm/min) |
|----------------------------|-------------|-------------|---------------------|
| 5 (0.2) | 80 | 25 | 22.5 (57.2) |
| 8 (0.32) | 70 | 30 | 13.0 (33.0) |
| 35 (1.4) | 80 | 25 | 1.9 (4.82) |

Table 3—Charpy V-Notch Test Results with Notches at the Positions in the FZ and HAZ shown in Fig 1.

| | 1 | 2 | 3 | 4 | 5 |
|-------------------------------|-------------|---------------------------------|---------------------|------------------------------------------------|-------------------|
| Notch position | Fusion zone | FZ-grain coarsened HAZ boundary | Grain coarsened HAZ | Grain coarsened HAZ-grain refined HAZ boundary | Grain refined HAZ |
| Temperature, F(C) | 5 (-15) | 14(-10) | 5(-15) | 12 (-11) | 10 (-12) |
| Charpy energy, ft-lb (joules) | 6 (8.1) | 3 (4.1) | 7 (9.5) | 30 (40.7) | 45 (61.0) |
| Temperature, F(C) | 4 (5.4) | 6 (8.1) | 10 (13.6) | 52 (70.5) | 48 (65.1) |
| Charpy energy, ft-lb (joules) | -22(-30) | -4(-20) | -24(-31) | -6(-21) | -2(-19) |
| Temperature, F(C) | 3 (4.1) | 3 (4.1) | 4 (5.4) | 26 (35.3) | 50 (67.8) |
| Charpy energy, ft-lb (joules) | 4 (5.4) | 5 (6.8) | 20 (27.1) | 52 (70.5) | 50 (67.8) |

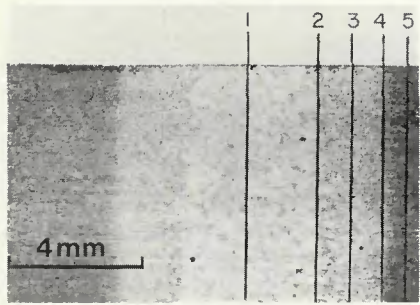


Fig. 1—Positions of the notch in Charpy V-notch impact test on 35 kJ/in. Weld: 1—fusion zone (FZ); 2—FZ-grain coarsened, heat-affected zone (GHAZ) boundary; 3—GHAZ; 4—GHAZ-grain refined heat-affected zone (GRHAZ) boundary; 5—GRHAZ

fundamental difficulty. The elastic stress field at the crack tip varies not simply as $r^{-1/2}$, where r is the distance from the crack tip, but as $(\rho + r)^{-1/2}$ where ρ is the crack tip radius.⁸ Thus the relatively large value of r for the blunt Charpy notch flattens the stress gradient. Because the yield strength of the base metal is much lower than the

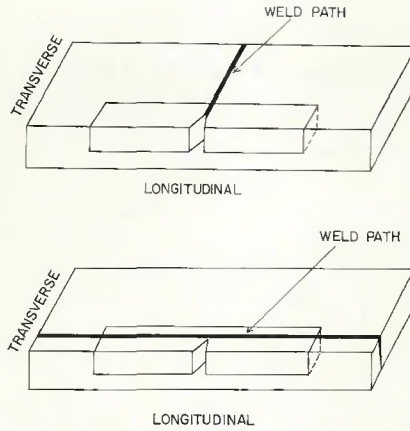


Fig. 2—Weld position in: A (top)—conventional Charpy V-notch specimen; B (bottom)—cross weld Charpy V-notch specimen

yield strength of the weld metal in the 5 kJ/in. (0.2 kJ/mm) weld, yielding could begin in the weaker base metal well away from the root of the notch on a plastic hinge and not at the notch surface as it would in a homogenous

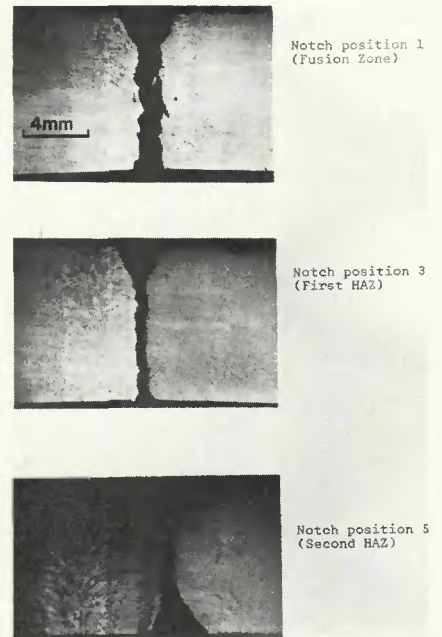


Fig. 3—Charpy impact fracture paths for the notch positions shown in Fig. 1

material. Such deformation would then relax the stress intensity at the root of the notch preventing crack initiation at the crack tip and facilitating ductile fracture on a plastic hinge.

This argument suggests that the sharper notch of Charpy specimens precracked in fatigue would reduce the plastic zone size, and therefore is more likely to confine the fracture to the fusion or HAZ to be tested. One of the authors is currently investigating the technical merits of this argument. However, the added cost of precracking Charpy specimens, the limited availability of fatigue machines for precracking, and the relative scarcity of published data on precracked specimens which would make it difficult to relate new results to previous work, limit the usefulness of precracked Charpy specimens.

The proposed cross weld Charpy test (CWCT) has the advantage of utilizing standard readily available CVN test facilities and is no more expensive than a conventional CVN test. To become an accepted test, its results must be correlated with conventional CVN results for homogenous materials. Although the work reported here is not sufficient to establish such a general correlation, the results are reasonable and justify further study, particularly since conventional CVN testing is shown to be entirely unreliable for narrow EB welds.

The +50 C (+122 F) FATT measured by the cross weld Charpy test for the 6kJ/in. (0.24 kJ/mm) weld is a reasonable value for the upper bainitic microstructure that the authors have determined by optical, SEM, replica



Fig. 4—Microhardness traverse in 35 kJ/in. (1.4 kJ/mm) weld

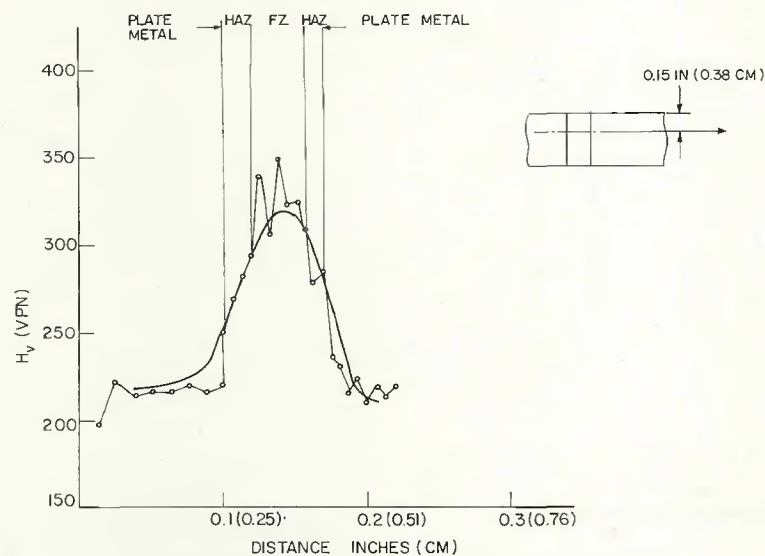


Fig. 5—Microhardness traverse on 5 kJ/in. (0.2 kJ/mm) weld

and thin foil TEM. For this microstructure in similar steels, Irvine and Pickering⁹ report the CVN transition temperature rose rapidly to +75 C (+167 F) as the yield strength increased to 135 ksi (931 MPa). Although they did not relate hardness to the CVN transition, a +50 C (+122 F) FATT and a yield strength near 120 ksi (827 MPa) is not unreasonable for weld metal with a hardness of 350 VPN.

Petch¹⁰ has reported the CVN transition temperature increases 2 C (3.6 F) per 1000 psi (6.9 MPa) increase in yield strength. On this basis the observed 80 C (162 F) increase in FATT would require a 45 ksi (310 MPa) increase in yield strength from 70 to 115 ksi (483 to 793 MPa). This is also in close agreement with the observed hardness increase from 210 VPN to 350 VPN for 5 kJ/in. (0.2 kJ/mm) weld metal.

Aronson¹¹ reported an increase in the FATT of 90 C (171 F) for an upper bainitic microstructure in a simulated HAZ in a 0.065 C, 1.06 Mn, 0.04 Nb steel. These three references and the results of this work suggest that +50 C (+122 F) FATT measured by the cross weld Charpy test is reasonable but the -37 C (-38 F) FATT measured by the conventional CVN test is not for the upper bainitic microstructure in 5 kJ/in. (0.2 kJ/mm) weld metal.

An argument can be made for relating the CWCT to the dynamic tear (DT) test by assigning the highest temperature at which fully brittle fracture is observed in the fusion zone as the nil ductility temperature (NDT). More precisely, this temperature would be a lower bound on the NDT for fusion zone metal for DT since an increase in section size and crack sharpness may show that the true NDT is somewhat higher. In this case the lower bound on the NDT would lie

between 21 and 50 C (70 and 122 F).

To the authors' knowledge, this inability of conventional CVN testing to measure the toughness of narrow fusion zones or HAZ has not been investigated previously. For example

IIW DOC-IX-902-74E entitled, "Recommendations for the Use of Charpy-V Impact Test as a Complementary Information Test on Embrittlement of the Heat Affect Zone (HAZ) of Weldments in Steel," does not mention this

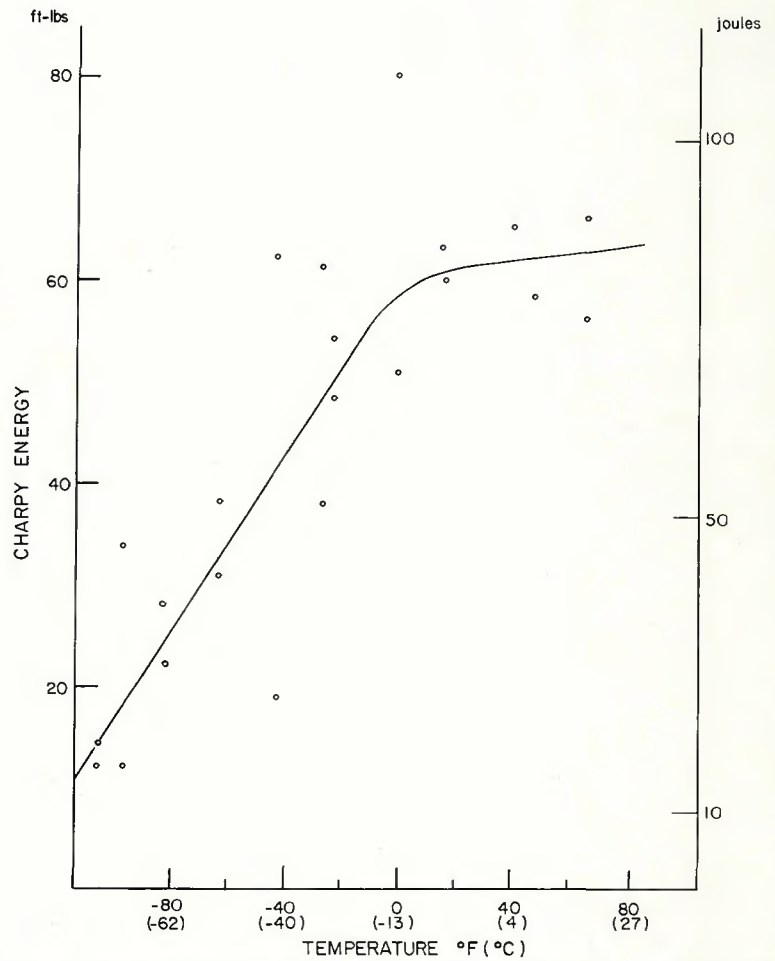


Fig. 6—Charpy V-notch energy vs. temperature curve for the 5 kJ/in. (0.2 kJ/mm)

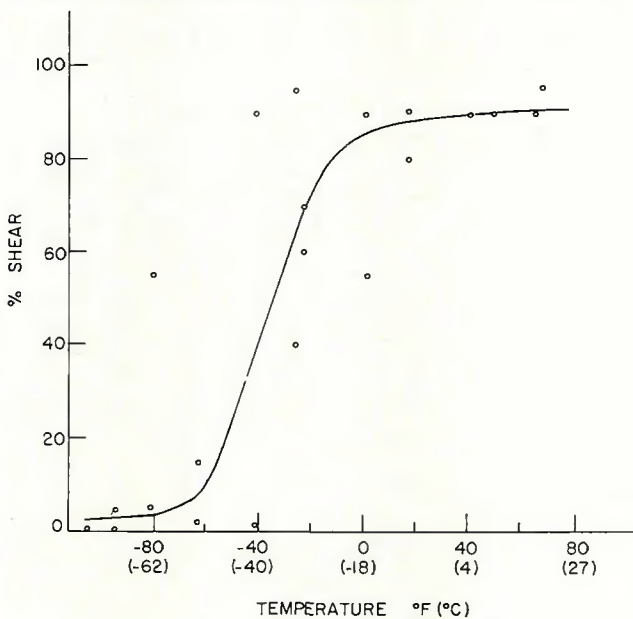


Fig. 7—FATT curve for the 5 kJ/in. (0.2 kJ/mm) weld

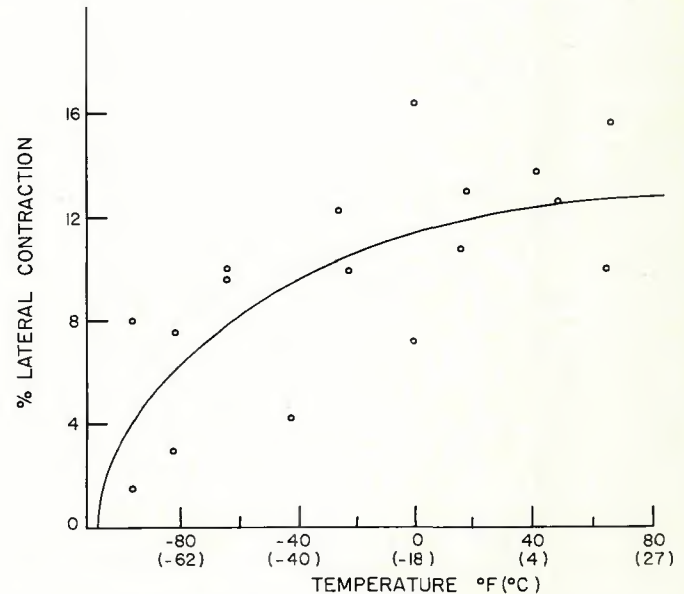


Fig. 8—Lateral contraction vs. temperature for the 5 kJ/in. (0.2 kJ/mm) weld

point.

The inability of conventional CVN tests to measure the toughness of narrow zones may alter the interpretation of CVN test results on laser welds reported by Breinan and Banas.¹² They carefully measured the CVN toughness

of single pass (20 kJ/in.) (0.8 kJ/mm) and two pass (10 kJ/in.) (0.4 kJ/mm) laser welds in 13.2 mm (0.52 in.) plate. Their base metal composition differed slightly from the steel shown in Table 1. The maximum weld metal hardness was VPN 373 for two pass welds and

VPN 291 for single pass welds compared to a base metal hardness of VPN 226. From CVN tests, they concluded the transition temperature for single pass welds was -9.4 C (15 F) and -51.1 C (-60 F) for two pass welds. They reported that no ductile fractures trav-

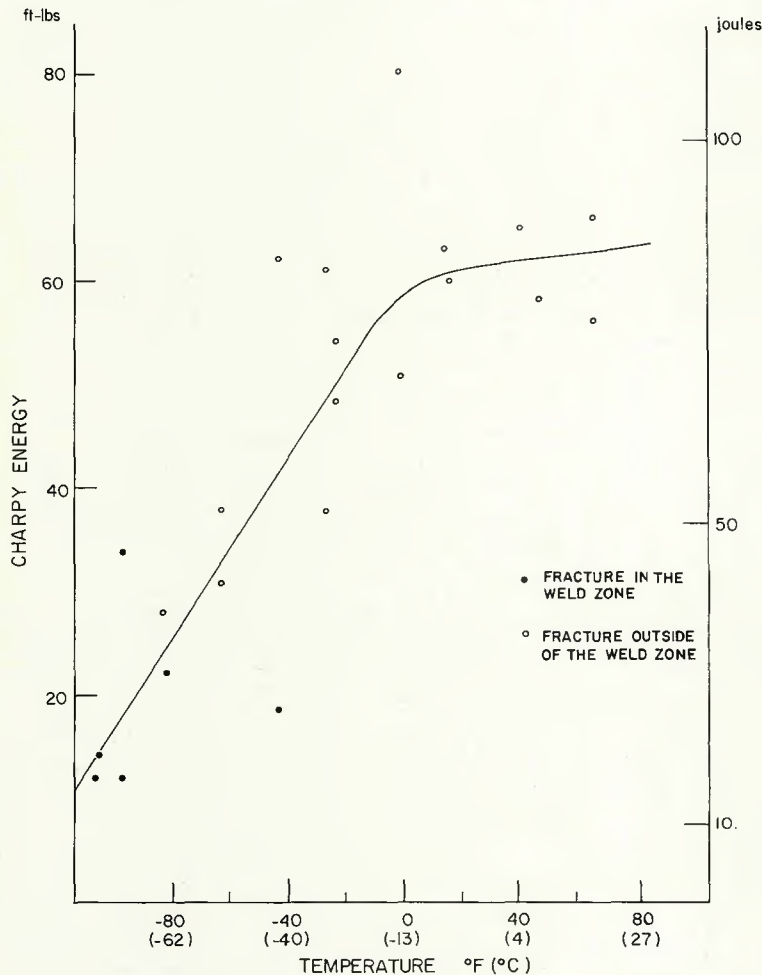


Fig. 9—CVN test results showing fracture traveled in base metal above -40 C (-40 F) and in the weld metal below -80 C (-112 F)

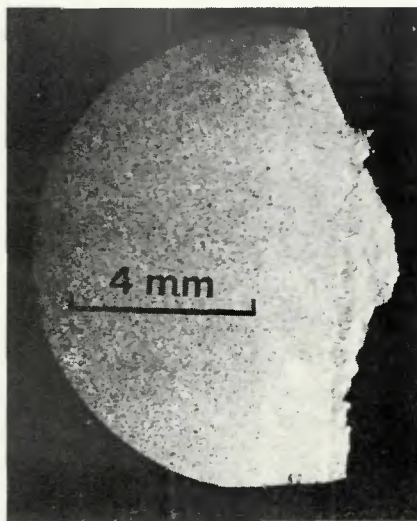


Fig. 10—CVN fracture paths: A (top)—following a plastic hinge 8 kJ/in. (0.31 kJ/mm), -64 C (-83 F), 72 ft-lb (97.6 J); B (bottom)—traveling in weld metal (8 kJ/in. (0.31 kJ/mm), -64 C (-83 F), 18 ft-lb (24.4 J))

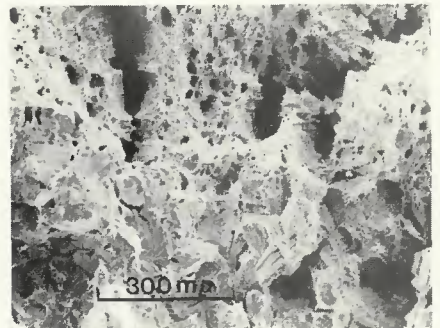


Fig. 11—SEM fractograph of cross weld Charpy test specimen (6 kJ/in. (0.24 kJ/mm), -3 C (+17.6 F), 46 ft-lb (62.4 J)) showing cleavage facets indicative of brittle fracture on the weld in the lower half of the photograph; the base metal has failed ductilely



Fig. 12—SEM fractograph of cross weld Charpy test specimen (6 kJ/in. (0.24 kJ/mm), +21 C (+70 F), 48 ft-lb (65.1 J)). The fracture in the weld metal on the lower half of the figure is entirely brittle; the base metal has failed ductilely by void coalescence

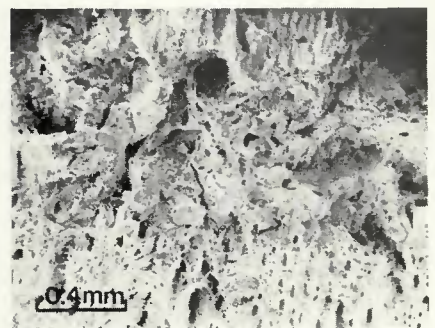


Fig. 13—SEM fractograph of cross weld Charpy test specimen (6 kJ/in. (0.24 kJ/mm), +50 C (+122 F), 50 ft-lb (67.8 J)). The fracture in the weld in the center of the photograph shows both cleavage facets and ductile dimples; the lower third of the photograph shows a ductile fracture in the base metal

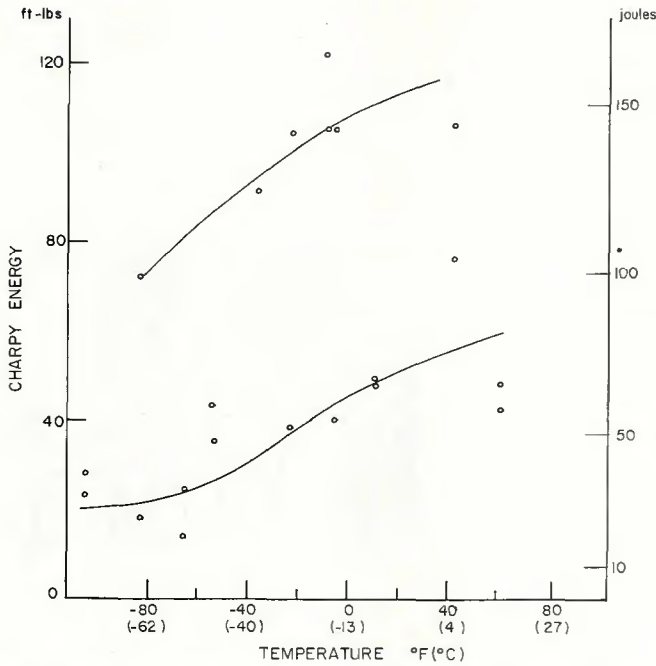


Fig. 14—CVN energy test results for 8 kJ/in. (0.32 kJ/mm) weld showing bimodal behavior. The fracture path in test points near the upper curve followed a plastic hinge; the fracture path in test points near the lower curve traveled in weld metal or HAZ

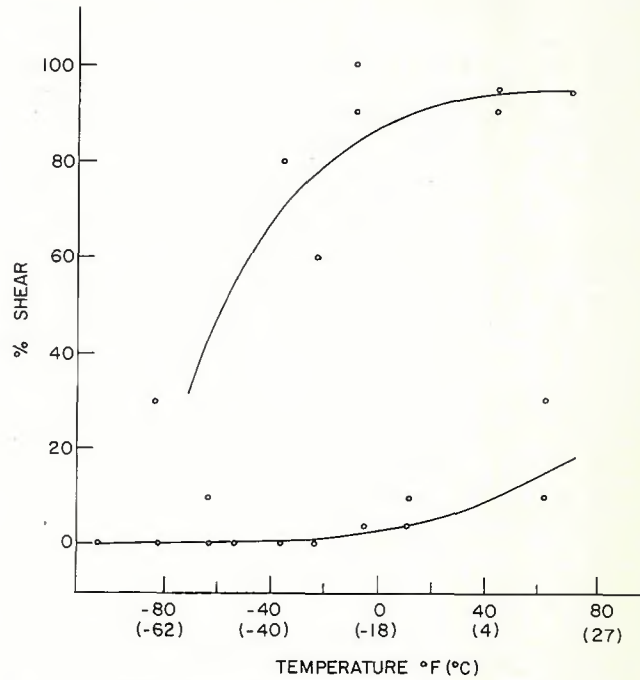


Fig. 15—CVN fracture appearance vs. temperature for 8 kJ/in. (0.32 kJ/mm) showing bimodal behavior. The fracture path in the points near the upper curve followed a plastic hinge; the fracture path of test points near the lower curve traveled in weld metal

eled through weld metal. Their results are so similar to the CVN results for the 5 kJ/in. (0.2 kJ/mm) weld reported here that it would be surprising if CWCT would not reveal a "FATT" for their laser weld metal near +50 C (122 F).

The fact that no precautions are considered necessary in interpreting the results of CVN tests in mechanically heterogeneous narrow welds presumably reflects a widely held notion that the crack will seek the lowest energy or most brittle path. However, if the yield strength of a narrow weld is much higher than the yield strength of the base metal, then it is possible that the base metal fracture

strain will be exceeded before the weld metal reaches its fracture strain. The fracture will then propagate through the base metal even if the weld metal has much lower toughness. Thus, the results reported here demonstrate the need to carefully reassess the notch toughness testing of narrow welds in particular and the HAZ in general. In particular, these results suggest that attempts to assess HAZ toughness by accurately locating the Charpy notch in the HAZ¹³ are futile under the above conditions and another approach is required. This may not apply to brittle zones with low yield strength and low fracture stress.

Arata et al¹⁴ have also reported

bimodal CVN results for EB welds in high strength structural steels that are similar to those shown in Figs. 14 and 15 for the 8 kJ/in. (0.32 kJ/mm) weld. They pointed out that in the bimodal region high energy fractures propagated through base metal and low energy fractures through weld metal. They reported the weld hardness was usually 100 points harder on a VHN scale than base metal hardness in steels containing 0.13 to 0.18 carbon. However, no bimodal behavior was observed in 0.18 carbon steel in which the weld hardness reached 330 VHN compared to a base metal hardness near 180 VHN. Therefore, bimodal behavior cannot of course be ascribed simply to differences in hardness between the weld and base metal.

A theoretical analysis of bimodal behavior would require an analysis of the plastic hinge fracture mode versus the logarithmic spiral fracture mode. This has been studied for mild steel¹⁵; however, the introduction of a narrow hard weld that has a quite different stress strain curve and presumably quite different fracture toughness from the base plate would make the analysis exceedingly difficult.

It could be argued that since the fracture did not propagate through weld metal above the CVN FATT in the 5 kJ/in. (0.2 kJ/mm) weld such a weld would not be likely to suffer brittle fracture in service. In other words, the toughness of weld metal and the resistance of a welded structure to brittle fracture could be quite different. However, as the size of specimen

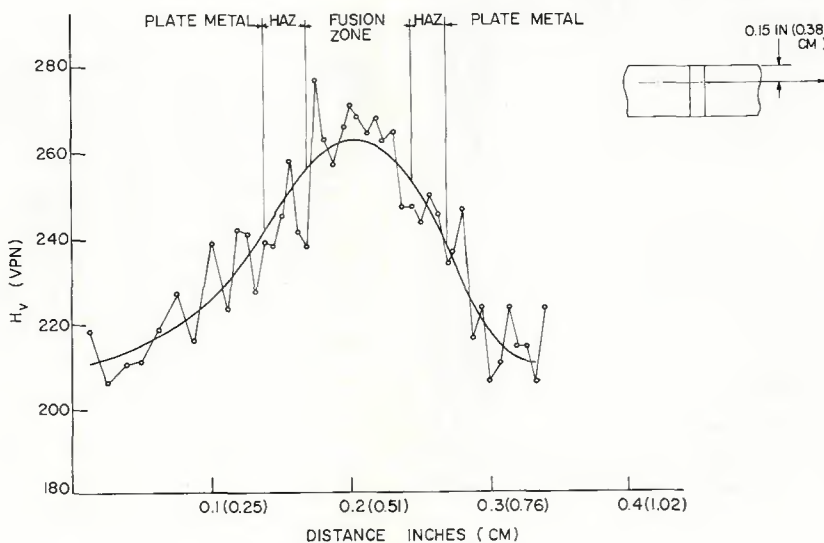


Fig. 16—Microhardness traverse on 8 kJ/in. (0.32 kJ/mm) weld

or the welded structure increases, the load required for slip on a plastic hinge is likely to increase rapidly, favoring a fracture path in the brittle weld metal. While this would be better answered by full scale tests or by dynamic tear tests, a NDT above 21 C (70 F) should seriously concern design engineers.

Conclusions

1. The ductile brittle transition temperature (DBTT) of a narrow fusion zone in an EB weld as measured by conventional Charpy-V notch tests was -37 C (-38 F) when the true DBTT was +50 C (122 F). This error of +90 C (162 F) is potentially dangerous.

2. Conventional Charpy-V notch tests of narrow zones in any weld including the HAZ of arc welds and the fusion zone of laser welds are susceptible to serious error.

3. The true DBTT of the fusion zone in low energy EB welds can be measured simply and economically with the cross weld Charpy test (CWCT).

Acknowledgments

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Local Heat Treatment of Welds in Piping and Tubing

In the manufacture of welded articles or structures in the shop or in the field, it may be desirable, for a variety of reasons, to heat the weld regions before welding (preheating), between passes (interpass heating), or after welding (postheating). This document presents in detail the various means commercially available for heating pipe welds locally, either before or after welding, or between passes. The relative advantages and disadvantages of each method are also discussed. Although the document is oriented principally toward the heating of welds in piping and tubing, the discussion of the various heating methods is applicable to any type of welded fabrication.

Topics covered include the following:

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- Induction Heating
- Electric Resistance Heating
- Flame Heating
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- Gas-Flame Generated Infrared Heating
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