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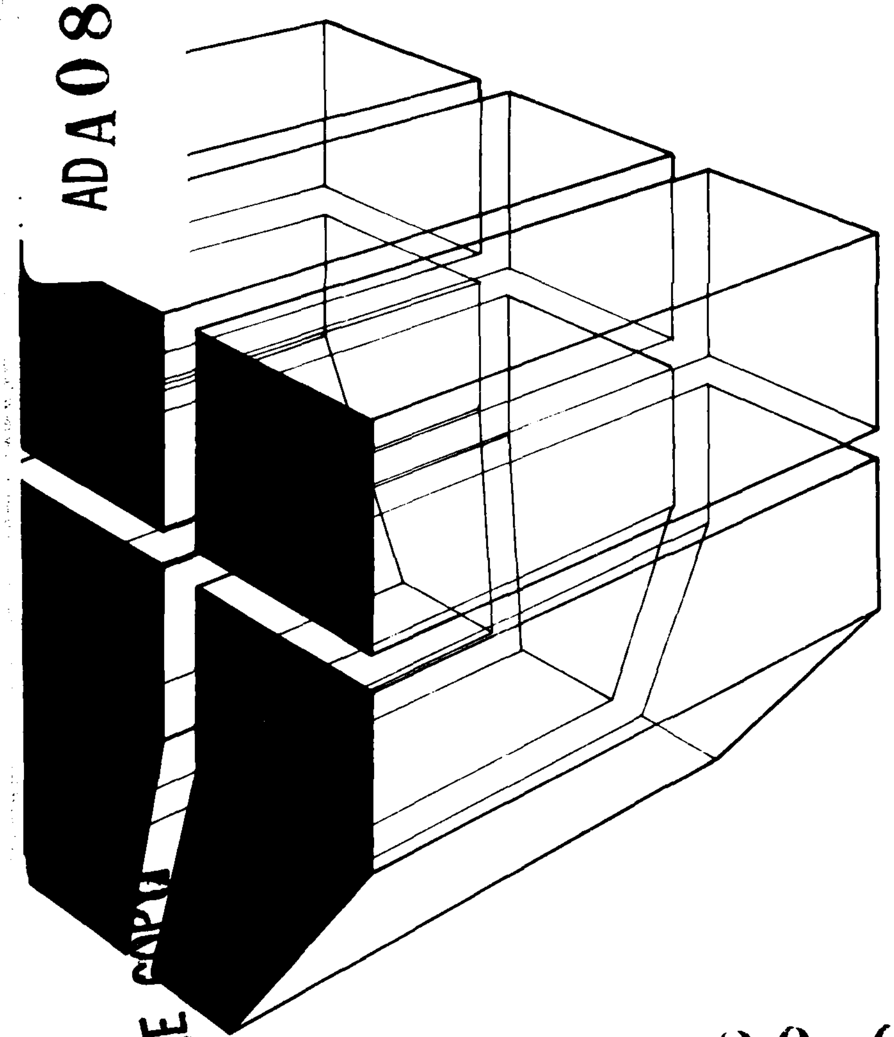
DETERMINATION OF THE EFFECT OF CURRENT AND TRAVEL SPEED OF GAS METAL-ARC WELDING ON THE MECHANICAL PROPERTIES OF A36, A516, AND A514 STEELS



by
R. Weber

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This study was performed to determine the limits on current and travel speed in particular, nugget area--as defined by the results of tests to determine tensile and impact properties of butt joint welds produced by fully automatic gas metal-arc welding (GMAW) in carbon steel (A36), pressure-vessel steel (A516), and high-strength, low-alloy steel (A514).

It was determined that sound welds can be produced with the E70S-3 and E110S electrodes used for this study.

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For A36 steel, heat-affected zone (HAZ) specimens exhibited lower yield strengths and impact energies than all-weld metal specimens. The HAZ impact energy of A36, A516, and A514 weldments was generally lower than that of the weld metal, while the yield strength showed varying results. The impact energy of all weldments showed limited dependency on the weld variables, exhibiting an effect only at the highest heat inputs (72 kJ/in. [2836 J/mm]) and largest nugget areas (0.150 sq in. [100 mm^2]).

FOREWORD

This investigation was performed for the Directorate of Military Programs, Office of the Chief of Engineers (OCE), under Project Number 4A762731AT41, "Military Facilities Engineering Technology"; Technical Area C, "Technology for Military Facilities"; Work Unit 005, "Weldability Criteria for Construction Materials." The applicable QCR is 3.07.024. The OCE Technical Monitor was Mr. I. A. Schwartz, DAEN-MPE-T.

This investigation was performed by the Engineering and Materials (EM) Division, U.S. Army Construction Engineering Research Laboratory (CERL). CERL personnel directly involved in the study were Mr. R. A. Weber, Mr. F. H. Kisters, Ms. R. E. Hannan, and Mr. S. Masters. Dr. G. R. Williamson is Chief of EM.

COL Louis J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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DETERMINATION OF THE EFFECT OF CURRENT AND TRAVEL SPEED OF GAS METAL-ARC WELDING ON THE MECHANICAL PROPERTIES OF A36, A516, AND A514 STEELS

1 INTRODUCTION

Background

Gas metal-arc welding (GMAW) is finding increased usage in Corps of Engineers construction. Although GMAW technology is relatively new, it has improved considerably since its introduction. There are now sophisticated welding power supplies, wire feed systems, and high-quality welding electrodes. Despite these improvements, however, the quality of the weldments depends on the operator's skill and experience. Thus, the operator's experience is generally the deciding factor in setting the welding variables, i.e., arc voltage, arc current, and travel speed.

For many years, the only control on welding has been by limiting the heat input (measured by Joules [J] per linear inch of weld). Heat input is determined by using this simple relation:

$$\text{Heat input} = \frac{\text{Voltage x Current}}{\text{Travel speed}} \qquad \text{[Eq 1]}$$

The heat input limit was generally set to a maximum of 55 kJ/in. (2167 J/mm). Dorschu and Shultz and Jackson have shown that for a given set of parameters, the strength and toughness of the weld can vary considerably.[1] Dorschu devised a method for controlling the strength of weldments by limiting the cooling rate of the weld beads. He developed a formula for the cooling rate that includes the variables of heat input, plate thickness, and initial plate temperature. In general form, this relation is:

$$\text{Cooling rate} = \frac{\text{Thickness x }(\underset{\text{Test}}{\text{temperature}} - \underset{\text{Plate}}{\text{temperature}})}{\text{Heat input}} \qquad \text{[Eq 2]}$$

Dorschu has shown that with American Society for Testing and Materials [ASTM] A201 mild steel up to 2 in. (51 mm) thick, the yield strength of the weld metal decreases at slow cooling rates; at high cooling rates, yield strengths can be increased from 15 to 20 ksi (103.4 to 137.9 MPa). Shultz and Jackson have gone one step further and determined that for a 5Ni-Cr-Mo-V steel, the arc voltage has no significant effect on the cooling rate; cooling rates appear to be determined by the current and travel speed only.

Shultz and Jackson conclude that there is a clear relationship between cooling rate and nugget area which, therefore, becomes a useful indicator of weld metal mechanical properties under the influence of weld cooling rate. Shultz and Jackson define nugget area as the cross-section of a single weld bead. This nugget area equation is:

$$\text{Nugget area} = \text{Constant x } \frac{\text{Arc current}^{1.55}}{\text{Travel speed}^{0.903}} \qquad \text{[Eq 3]}$$

Unfortunately, Shultz and Jackson do not describe a way to determine the voltage, current, and travel speed limits that will insure proper weld metal strength levels.

The Corps of Engineers has begun a three-part research program to determine these limits for various plate steels and welding electrodes. In the first part of the study, the limits on electrode travel speed and voltage for shielded metal-arc welding electrodes were determined on the basis of bead-on-plate studies.[2] These limits were established using amperage values contained in the American Welding Society (AWS) specifications.[3] Operating ranges were also determined for GMAW electrodes.

During the second part of the study, which is intended to refine the limits of current, travel speed, and voltage using their interrelationship with nugget area based on weld joint mechanical properties, the limits for shielded metal-arc welding electrodes in combination with carbon steel, pressure-vessel steel, and high-strength, low-alloy steel are being investi-

[1] K. E. Dorschu, "Control of Cooling Rates in Steel Weld," *Welding Journal*, Vol 47 (February 1968), Research Supplement; and B. L. Shultz and C. E. Jackson, "Influence of Weld Bead Area on Weld Mechanical Properties," *Welding Journal*, Vol 52 (January 1973), Research Supplement.

[2] R. A. Weber, *Determination of Arc Voltage, Amperage, and Travel Speed Limits by Bead-on-Plate Welding*, Technical Report M-197/ADA033684 (U.S. Army Construction Engineering Research Laboratory [CERL], December 1976).

[3] *Specification for Mild Steel Covered Arc Welding Electrodes*, American Welding Society (AWS) A5.1-69 (AWS 1969).

gated.[4] Limits for the high-strength, low-alloy steel are also being determined.

The third part of the study will seek to confirm or adjust these limits with regard to restraint and cracking in the weld joints.

Objective

The objective of this report, which addresses the GMAW portion of the second part of the Corps of Engineers weld limits study, is to present the limits on current and travel speed–in particular, nugget area–as defined by the results of tests to determine the tensile and impact properties of butt joint welds produced by fully automatic GMAW in carbon steel (A36), pressure-vessel steel (A516), and high-strength, low-alloy steel (A514).

Mode of Technology Transfer

The information in this report is part of a long-term research effort designed to maintain Corps of Engineers Guide Specifications CE-05141 and CE-15116, and Army Technical Manuals (TM) 5-805-7 and 9-237.[5]

2 APPROACH

Materials

Table 1 identifies the plate steel and electrodes used in this investigation. Electrode types were selected for use with plate material based on the AWS *Structural Welding Code* and the common usage for Corps of Engineers construction.[6] One type of plate steel was chosen from each of the three categories of steel used frequently in Corps of Engineers construction:

1. Carbon steel (ASTM A36)
2. Pressure-vessel steel (ASTM A516)
3. High-strength, low-alloy steel (ASTM A514).

Table 2 lists the specification limits for each of the materials used in this investigation.

Experimental Procedure

The weld joint used in this investigation was a 60-degree included angle, single-V butt joint with a 1/8 in. (3.2 mm) root opening (Figure 1). The weld length was about 30 in. (762 mm). The completed joint was about 12 x 30 in. (305 x 762 mm). Each material type required 9 joints–a total of 27 joints. All plate material was cut and beveled using an oxy-acetylene cutting apparatus, and then surface ground to remove oxides and slag from the joint area. X-ray radiography was used to non-destructively examine each completed weldment for soundness.

One macrospecimen, three tensile specimens, and twelve impact (dynamic tear) specimens were machined from each completed sound weld. (Figure 2 shows a schematic of specimen locations as machined from the weldments.)

The impact specimens were machined so that half were notched in weld metal and half were notched adjacent to the weld in the heat affected zone (HAZ). They were then tested in temperatures ranging from -40 to +40°C according to ASTM standards.[7]

[4] R. A. Weber, *Determination of the Effect of Current and Travel Speed of Shielded Metal-Arc Welding on the Mechanical Properties of A36, A516, and A514 Steels*, Interim Report M-248/ADA06231 (CERL, November 1978).

[5] *Welding, Structural*, U.S. Army Corps of Engineers Guide Specification, CE-05141 (April 1975); *Welding, Mechanical*, U.S. Army Corps of Engineers Guide Specification, CE-15116 (October 1974); *Welding: Design, Procedures, and Inspection*, Army Technical Manual (TM) 5-805-7/Air Force Technical Order AFM 88-44, Chapter 7 (Departments of the Army and the Air Force, March 1968), and *Operators Manual: Welding Theory and Application*, TM 9-237 (Department of the Army, October 1976).

[6] *Structural Welding Code*, D1.1-75 (AWS, 1975; revised 1976 and 1977).

[7] "ASTM Proposed Method for 5/8 in. (16 mm) Dynamic Tear Test of Metallic Materials," *1976 Annual Book of ASTM Standards*, Part 10 (American Society for Testing and Materials [ASTM], 1976).

Table 1
Materials Used for GMAW Butt Joints

ASTM No.	Plate Material Thickness, in. (mm)	Electrode	Diameter, in. (mm)
A36	3/4 (19)	E70S-3	1/16 (1.6)
A516, Grade 70	1 (25.4)	E70S-3	1/16 (1.6)
A514, Grade F	3/4 (19)	E110S	1/16 (1.6)

Table 2
Mechanical Property Requirements for Electrodes and Plate Material

Material	Specification	Minimum Yield Strength ksi (MPa)	Ultimate Tensile Strength ksi (MPa)
E70S-3 GMAW electrodes	AWS A5.18-69	60 (414)	72 minimum (496)
E110S GMAW electrodes	AWS A5.18-69	98 (676)	110 minimum (758)
A36 plate	ASTM A36	36 (248)	58-80 (400-552)
A516 plate	ASTM A516	38 (262)	70-90 (483-621)
A514 plate	ASTM A514	100 (689)	110-130 (758-896)

Two of the tensile specimens were machined from the weld metal; the third was machined from the HAZ. All the tensile specimens were tested at ambient temperature according to Military Standard (MIL-STD) 418C.[8] The tensile test results include the yield strength, ultimate tensile strength, true fracture stress, and the true fracture strain. (The true fracture strain, which is the natural logarithm of the initial area divided by the final area, was used to indicate the ductility exhibited by the tensile specimen. It is a dimensionless number and shows increasing ductility with higher numbers.)

The macrospecimens were polished and etched using ammonium persulfate etchant, and visually examined for small flaws not shown by radiography. The nugget area was determined using the nomograph presented by Shultz and Jackson (Figure 3).[9]

Welding Procedure

Arc voltage, current, and travel speed for all specimens were selected based on the results of a previous study.[10] Table 3 shows the welding variables for the weldments using 1/16 in. (1.6 mm) diameter E70S-3 and E110S GMAW electrodes and direct current, reverse polarity. Figures 4, 5, and 6 show typical cross-sections of the A36, A516, and A514 weldments, respectively. The joint design was the same for all three steels.

The heat input for the A36 and A516 weldments varied from 15 to 72 kJ/in. (591 to 2835 J/mm), while the nugget area varied from 0.035 to 0.150 sq in. (24 to 100 mm^2). For the A514 weldments, the heat input varied from 10 to 50.4 kJ/in. (394 to 1984 J/mm), and the nugget area varied from 0.026 to 0.130 sq in. (16.8 to 80 mm^2).

3 DATA ANALYSIS AND DISCUSSION

A36 Weldments

Tensile Test Results

Table 4 and Figures 7 and 8 present the tensile test results for the E70S-3 weld metal and the A36 HAZ specimens over the respective ranges of heat input and nugget area tested. The weld metal yield strengths are spread over 21.1 ksi (145.4 MPa) range. Figures 7 and 8 show the weld metal strength data plotted against heat input and calculated nugget area, respectively. Both figures show a linear trend of weld metal yield strength decreasing as heat input and nugget area increase. To determine which parameter (heat input or nugget area) was a more sensitive predictor of yield strength, linear correlation coefficients (r)

[8] *Military Standard Mechanical Tests for Welded Joints*, MIL-STD-418C (June 1972).

[9] B. L. Shultz and C. E. Jackson, "Influence of Weld Bead Area on Weld Mechanical Properties," *Welding Journal*, Vol 52 (Janaury 1973), Research Supplement.

[10] R. A. Weber, *Determination of Arc Voltage, Amperage, and Travel Speed Limits by Bead-on-Plate Welding*, Technical Report M-197/ADA033684 (CERL, December 1976).

Table 3
Weld Variables for GMAW Weldments of A36, A516, and A514 Steels*

Specimen	Material	Electrode	Current	Volts	IPM (min/s) Travel Speed	Heat Input (kJ/in.)(J/mm)	Nugget Area sq in. (mm^2)	Plate Thickness in. (mm)	Number of Passes
B22	A36	E70S-3	400	30	10	72 (2835)	0.150 (100)	0.75 (19)	5
B23	A36	E70S-3	400	30	20	36 (1417)	0.080 (52)	0.75 (19)	6
B24	A36	E70S-3	400	30	30	24 (945)	0.055 (40)	0.75 (19)	8
B25	A36	E70S-3	300	25	30	15 (591)	0.035 (24)	0.75 (19)	11
B26	A36	E70S-3	300	25	20	22 (886)	0.050 (35)	0.75 (19)	8
B27	A36	E70S-3	300	25	10	45 (1772)	0.095 (65)	0.75 (19)	6
B28	A516	E70S-3	300	25	10	45 (1772)	0.095 (65)	1.00 (25.4)	19
B29	A516	E70S-3	300	25	20	22 (886)	0.050 (35)	1.00 (25.4)	30
B30	A516	E70S-3	300	25	30	15 (591)	0.035 (24)	1.00 (25.4)	44
B31	A516	E70S-3	400	30	30	24 (945)	0.055 (40)	1.00 (25.4)	34
B32	A516	E70S-3	400	30	20	36 (1417)	0.080 (52)	1.00 (25.4)	22
B33	A516	E70S-3	400	30	10	72 (2835)	0.150 (100)	1.00 (25.4)	10
B34	A514	E110S	350	24	10	50.4 (1984)	0.130 (80)	0.75 (19)	8
B35	A514	E110S	350	24	20	25.2 (992)	0.065 (42)	0.75 (19)	19
B36	A514	E110S	350	24	30	16.8 (661)	0.045 (30)	0.75 (19)	27
B37	A514	E110S	250	20	10	30.0 (1181)	0.070 (45)	0.75 (19)	14
B38	A514	E110S	250	20	20	15.0 (591)	0.038 (26)	0.75 (19)	29
B39	A514	E110S	250	20	30	10.0 (394)	0.027 (18)	0.75 (19)	31

*Mechanical properties for the range of heat inputs and nugget area are listed in Tables 4, 5, and 6.

were computed for both.* The coefficients for heat input (r=-0.967) and nugget area (r=-0.969) were not significantly different, indicating that for the test conditions under study, both were equal predictors of yield strength. But a review of the difference between the heat inputs and the nugget areas tested indicates that relative differences between them were insignificant; in essence, one was a scaled version of the other. This made it impossible to determine the relative sensitivities of the two welding parameters to any of the physical test results on the A36 steel and weldments.

The HAZ yield strengths were relatively uniform—between 44 and 57 ksi (303 and 393 MPa). The yield strength did not correlate significantly with either nugget area (r=-0.250) or heat input (r=-0.235), and therefore neither could be used to predict HAZ yield strength.

*The correlation coefficient is the ratio of the explained variation to the total variation. For zero explained variation, the correlation coefficient is zero; for completely explained variation, the coefficient is ±1. All other coefficients vary between +1 and -1, with increasingly explained variations approaching ±1.

The ultimate tensile strength (UTS) of the weld metal specimens varied between 72 and 88 ksi (496 and 607 MPa); *increasing heat inputs and nugget areas* were associated with decreasing UTS. The linear correlation coefficients for the UTS of the weld metal to heat input and nugget area were -0.897 and -0.909, respectively. The trends observed in the weld metal UTS results are similar to those observed for the yield strength data.

The UTS of the HAZ specimens varied between 69 and 75 ksi (476 and 517 MPa). As with the yield strengths, the HAZ UTS did not correlate significantly with either heat input (r=0.136) or nugget area (r= -0.151); therefore, neither could be used to predict HAZ tensile strength.

The true fracture stress and the true strain at fracture were calculated to provide information on the strength and ductility of the weldments. There was no significant correlation between either heat input or nugget area with these two quantities.

Impact Test Results

Figures 9 through 14 graph the dynamic tear (DT) impact energy vs test temperature for each

Table 4
Tensile Data for GMAW Weldments of A36 Steel

Weld Specimen Code	Tensile Properties ksi*	Ultimate Tensile Strength ksi	True Fracture Stress ksi	True Strain at Fracture
		Weld Metal		
B22	53.9	73.4	168.9	1.176
(A36)	54.1	72.0	160.5	1.204
B23	65.5	80.0	119.3	0.662
(A36)	62.0	77.4	157.0	1.064
B24	68.3	82.4	149.7	0.847
(A36)	67.1	80.6	137.5	0.741
B25	75.0	88.2	168.6	0.909
(A36)	70.2	83.4	160.2	0.909
B26	71.4	87.0	165.8	0.946
(A36)	69.7	84.4	156.2	0.859
B27	61.4	75.2	161.3	1.092
(A36)	61.2	76.0	147.0	0.959
		HAZ		
B22 (A36)	53.1	74.2	150.8	1.024
B23 (A36)	44.1	69.4	161.8	1.176
B24 (A36)	149.6	71.0	163.1	1.176
B25 (A36)	56.0	75.2	143.1	0.972
B26 (A36)	57.7	75.2	117.6	0.776
B27 (A36)	49.1	70.0	145.3	1.064

*1 ksi = 6.89 MPa

weldment. Each figure contains the all-weld metal impact results and the associated HAZ impact results. The impact energy at a given temperature for the HAZ specimens is lower than that of the all-weld metal specimens. The transition temperatures* of the HAZ specimens were all above 20°C, whereas the transition temperatures for the all-weld metal specimens were below 12°C (Figures 15 and 16). The linear correlation coefficient of HAZ transition temperatures vs heat input or nugget area was low (-0.258 and -0.270, respectively). The correlation coefficient of the weld metal transition temperatures vs heat input or nugget area was relatively higher (0.620 and 0.616, respectively), but still of only marginal significance.

*Note: transition temperature, for the purpose of this report, was computed as the knee of the DT curve at the lower shelf.

General

In a general analysis of the mechanical properties of the A36 weldments, it is important to compare the properties of the weld metal and HAZ to that required for the base plate and electrodes. Table 2 indicates that the AWS A5.18 minimum yield strength of the E70S-3 electrode is 60 ksi (414 MPa); the A36 steel is 36 ksi (248 MPa).[11] As indicated in Figures 7 and 8, all the HAZ yield strengths significantly exceeded the specified minimum and the reported actual yield strength (36 and 37 ksi [248 and 255 MPa], respectively) of the A36 base plate over the respective ranges of heat input and nugget area investigated. At heat inputs and nugget areas greater than 50 kJ/in. (1970 J/mm)

[11] *Specification for Mild Steel Base Welding Electrodes*, AWS 5.18-69 (AWS, 1969).

and 0.108 sq in. (0.696 mm^2) respectively, the weld metal yield strengths fall below the 60 ksi (414 MPa) weld metal minimum, but not below the 36 ksi (248 MPa) base plate criterion.

The UTS of the HAZ specimens fell within the specified range of 58 to 80 ksi (400 to 552 MPa) for A36 steel and about equal to the reported value of 71 ksi (490 MPa).[12] The UTS of all the weld metal specimens exceeded the 72 ksi (497 MPa) minimum requirement. However, at the highest heat input (72 kJ/in. [2836 J/mm]) and the largest nugget area (0.150 sq in. [0.967 mm^2]), the UTS of the weld metal declined to the minimum requirement.

The A36 base plate and the E70S-3 electrode do not have specified DT impact requirements. However, Barson and Rolfe have reported that the transition temperature for A36 steel is about -6°C.[13] Figures 15 and 16 indicate that the HAZ and weld metal have significantly higher transition temperatures than the -6° C value reported for the base plate. Thus, the impact resistance of the HAZ and weld metal between +30 and -6°C is significantly less than the base plate, and should be considered in the design and fabrication of A36 welded components if impact resistance is critical.

During test plate fabrication, side wall fusion and depth of penetration become increasingly difficult to control at heat inputs and nugget areas less than 20 kJ/in. (788 J/mm) and 0.045 sq in. (0.290 mm^2), respectively. This, when coupled with the above weld metal yield strength criteria, places the acceptable range for heat input at 20 to 50 kJ/in. (788 to 1970 J/mm) and nugget area at 0.045 to 0.108 sq in. (0.290 to 0.696 mm^2) for the GMAW using the E70S-3 electrodes and carbon dioxide shield gas on A36 steel.

A516 Weldments

Tensile Test Results

Table 5 and Figures 17 and 18 present the tensile test results for the E70S-3 weld metal and the A516 HAZ specimens. The weld metal yield strengths are spread over a 21 ksi (145 MPa) range varying from 52.1 to 73.2 ksi (359.3 to 504.8 MPa). The weld metal yield strengths per heat input or nugget area for the A516 weldments with the E70S-3 electrodes are nearly identical to the A36 weldments with the same electrodes (Table 4 vs Table 5). Figures 17 and 18 show the weld metal yield strength data plotted against heat and nugget area, respectively. Both figures show a linear trend of weld metal yield strength decreasing as heat input and nugget area increase. The linear correlation coefficient for the weld metal yield strength vs heat input is -0.917; for the weld metal yield strength vs nugget area, it is -0.923. The A516 weldment test series used the same range of nugget areas and heat inputs as the A36 series. Thus, as for the A36 series, the relative difference between nugget area and heat input values is insufficient to evaluate the relative sensitivities of the two parameters to the physical test results.

The HAZ yield strengths varied between 68.5 and 56.2 ksi (472.4 and 387.5 MPa), with increasing heat inputs and nugget areas producing lower yield strengths (Figures 17 and 18). The linear correlation coefficient for HAZ yield strength vs heat input was -0.718; the linear correlation coefficient for HAZ yield strength vs nugget area was -0.723. Thus, the HAZ yield strength data of the A516 weldments gave closer correlation with heat input and nugget area than the A36 specimens.

The UTS of the weld metal specimens varied between 69 and 89 ksi (476 and 614 MPa), with increasing heat inputs and nugget areas associated with decreasing UTS. As with the yield strengths, the UTS of the A516 weldments for each heat input or nugget area was nearly identical to the A36 weldments with the same electrodes. The linear correlation coefficients for the weld metal vs heat input and nugget area were -0.866 and -0.871, respectively.

The UTS of the A516 HAZ specimens varied between 74 and 88 ksi (510 and 607 MPa), with increasing heat inputs and nugget areas associated with decreasing UTS. The linear correlation coefficients for the HAZ UTS vs heat input and nugget area were -0.634 and -0.633, respectively. As with the yield strengths, the A516 HAZ UTS correlated better with heat input and nugget area than did the A36 HAZ UTS.

The true fracture stress and the true strain at fracture were calculated for all specimens tested to provide an indication of the strengths and ductility

[12] *Structural Alloys Handbook: Vol 1*, Mechanical Properties Data Center (Battelle's Columbus Laboratories, 1977).

[13] J. M. Barson and S. T. Rolfe, "Correlation Between K_{IC} and Charpy V-notch Test Results in the Transition Temperature Range," *Impact Testing of Metals*, ASTM STP 466 (ASTM, 1970).

Table 5
Tensile Data for GMAW Weldments of A516 Steel

Weld Specimen Code	Tensile Properties ksi*	Ultimate Tensile Strength ksi	True Fracture Stress ksi	True Strain at Fracture
		Weld Metal		
B28	64.9	78.2	147.0	0.959
(A516)	61.9	76.0	164.0	1.051
B29	69.5	82.6	176.2	1.092
(A516)	67.2	80.2	178.7	1.119
B30	72.2	84.2	116.2	0.533
(A516)	72.4	85.8	165.0	0.884
B31	73.2	88.6	170.8	0.884
(A516)	65.3	79.2	140.2	0.776
B32	61.6	76.2	169.7	1.105
(A516)	58.9	73.2	134.6	0.896
B33	53.1	70.2	162.8	1.248
(A516)	52.1	69.2	172.0	1.278
		HAZ		
B28 (A516)	68.5	86.2	189.4	1.147
B29 (A516)	71.7	78.8	189.5	1.064
B30 (A516)	65.1	85.8	203.9	1.204
B31 (A516)	71.0	87.6	160.5	0.871
B32 (A516)	61.1	84.0	179.3	1.024
B33 (A516)	56.2	74.3	146.5	0.959

*1 ksi = 6.89 MPa

of the weldments. There was no significant correlation between either heat input or nugget area with these two quantities.

Impact Test Results

Figures 19 through 24 graph the DT impact energy absorbed vs test temperature for each weldment for a range of nugget areas from 0.015 sq in (10 mm^2) to 0.095 sq in (65 mm^2). Each figure contains the all-weld metal impact results and the associated HAZ impact results. As with the A36 impact tests, the impact energy at a given temperature for the HAZ specimens is lower than those of the all-weld metal specimens. With the exception of the highest heat input and nugget area specimens (72 kJ/in. [2836 J/mm] and 0.150 sq in. [0.967 mm^2]), the transition temperatures of the HAZ specimens were all above 20° C (Figures 25 and 26). The transition temperatures of the all-weld metal specimens varied between 25 and 10° C, with the exception of the 72 kJ/in. (2836 J/mm) heat input specimen that had a transition temperature of -30° C. Additionally, Figures 25 and 26 illustrate that for each heat input and nugget area, the HAZ specimens have higher transition temperatures than the all-weld metal specimens. Unlike the A36 DT test results, both HAZ and weld metal transition temperatures decreased with increasing heat input and nugget area. The linear correlation coefficients for the HAZ and weld metal transition temperatures vs heat input and nugget area varied between -0.825 and -0.831, indicating a significant level of linear correlation. (The two HAZ transition temperatures that were above 40° C were not included in the linear regression analysis; if these values were used, they would have significantly altered the results of the regression analysis.)

General

The mechanical properties of the A516 weldments, when compared with the specification requirements, indicate that the yield strength of the E70S-3 electrode drops below the 60 ksi (414 MPa) minimum requirement at heat inputs and nugget areas near 50 kJ/in. (1970 J/mm) and 0.105 sq in. (0.677 mm^2), respectively (Figures 17 and 18). But none of the HAZ weld metal yield strengths dropped below the 38 ksi (262 MPa) minimum yield strength specified for the base plate or the reported value for base plate yield strength of 45 ksi.

The UTS of the weld metal specimens dropped below the 72 ksi (497 MPa) minimum requirement of A518 at heat inputs and nugget areas greater than 60 kJ/in. (2864 J/mm) and 0.127 sq in. (0.819 mm^2), respectively. The UTS of the HAZ specimens were within the specified 70 to 90 ksi (483 to 621 MPa) range for ASTM A516 base plate.

Neither the A516 plate nor the E70S-3 electrodes have specified DT impact requirements. But it has been reported that the transition temperature for the A516 steel is -73°C.[14] Figures 25 and 26 indicate that the HAZ and weld metal have significantly higher transition temperatures than the -73°C value reported for the base plate. Thus, the impact resistance of the HAZ and weld metal may be significantly less than the base plate, and should be considered in the design and fabrication of A516 welded components if impact resistance is critical.

As with the A36 plate, side wall fusion and depth of penetration became increasingly difficult to control at heat inputs and nugget areas less than 20 kJ/in. (788 J/mm) and 0.045 sq in. (0.290 mm^2), respectively. This, when coupled with the weld metal yield strength criterion, places the acceptable range for heat input at 20 to 50 kJ/in. (788 to 1970 J/mm) and the nugget area at 0.045 to 0.105 sq in. (0.290 to 0.677 mm^2) for the GMAW using the E70S-3 electrodes and carbon dioxide shield gas on A516 steel.

A514 Weldments

Tensile Test Results

Table 6 and Figures 27 and 28 present the tensile test results for the E110S weld metal and A514 HAZ specimens over the ranges of heat input and nugget areas tested. With the exception of one test specimen (yield strength 86.1 ksi [593.7 MPa]), the weld metal yield strengths were between 105 and 144 ksi (724 and 993 MPa). Figures 27 and 28 show the weld metal yield strength data plotted against heat input and nugget area, respectively. Both figures showed a linear trend (r = -0.752 for yield strength vs heat input and r = -0.747 for yield strength vs nugget area) of weld metal yield strength decreasing as heat input and nugget area increase.* As with the A36 and A516 test series, the relative difference between nugget area and heat input values is insufficient to evaluate the relative sensitivity of the two parameters to the physical test results.

The HAZ yield strengths varied between 47 and 137.4 ksi (324 and 947.5 MPa). The HAZ yield strengths did not correlate very well with either heat input (r = -0.491) or nugget area (r = -0.510), but tended to decrease with increasing heat inputs and nugget areas. The extremely low HAZ yield strength, 47 ksi (324 MPa), of the highest heat input and largest nugget area specimen (B-34) occurred because the heat of welding changed the microstructure of the base material in the HAZ from a quench and tempered martensitic structure to a pearlitic/banitic structure. For this reason, the highest heat input and nugget area specimen was not used in the linear regression analysis of the HAZ yield strengths.

The UTS of the weld metal specimens varied between 114 and 150 ksi (786 and 1034 MPa). The weld metal UTS did not correlate very well with either heat input (r = -0.461) or nugget area (r = -0.462), but as with yield strength, tended to decrease with increasing heat input and nugget area. The UTS of the two specimens (B-34) with defects was not used in the regression analysis.

The UTS of the HAZ specimens varied between 69.5 and 140 ksi (479.3 and 966 MPa). As with the HAZ yield strengths, the HAZ UTS did not correlate very well with either heat input (r = -0.503) or nugget

[14] J. M. Barson and S. T. Rolfe, "Correlation Between K_{IC} and Charpy V-notch Test Results in the Transition Temperature Range," *Impact Testing of Metals*, ASTM STP 466 (ASTM, 1970).

*Two weld metal specimens contained defects; their test results were not used to evaluate the correlations.

Table 6
Tensile Data for GMAW Weldments of A514 Steel

Weld Specimen Code	Tensile Properties (ksi)*	Ultimate Tensile Strength (ksi)	True Fracture Stress (ksi)	True Strain at Fracture
		Weld Metal		
B34	86.1	114.5	140.2	0.346 (defect)
(A514)	111.3	130.1	293.3	1.190
B35	114.8	120.5	225.8	1.092
(A514)	105.3	114.3	137.7	0.318 (defect)
B36	118.8	125.3	274.2	1.324
(A514)	116.3	123.3	251.0	1.248
B37	116.5	124.3	234.0	1.119
(A514)	118.1	134.5	240.0	1.038
B38	130.5	136.0	287.0	1.219
(A514)	135.3	146.0	259.6	1.011
B39	143.4	144.4	296.2	1.248
(A514)	140.0	149.4	312.5	1.161
		HAZ		
B34 (A514)	46.9	69.5	144.7	1.064
B35 (A514)	110.1	118.1	276.3	1.370
B36 (A514)	107.8	116.5	237.4	1.219
B37 (A514)	103.5	112.3	250.9	1.324
B38 (A514)	137.4	140.5	284.0	1.105
B39 (A514)	113.0	120.5	257.1	1.248

*1 ksi = 6.89 MPa

area (r = -0.519), but tended to decrease with increasing heat inputs and nugget areas. The high heat input/largest nugget area HAZ specimen UTS results were not used in the linear regression analysis because of the phase change.

Impact Test Results

Figures 29 through 34 graph the DT impact energy vs test temperature for each weldment. Each figure contains the all-weld metal impact results and the associated HAZ impact results. In all cases, the impact energy at a given temperature for the HAZ specimens is lower than that of the all-weld metal specimens. Additionally, it appears that, for the range of temperatures tested (-40 to +40° C), the HAZ specimens were all on the lower shelf and the all-weld metal specimens were on the upper shelf. Thus, it was impossible to compare the influence of heat input and nugget area on transition temperatures for either the HAZ or weld metal specimens. But the HAZ specimens were all on the lower shelf and the weld metal specimens on the upper shelf; this, then, would indicate that the HAZ transition temperatures were all above 30 or 40° C and the weld metal transition temperatures were below -30° C.

General

The mechanical properties of the A514 weldments, when compared with the specification requirements, indicate that the yield strength of the E110S weld metal drops below the 98 ksi (676 MPa) minimum requirement at heat inputs and nugget areas greater than 55 kJ/in. (2167 J/mm) and 0.130 sq in. (0.838 mm^2), respectively (Figures 27 and 28). The HAZ yield strengths dropped below the 100 ksi (690 MPa) minimum ASTM A514 base plate requirement at heat inputs and nugget areas greater than 37 kJ/in. (1457 J/mm) and 0.087 sq in. (0.561 mm^2), respectively. But it should be remembered that the HAZ values are based on linear regressions and had suspiciously low correlation coefficients that did not include the highest heat input specimens.

The weld metal did not drop below the 110 ksi (759 MPa) minimum required for the entire heat input and nugget area test range. But the HAZ UTS dropped below the 110 ksi (759 MPa) minimum UTS base plate requirement at heat inputs and nugget areas greater than 36 kJ/in. (1418 J/mm) and 0.085 sq in. (0.548 mm^2), respectively. But, as for the HAZ yield strengths, the HAZ UTS are based on linear regressions that have correlation coefficients less than -0.52.

As with the previous test series, neither the A514 plate or the E110S electrodes have specified DT impact requirements. But the reported transition temperature of the A514 steel, -73°C when compared to the impact test data, indicates that the HAZ transition temperatures are all significantly higher (above 30°C). Thus, for the most common operating temperatures, the impact resistance of the HAZ is significantly less than the base plate and should be considered in the design and fabrication of A514 welded components if impact resistance is critical.

As with the other tests, plate side wall fusion and depth of penetration becomes increasingly difficult to control at heat inputs and nugget areas below 15 kJ/in. (591 J/mm) and 0.038 sq in. (0.245 mm^2), respectively. This, coupled with the HAZ yield strength and UTS restrictions, makes an acceptable range of heat input at 15 to 30 kJ/in. (591 to 1182 J/mm) and nugget area at 0.038 to 0.069 sq in. (0.245 to 0.445 mm^2) for the GMAW using the E110S electrode and the argon plus 2 percent oxygen on A514 steel. The upper limits, 30 kJ/in. (1182 J/mm) and 0.069 sq in. (0.445 mm^2), were chosen conservatively because of the low correlation coefficients for the HAZ test data and the tendency of the HAZ microstructure to change at high heat inputs.

4 CONCLUSIONS

The following conclusions are based on the results of research into the effects of weld variables on the mechanical properties of deposited weld metal and HAZ for A36, A514, and A516 weldments.

1. Sound welds can be produced with the E70S-3 and E110S electrodes used in this investigation.

2. The HAZ impact energy of A36 and A516 weldments was generally lower than that of the weld metal, while the yield strength showed varying results. The impact energy of all the weldments showed limited dependency on the weld variables, exhibiting an effect only at the highest heat inputs (72 kJ/in. [2836 J/mm]) and largest nugget areas (0.150 sq in. [100 mm^2]).

3. There are not enough data to determine the maximum heat input and nugget area for A514 weldments because of the microstructural change in the HAZ caused by the heat of welding. Although the data indicate that the HAZ yield strength and UTS fall below the specification minimums at 36 kJ/in. (1418 J/mm) and 0.085 sq in. (0.554 mm^2), these values are not specific because of the data's poor correlation coefficients.

4. A36 steel weldments using E70S-3 GMAW electrodes can be produced with heat inputs between 20 and 50 kJ/in. (787 and 1968 J/mm) and nugget areas between 0.045 and 0.108 sq in. (29 and 69.7 mm^2).

5. A516 steel weldments with E70S-3 GMAW electrodes can be made with heat inputs between 20 and 50 kJ/in. (787 and 1968 J/mm) and nugget areas between 0.045 and 0.104 sq in. (29 and 67 mm^2).

6. Fabrication of A514 steel weldments with E110S GMAW electrodes can be limited to a minimum heat input of 15 kJ/in. (591 J/mm) and a nugget area of 0.038 sq in. (26 mm^2).

7. The designer must consider service temperatures whenever A36, A514, and A516 weldments are to be used in a structure. Tensile properties which meet specification requirements may not assure adequate performance at low temperatures. Such features can only be determined by an adequate impact test.

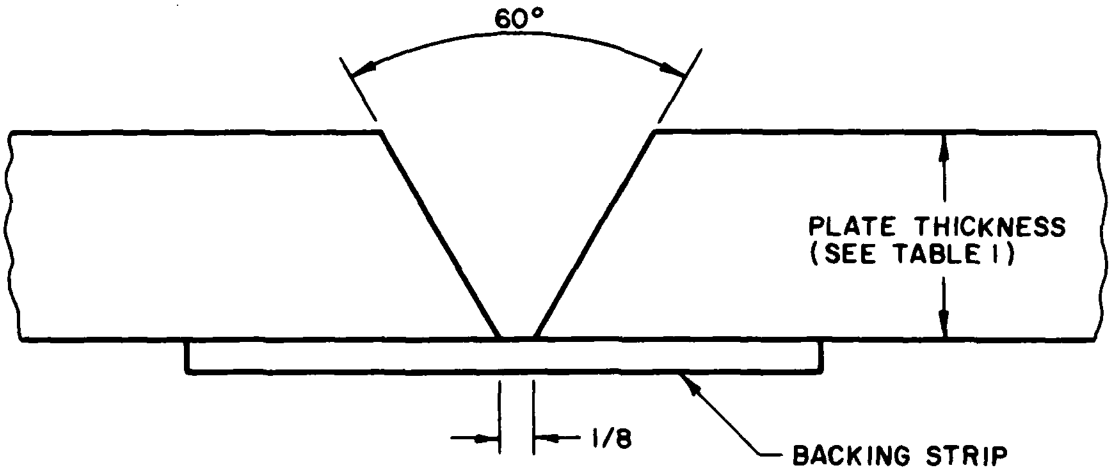
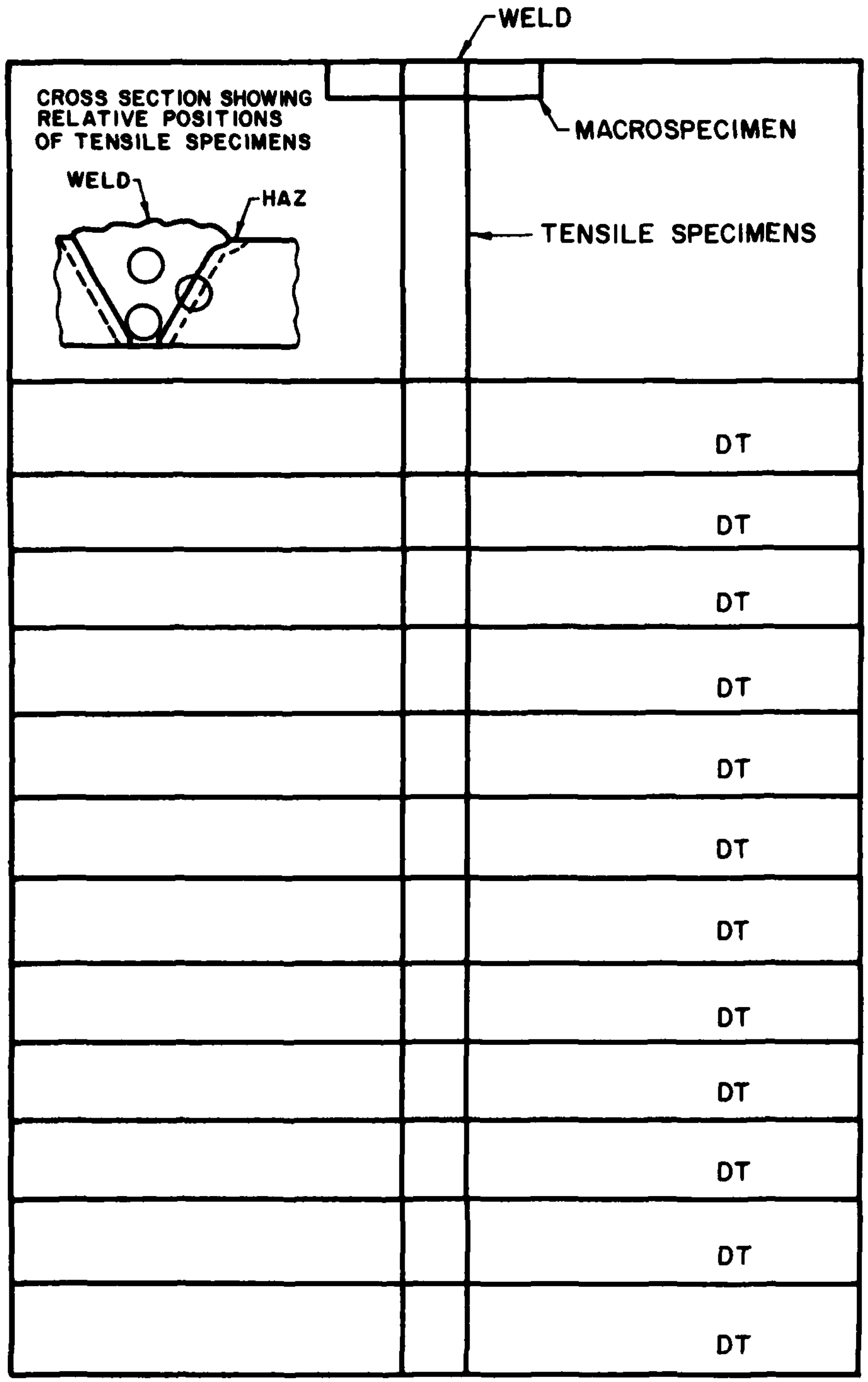


Figure 1. Joint design used for GMAW of A36, A514, and A516 steel.



NOTE: Half of DTs Notched in Weld Metal, and Half of DTs Notched in HAZ.

Figure 2. Schematic showing specimen location as machined from weldment.

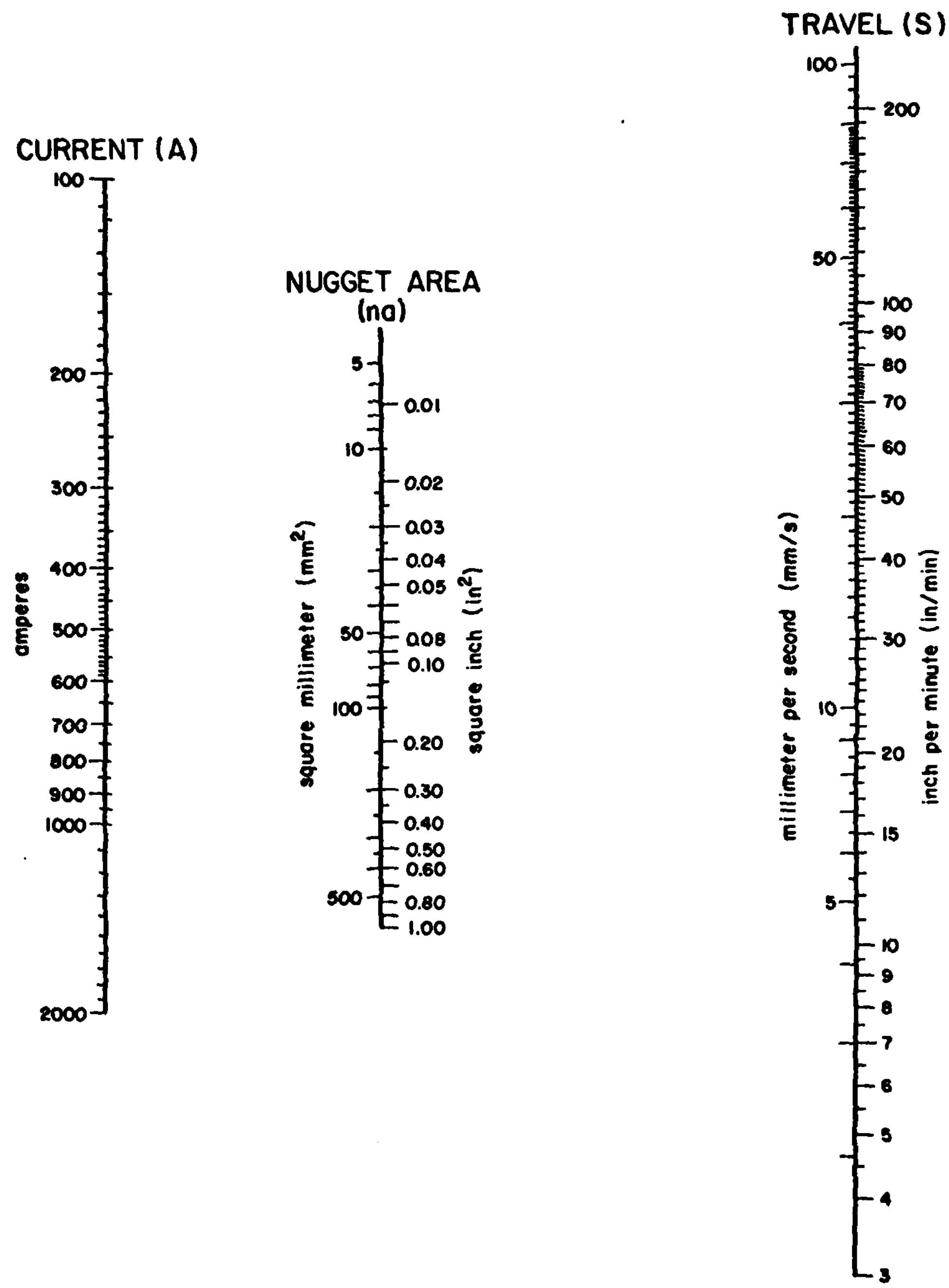


Figure 3. Nomograph for determining nugget area (from B. L. Shultz and C. E. Jackson, "Influence of Weld Bead Area on Weld Mechanical Properties," *Welding Journal*, Vol. 52 [January 1973], Research Supplement, p. 36s).

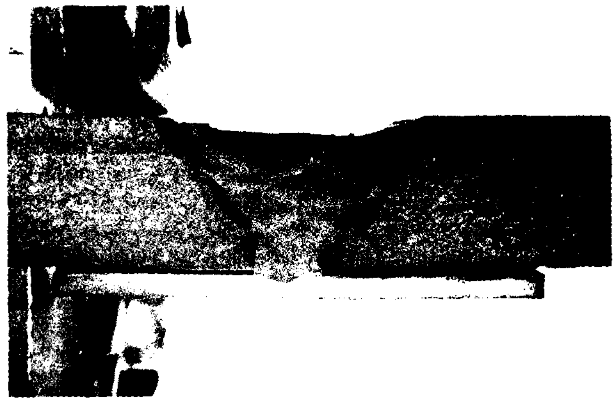


Figure 4. Typical cross section of A36 GMAW weldment (3/4 in. [19 mm] thick).

Figure 5. Typical cross section of A516 GMAW weldment (1 in. [25.4 mm] thick).

Figure 6. Typical cross section of A514 GMAW weldment (3/4 in. [19 mm] thick).

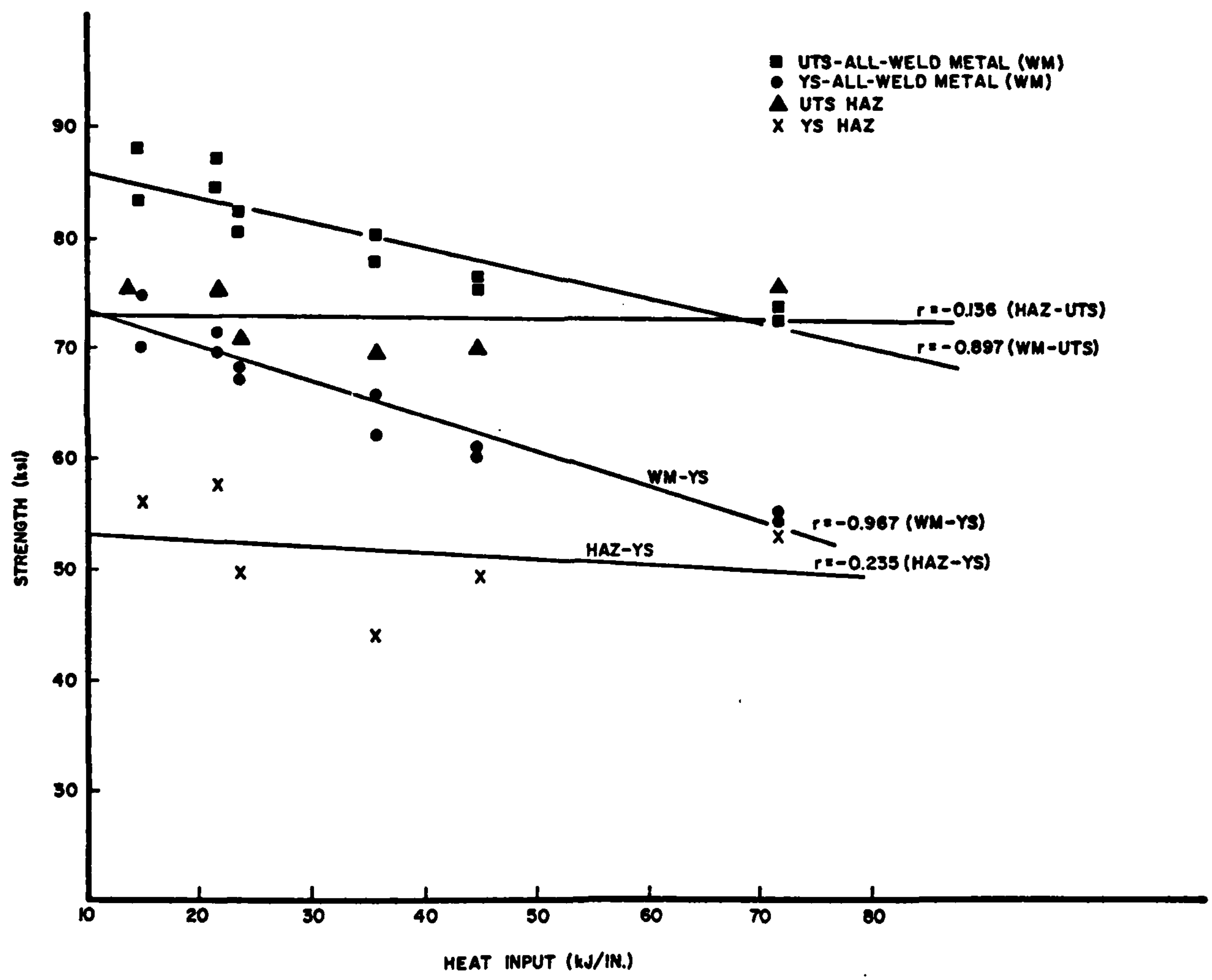


Figure 7. Weld metal and HAZ tensile and yield strength vs heat input for A36 weldments.

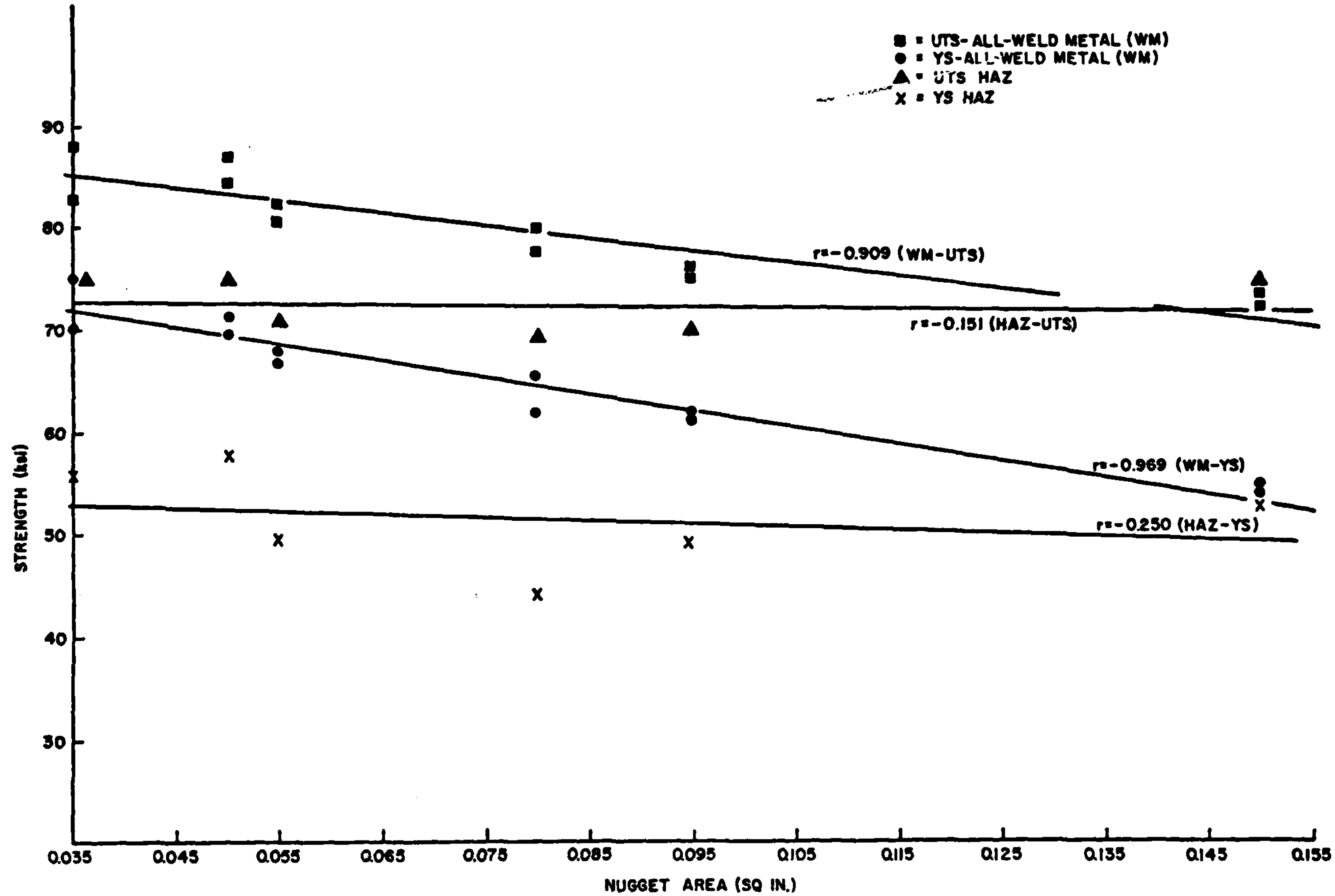


Figure 8. Weld metal and HAZ tensile and yield strength vs nugget area for A36 weldments.

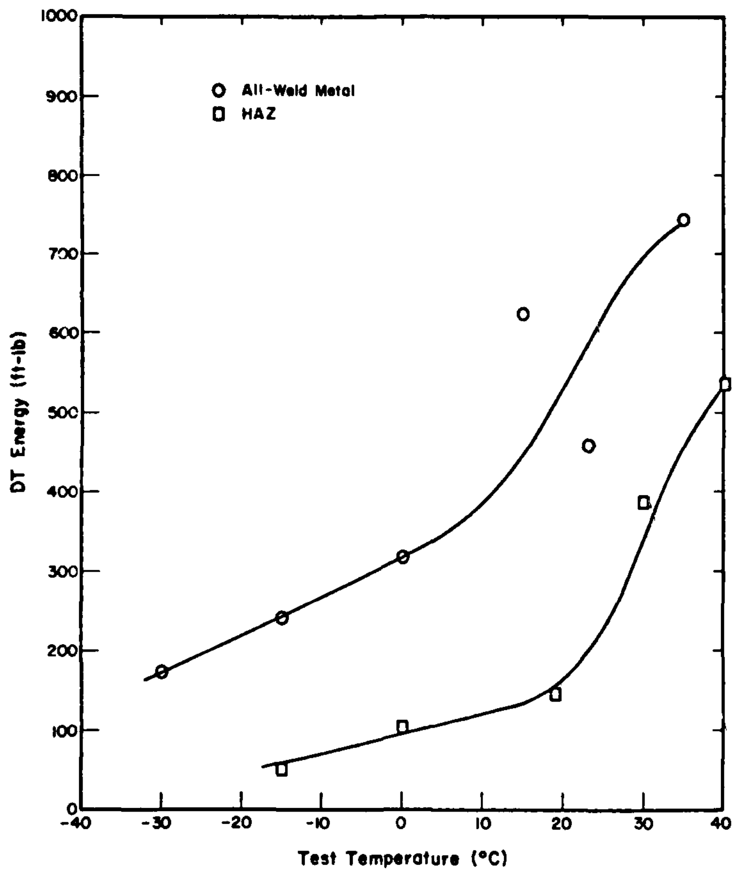


Figure 9. Dynamic tear impact energy vs test temperature for A36 weldment B22 (nugget area: 0.150 sq in. [100 mm^2]).

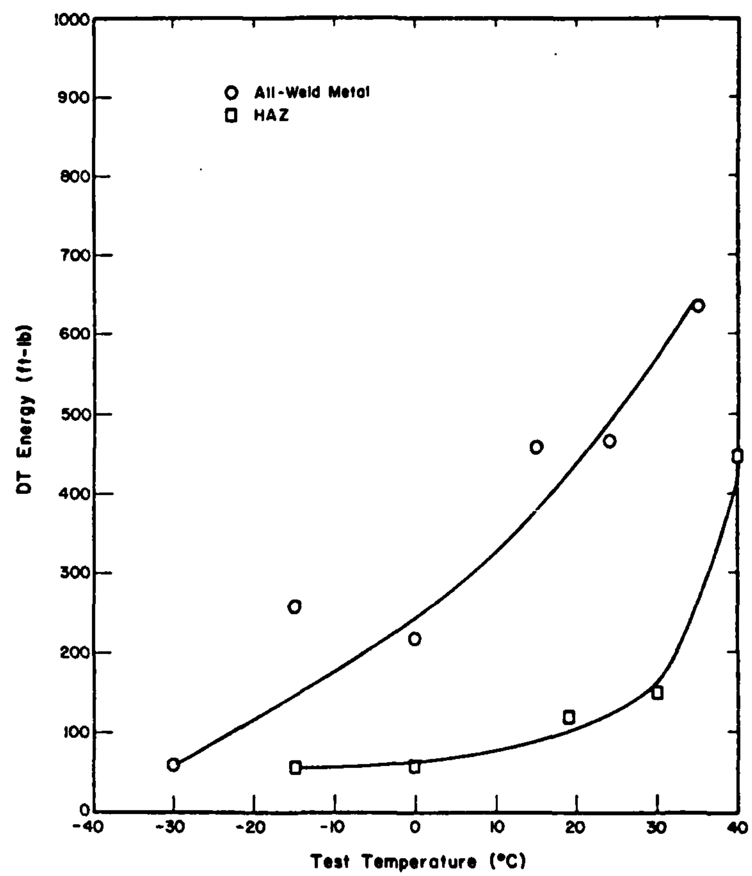


Figure 10. Dynamic tear impact energy vs test temperature for A36 weldment B23 (nugget area: 0.080 sq in. [52 mm^2]).

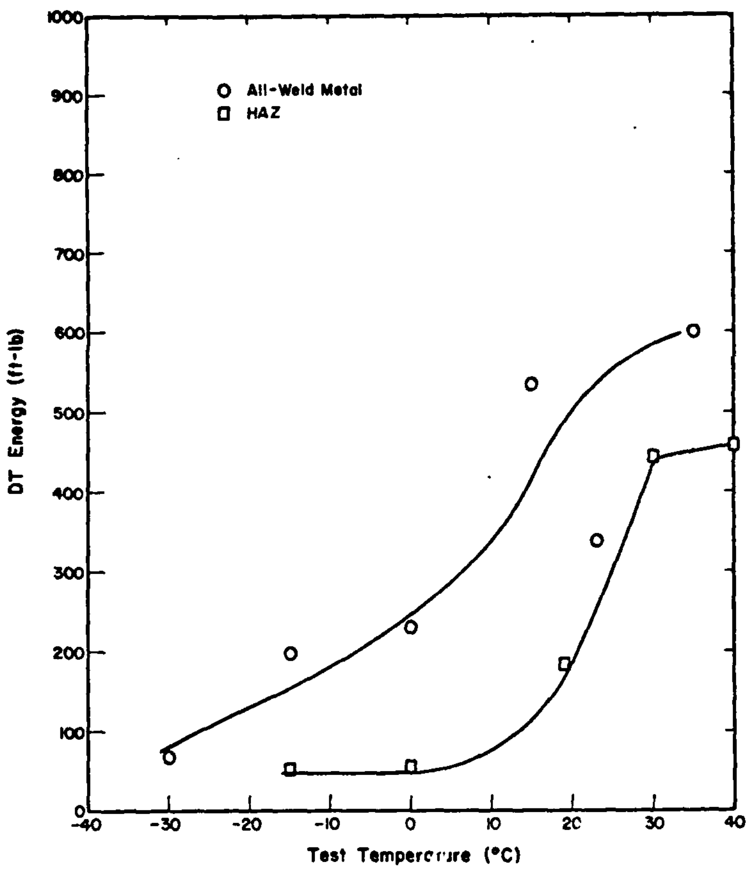


Figure 11. Dynamic tear impact energy vs test temperature for A36 weldment B24 (nugget area: 0.055 sq in. [40 mm^2]).

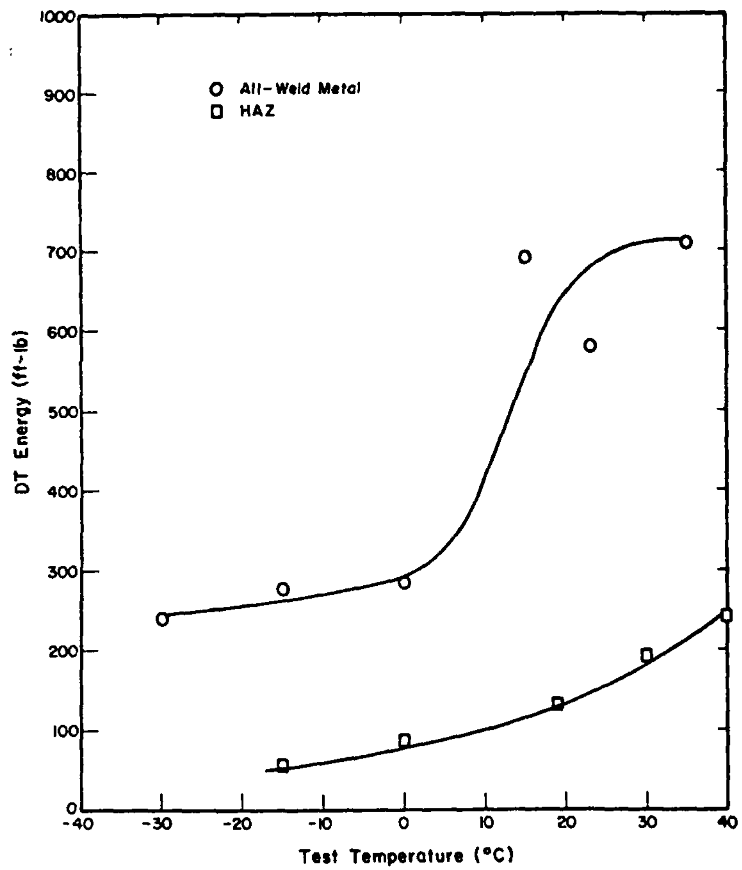


Figure 12. Dynamic tear impact energy vs test temperature for A36 weldment B25 (nugget area: 0.035 sq in. [24 mm^2]).

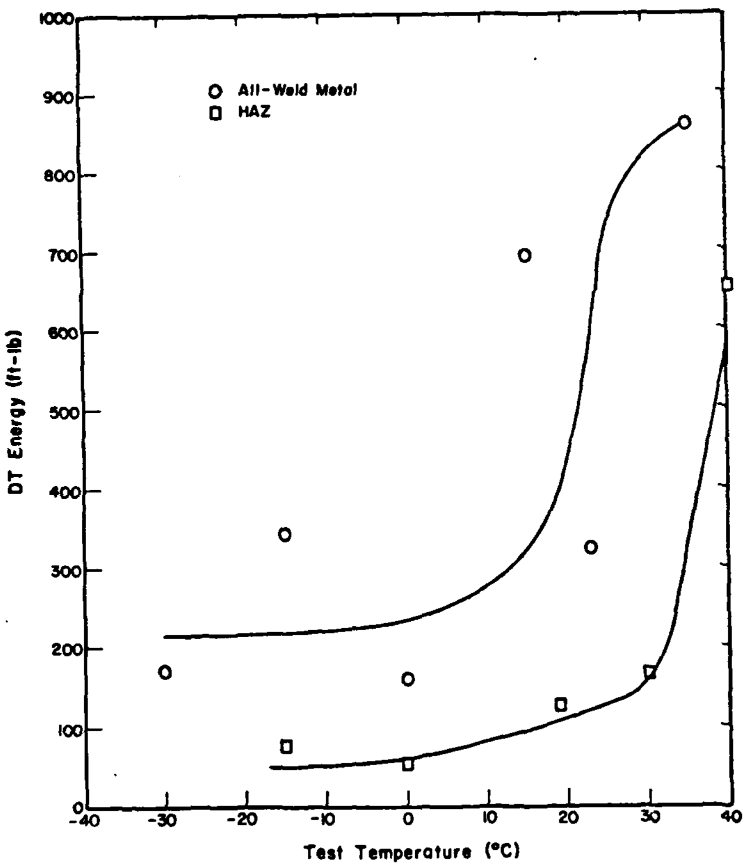


Figure 13. Dynamic tear impact energy vs test temperature for A36 weldment B26 (nugget area: 0.050 sq in. [35 mm^2]).

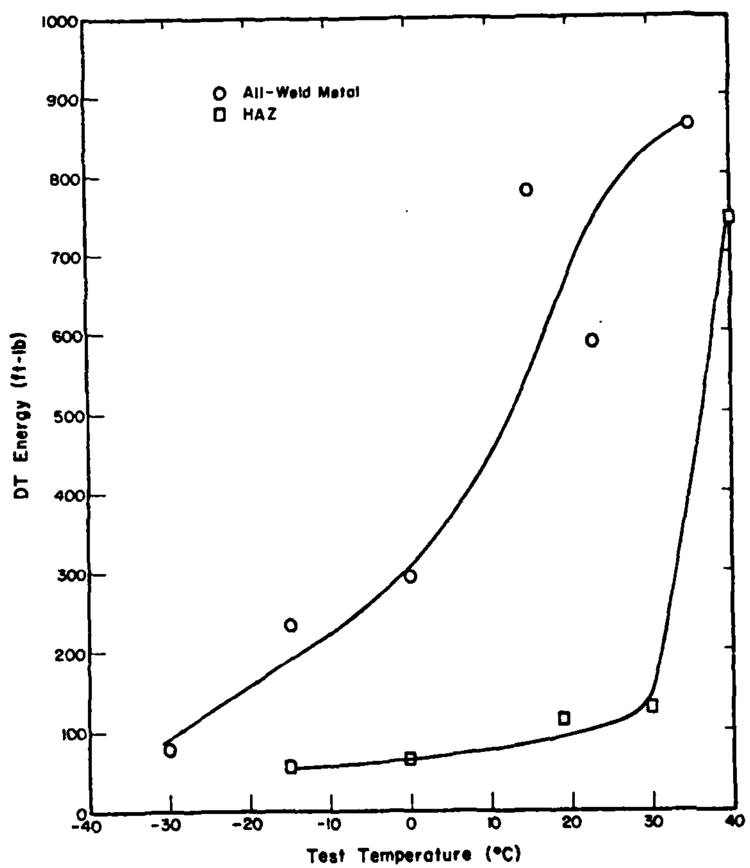


Figure 14. Dynamic tear impact energy vs test temperature for A36 weldment B27 (nugget area: 0.095 sq in. [65 mm^2]).

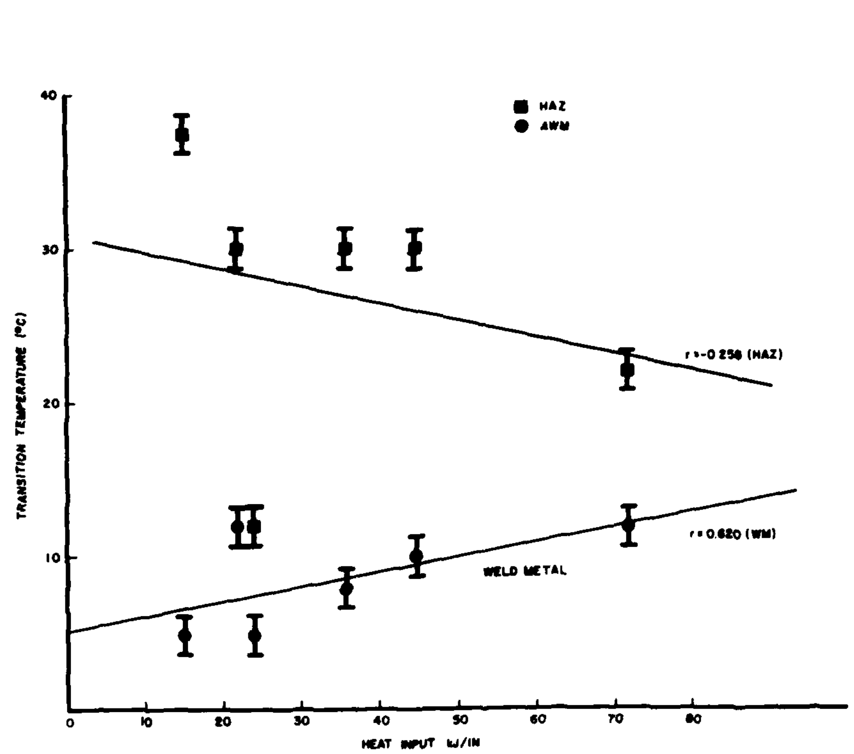


Figure 15. Dynamic tear transition temperature vs heat input for A36 steel weldments.

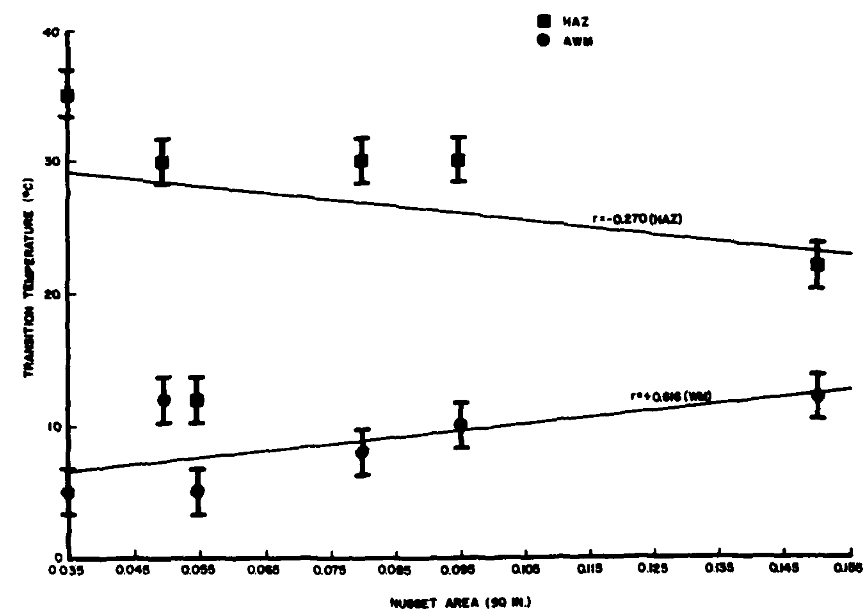


Figure 16. Dynamic tear transition temperature vs nugget area for A36 steel weldments.

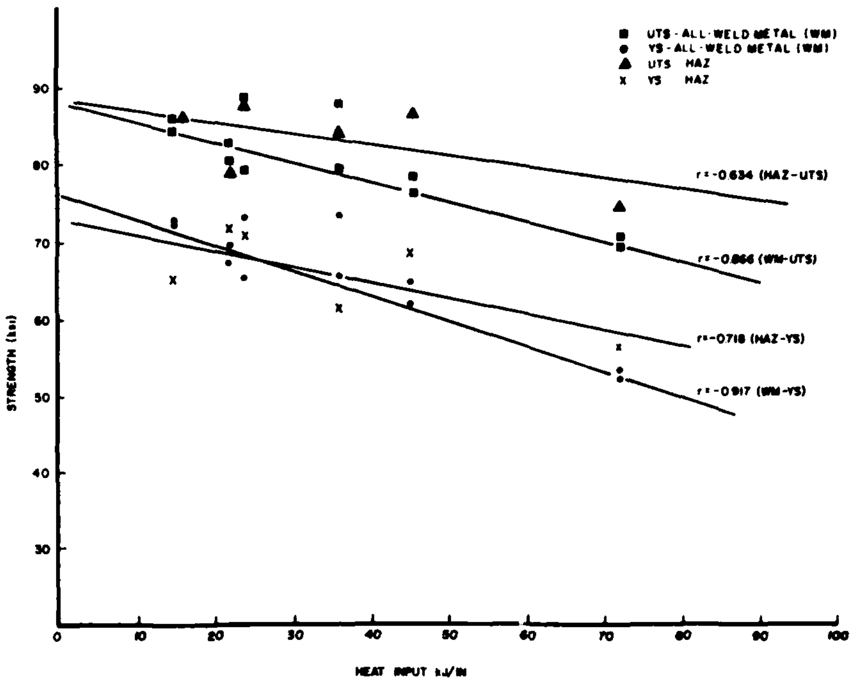


Figure 17. Weld metal and HAZ tensile and yield strength vs heat input for A516 steel weldments.

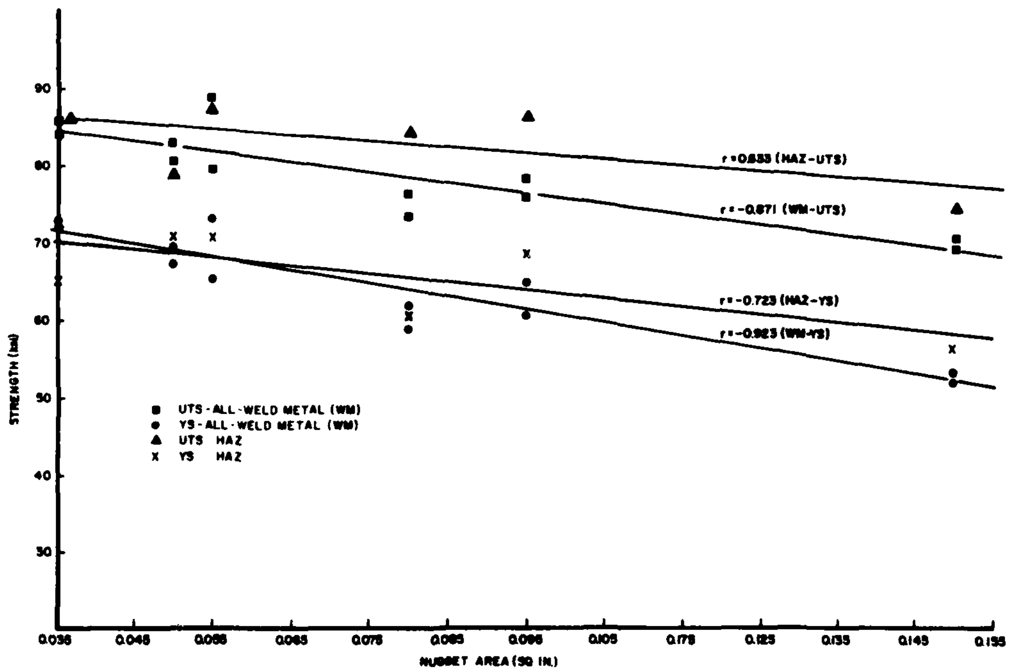


Figure 18. Weld metal and HAZ tensile and yield strength vs nugget area for A516 steel weldments.

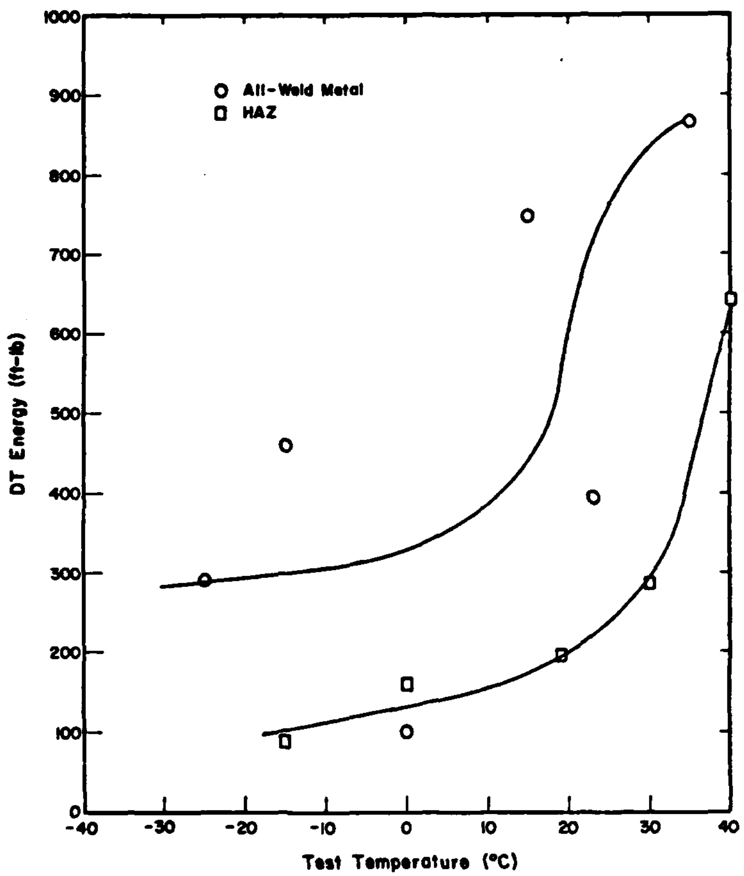


Figure 19. Dynamic tear impact energy vs test temperature for A516 weldment B28 (nugget area: 0.095 sq in. [65 mm^2]).

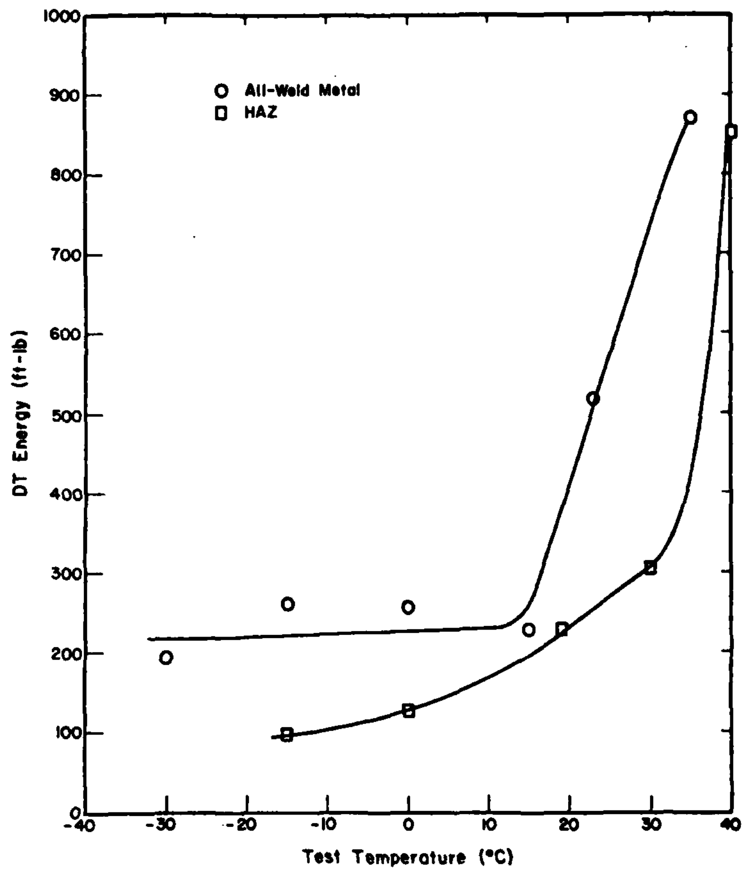


Figure 20. Dynamic tear impact energy vs test temperature for A516 weldment B29 (nugget area: 0.050 sq in. [35 mm^2]).

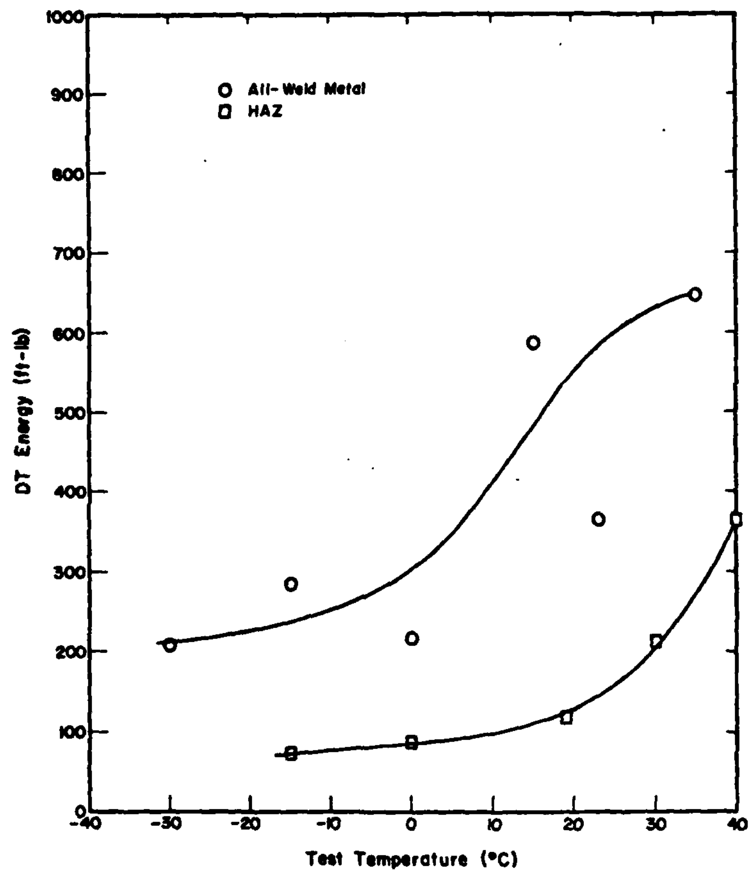


Figure 21. Dynamic tear impact energy vs test temperature for A516 weldment B30 (nugget area: 0.035 sq in. [24 mm^2]).

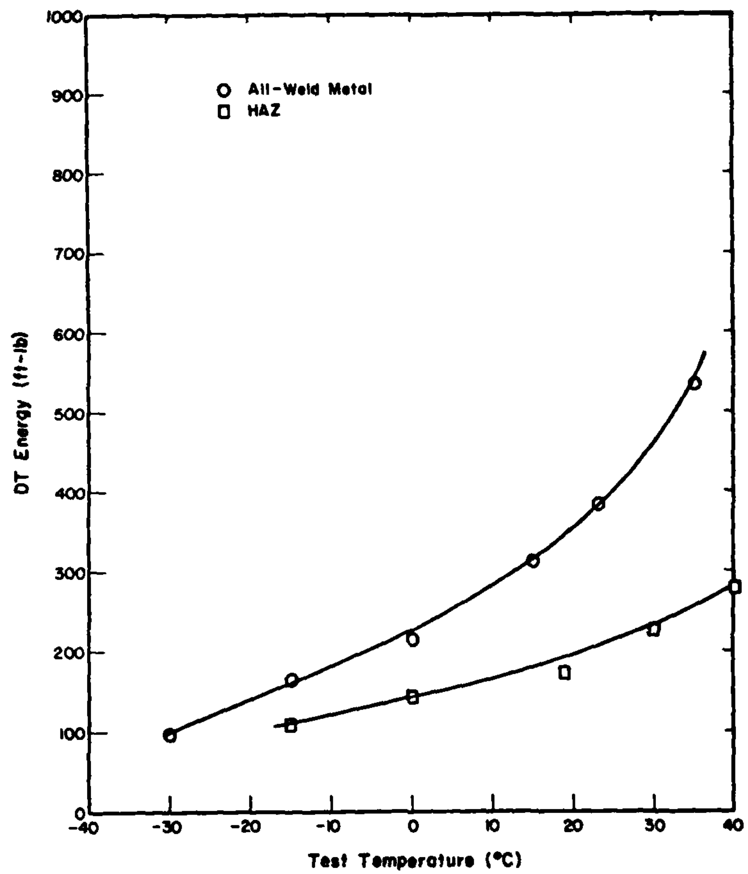


Figure 22. Dynamic tear impact energy vs test temperature for A516 weldment B31 (nugget area: 0.055 sq in. [40 mm^2]).

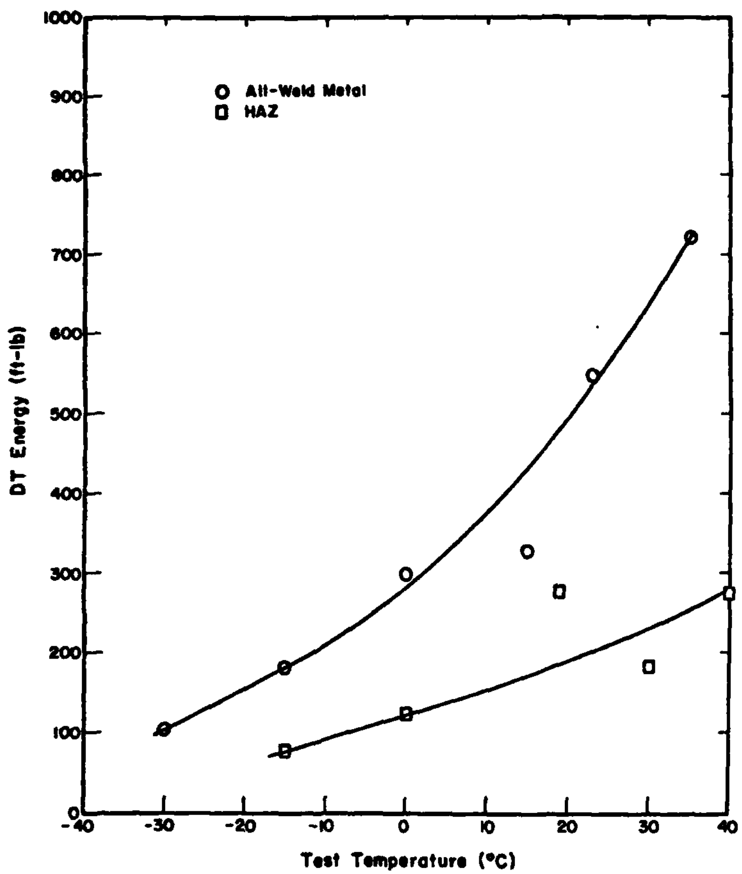


Figure 23. Dynamic tear impact energy vs test temperature for A516 weldment B32 (nugget area: 0.080 sq in. [52 mm^2]).

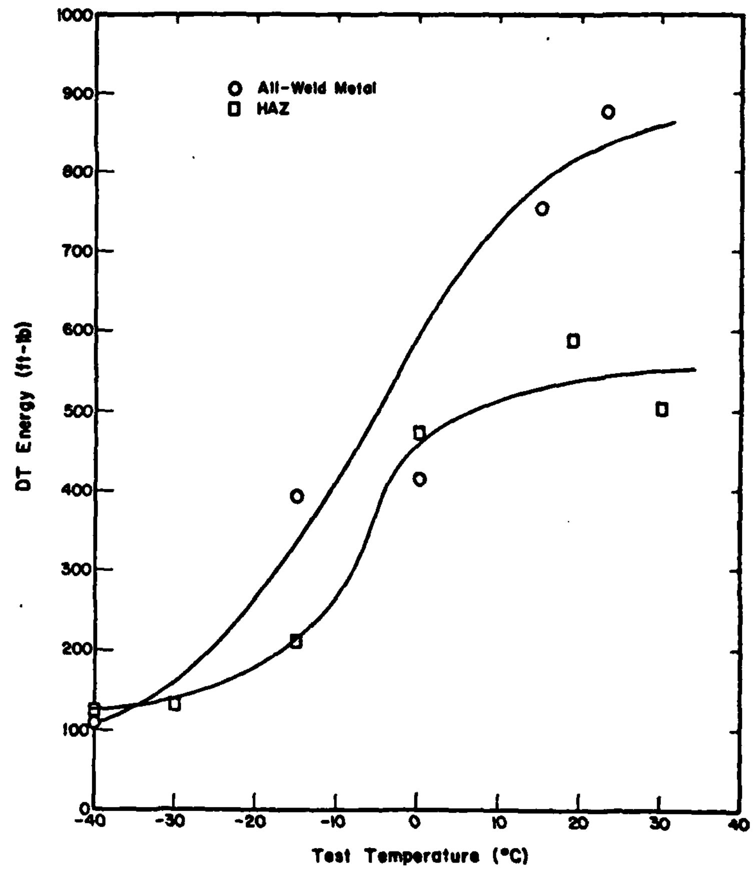


Figure 24. Dynamic tear impact energy vs test temperature for A516 weldment B33 (nugget area: 0.150 sq in. [100 mm^2]).

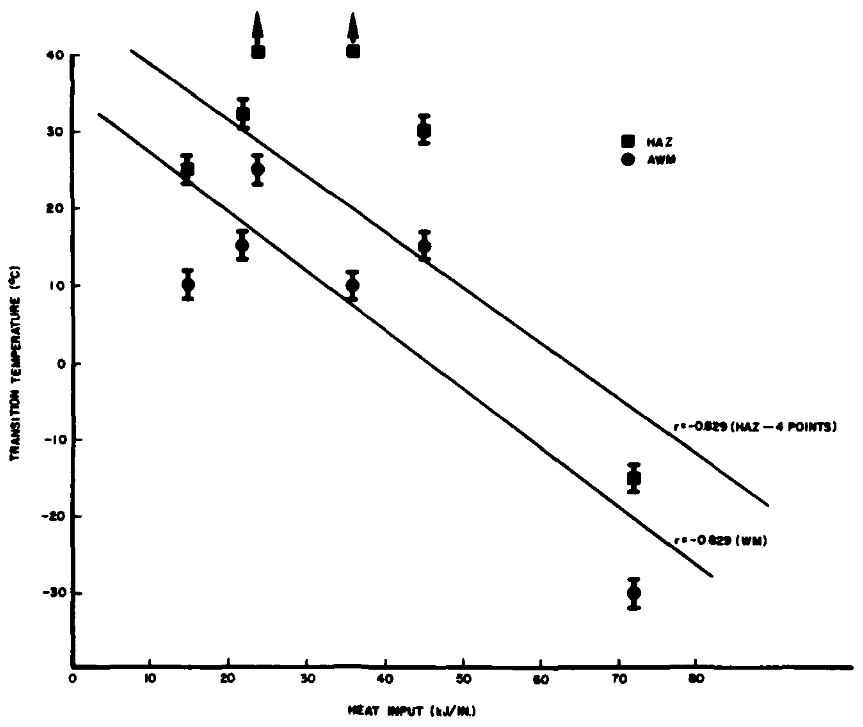


Figure 25. Dynamic tear transition temperature vs heat input for A516 steel weldments.

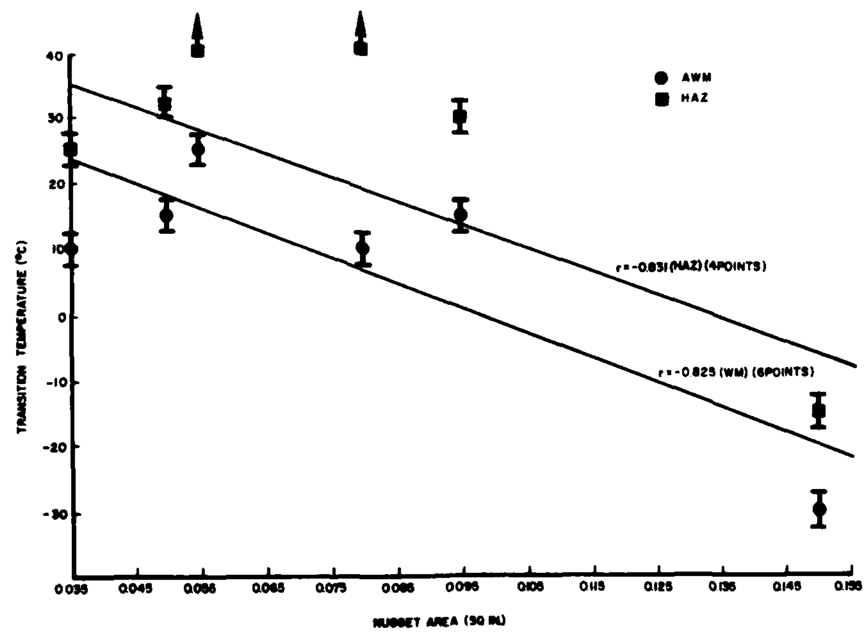


Figure 26. Dynamic tear transition temperature vs nugget area for A516 steel weldments.

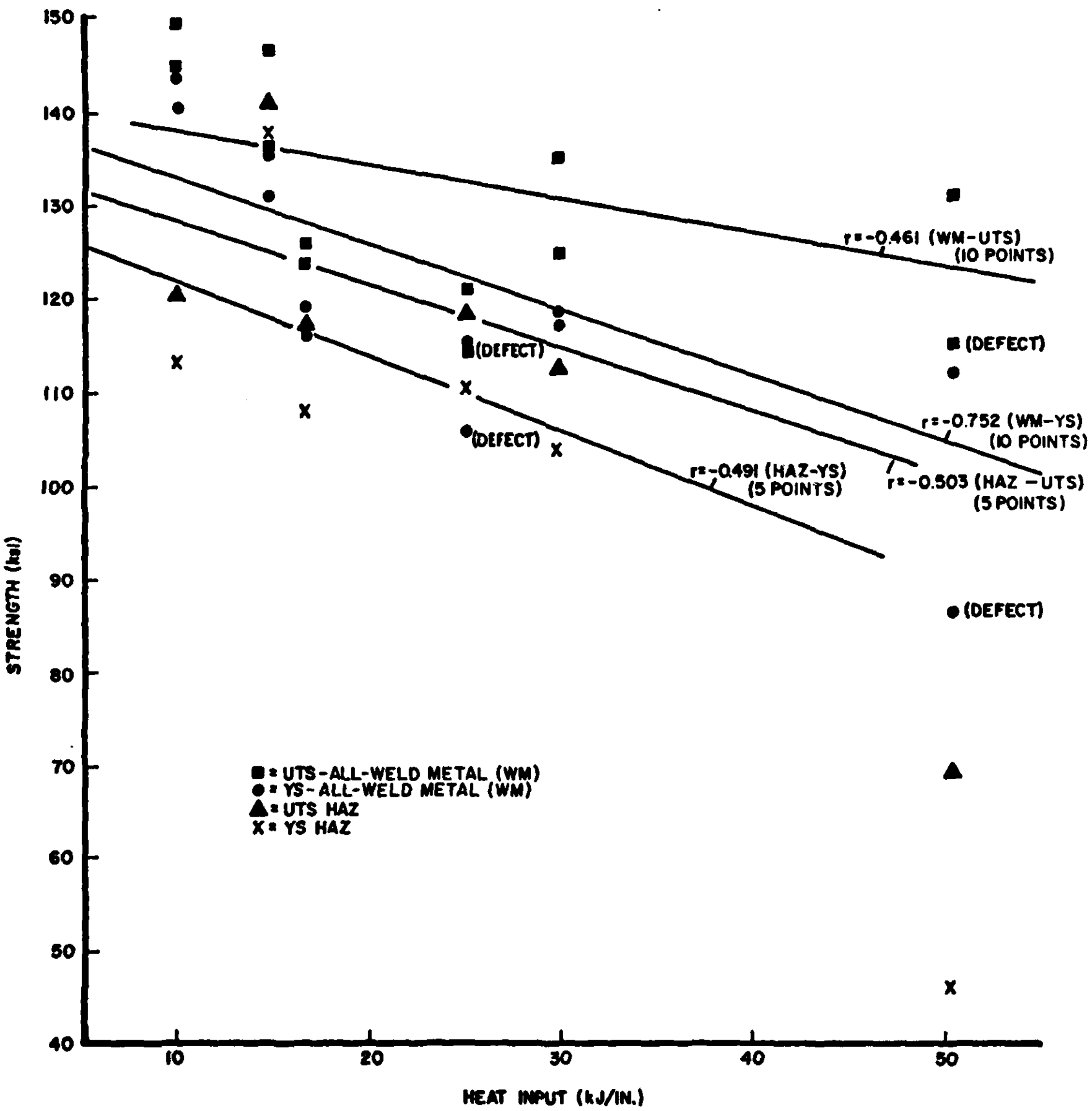


Figure 27. Weld metal and HAZ tensile and yield strength vs heat input for A514 steel weldments.

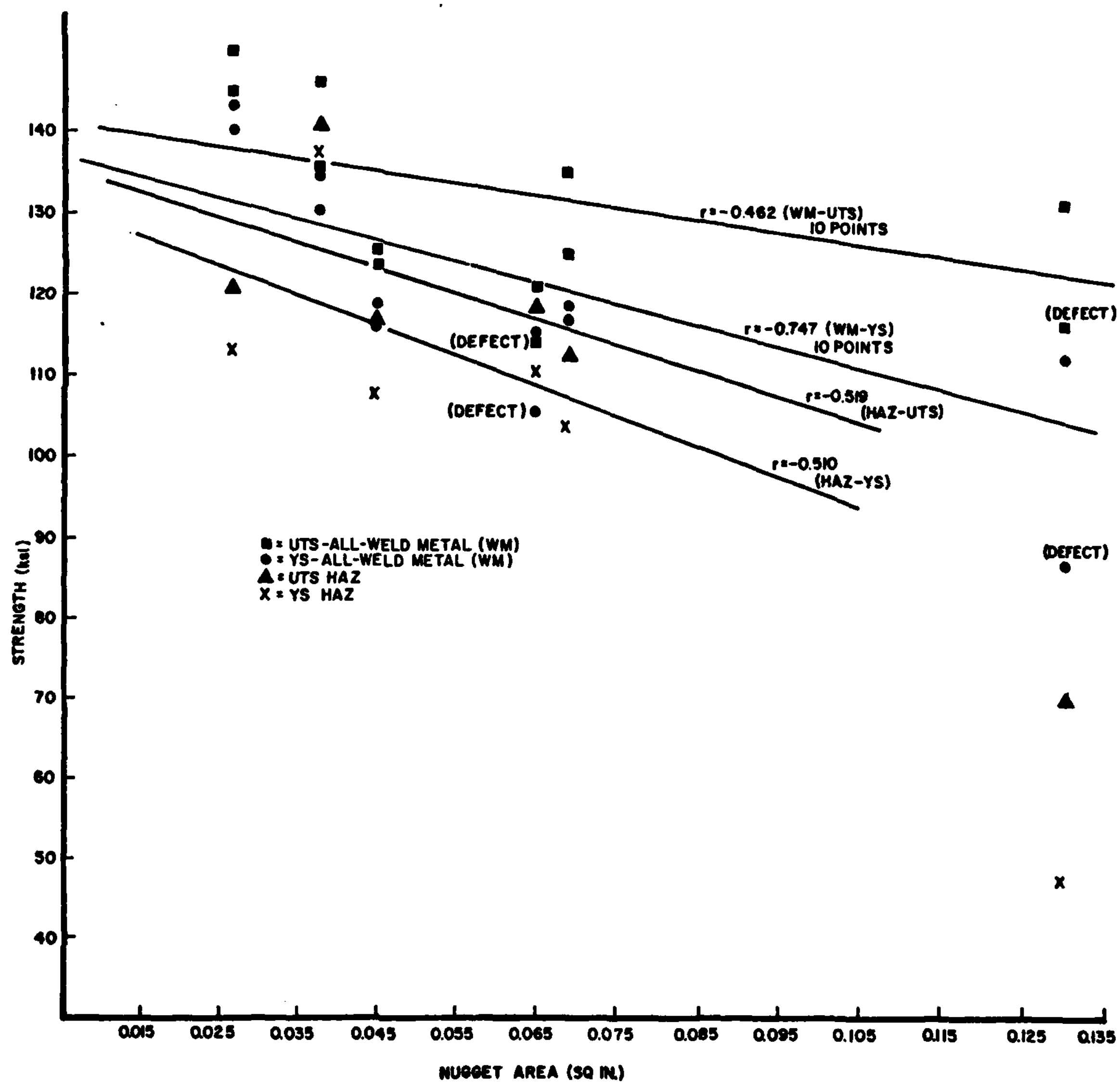


Figure 28. Weld metal and HAZ tensile and yield strength vs nugget area for A514 steel weldments.

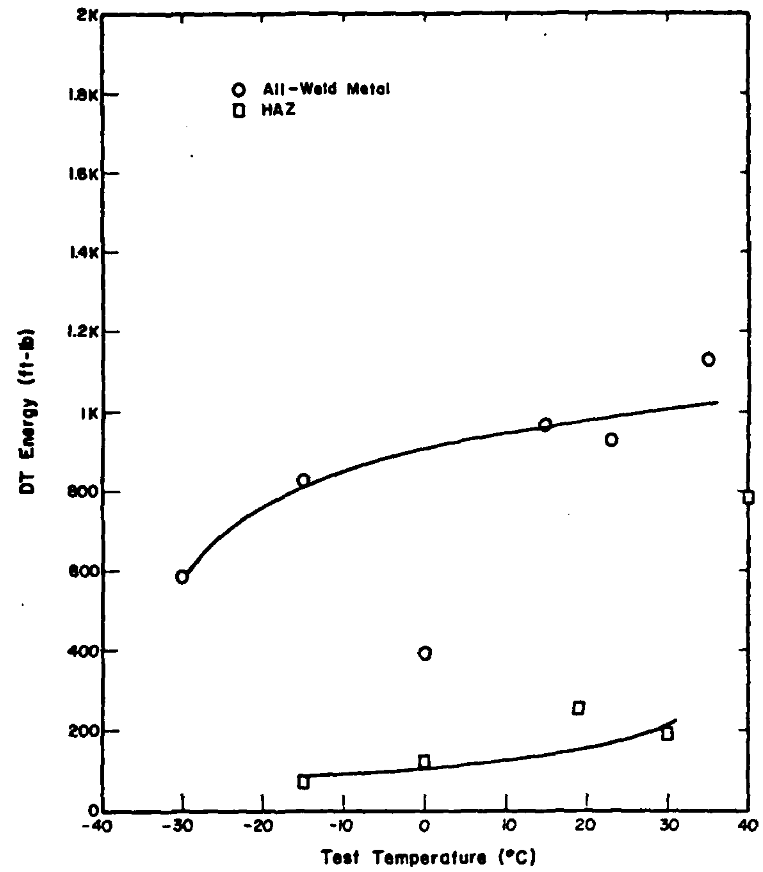


Figure 29. Dynamic tear impact energy vs test temperature for A514 weldment B34 (nugget area: 0.130 sq in. [80 mm^2]).

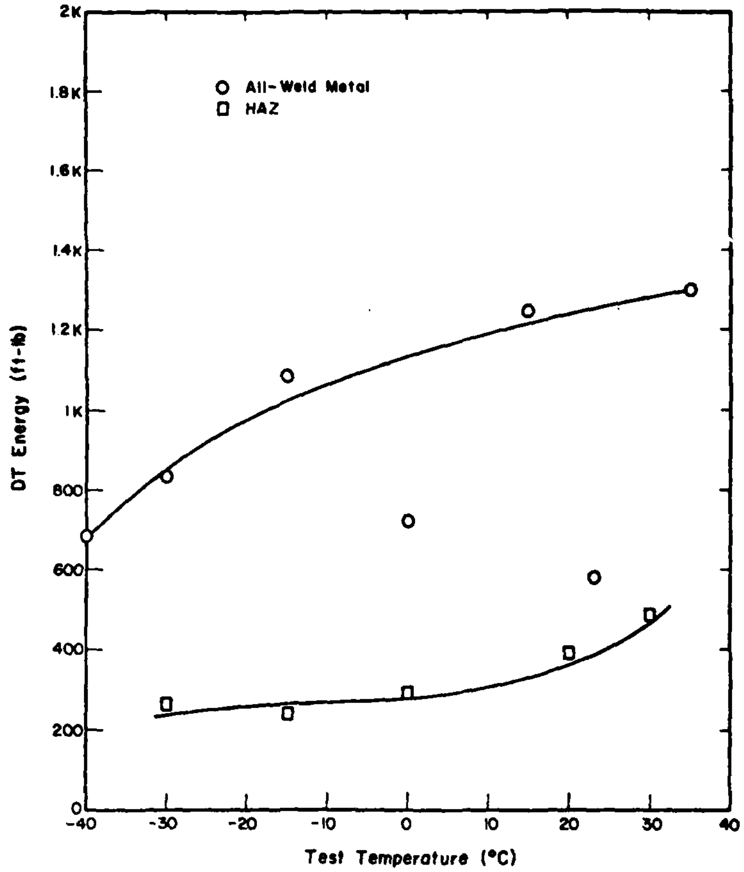


Figure 30. Dynamic tear impact energy vs test temperature for A514 weldment B35 (nugget area: 0.065 sq in. [42 mm^2]).

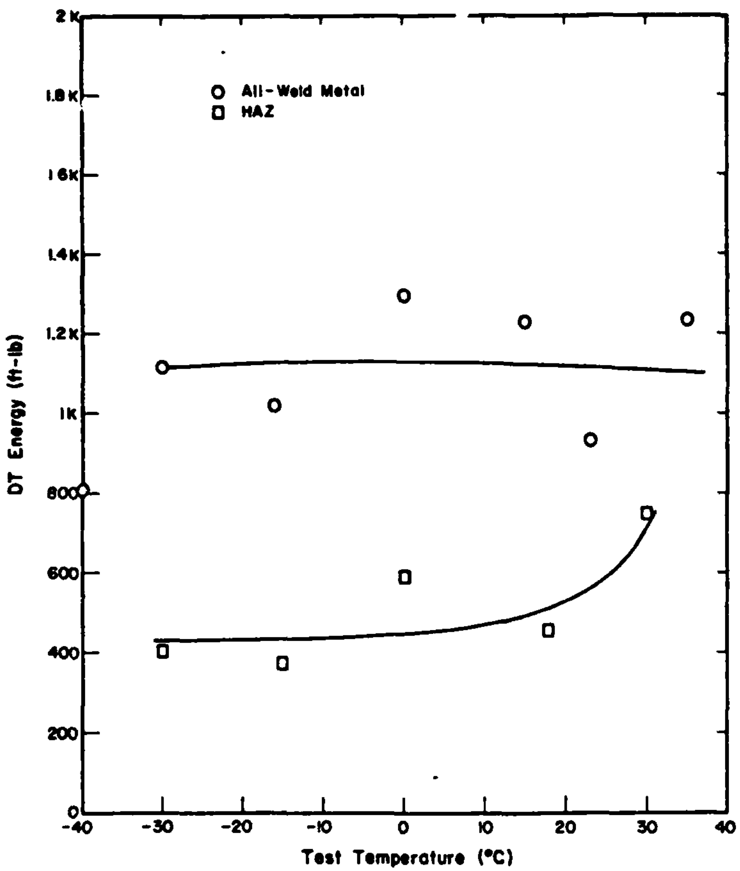


Figure 31. Dynamic tear impact energy vs test temperature for A514 weldment B36 (nugget area: 0.045 sq in. [30 mm^2]).

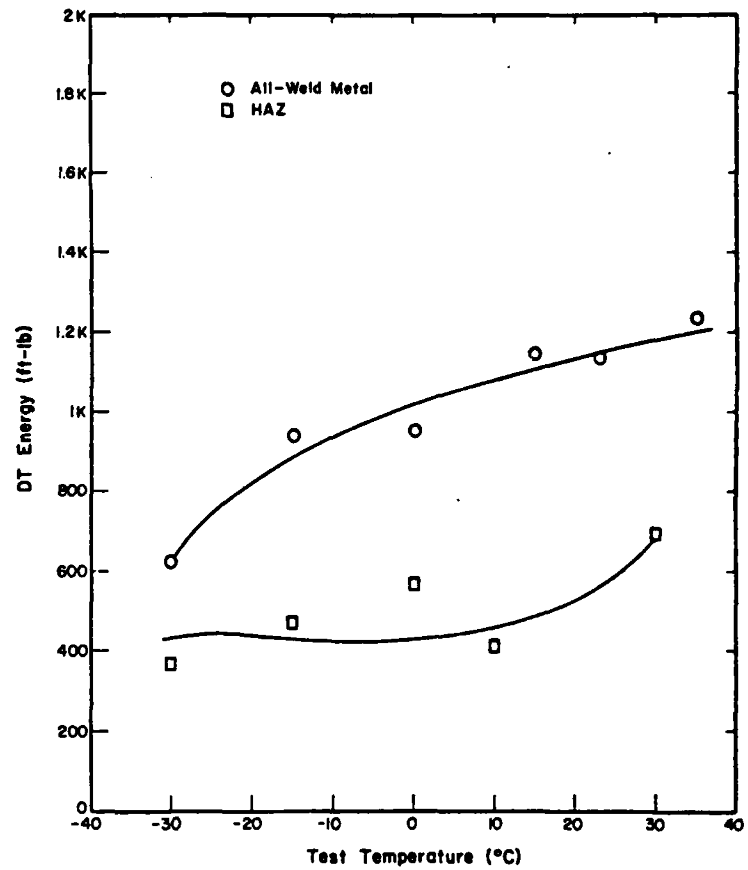


Figure 32. Dynamic tear impact energy vs test temperature for A514 weldment B37 (nugget area: 0.070 sq in. [45 mm^2]).

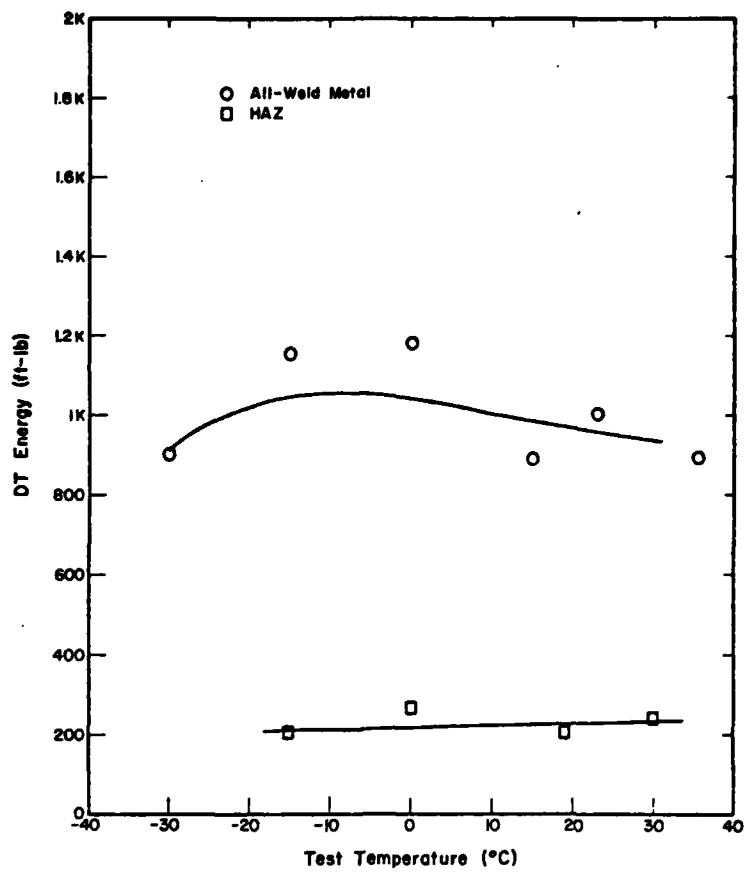


Figure 33. Dynamic tear impact energy vs test temperature for A514 weldment B38 (nugget area: 0.038 sq in. [26 mm^2]).

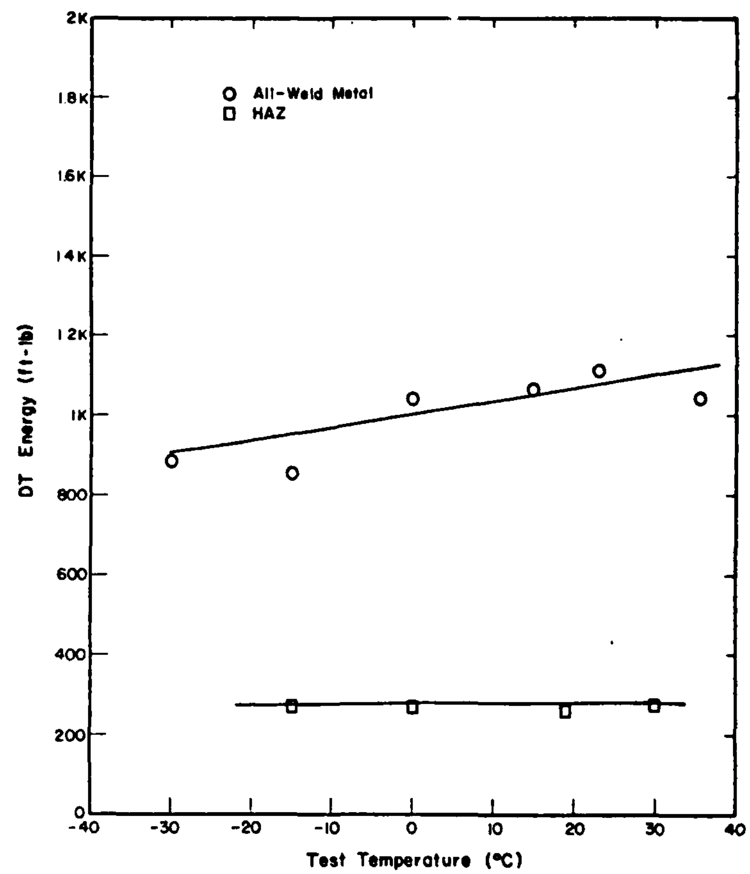


Figure 34. Dynamic tear impact energy vs test temperature for A514 weldment B39 (nugget area: 0.027 sq in. [18 mm^2]).

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