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THE FRACTURE BEHAVIOR OF A588 GRADE A AND A572 GRADE 50 WELDMENTS

by

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ABSTRACT

An experimental study was conducted on ASTM A588 Grade A and ASTM A572 Grade 50 microalloyed steels submerged arc welded with Linde 40B weld metal to determine the fracture properties of base plates, weld metal and heat affected zones. The effects of plate orientation, heat treatment, heat input, and post weld heat treatments on heat affected zone toughness were the primary focus of the investigation. Tensile properties were evaluated for the weld metal and base plates. Hardness tests were done on weld heat affected zones (HAZ). Charpy impact tests were performed over a temperature range for plates, welds and heat affected zones. The nil-ductility transition temperature was determined for the plates and the weld metal.

The weld metal tensile tests showed that the Linde 40B weld metal overmatched the baseplates in strength. Post weld heat treatment had minimal effect on either the strength or ductility of this weld metal.

Charpy impact test results showed that the longitudinal orientation HAZ was superior in shelf toughness to the transverse for all conditions. The impact transition temperature of the HAZ was as good or as superior to that of the as-rolled baseplate for all conditions of welding and heat treatment. Post-weld stress-relief heat treatments generally degraded toughness in the HAZ for A588-A but improved it for A572-50. From the HAZ impact toughness standpoint, a heat input of 3.5 KJ/mm was found to be near optimal.

Weld metal toughness was found to be variable and the effects of post weld heat treatments on weld metal were inconsistent. Transition temperatures obtained for the Linde 40B weld metal were as good as or superior to the as-rolled plates. The nil-ductility transition temperature of the weld metal was superior to that of as-rolled plates.

I. INTRODUCTION

The Pressure Vessel Research Committee (PVRC) of the Welding Research Council (WRC) has recently sponsored a number of research investigations aimed at determining the basic mechanical characteristics of commonly used or prospective pressure vessel and structural high strength low alloy (HSLA) steels. These studies have included determinations of strength, impact toughness and fracture toughness for baseplate materials [1-6] and weldments.[7-9] For the base plate materials, the mechanical characterization has involved both as-rolled and normalized material and emphasis has been placed on the effects of strain aging and stress relief heat treatments. In the weldment studies, the effects of heat input and post-weld heat treatment (PWHT) on the strength and toughness of weld metals and heat affected zones (HAZ) have been evaluated.

This report presents data on the fracture behavior of weldments of A588-Grade A and A572 Grade 50 microalloyed steels. They were selected for study because responses to a PVRC survey [10] of fabricators of structural steel pressure vessel and component supports suggested that there was a great deal of interest in obtaining data on these grades. Primary emphasis in the program was on the properties of weldments, but comparison is made to the baseplate properties when appropriate.

One of the items of greatest interest to uses of these grades was the toughness of the weld heat affected zone (HAZ). Weld metal properties can, in part, be controlled independently by weld metal composition selection. The weld heat affected zone composition is that of the plate. Properties of the HAZ must therefore be controlled by welding heat input, prior microstructure and post-weld heat treatment. The effects of these variables on HAZ toughness properties is the main focus of this investigation.

II. EXPERIMENTAL PROCEDURES

Materials

The materials used in this investigation were supplied by Lukens Steel company and met the composition requirements for ASTM A588 Grade A and ASTM A572 Grade 50 high strength low alloy structural steels. The compositions of these heats of material are given in Table 1. Plate thickness was 38 mm (1.5 in.) for the A588-A and 45 mm (1.75 in.) for the A572-50. Normalized material used in this study was obtained by heating as rolled plates in a forced air furnace at 900°C (1650°F) for 1.5 hr. (at temperature) followed by air cooling.

Weldment Preparation

Prior to fabrication of the primary weldments used in this study, several preliminary welds were prepared in order to determine the effect of heat input on HAZ impact toughness in normalized A588-A and in as-rolled and normalized A572-50. The flux cored arc welding process was used with an E70T1 weld wire and 100% CO_2 shield to prepare weld pads for study. Three heat inputs were used to produce the welds, 1.6, 3.5 and 5.5 KJ/mm (40, 90 and 140 KJ/in.). No preheat was used but a maximum interpass temperature of 93°C (200°F) was maintained. It was intended to maintain the fusion plane perpendicular to the plate surface. By prepositioning the weld groove such that a flat HAZ perpendicular to the plate surface was maintained on at least one side of the weld joint. This was generally successful, but a few specimens had HAZ's which were slightly diagonal to the specimen axis. No weld metal tests were made of the flux cored arc specimens; they were for the evaluation of HAZ only.

The weldments for full evaluation were fabricated by Lukens Steel Company using the submerged arc welding process with Linde 40B weld metal and Lincoln 860 flux. The nominal compositions of the weld metal and flux are given in Table 1. From the results of the preliminary welds, a 3.5 KJ/mm (90 KJ/in) heat input was chosen for study. A K-shaped joint geometry, Figure 1, was used in order to produce a flat HAZ perpendicular to the plate surface and the procedure employed is shown in Table 2. A typical preheat of 95°C (200°F) was used and the maximum interpass temperature was maintained at 121°C (250°F). Twenty-three to twenty-five passes were required to complete each joint, an example of which is shown in Figure 2. It is seen that a flat HAZ is produced in the midsection of the plate. For this reason, and to minimize effects from through thickness variations in chemistry, only the midsection of the plate was used for subsequent testing.

The effect of orientation on the Charpy impact energy for as-rolled and normalized A588-A and A572-50, taken from the data of Erazo and Pense,[6] is shown in Figures 3a and b. The longitudinal orientation specimens exhibit higher toughness than the transverse orientation at all temperatures. With this in mind, the welding direction chosen for the commercial weldments was parallel to the rolling direction. Therefore the HAZ test specimens taken from the commercial weldments were transverse to the rolling direction and represent a worst case situation with respect to toughness.

Stress Relief

Post-weld stress relief heat treatments were performed on the HAZ weld pads for various time periods at 620°C (1150°F) or 650°C (1200°F), while for the submerged arc welds, stress relief treatments of 2 or 10 hours at 620°C (1150°F) were used. All heat treatments were carried out in a forced air furnace. The material was furnaced cooled from the stress relief temperature at a rate of 30°C (55°F) per hour to 250°C (482°F) and subsequently air cooled from this temperature.

Hardness Testing

Diamond pyramid hardness tests were used to characterize the hardness of the HAZ of the steels. The hardness tests were used to determine the peak as-welded HAZ hardness and the effect of PWHT on the peak HAZ hardness. The peak HAZ hardness was found by taking a microhardness traverse across the HAZ in 0.25mm (.010 in.) steps.

Tension Testing

Tensile tests were performed on the base metal in the as-rolled and stress relieved conditions. Transverse orientation 6 mm (0.25 in.) diameter button-head type specimens tested according to ASTM specification E-8 were used. Tensile tests were also performed on the Linde 40B weld metal. Since the width of the metal was limited, modified 6 mm

(0.25 in.) button-head type specimens were used. These specimens were ground down in the center of the gauge length as shown in Figure 4 to insure that weld metal was tested. Since the gauge diameter continuously varied in these specimens, no extensometer was used. Tests were conducted at ambient temperature on a 44.5 KN (10,000 lb.) capacity Instron Universal Tester at a crosshead speed on 1.27 mmpm (0.05 ipm).

Charpy Impact Testing

Standard type A impact specimens were machined from the weld metal and HAZ as shown in Figure 5. The flux cored arc weld pad specimens for the A588-A were in the plate longitudinal (LT) orientation, while the A572-50 HAZ specimens were in the transverse (TL) orientation. For the submerged arc weldments of both steels, the welds were longitudinal to the rolling direction and the HAZ specimens were in the transverse (TL) orientation. All tests for the A588-A were of the normalized condition. A572-50 was tested in both the normalized and as-rolled condition. Heat affected zone specimens were notched within 1 mm from the fusion line. This procedure was controlled by etching the Charpy blanks prior to notching. Testing was conducted on a certified calibrated Satec SI-1 impact testing machine according to ASTM specification E23. A mechanically stirred bath of methanol cooled by liquid nitrogen was used to achieve low temperature. The specimens were maintained at temperature a minimum of 15 minutes prior to testing and were tested within 5 seconds following removal from the cooling bath. Impact energy and lateral expansion was measured for each specimen according to ASTM specification E23.

Nil-Ductility Transition Temperature Testing

Nil-ductility transition temperature tests were performed in accordance with ASTM specification E208. As-rolled baseplate and as-welded weld metal were evaluated by this method. For the as-rolled baseplate the specimen orientation was transverse to the rolling direction.

The weld metal specimens were orientated transverse to the welding direction. Type P3 specimens were used and a Murex-Hardex-N electrode was used for the crack starter weld bead. A single weld bead was deposited using approximately 160-180 amperes at approximately 25 volts and a travel speed of 1.5mm/sec (3.5 i/min).

A mechanically stirred bath of methanol cooled with liquid nitrogen was used to achieve low temperature. The specimens were maintained at temperature a minimum of 20 minutes prior to testing and were tested within 10 seconds following removal from the cooling bath. Impact energies of 475 J (350 ft-lb) and 543J (400 ft-lb) were required to produce the specified deflection for the as-rolled baseplate and weld metal, respectively.

III. RESULTS AND DISCUSSION

Tensile Tests

The results of the plate and weld metal tensile tests are presented in Table 3. For the A588-A base plate in the as-rolled condition, a marked anisotropy in yield strength and ductility with specimen orientation is noted. This result, however, is not unexpected since A588-A was neither cross-rolled nor usually inclusion shape controlled. Normalizing lowered strength overall, but reduced the discrepancies in strength and ductility for the two testing directions. The reduction in strength upon normalizing presumably resulted from the elimination of residual rolling stresses and alteration of the microstructure (precipitate size and distribution). The tensile properties for the A572-50 base plate were similar to the A588-A for similar conditions, however this material was only tested in the transverse orientation.

The Linde 40B weld metal overmatches the baseplates in yield strength and was similar to the as-rolled baseplates in tensile strength. Weld metal ductility, as measured by reduction in area, was lower than both as-rolled and normalized baseplate. As noted in the experimental procedure section, however, a nonstandard specimen was used for these tests. Considering the geometry of this specimen, a somewhat lower ductility would be expected as compared to a standard tensile specimen. Post weld heat treatment of 2 hours at 621°C (1150°F) did not appreciably alter strength or tensile ductility for this weld metal.

Heat Affected Zone Toughness Properties

The HAZ impact energy transition curves produced by the flux cored arc welding process are shown in Figures 6 and following. The transition temperatures are listed in Table 4. For these and many of the subsequent figures, the toughness trend curves are shown without data points. This was done to reduce the number of figures to be presented by including 2 or more curves on each figure. As in all HAZ toughness studies, there is considerable scatter in testing, making presentation of multiple curves on one figure difficult to interpret. In several of these curves, Figures 3 and 19, the data points are left on to give the reader an indication of typical experimental data scatter in the investigation.

For the A588-A, the 34J (25 ft-lb) HAZ transition temperatures for the 1.6 and 3.5 KJ/mm heat inputs, seen in Figure 6, were virtually identical, -40°C (-40°F), while that for the 5.5 KJ/mm heat input occurred at approximately -32°C (-26°F). These differences are relatively small. The upper shelf energy for the 1.6 KJ/mm A588-A weld was much lower than that for the higher heat inputs, probably because of the formation of low temperature transformation products in the HAZ. These results indicate that the 3.5 KJ/mm heat input used in the major portion of this study was near optimal. For the A588-A, heat inputs lower than 3.4 KJ/mm exhibited low upper shelf energies with no benefit in transition temperature, while heat inputs higher than 3.5 KJ/mm exhibited higher transition temperatures with little or no benefit in upper shelf energy.

For the A572-50, Figure 7, the effect of the heat input was small. The 34 J (25 ft-lb) HAZ transition temperatures shifted by only 10°C (18°F) overall. The highest HAZ transition temperature was -12°C (10°F) for the 1.6 KJ/mm weld. The lower HAZ transition temperatures for the A588-A as compared to A572-50 are probably due to specimen orientation and base plate heat treatment. For the A572-50, 3.5 KJ/mm produced the lowest HAZ transition temperature. Shelf energy was little effected. The 5.5 KJ/mm HAZ had an intermediate transition temperature.

The effects of post weld heat treatment (PWHT) on impact properties of the A588-A HAZ are shown in Figures 8-10 and Table 4. For the 1.6 KJ/mm HAZ, Figure 8, PWHT increases energy absorption in the upper shelf region while having little effect on the 34J (25 ft-lb) transition temperature. For the 3.5 KJ/mm HAZ, Figure 9, PWHT substantially decreases its toughness. The effect of PWHT on the 5.5 KJ/mm HAZ, Figure 10, was similar to the 3.5 KJ/mm HAZ, i.e., toughness transition temperature increases with PWHT.

The effect of specimen orientation on the impact toughness of the HAZ is seen in Figure 11 for A588-A steel. Here the toughness differences for transverse and longitudinal orientation specimens for one heat input, 3.5 KJ/mm (90 KJ/m) are apparent. The as-welded transverse orientation specimens were much lower in shelf toughness than the longitudinal ones. The response to PWHT of these transverse orientation HAZ specimens is similar to that of the longitudinal ones, as seen in Figure 12. The PWHT was not effective in improving toughness but rather decreased it.

The effects of PWHT on the A572-50 HAZ, as seen in Figures 13-15 and in Table 4 contrast with those found in A588-A. For these welds, the PWHT either had little effect or improved the HAZ toughness. The improvement was most pronounced for the low and medium heat input HAZ welds.

Comparison was also made between the toughness of the HAZ in as-rolled and normalized material, i.e. the effect of prior treatment. An example of such a comparison is seen in Figure 16 for A572-50. Normalizing the plate material prior to welding significantly improved. the toughness of the HAZ. The effect of PWHT on this normalized condition HAZ was similar to that of the as-rolled in the same steel, some improvement in toughness with PWHT. This is shown in Figure 17.

Hardness Tests on the HAZ

Hardness values on the HAZ of the various weldments gave some further insight into the properties of this zone. Figure 18 summarizes these data. It shows that the hardness of the A588-A HAZ exceeds that of the A572-50 for most conditions, especially at low heat input. This is consistent with the higher hardenability of the A588-A. Post weld heat treatment is shown to be effective in lowering HAZ hardness for both steels, but the hardness of the A572-50 HAZ is still consistently below that of the A588-A.

Weld Metal Properties

Figure 19 and Table 5 show the Linde 40B weld metal impact properties. In addition to properties in the as-deposited condition, properties after post-weld heat treatments of 2 and 10 hours at 620°C (1150°F) are also shown. Due to a lack of sufficient material in the original A588-A weldment, weld 1, a second weldment of the same type, weld 2, was made in A588-A to provide sufficient material to complete the weldment study. A third weldment was made using the same procedure for A572-50, weld 3. These welds were made commercially and different wire lots were used. Data from all these welds are shown in Figure 19. The as-welded toughnesses of these weld metals are quite different. Weld 1 had a 35J (25 ft-lb) transition temperature of -21°C (-6°F), weld 2, a transition temperature of -8°C (+18°F), and weld 3, a transition temperature of -35°C (-31°F). In addition to the fact that the as-welded impact properties of these welds were not consistent, the PWHT response of the materials appeared to be different. For weld 1, PWHT of 2 hours at 620°C (1150°F) appeared to improve transition temperature and upper shelf energy slightly while for weld 2, PWHT of 10 hours at 620°C (1150°F) appeared to slightly degrade the impact toughness. For weld 3, PWHT for 2 or 10 hours appeared to have little effect. It is proposed that the differences in PWHT response are the result of differences in minor process variables during welding, although none were apparent from the weld procedure reports.

The general trends indicate that the impact transition temperatures of the welds are as good as or superior to the as-rolled plates. PWHT does not consistently improve the transition temperature for the weld metal.

Baseplate and Weld Metal Nil-Ductility Temperature Testing

Drop weight tests on the A588-A as-rolled baseplate yielded a nil-ductility transition (NDT) temperature of -10°C (14°F). This value occurred near the upper end of the lower shelf region of the impact transition curve for as-rolled material. The NDT temperature for the as-rolled A572-50 was -15°C (5°F).

Due to insufficient material, the nil-ductility transition temperature for the Linde 40B weld metal 1 was not uniquely determined. However, two partly cracked but technical "no break" specimens were observed at -50°C (-58°F) and therefore the NDT temperature was close to this temperature. For weld 3 the NDT temperature was -45°C (-49°F). Therefore, weld metal toughness, as measured by the NDT temperature, is superior to A588-A or A572-50 in the as-rolled condition. This is consistent with Charpy test results. PWHT of weld 3 at 620°C (1150°F) for 10 hours raised its NDT temperature 10°C (18°F), which is also consistent with its behavior in the Charpy test.

SUMMARY AND CONCLUSIONS

The primary results of this investigation may be summarized as follows:

1) The Linde 40B weld metal overmatched as-rolled and normalized A588-A and A572-50 baseplates in terms of strength. PWHT at 620°C had minimal effect on its strength. At room temperature, the yield strength of the weld metal as welded was about 490 MPa (71 ksi) compared to about 380 MPa (55 ksi) for normalized A588-A and A572-50. Its tensile strength was about 590 MPa (85 ksi) as compared to about 545 MPa (79 ksi) for the baseplates.

2) The longitudinal orientation in the HAZ exhibited higher Charpy shelf toughness than the transverse orientation for all conditions tested. The HAZ in normalized material was higher in shelf toughness than the HAZ in as-rolled material.

3) A heat input of 3.5 KJ/mm (90 KJ/in) was found to be optimal from a as-welded heat affected zone impact toughness standpoint. Higher and lower heat inputs (4.4 KJ/mm (140 KJ/in)), (1.6 KJ/mm (45 KJ/in) respectively), produced higher transition temperatures or lower shelf toughnesses. The transition temperature differences were small, on the order of 10°C (18°F).

4) PWHT at 620°C (1150°F) generally increased the transition temperature of the A588-A HAZ, but also increased the upper shelf energy for low heat inputs. PWHT at 620°C (1150°F) decreased the transition temperature of the A572-50 HAZ and also raised its shelf toughness.

5) Impact tests of the Linde 40B weld metal in three different welds made under similar conditions were inconsistent, and the effect of PWHT on this weld metal could not be determined with certainty. However, the range of transition temperatures obtained for this material, approximately -40 to 10°C (-40 to 50°F) for the 34J (25 ft-lb) level is at or below that for the as-rolled plates.

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TABLE 1

Composition (wt%) of the Materials

Material	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al	Cu	O
A588-A	.14	1.03	.012	.020	.45	.20	.60	.05	.072	.030	.31	--
A572-50	.16	1.19	.010	.023	.23	.19	.12	--	.04	.040	.27	--
Linde 40B												
Weld (1)	.052	1.23	.017	.019	.32	.079	.19	.35	.022	--	.17	.058
Weld (2)	.053	1.25	.016	.023	.28	.077	.14	.38	.015	--	.25	.046
Weld (3)	.057	1.18	.017	.018	.21	.071	.05	.40	.008	---	.23	.080

Lincoln 860	SiO_2	Al_2O_3	FeO	CaF_2+CaO	MgO	Na_2O	MnO	TiO_2	K_2O
Flux	18.77	29.94	9.61	8.23	19.48	1.8	9.84	1.96	.1

TABLE 2

Submerged Arc Welding Procedures

Wire: Linde 40B 3.9 mm (5/32 in.) Dia.

Flux: Lincoln 860

Preheat 93°C (200°F) Min.; Interpass 121°C (250°F) Max.

Weld No.	Pass No.	Amps. (A)	Volts (V)	Travel Cm/Min	H KJ/mm
1	1-2	350	32	50.8	1.3
	3-4[1]	400	32	38.1	2.0
	5-6	350	32	50.8	1.2
	7	350	32	40.6	1.6
	8	525	34	40.6	2.6
	9[1]	625	32	33.0	3.6
	10-23[2]	625	32	33.0	3.6
2	1-2	350	32	48.3	1.4
	3-4	375	32	40.6	1.9
	5-6[1]	450	32	40.6	2.1
	7	350	32	45.7	1.5
	8	450	32	45.7	1.9
	9	625	32	43.2	2.6
	10	625	32	38.1	3.1
	11-24[3]	625	32	33.0	3.6
3	1-2	350	32	48.3	1.4
	3-4	375	32	40.6	1.9
	5-6[1]	450	32	40.6	2.1
	7	350	32	45.7	1.5
	8	450	32	43.2	2.0
	9	625	32	40.6	1.9
	10-25[4]	625	32	33.0	3.6

1. Plate turned after this pass.
2. Plate turned after 11, 13, 15, 17 and 20 passes.
3. Plate turned after 14 and 20 passes.
4. Plate turned after 10, 14 and 21 passes.

TABLE 3

Baseplate and Weld Metal Tension Test Results

Condition and Orientation	Yield MPa	Strength (KSI)	Tensile MPa	Strength (KSI)	Reduction of Area %	Elongation %
			A588 GRADE A			
As-rolled (long)	435	(63.1)	599	(86.9)	74.1	28.6
As-rolled (trans.)	387	(56.2)	589	(85.4)	56.3	24.1
Normalized (long)	372	(53.9)	542	(78.6)	73.7	35.8
Normalized (trans.)	378	(54.8)	546	(79.2)	61.4	31.4
			A572 GRADE 50			
As-rolled (trans.)	378	(54.8)	546	(79.2)	64.6	28.0
Normalized (trans.)	345	(50.1)	487	(70.7)	64.5	34.4
As-rolled (long.)	352	(51.1)	531	(77.2)	64.7	25.9
Normalized (long.)	341	(49.5)	484	(70.2)	65.6	34.4
			LINDE 40B WELD METAL (1)			
As-welded	490	(71.2)	591	(85.8)	41.9	----
PWHT 2 hr at 620°C	495	(71.9)	587	(85.2)	44.5	----
			LINDE 40B WELD METAL (3)			
As-welded	496	(71.9)	589	(85.5)	64.3	----
PWHT 2 hr at 620°C	498	(72.2)	596	(86.4)	61.5	----
PWHT 10 hr at 620°C	492	(71.4)	589	(85.5)	63.0	----

TABLE 4

Impact Transition Temperatures for the Steels and Weldments

A. A588 Grade A Condition		34J (25 ft-lb) °C	34J (25 ft-lb) (°F)	0.88 mm(35 mil) °C	0.88 mm(35 mil) (°F)
As Rolled	Longitudinal	-6	(21)	3	(37)
	Transverse	8	(46)	20	(68)
Normalized	Longitudinal	-62	(-79)	-53	(-63)
	Transverse	-43	(-45)	-32	(-26)
HAZ Longitudinal 1.6 KJ/mm	As-welded	-40	(-40)	-4	(25)
	PWHT 650°C	-44	(-47)	-18	(0)
HAZ Longitudinal 3.5 KJ/mm	As-welded	-42	(-43)	-36	(-33)
	PWHT 620°C	-6	(21)	6	(43)
HAZ Longitudinal 5.5 KJ/mm	As-welded	-30	(-22)	-22	(-8)
	PWHT 620°C	-4	(25)	0	(32)
HAZ Transverse 3.5 KJ/mm	As welded	-42	(-44)	-18	(0)
	PWHT 620°C 2 hr	-20	(-4)	-14	(7)
	PWHT 620°C 10 hr	-12	(10)	3	(37)

Table 4. continued.

B. A572-50		34J (25 ft-lb)		0.88 mm (35 mil)	
Condition		°C	(°F)	°C	(°F)
As Rolled Longitudinal		-10	(14)	16	(61)
As Rolled Transverse		8	(46)	23	(73
Normalized Longitudinal		-55	(-67)	-50	(-58)
Normalized Transverse		-51	(-60)	-39	(-38)
HAZ Transverse 1.6 KJ/mm	As Welded	-12	(10)	14	(57)
	PWHT 620°C-2 hr	-47	(-53)	-11	(12)
HAZ Transverse 3.5 KJ/mm	As Welded	-22	(-8)	-1	(30)
	PWHT 620°C-2 hr	-41	(-42)	-17	(1)
	PWHT 620°C-10 hr	-32	(-26)	-17	(1)
HAZ Transverse 5.5 KJ/mm	As Welded	-14	(7)	4	(39)
	PWHT 620°C-10 hr	-18	(0)	-4	(25)
Normalized HAZ Transverse 3.5 KJ/mm	As Welded	-30	(-22)	-28	(-18)
	PWHT 620°C-2hr	-58	(-72)	-40	(-40)
	PWHT 620°C-10 hr	-43	(-45)	-34	(-29)

C. LINDE 40B		35J (25 ft-lb)		0.88 mm (35 mil)	
Condition		°C	(°F)	°C	(°F)
Weld 1 3.6 KJ/mm	As Welded	-21	(-6)	-18	(0)
	PWHT 620°C-2 hr	-46	(-51)	-35	(-31)
Weld 2 3.6 KJ/mm	As Welded	-8	(+18)	-3	(+26)
	PWHT 620°C-2 hr	-8	(+18)	-3	(+26)
	PWHT 620°C-10 hr	+10	(+50)	+19	(+66)
Weld 3 3.6 KJ/mm	As Welded	-35	(-31)	-27	(-17)
	PWHT 620°C-2 hr	-36	(-33)	-29	(-20)
	PWHT 620°C-10 hr	-28	(-18)	-18	(0)

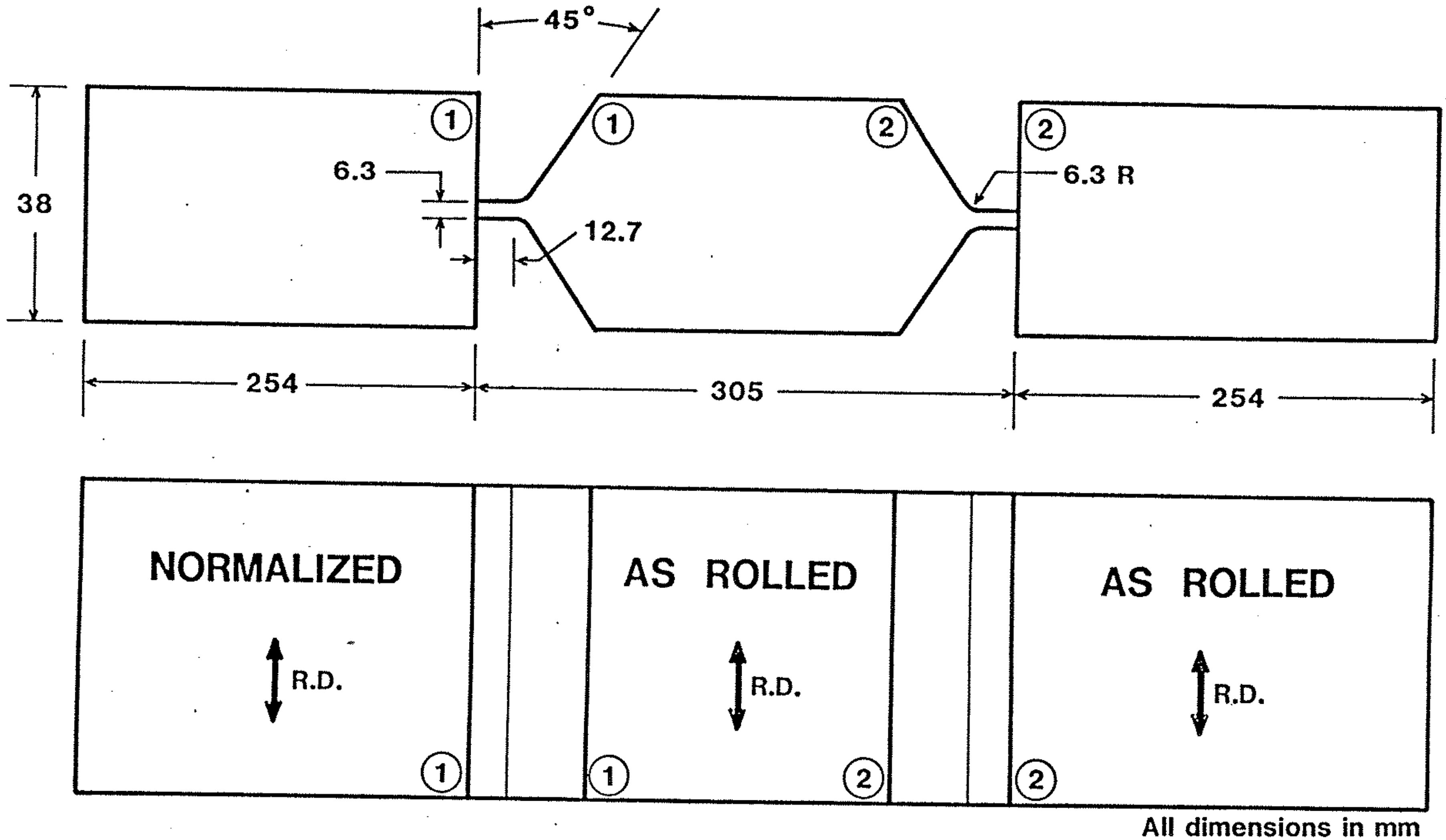

Figure 1: Schematic diagram of joint configuration for submerged arc weldment.

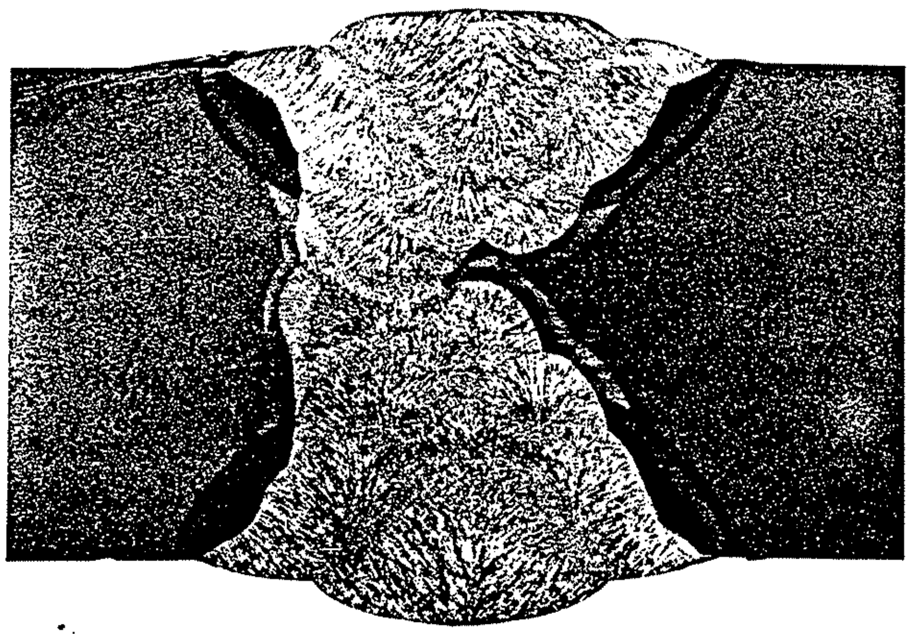

Figure 2 Macrostructure of A588-A weldment.

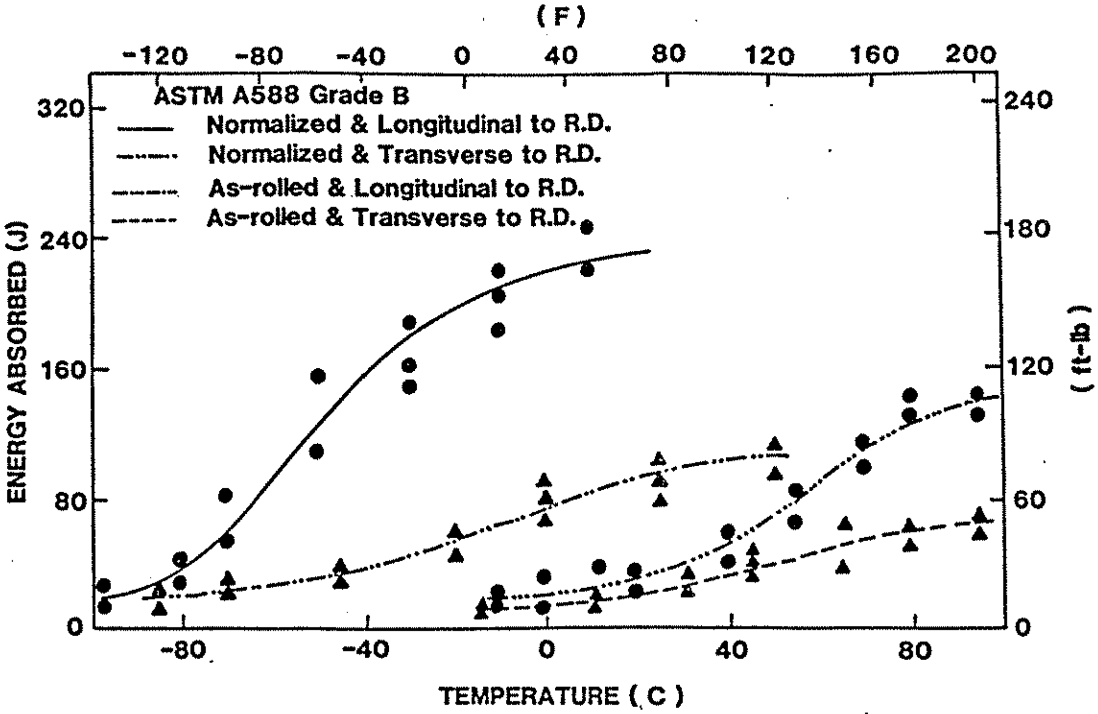

Figure 3a. Charpy impact toughness of A588-A base plate.

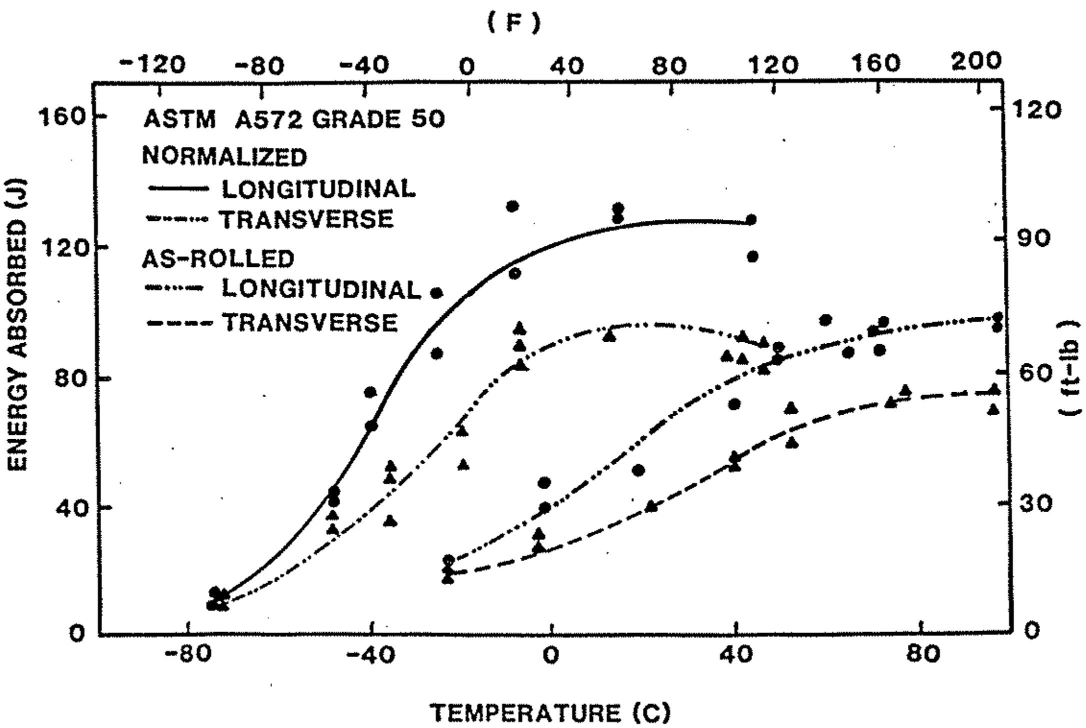

Figure 3b. Charpy impact toughness of A572-50 base plate.

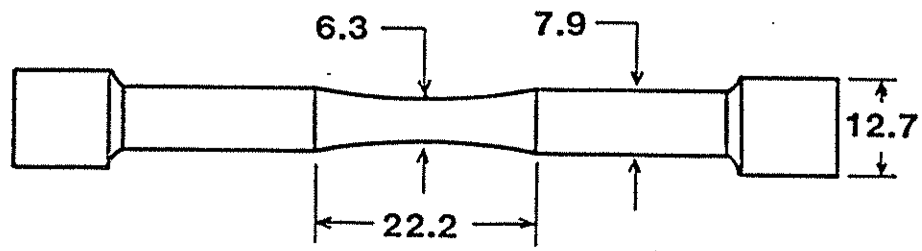

Figure 4: Weld metal tensile specimen. (Dimensions in mm.)

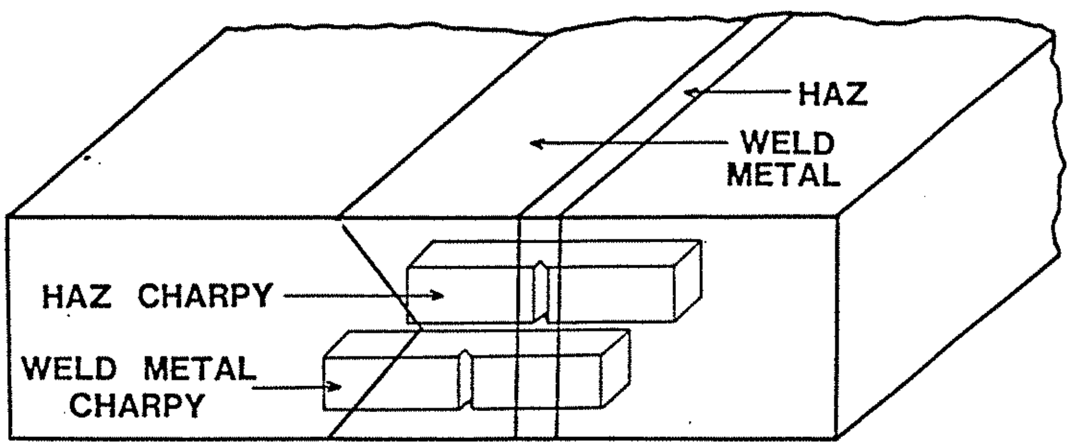

Figure 5: Diagram showing specimen placement with respect to weldment configuration.

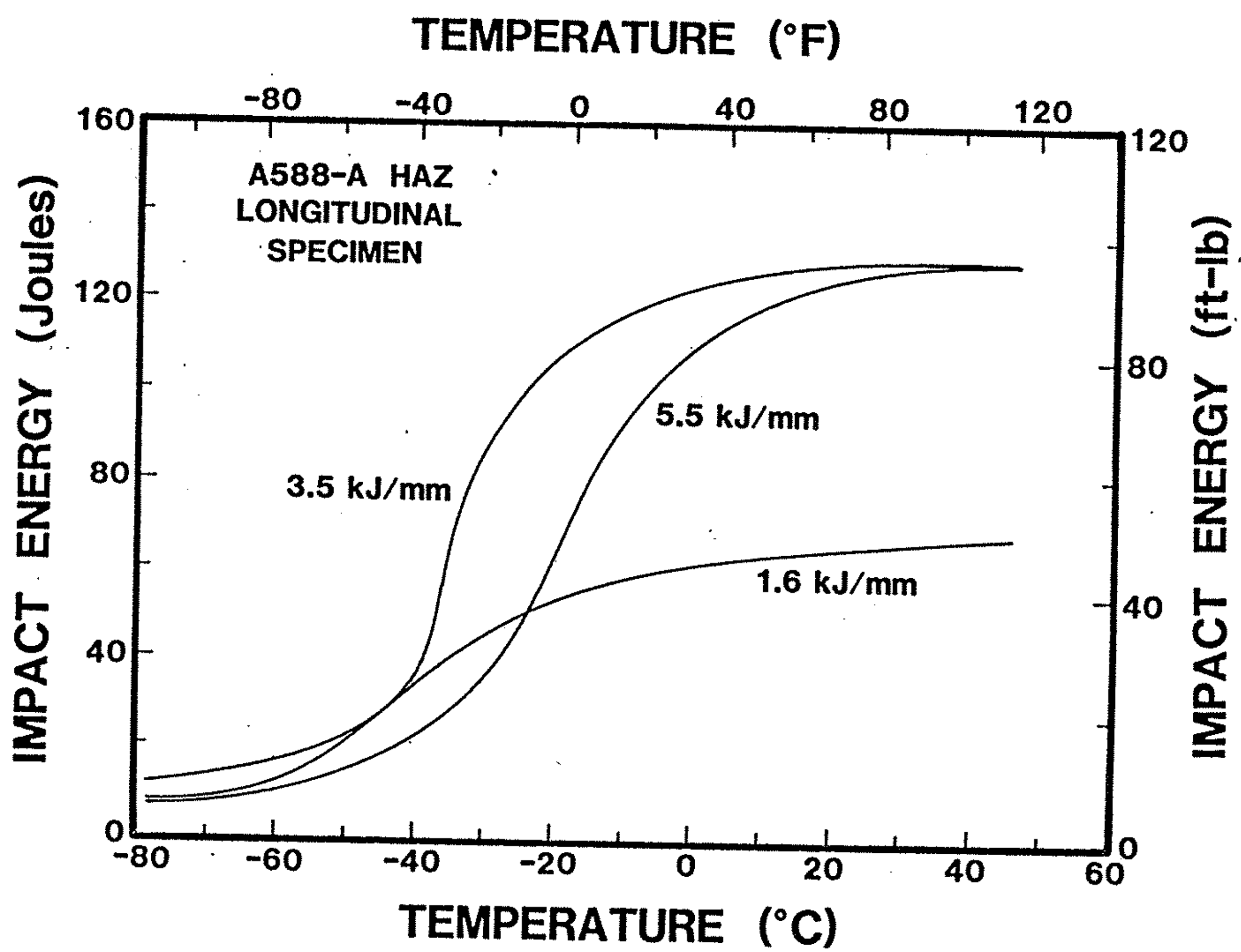

Figure 6. Heat affected zone toughness for A588-A welded at three heat inputs, flux cored arc weld.

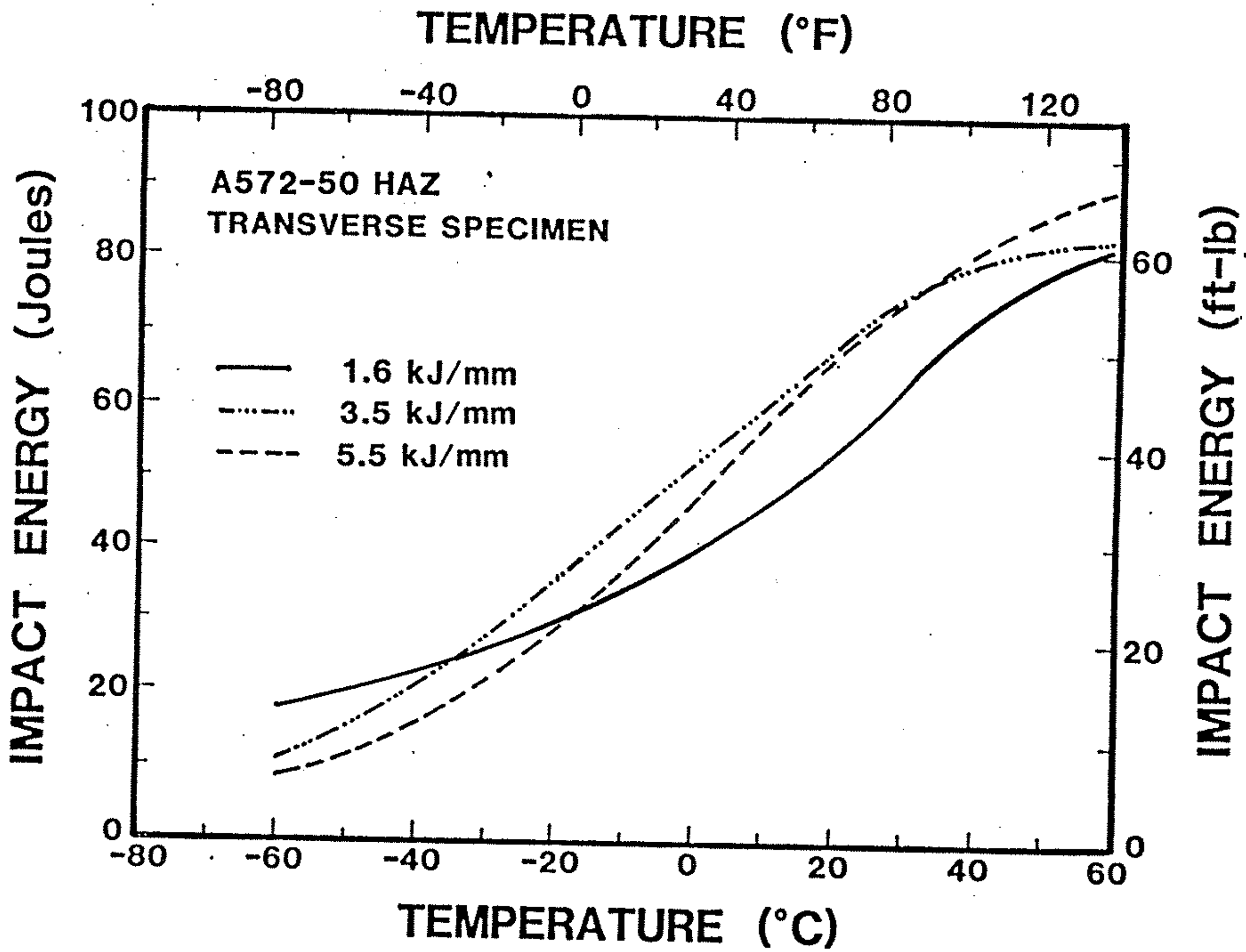

Figure 7. Heat affected zone toughness for A572-50 welded at three heat inputs, flux cored arc weld.

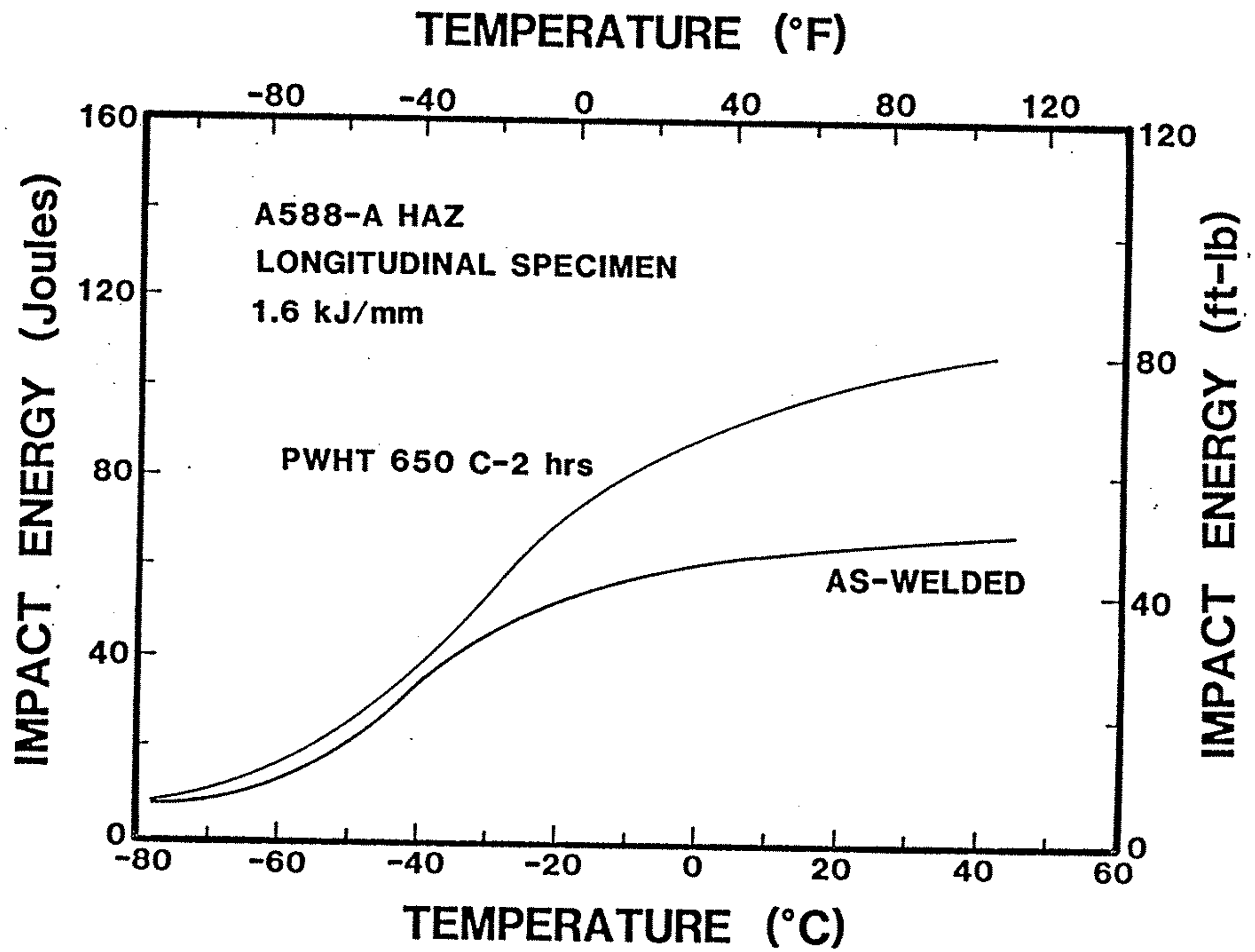

Figure 8. The effect of PWHT on low heat input HAZ toughness in A588-A, flux cored arc weld.

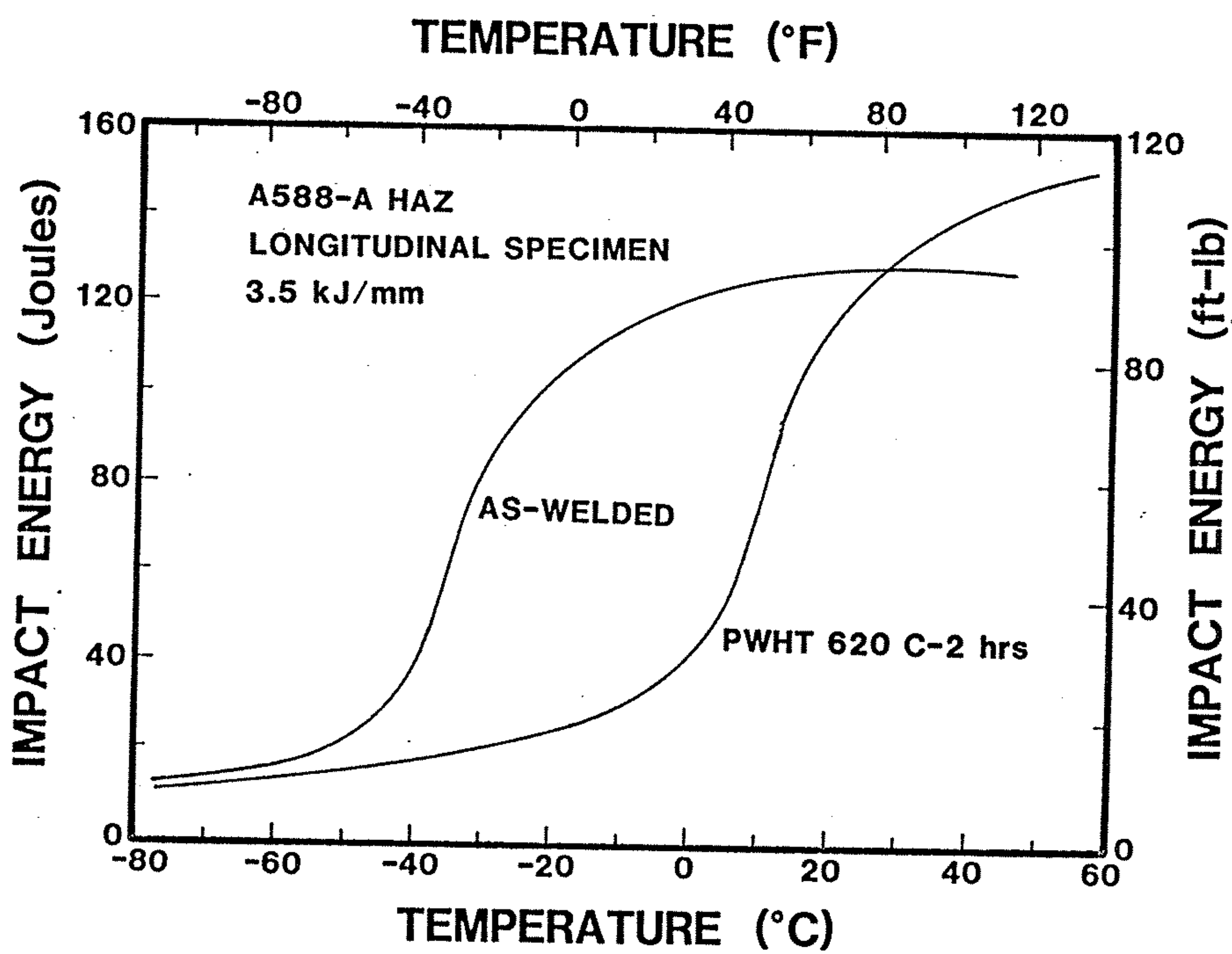

Figure 9. The effect of PWHT on medium heat input HAZ toughness in A588-A, flux cored arc weld.

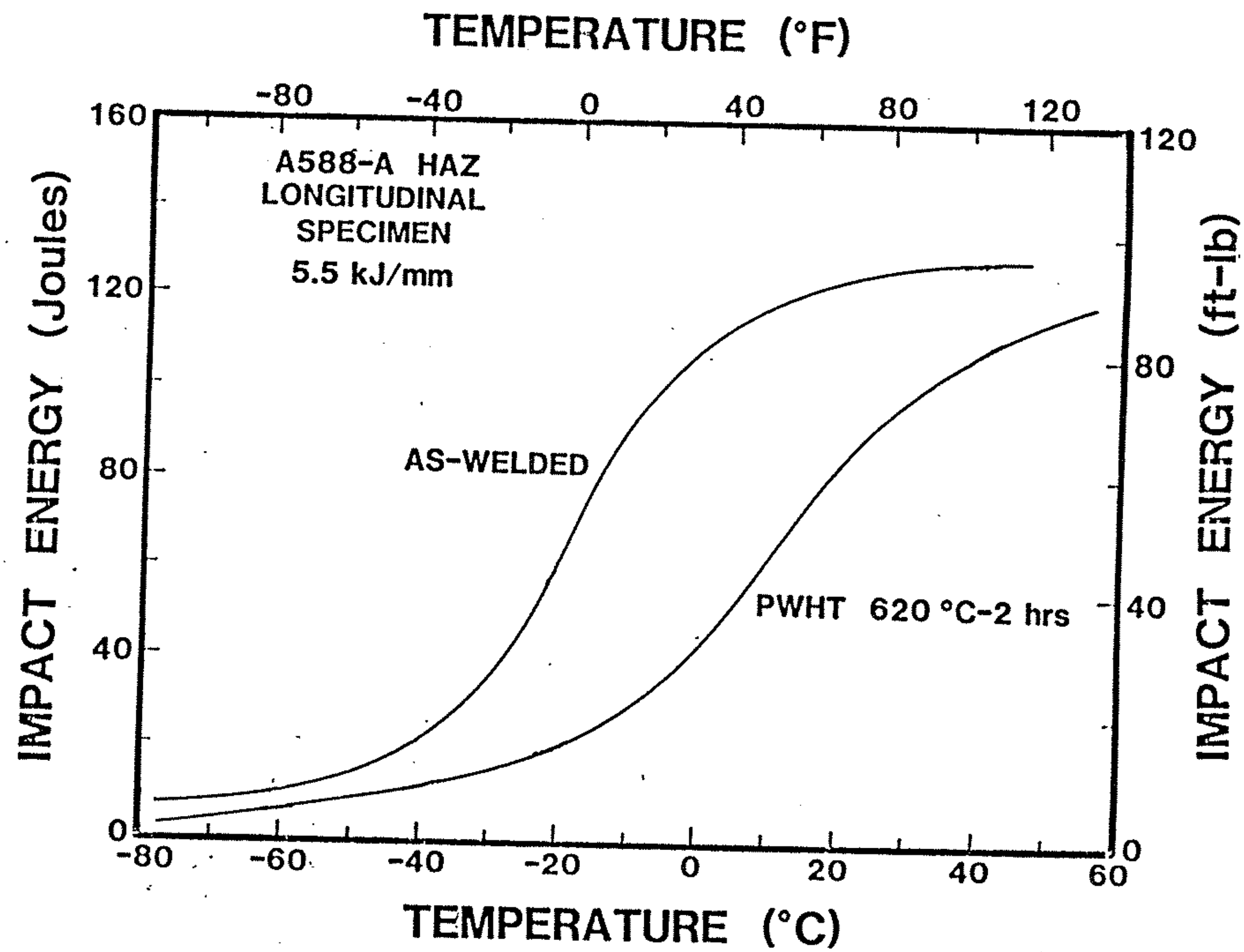

Figure 10. The effect of PWHT on high heat input HAZ toughness in A588-A, flux cored arc weld.

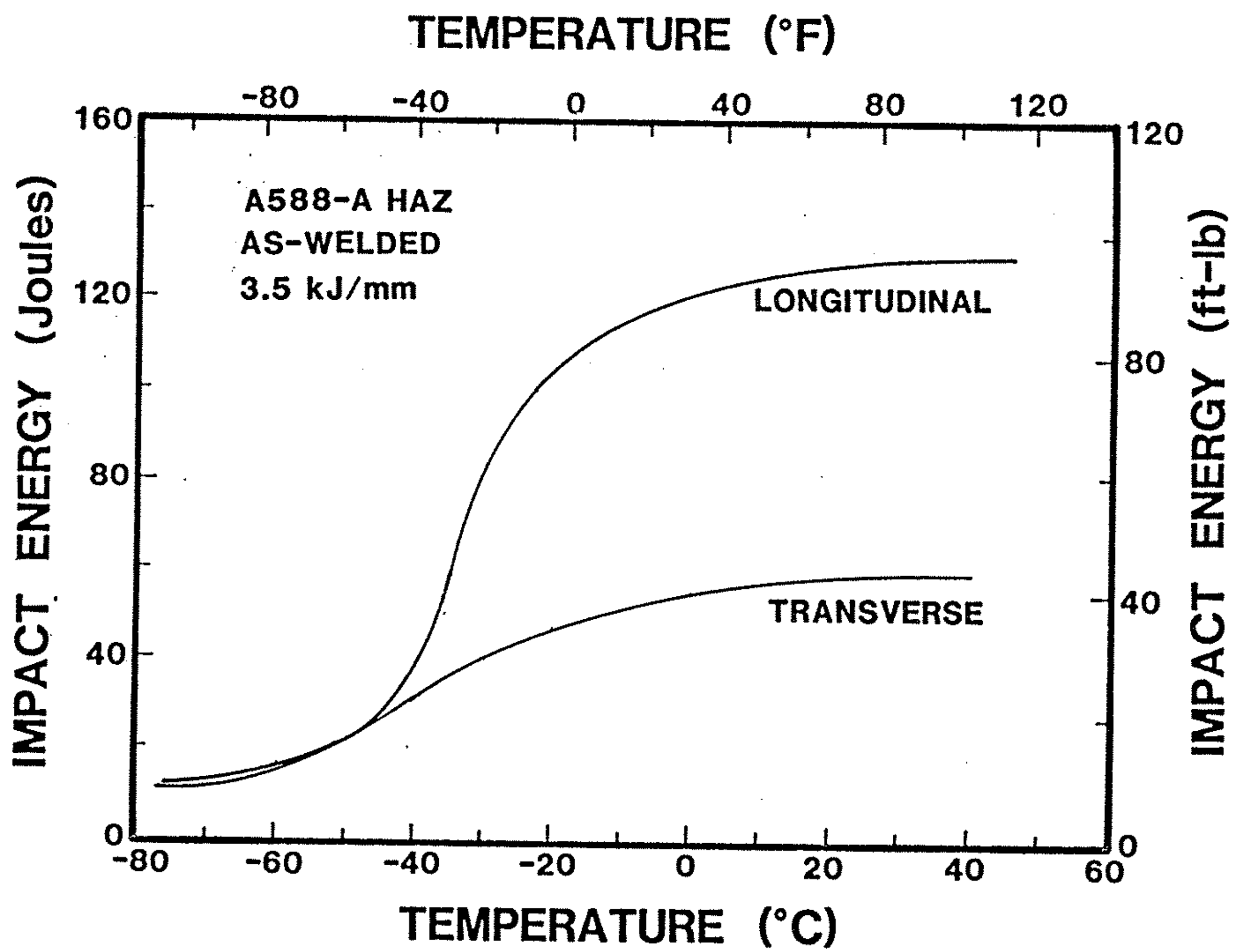

Figure 11. The effect of specimen orientation on HAZ toughness in A572-50, flux cored arc weld.

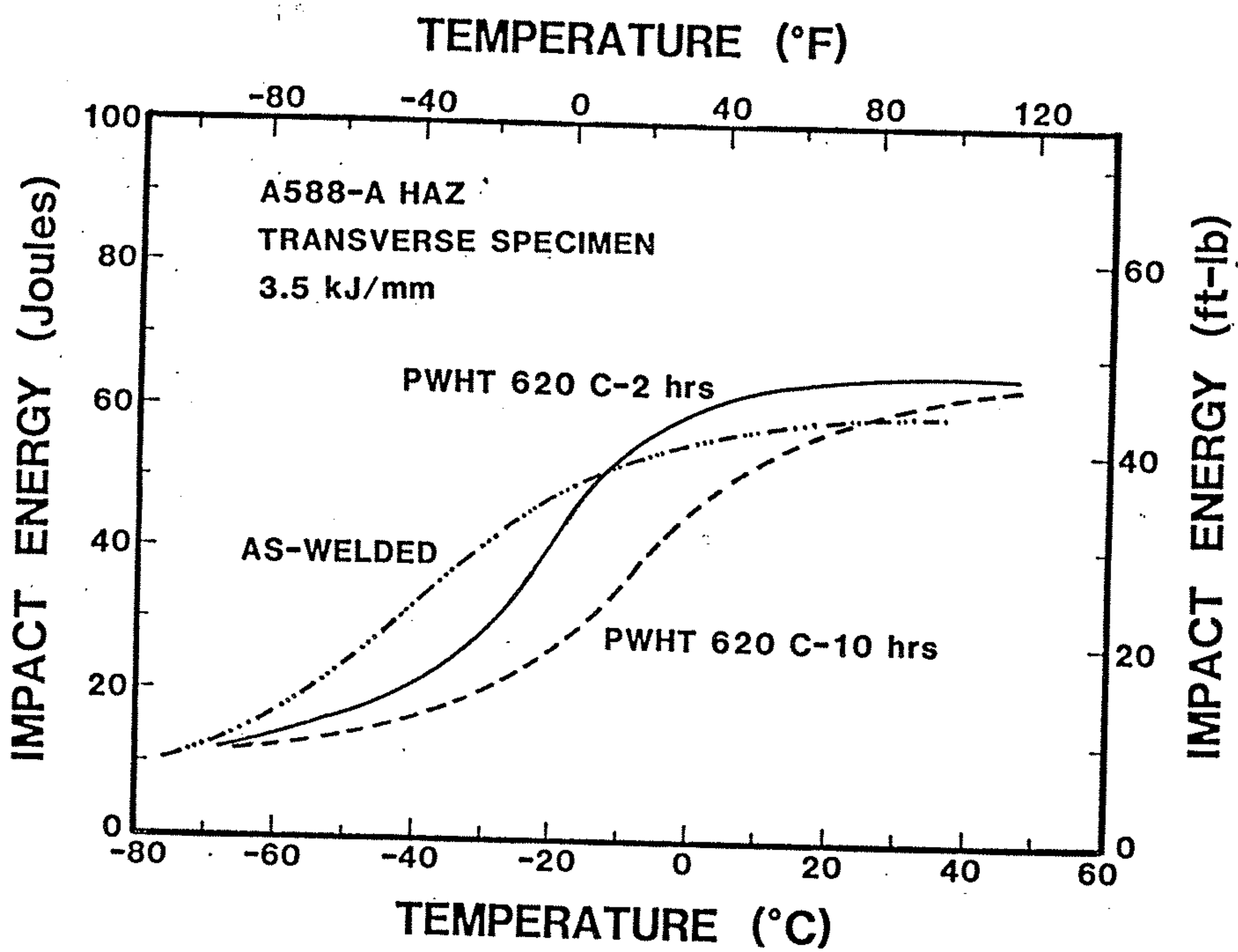

Figure 12. The effect of PWHT on the HAZ tougness of A588-A, submerged arc weld.

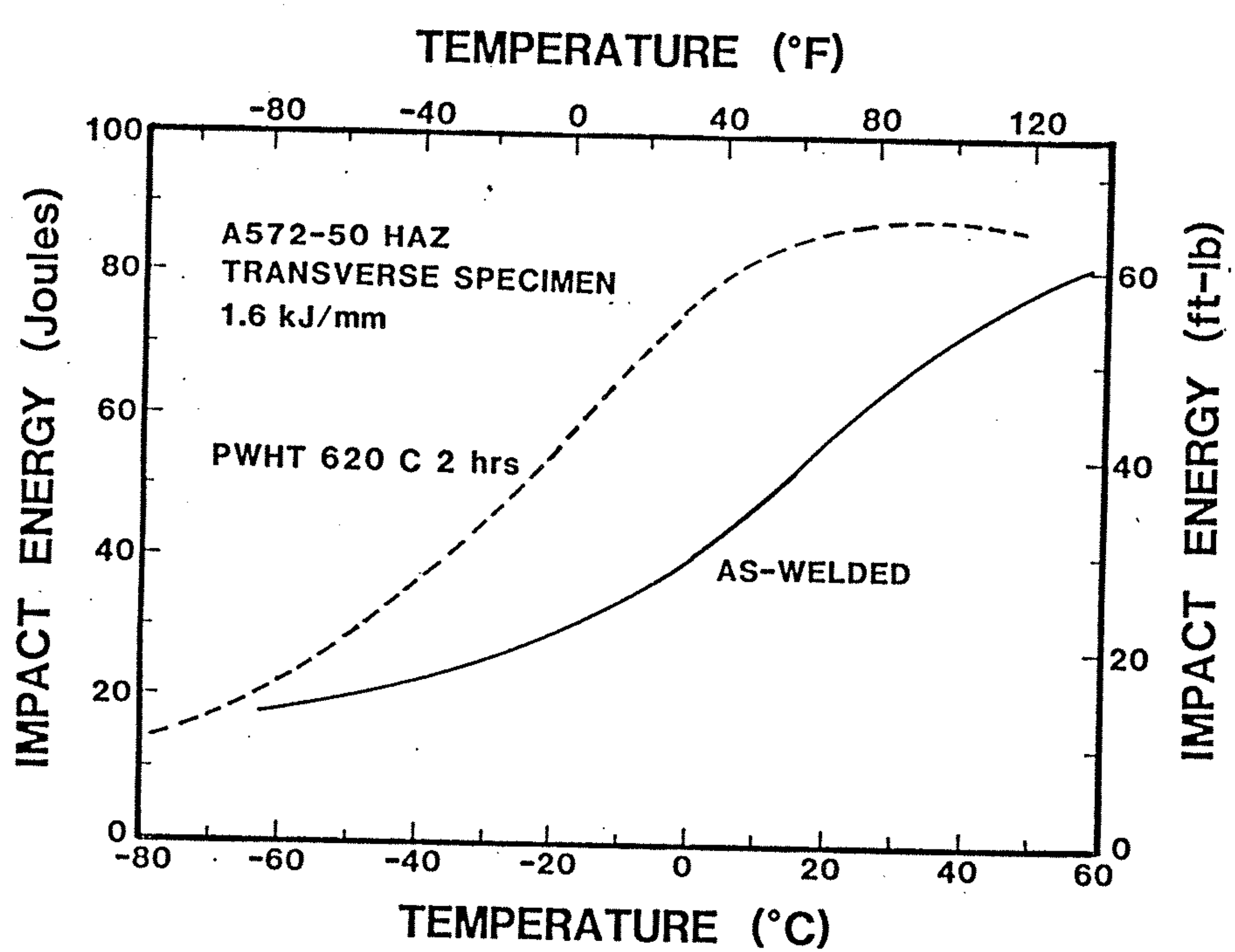

Figure 13. The effect of PWHT on the low heat input HAZ toughness of A572-50, flux cored arc weld.

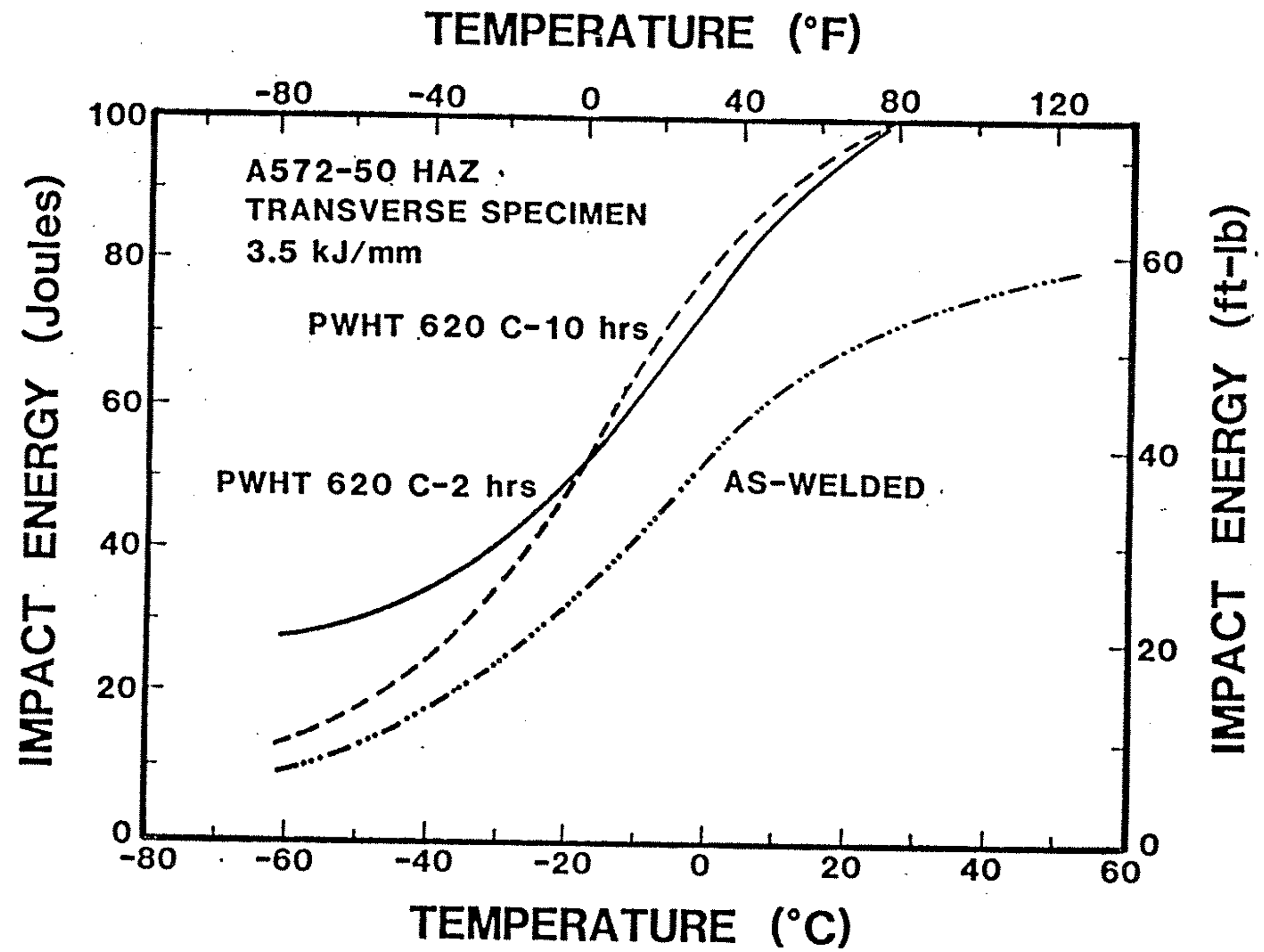

Figure 14. The effect of PWHT on the medium heat input HAZ toughness of A572-50, flux cored arc weld.

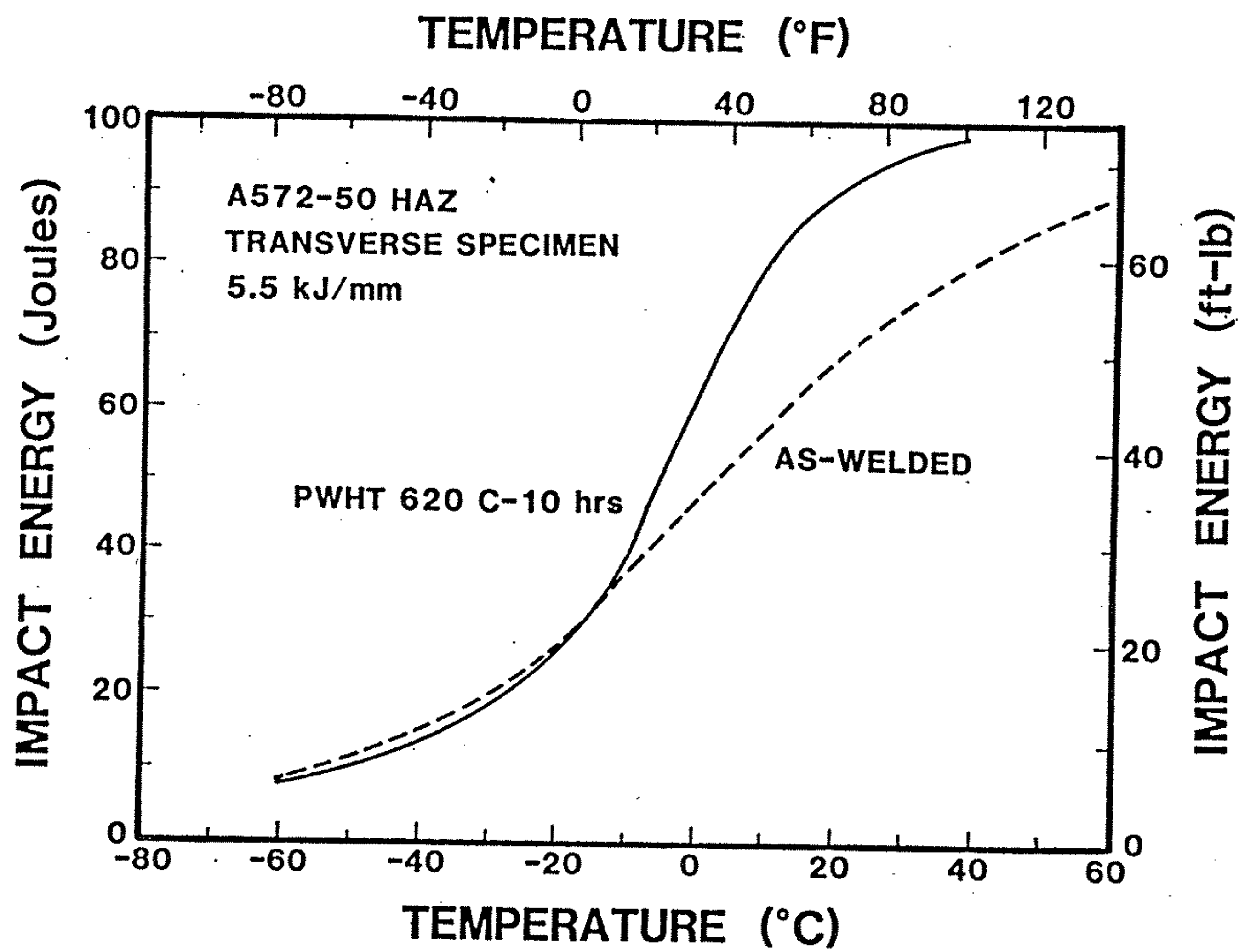

Figure 15. The effect of PWHT on the high heat input HAZ toughness of A572-50, flux cored arc weld.

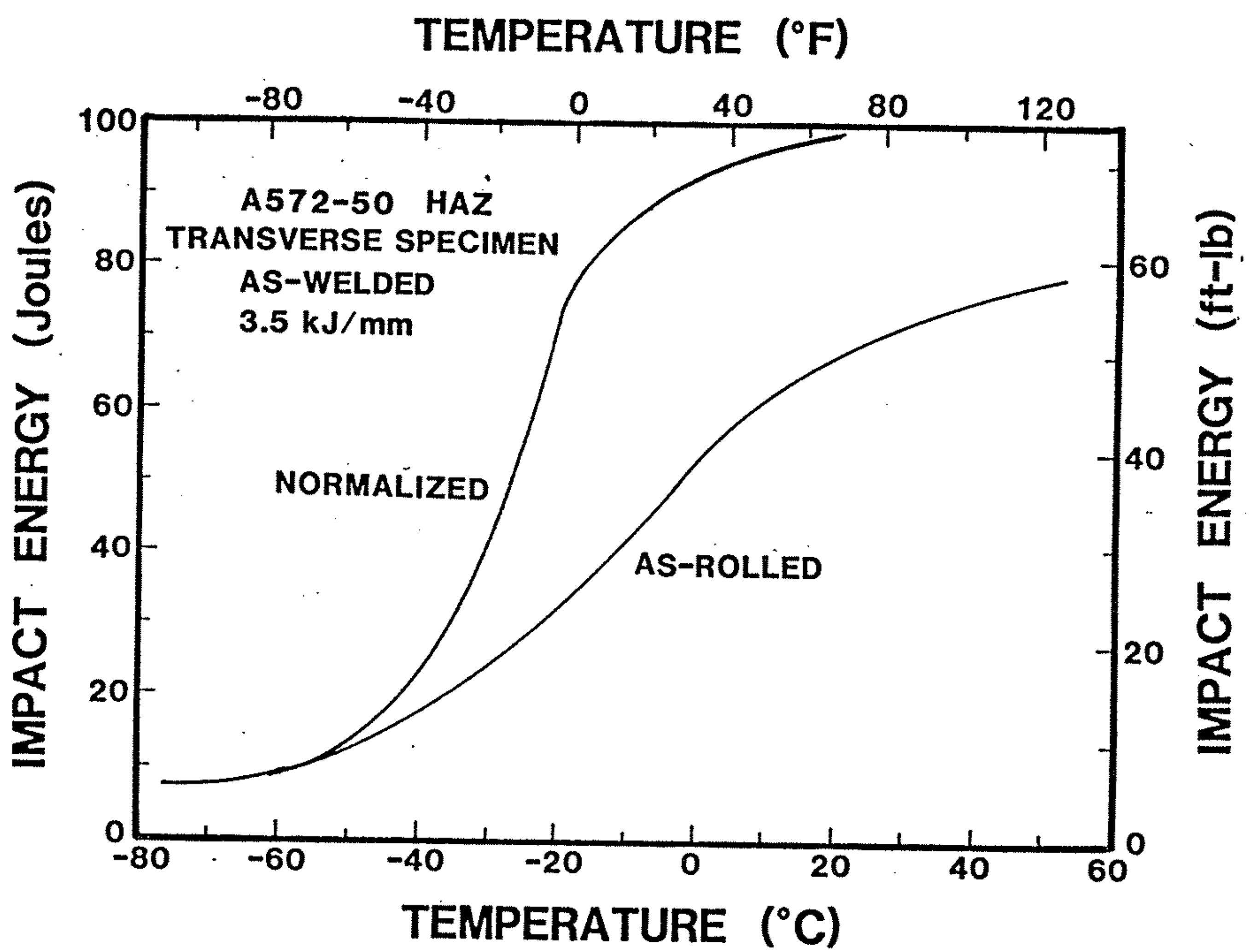

Figure 16. The effect of prior heat treatment on the HAZ toughness of A572-50; flux cored arc weld.

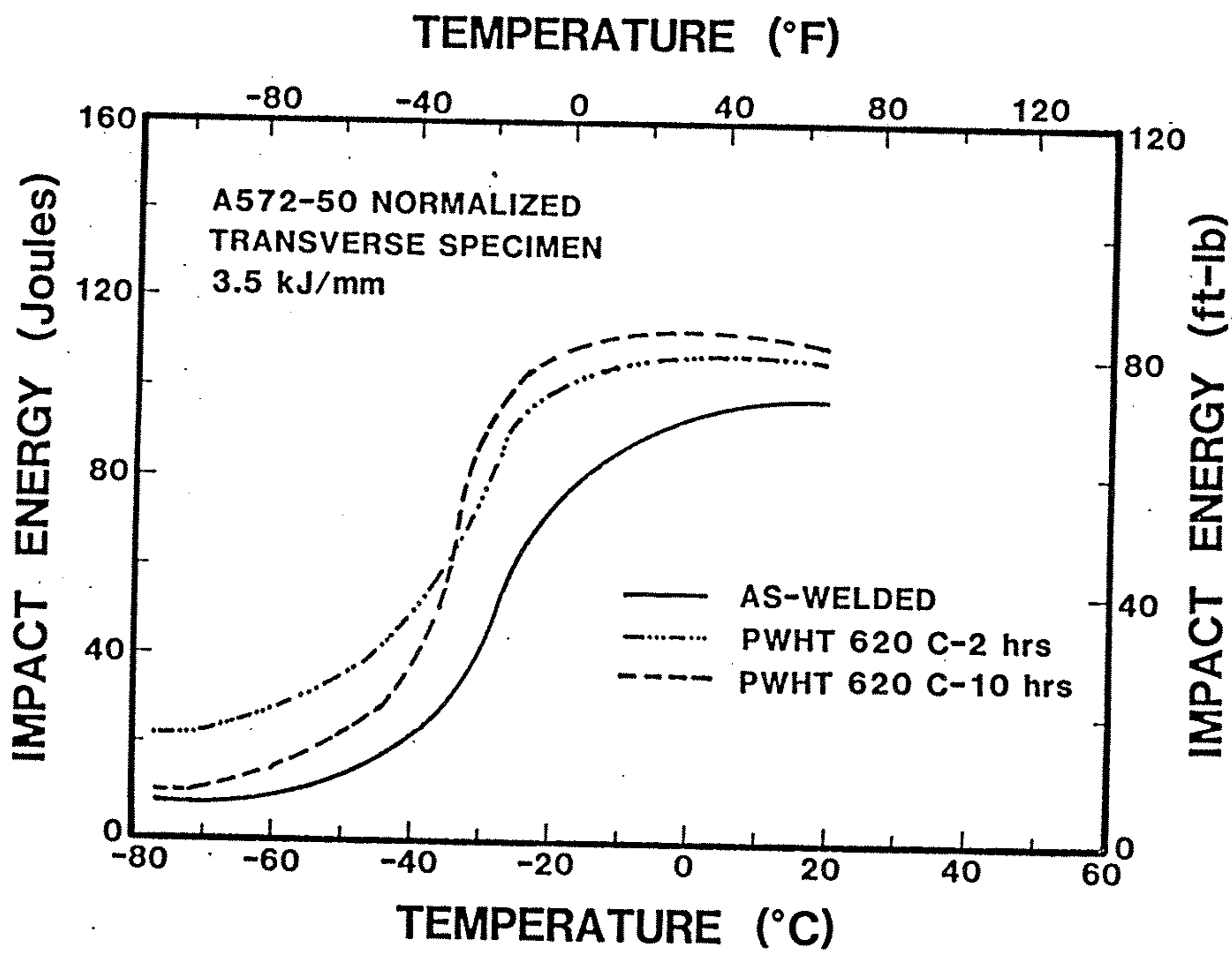

Figure 17. The effect of PWHT on the HAZ toughness of normalized A572-50, submerged arc weld.

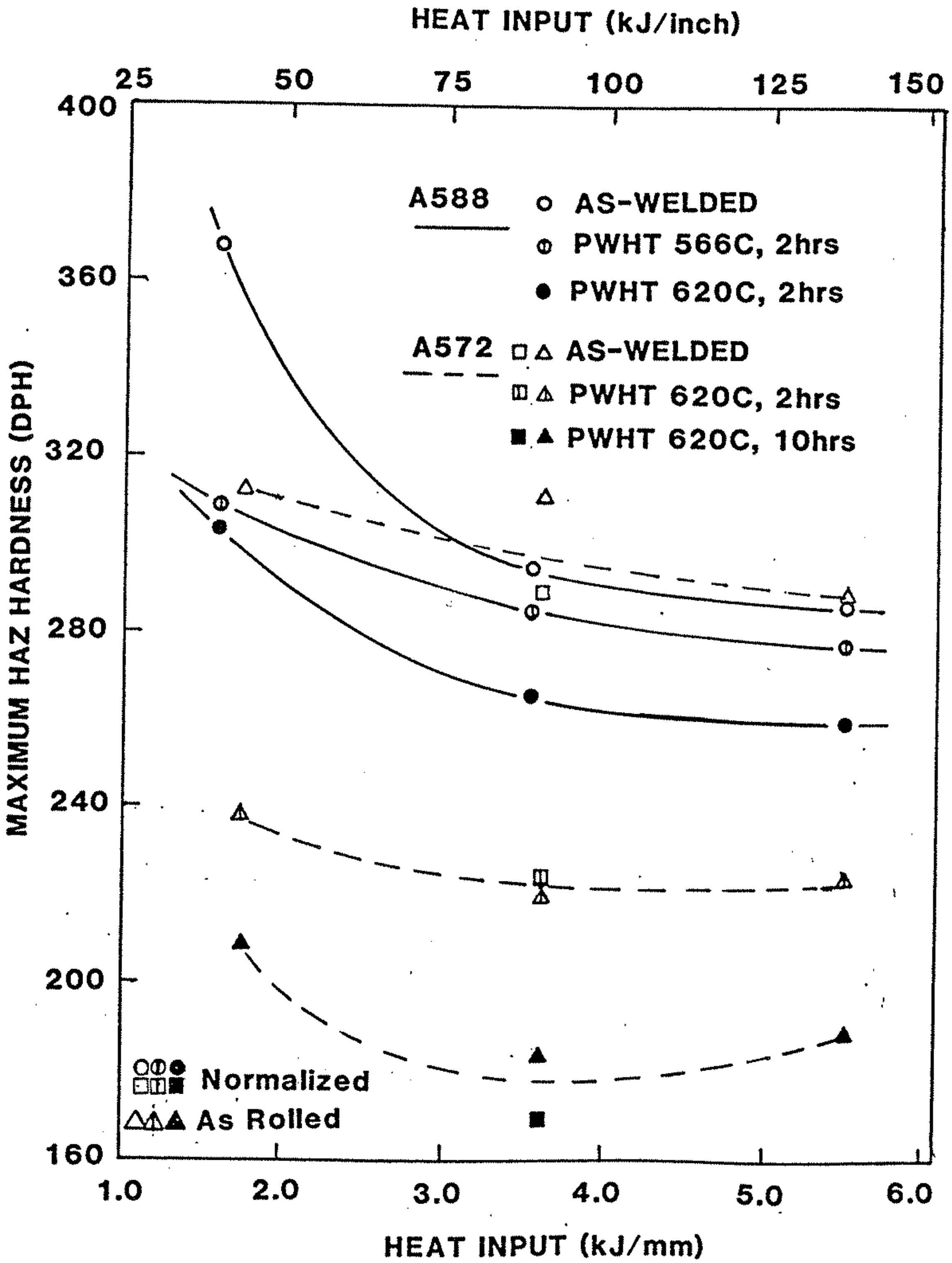

Figure18. Peak HAZ hardnesses for A588-A and A572-50 steels, as welded and after PWHT.