Bead Tempering Effects on FCAW Heat-Affected Zone Hardness

Using base metal chemical composition, weld cooling time, and temper bead placement, an empirical formula was developed to estimate bead tempering effect on the HAZ of carbon manganese steel

BY J. H. KIEFER

ABSTRACT. Hardness limits for welding procedure qualification are often imposed to lessen the chances of delayed hydrogen cracking during production fabrication. Temper bead techniques have been used by fabricators during these qualifications to improve their chances of success. This practice involves using the heat of additional weld beads to soften the heat-affected zone (HAZ) hardness in the base metal next to the weld where the hardness is the greatest. The technique works under controlled conditions, but the consistency for field use was questionable. Experience has shown that bead placement is very difficult to control in the field and in the past there have been few or no limits on the accuracy required for bead placement.

This report describes an investigation of the effect of welding parameters, base metal chemical composition, and weld bead placement on HAZ softening. An empirical formula developed from base plate chemical composition, weld cooling time, and temper bead placement can be used to estimate the amount of HAZ tempering. Combined with an appropriate hardness prediction formula, it can help find the welding procedure needed to achieve a desired maximum HAZ hardness, or predict the HAZ hardness of existing welds. Based on the results of the study, bead tempering is not recommended for HAZ hardness control on large scale fabrications. It is suitable, however, for specialized applications where high as-welded HAZ hardness is a concern and close control over the welding techniques can be maintained.

J. H. KIEFER is a Sr. Welding Engineer with Conoco, Inc., Houston, Tex.

Introduction

Bead tempering is a technique that has been used for many years to reduce the hardness of heat-affected zones (HAZ) for reducing the chances of hydrogen cracking. Hydrogen cracking can occur because of factors with the welding process, or from exposure to hydrogen-producing corrosive environments such as hydrogen sulfide (H_2S). Applications have included pressure vessels, pipeline hot tapping, structural welding, and underwater wet welding. The technique has been used in the pressure vessel industry for field repairs when post-weld heat treatment is impractical. In some pressure vessel applications, incorrectly located temper beads have resulted in higher instances of reheat cracking (Ref. 1). Pipeline hot tapping presents a condition with very high cooling rates. Due to the quenching effect of fluids flowing through the pipeline, this can result in HAZ hardnesses higher than from the original weld (Ref. 2). In underwater wet welding, which has extremely high cooling rates, temper beads have been used to mitigate hydrogen underbead cracking (Ref. 3). Ibarra, *et al.*, suggested that the time interval between placement of the edge bead and temper bead should be minimized to promote hydrogen release (Ref. 4).

KEY WORDS

FCAW
Bead Tempering
HAZ Hardness
Bead Placement
Weld Parameters
Chemical Composition
Cooling Time
Empirical Formula
Separation Distance
Alloy Hardenability

Bead tempering is accomplished by using the heat of a weld bead to soften the microstructure of an adjacent area. It is employed on low heat input welds where base metal HAZs are too hard. Processes such as submerged arc welding (SAW) usually have sufficient heat input that the HAZs are autotempered and do not have high hardness. HAZs contained within weld metal are not as susceptible to high hardness because they are generally lower in carbon content than the base metal on which they are being used. Beads on the surface of a weldment, and located immediately adjacent to the base metal, produce heat-affected zones of the highest hardness. These surface weld beads are described here as edge beads. By placing a subsequent weld pass (temper bead) very close to the edge bead without fusing into the base metal, the local hard spot created by the edge bead can be softened. Figure 1 illustrates a typical temper bead placement. The temper bead must not be so close to the weld interface that it remelts the base material and creates a new hardened HAZ.

Industry standards often include hardness limits that fabricators are required to meet during welding procedure qualification (Refs. 5, 6). Temper bead techniques have been used during qualification to improve the chances of passing the hardness test. Experience has shown

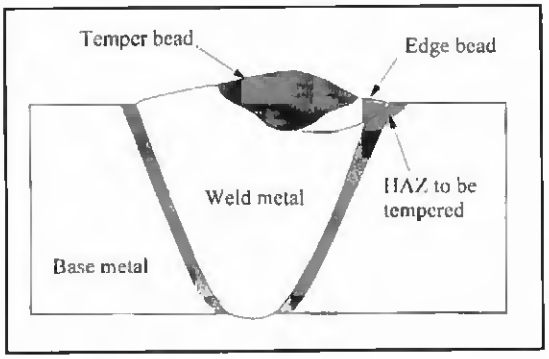

Fig. 1 — Typical temper bead.

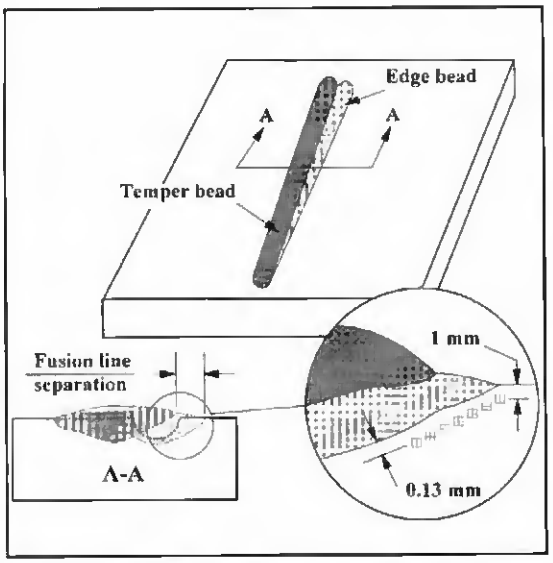

Fig. 2 — Typical bead-on-plate test assembly.

Fig. 3 — Typical macrograph of edge bead and temper bead overlap.

that the technique works if the metallographic sample is taken from the procedure test material where the edge of the temper bead is within 1 to 3 mm (0.04–0.12 in.) from the HAZ to be softened. Using temper beads during procedure qualification has been accepted by Conoco in the past because it was treated as an essential variable. That is, if it is used for qualification, it must be employed on all field welds that use that procedure. Experience has shown that control of the bead placement in the field is very difficult and there have been no specific limits on the tolerance for bead placement. Thus, the effectiveness of using this technique for large scale fabrications was questionable.

The goal of this study was to obtain more quantitative information to access how effective temper bead welding is from a practical standpoint and to determine whether to allow its use for future welding procedure qualification.

Experimental Procedure

Experimental design software RS/1 (BBN Software Products Corp.) was used to define a test matrix for bead-on-plate welds with the gas-shielded flux cored arc process. The main response of interest was the extent of HAZ softening as related to the steel chemical composition, welding conditions and bead placement. Adjustments in four independent variables were made including base plate carbon equivalent, cooling time for the edge bead, cooling time for the temper bead, and the distance from the toe of the temper bead to the toe of the edge bead (toe separation). A minimum of 27 test runs were prescribed with various combinations of these variables in order to obtain sufficient data to develop a predictive response equation.

Three carbon manganese steel plates with carbon equivalents of 0.17, 0.25, and 0.30% based on the Ito Bessyo P_{cm} formula were used. Table 1 shows the chemical compositions. The lower carbon equivalent metal was thermomechanical control process (TMCP) steel and the other two were normalized and tempered. Plate thicknesses were 1 1/4 in. (32 mm), 1 1/2 in. (38 mm), and 2 in. (51 mm) thick, respectively.

Weld beads were deposited with 0.045-in. (1.1-mm) diameter E71T-1 class electrodes. The shielding gas was 75% argon/25% CO_2 at a flow rate of 40 ft^3/h (19 L/min). The initial beads, or edge beads, were deposited in U-grooves so that the bead profile would be only slightly convex. This provided a more uniform surface profile and thus stable welding conditions for the temper bead deposit. The temper bead was then made over the edge bead on a crossing angle of three degrees. This way, microhardness sections could be taken at selected bead separation distances depending on the position along the weld length. This is illustrated in the test plate schematic in Fig. 2. The temper bead was made with an electrode of different chemical composition (E91T1-K2) to help distinguish between the microstructures of the two weld beads. A typical macrograph is shown in Fig. 3.

Since weld cooling times can only be controlled indirectly through the welding parameters and preheat, some preplanning was done to insure that incremental changes in the cooling times, and therefore HAZ hardness, were being achieved. Welding parameters were selected to produce a range of starting HAZ hardnesses in both the low- and high-P_{cm} steel. That is, the thermal cycle range needed to be fast enough to produce hardening differences on the low-P_{cm} steel and slow enough to produce significant hardness differences in the high-P_{cm} material. Welding preheat was set at 40°C (104°F) on all weld beads for simplicity.

Table 1 — Base Metal Chemical Composition

	A537 C11	API 2H 50	API 2W 50
C	0.19	0.16	0.08
Mn	1.46	1.24	1.45
Si	0.46	0.31	0.34
P	0.014	0.011	0.01
S	0.005	0.001	0.003
Cr	0.23	0.19	0.02
Mo	0.06	0.05	0.00
Cu	0.13	0.01	0.01
Ni	0.18	0.14	0.01
V	0.004	0.003	0.005
B	—	—	0.0001
Nb	0.003	0.028	0.021
Al	0.077	0.021	0.026
Ti	—	—	0.017
N	—	—	0.003
P_{cm}	0.30	0.25	0.17
CE_{IIW}	0.51	0.43	0.33

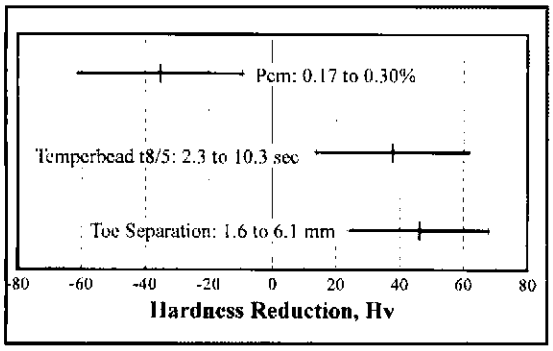

Fig. 4 — Main effects of independent variables.

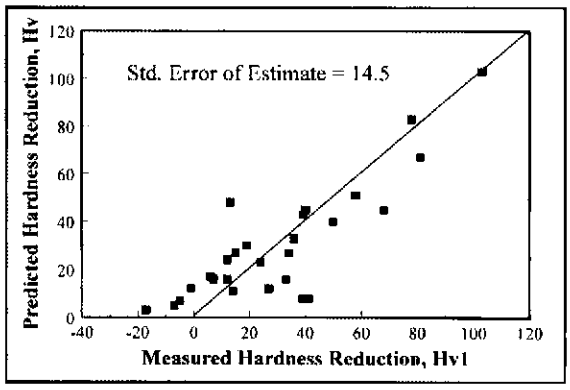

Fig. 5 — Prediction characteristics of Equation 3.

The $t_{8/5}$ (800°–500°C) cooling times were calculated with the formula given in Equation 1 for bead-on-plate conditions for thick metal (Ref. 7). Predictions of the maximum HAZ hardness were made using Suzuki's BL70S formula shown in Equation 2 (Ref. 8). Suzuki's equation was selected out of the many equations available because it uses a relatively well-known carbon equivalent equation (P_{cm}) and was confirmed in separate tests by the author to give good predictability. By substituting $t_{8/5}$ of Equation 1 into Equation 2, the HAZ hardness can be predicted from the metal chemical composition and welding parameters. Table 2 shows the welding parameters that were established for the test and the predicted cooling times and HAZ hardnesses.

$$t_{8/5} = \mu \frac{A^{(1.24+0.0005P-0.0055S)} V^{0.59}}{108S^{(0.78-0.0005P)}} \quad (1)$$

Where: $t_{8/5}$ = 800°–500°C cooling time (s); μ = arc efficiency (0.79 for gas-shielded FCAW); A = current (amperes); S = travel speed (in./min); V = arc voltage; P = preheat (°C).

$$H_{max} = 884C + 287 - K + \frac{K}{\left[1 + e^{a(\log t_{8/5} - Y_5)}\right]} \quad (2)$$

Where: H_{max} = maximum HAZ hardness (HV); C = carbon (wt-%); K = 237 + 1633C – 1157 P_{cm}; aK = 566 + 5532 C – 2280 P_{cm}; Y_5 = 0.30 – 6.0C + 7.77 P_{cm}; P_{cm}(%) = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B.

Table 2 — Preliminary Hardness Predictions

Base Material P_{cm}, %	$t_{8/5}$ cooling time A 2.5 s	B 6.3 s	C 9.9 s
0.17	327 HV	274	245
0.25	410	357	315
0.30	450	424	392

Welding parameters for A, B, and C.
A—150A, 23V, 350mm/min, 40°C preheat
B—185A, 25V, 190mm/min, 40°C preheat
C—220A, 26V, 150mm/min, 40°C preheat

The same welding parameters were used for both the edge bead and temper bead. A CRC Arc Data Monitor was used to record the actual values during each test run. Since the edge bead was made in a groove, the cooling times predicted by Equation 1 will be longer than actual. This was confirmed by plunging tungsten-tungsten/rhenium thermocouples into three edge beads to compare the cooling times in the grooves for each heat input condition. A digital data acquisition system was used to collect the thermocouple data. Based on the measured results, a 20% reduction to the edge bead cooling time predictions was made so that the data analysis would more accurately represent the true values.

Seven Vickers hardness measurements were made with a 1-kg load. They were taken in the HAZ of the edge bead on each test specimen. Hardness indents started 1 mm (0.04 in.) from the plate surface, were located 0.13 mm (0.005 in.) from the weld interface, and spaced at 0.25 mm (0.01 in.). Hardness reductions were determined by subtracting the tempered hardness from original hardness for each test run. Since it is impossible to find the true original hardness at each location of interest, the untempered hardness was established at an alternate position along the length of the weld where the toe separation was greater than 10 mm (0.4 in.). Cross-sections were at least 100 mm (4 in.) from the ends of the beads to avoid higher end effect cooling rates. The test results will show 10 mm is sufficient toe separation to avoid tempering effects. The same maximum hardness was used for the untempered value on all edge bead samples of like chemical compositions and weld cooling time.

Results and Discussion

Experimental test conditions and results for each test run are given in Table 3. The 800°–500°C cooling times are calculated based on the recorded welding parameters. Maximum HAZ hardness values are given for both original and tempered HAZs. The reduction in hardness from tempering is based on the difference between maximum original HAZ hardness value and the tempered value at each different toe separation. Some results computed a negative hardness reduction. These are believed to be caused by variability in the hardness test.

The statistical analysis feature of RS/1 was used to show the main effects and any interactions that each variable had on the HAZ hardness reduction. Although the cooling time of the edge bead influences the starting HAZ hardness, it did not affect the amount of hardness reduction, nor did it have any interaction effects with the other variables. Figure 4 shows the amount of hardness reduction expected if each of the remaining three parameters is varied independently through the range noted next to the bar. The width of the bar represents a 95% confidence interval.

RS/1 automatically computes a polynomial expression retaining only the equation components that have statistical significance. Polynomials can be cumbersome to use and are unsuitable for any predictions outside the experimental envelope. A power law formula (Equation 3) was developed that includes terms for the three influencing variables shown to be significant by the original polynomial equation. Therefore, an interaction effect was obtained between the cooling time of the temper bead and toe separation. This is represented by the toe separation term in the exponent of the $t_{8/5}$ parameter.

$$\Delta H_{max} = \frac{1108 P_{cm}^{1.28} t_{8/5}^{(1.17-0.055d)}}{d^{0.65}} \quad (3)$$

Where: ΔH_{max} = hardness reduction (HV); P_{cm} = base material carbon equiva-

Table 3 — Test Conditions and Results

		Welding Parameters									Maximum HAZ Hardness		
		Edge Bead				Temper Bead							
Run No.	P_{cm} (%)	A	V	Travel (mm/s)	Calc. $t_{8/5}$[a] (s)	A	V	Travel (mm/s)	Calc. $t_{8/5}$ (s)	Toe Separation (mm)	Original HAZ (HV)	Tempered HAZ (HV)	Hardness Difference (HV)
1	0.30	144	23	35	1.9	182	25	20	5.9	3.7	445	387	58
2	0.30	188	25	20	5.0	224	26	16	9.7	4.4	459	378	81
3	0.30	189	25	20	5.0	183	25	20	5.9	1.7	459	356	103
4	0.30	186	25	20	4.9	180	25	20	5.8	5.5	459	423	36
5	0.30	190	25	20	5.0	153	23	35	2.6	3.7	459	435	24
6	0.30	224	26	16	7.8	186	25	20	5.9	3.9	422	409	13
7	0.25	149	23	35	2.0	222	26	16	9.5	3.6	416	376	40
8	0.25	150	23	35	2.0	150	23	35	2.5	3.8	416	417	−1
9	0.25	151	23	35	2.0	185	25	20	6.0	5.9	416	410	6
10	0.25	150	23	35	2.0	187	25	20	6.0	2.3	416	348	68
11	0.25	182	25	20	4.7	188	25	20	6.1	4.4	413	401	12
12	0.25	180	25	20	4.6	228	26	15	10.3	5.9	413	398	15
13	0.25	180	25	20	4.7	228	26	15	10.1	2.1	413	335	78
14	0.25	186	25	21	4.8	146	23	36	2.3	2.4	413	401	12
15	0.25	189	25	20	4.9	189	25	20	6.3	3.6	413	394	19
16	0.25	189	25	20	4.9	147	23	33	2.6	5.7	413	372	41
17	0.25	189	25	20	4.9	181	25	20	5.8	3.7	413	379	34
18	0.25	218	26	16	7.5	187	25	20	6.0	6.1	371	338	33
19	0.25	222	26	16	7.7	214	26	15	9.3	4.0	371	321	50
20	0.25	226	26	16	7.7	150	23	35	2.5	3.9	371	344	27
21	0.25	221	26	16	7.6	186	25	20	6.0	2.4	371	332	39
22	0.17	154	23	35	2.1	186	25	20	6.0	3.5	331	292	39
23	0.17	189	25	20	5.0	221	26	15	9.7	4.3	268	254	14
24	0.17	196	25	20	5.3	186	25	21	5.8	1.6	268	261	7
25	0.17	192	25	20	5.1	184	25	21	5.8	5.8	268	275	−7
26	0.17	196	25	19	5.5	147	23	35	2.4	3.7	268	285	−17
27	0.17	229	26	16	8.1	182	25	21	5.6	4.0	258	263	−5

(a) Edge bead 800°–500°C cooling time based on Equation 1 with 20% reduction to correct for effect of welding in a groove vs. bead-on-plate.

lent (%); $t_{8/5}$ = temper bead cooling time (s); d = toe separation (mm).

The formula is useful for finding the welding procedure needed to achieve a desired HAZ hardness reduction. Predictions of the maximum untempered HAZ hardness of existing welds can be obtained from the welding procedure and Equations 1 and 2. Figure 5 shows the prediction characteristics of Equation 3 compared to the measured hardness reductions. The predictions are based on the actual welding conditions measured for each test run.

To better visualize the influence of each variable, three-dimensional plots of Equation 3 were made. Figure 6 shows the predicted hardness reductions for a range of cooling times and toe separations. This graph is based on a P_{cm} carbon equivalent of 0.24%. Hardness reductions less than 25 HV are considered insignificant mainly because this is near the typical level of scatter in the data. A contour line was, therefore, plotted at 25 HV and the graph base shaded for 25 HV and less. By inspecting this lower boundary, some observations can be made about when temper bead techniques become effective. At 2-mm (0.08-in.) toe separations, the temper bead cooling time greatly affected hardness reduction. Based on examination of the temper bead HAZ width, this is dangerously close to re-austenitizing and forming new martensite at the edge bead HAZ. At toe separations greater than 5 or 6 mm, there was virtually no tempering effect even at the highest cooling time tested. Studies by Olsen, *et al.*, (Ref. 9) also found that too short a distance to the base plate leads to re-austenitizing, and too long a distance gives insufficient tempering.

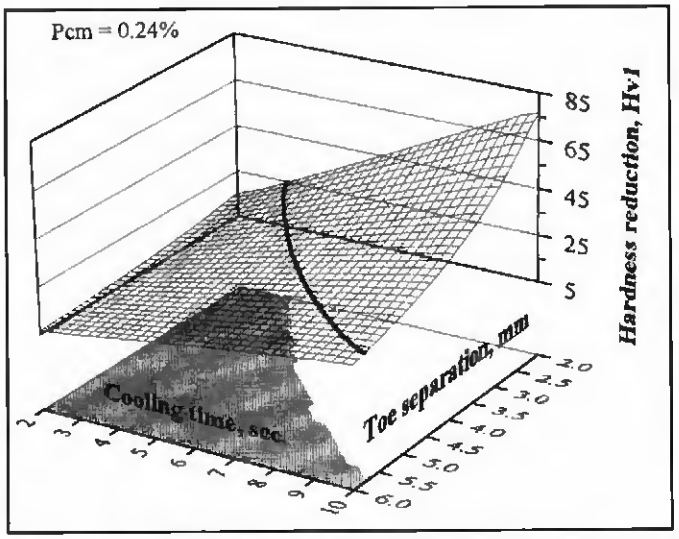

Fig. 6 — Three-dimensional plot of hardness reduction vs. temper bead cooling time and toe separation for P_{cm} carbon equivalent = 0.24%.

Capping passes made with downhill progression is a technique often used to obtain smooth weld profiles in offshore platform construction. These produce 800°–500°C cooling times of approximately 3 to 5 s, depending on the welding process and level of preheat used. At 4 s cooling time, tempering becomes effective only at the closest of toe separations. These data show that the close control needed for effective and consistent bead tempering is beyond the practical limit for downhill capping passes. Uphill capping does not produce as smooth a weld profile, but the increased heat input from the slower travel speed helps avoid the high initial HAZ hardness.

Figure 7 is a similar three-dimensional plot showing the relationship between

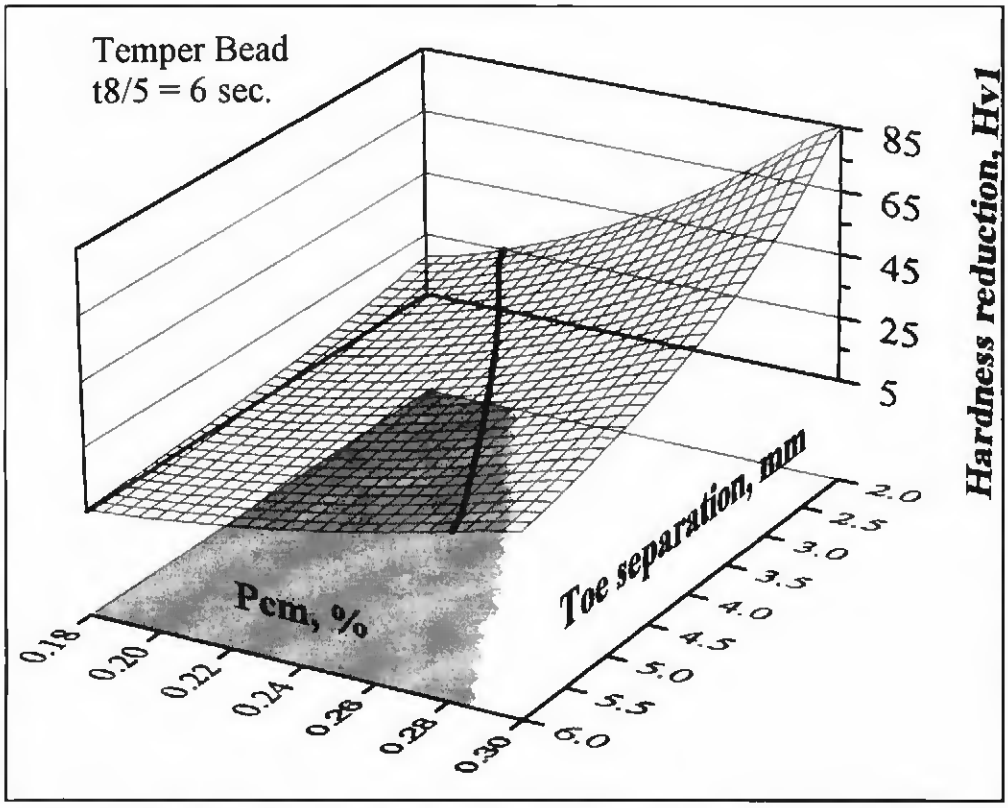

Fig. 7 — Three-dimensional plot of hardness reduction vs. P_{cm} and toe separation for $t_{8/5}$ cooling time = 6 s.

P_{cm} and toe separation. This graph is for a nominal temper bead cooling time of six seconds. It shows, as expected, that lower carbon equivalent steel is more difficult to temper (conversely less hardenable). The initial hardness, however, is lower. If HAZ hardness reductions are still needed, this could be accomplished with the application of higher preheat.

Conclusions and Recommendations

An empirical formula developed from base plate chemical composition, weld cooling time, and temper bead placement can be used to estimate the amount of HAZ tempering. Combined with an appropriate hardness prediction formula, it can help find the welding procedure needed to achieve a specified maximum HAZ hardness, or estimate the HAZ hardness of existing welds. For this technique to be effective, however, close control over weld bead spacing is critical. It is, therefore, only recommended for applications where such control is practical and economical. The following are some specific conclusions drawn from the results of this study:

1) Bead tempering capability decreased with decreasing base metal carbon equivalent.

2) The cooling time of the first pass that affects starting HAZ hardness did not affect the amount of hardness reduction achievable through tempering.

3) Temper bead cooling times (800°–500°C) less than 5 or 6 s are generally ineffective.

4) The edge of the temper bead pass should be place within 2 to 5 mm (0.08–0.20 in.) of the edge of the HAZ to be tempered.

5) Bead tempering under close control can be a feasible method for reducing the heat-affected zone hardness in weldments. It is not, however, recommended for HAZ hardness control on large scale fabrications.

Acknowledgments

The author gratefully acknowledges the Conoco management for its support and permission to publish this work, and the laboratory assistance of George Stuever.

References

1. Guembe, P. V. 1979. Comments on reheat cracking. *Trends in Reactor Pressure Vessel and Circuit Development, Proceedings.* Applied Science Publ., Madrid, pp. 127–139.

2. Bruce, W. A., and Threadgill, P. L. 1991. Welding onto in-service pipelines. *Welding Design & Fabrication*, pp. 423–459.

3. Ibarra, S., Reed, R. L., and Smith, J. K. 1990. Underwater wet-welding techniques for repair of higher-carbon-equivalent steels. *Offshore Technology Conference, Conf. Proc.*, OTC 6214, pp. 135–142.

4. Ibarra, S., Reed, R. L., and Smith, J. K. 1991. The structural repair of a North Sea platform using underwater wet welding techniques. *Offshore Technology Conference, Conf. Proc.*, OTC 6652, pp. 57–166.

5. American Petroleum Institute. 1993. *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms Working Stress Design*, API RP 2A-WSD, 20th Edition, Washington, D.C.

6. NACE International. *Sulfide Stress Cracking Resistant Metallic Materials for Oilfield Equipment*, MR0175-94, Houston, TX.

7. Kiefer, J. H. 1990. Effects of welding parameters on FCAW HAZ cooling. *The Metallurgy, Welding, and Qualification of Microalloyed (HSLA) Steel Weldments, Conf. Proc.*, pp. 780–799.

8. Suzuki, H. 1985. A new formula for estimating HAZ maximum hardness in welded steel. Trans. JWS, Vol. 16, No. 2, pp. 25 – 32, October.

9. Olsen, K., Olson, D. L., and Christensen, N. 1982. Weld bead tempering of the heat-affected zone. *Scandinavian Journal of Metallurgy* 11: 163–168.