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Estimating Welding Preheat Requirements for Unknown Grades of Carbon and Low-Alloy Steels

Preheat and interpass temperatures were determined by using HAZ hardness measurements and the estimated martensite transformation temperature

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ABSTRACT. When the steel grade or composition is unknown, the measurement of oxygen-cut surface maximum heat-affected zone (HAZ) hardness can be an aid in developing or confirming reliable welding procedures. If the chemical analysis of a carbon or low-alloy steel is not available or is not practical to obtain, weld repair or new fabrication welding of a component made of an unknown grade of steel in the field or in the shop is hazardous. A sequence of field or shop oxygen-cut surface hardness measurements is recommended to help ensure the success of this type of weld repair or fabrication. These procedures are for multibead weldments of cast and wrought steel components more than 25 mm (1 in.) in thickness but do not take into account weld joint complexity or hydrogen relief. The development of minimum preheat temperatures and maximum interpass temperatures was demonstrated by a Welder Training & Testing institute (WTTI) test of the maximum oxygen-cut surface heat-affected zone (HAZ) hardness of three unknown grades of steels.

Introduction

Although the weld applications of the enclosed methods presented and discussed can be applied to new carbon and low-alloy steel fabrications, these methods are usually applied to weld-repair applications and broken components provided that these are not components that require code weldments. In general, the higher the carbon and alloy contents of carbon and low-alloy steels, the higher the preheat temperatures required (Ref.1). However, when the combined carbon and low-alloy contents are relatively high (5% maximum total content) for steels, the nearly complete (90%) martensite transformation temperature for that steel can be below the preheat temperature and subsequent interpass temperatures. If the preheat and interpass temperatures are high relative to a low 90% martensite transformation temperature for that steel, substantial retained austenite in the HAZ can occur. When the weldment cools, retained austenite can transform to martensite to produce high residual tensile stresses and an increased probability of delayed cracking. For example, the measured as-quenched hardness of steel, the reported 90% martensite transformation temperature (M_{90}), and the calculated carbon equivalent (CE) listed in Tables 1 and 2 were taken from actual data reported in Ref. 2. The grades of steels listed in Tables 1 and 2 show that higher low-alloy composition content and higher carbon content (higher CE) result in higher as-quenched hardness and a lower M_{90} temperature. Steel grades listed in Tables 1 and 2 that are difficult to weld include AISI 4340, 1050, 6150, 8660, and 4360.

KEYWORDS

Carbon Equivalent
Carbon Steel
Hardness Equivalent
HAZ
Low-Alloy Steel
Martensite Transformation
Unknown Steel Grades

More accurate welding procedures for unknown steel grades can be developed by oxygen cutting the unknown steel at ambient or room temperature using standard through-thickness oxygen-cutting settings, by removal of the oxide scale from the oxygen cut surface and by making a small or shallow hardness measurement on the steel to obtain the maximum hardness of the oxygen-cut surface. Note that large indentation hardness measurements, such as a 10-mm-diameter Brinell impression, are not recommended because the maximum hardness of an oxygen-cut surface is just below the thin (usually 0.004-in.-deep) decarburized layer below the oxygen-cut oxide scale. This method is not presented to replace welding procedures that take into account steel joint size and complexity or hydrogen relief where the steel grade, certified composition, or check composition of the steel is available. For example, weld repair of a critical component that has failed in service and cannot be immediately replaced with a spare component could rely on an ambient oxygen-cut and maximum surface hardness determination of potential repair weldability. When the steel grade or composition is unknown, the determination of oxygen-cut surface maximum HAZ hardness can be an aid in developing or confirming reliable welding procedures. These procedures do not apply to code-welded steel applications where code-related weld repairs are required. For examples of code welding requirements, see Refs. 3–7.

Experimental Procedures

In order to demonstrate the method of obtaining hardness equivalent (HE) weld-

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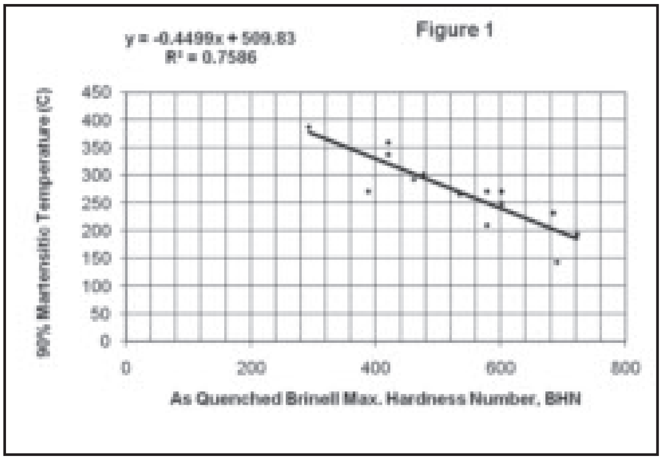

Fig. 1 — Line graph from least-squared fit of 90% martensite transformation temperatures vs. Jominy bar as-end-quenched Brinell hardness. (Table 1).

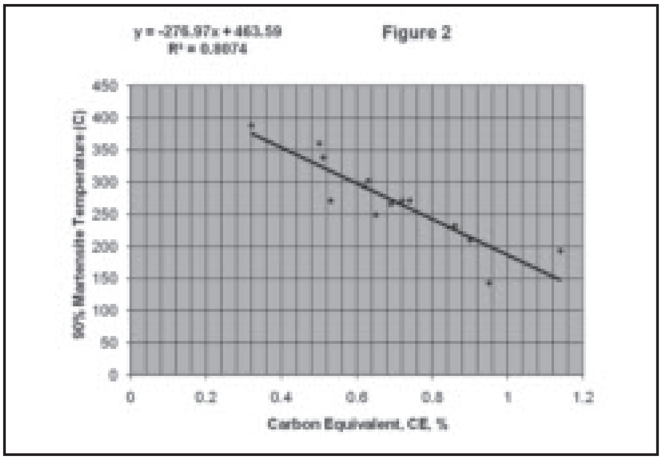

Fig. 2 — Line graph from least squared-fit of 90% martensite transformation temperatures vs. carbon equivalents (CE) (Tables 1 and 2).

ing procedures proposed herein, three grades of steel billets saw cut to 1-in. lengths. Accurate checks of chemical compositions of these three billets are listed in Table 3. The hot-rolled AMS 6414 (modified AISI 4340) steel billet had 4 1⁄2-in. square cross sections. The as-cast ASTM A36 and ASTM 616 Grade 60 billets had 5-in. square cross sections. These billet samples were "cold-stamp" identified as A, B, and C and sent to the Welder Training & Testing Institute (WTTI) as unknown steel samples.

A welding instructor, with student observers, oxygen-cut one sample from each of the three grades of steel at ambient temperature to produce two half pieces of smooth 1-in.-thick steel. The oxygen-cut oxide scale on the surface was lightly ground away. The oxygen-cut half-sample with a parallel uncut surface was placed in a Rockwell hardness tester. Rockwell A hardness was measured using a 60-kg load with a diamond Brale indenter to produce shallow, small hardness indentations on the oxygen-cut surface.

After a number of shallow, small indentation hardness measurements were made on the first surface, other shallow (0.004-in.-deep) grinds were made with a flat grinder and additional hardness measurements were made and tabulated. These hardness results were correlated between the maximum oxygen-cut HAZ hardness converted to Brinell hardness (Ref. 8) and the chemical carbon equiva-

Table 1 — Welding Preheat Parameters Estimated from End-Quenched Maximum Hardness

AISI Grade(a)	Measured(b) Maximum (As quenched) Hardness BHN	Reported(c) 90% (M_{90}) Martensite Temperature °C (°F)	Composition(d) Carbon Equivalent CE	End Quenched(e) Hardness Equivalent HEQ	Estimated(f) 90% (M_{90}) Martensite Temperature °C (°F)	HEQ Preheat(g) Temperature °C (°F)
1019	293	388 (730)	0.32	0.36	378 (712)	(h)
USST-1	363	—	0.59	0.46	347 (660)	(h)
4317	388	271 (520)	0.53	0.50	335 (635)	127 (261)
8620	420	360 (680)	0.50	0.54	321 (610)	156 (313)
4130	477	302 (575)	0.63	0.63	295 (563)	206 (403)
1320	420	338 (640)	0.51	0.54	321 (610)	156 (313)
8630	461	293 (560)	0.62	0.60	303 (548)	191 (344)
1340	534	266 (510)	0.69	0.71	270 (518)	242 (468)
4140	578	271 (520)	0.74	0.77	250 (482)	266 (511)
5140	601	271 (520)	0.72	0.81	240 (464)	281 (538)
4340	578	210 (410)	0.90	0.77	250 (482)	266 (511)
1050	601	249 (480)	0.65	0.81	240 (464)	281 (538)
6150	684	232 (450)	0.86	0.93	202 (396)	321 (610)
8660	690	143 (290)	0.95	0.94	200 (392)	324 (616)
4360	722	193 (380)	1.14	0.98	185 (365)	337 (638)

(a, b, c) Reported compositions for carbon equivalents, maximum water-quenched end of bar hardness and 90% complete martensite transformation temperatures were taken from Ref. 2. Steel compositions from Ref. 2 are listed in Table 2.
(d) CE = C+ (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15. Compositions from Ref. 2.
(e) CE = (end-quenched maximum BHN hardness equivalent) HEQ = (BHN-44)/667.
(f) M_{90} = 510°C - 0.45 (maxium as-end-quenched BHN).
(g) Minimum preheat temperature (PH) = 450°C $\sqrt{(HEQ–0.42)}$ From Ref. 2 data.
(h) No metallurgical preheat was necessary to retard the HAZ cooling rate because the HEQ was below 0.47. A surface heat to 200°F to remove surface moisture is recommended.

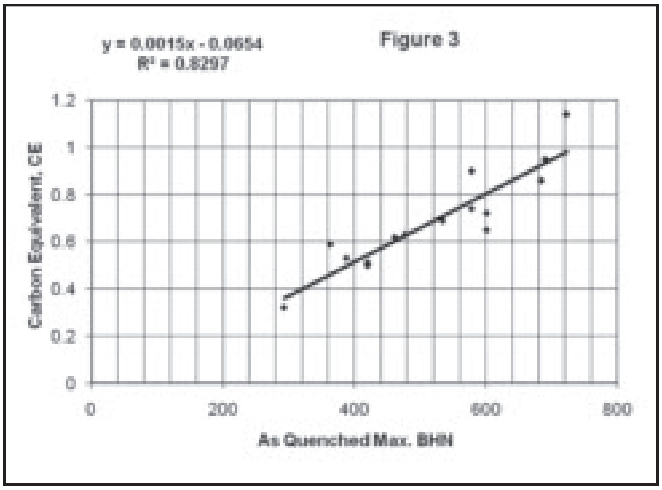

Fig. 3 — Line graph from least-squared fit of carbon equivalents and Jominy bar as-end-quenched Brinell hardnesses (Tables 1 and 2).

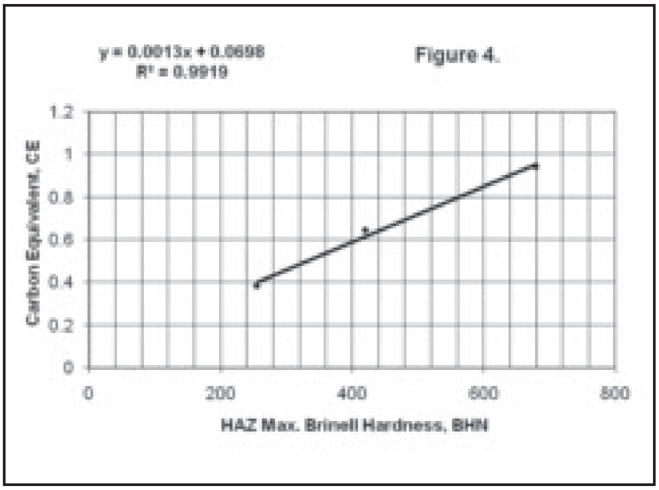

Fig. 4 — Line graph from least-squared fit of carbon equivalents (CE) and maximum oxygen-cut HAZ Brinell hardnesses (Table 4).

lent for each grade.

The same WTTI welding instructor welded the three steel grades that were V-grooved from 1-in.-thick samples using the welding procedures, including interpass and preheat temperatures, from the correlation of maximum oxygen-cut HAZ hardnesses and carbon equivalents. The maximum interpass temperature from the maximum oxygen-cut HAZ hardness was determined from the correlation of Jominy bar as-quenched hardness and 90% martensite completion temperature (Table 1).

The basis for the correlation between maximum oxygen-cut HAZ hardness and an estimate of weldability of the flame-cut steel with sufficient steel mass for cooling on either side of the oxygen-cut is the similarity of the weld/base metal HAZ of this same steel. A normal, smooth, oxygen-cut through-thickness that progresses without hesitation will produce a large prior austenite grain size near the melted surface, will dissolve most of the carbides in this hot zone, and upon rapid cooling as the oxygen-cut goes further will transform this hot zone to martensite. Cooling transformation diagrams for a variety of steels are shown in Ref. 9. Similar HAZ behavior of base steel occurs when heated to a near-melting temperature near the molten weld metal except a lower cooling rate and lower HAZ hardness occurs when the base steel is preheated prior to welding or during multiple temper-bead welding.

Results

Steel Composition and Preheat for Welding

In general, the higher the carbon content in a steel, the more difficult the steel is to weld, especially at ambient temperatures because of HAZ cooling rates. For example, AISI 1020 (0.20% carbon content) welds can be welded without preheat except to dry the surface of moisture with a surface preheat of 200°F. In contrast, AISI 1050 (0.50% carbon content) steel is difficult to weld and requires a relatively high preheat temperature throughout the base steel to reduce the cooling rate and potential hardness in the HAZ of the base metal. A high preheat temperature reduces the hardness of the HAZ by reducing the cooling rate and the amount of hard martensite in the HAZ. The as-water-quenched maximum hardness (Ref. 2) of various grades of steel subjected to a Jominy bar end quench is listed in Table 1. In general, the Jominy bar as-water-quenched maximum hardness is higher than the oxygen-cut surface maximum hardness of the same steel. The longer

Table 2 — Chemical Compositions of Steels

AISI Grade[(a)]	C	Mn	Ni	Cr	Cu	Mo	V	CE[(b)]
1019	0.17	0.92	— [(c)]	—	—	—	—	0.32
USS T1	0.15	0.92	088	0.50	0.32	0.46	0.06	0.59
4317	0.17	0.57	1.87	0.45	—	0.24	—	0.53
8620	0.18	0.79	0.52	0.56	—	0.19	—	0.50
4130	0.33	0.53	—	0.90	—	0.18	—	0.63
1320	0.20	1.88	—	—	—	—	—	0.51
8630	0.30	0.80	0.54	055	—	0.21	—	0.62
1340	0.43	1.58	—	—	—	—	—	0.69
4140	0.37	0.77	—	0.98	—	0.21	—	0.74
5140	0.42	0.68	—	0.93	—	—	—	0.72
4340	0.42	0.78	1.79	0.80	—	0.33[(d)]	—	0.90
1050	0.50	0.91	—	—	—	—	—	0.65
6150	0.53	0.67	—	0.93	—	—	0.18	0.86
8660	0.59	0.89	0.53	0.64	—	0.22	—	0.95
4360	0.62	0.64	1.79	0.60	—	0.32[(d)]	—	1.14

(a) Compositions reported in Ref. 2 in percent by weight. Silicon contents were not reported except for 4360 (0.67 Si modified).
(b) CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 in percent by weight.
(c) — Element not reported in Ref. 2.
(d) Element concentration is higher than maximum specified for AISI grade.

Table 3 — Check Compositions and Carbon Equivalents (CE) of Steels A, B, and C Studied in This Investigation

Steel ID	Steel Grade	C	Si	Mn	Ni	Cr	Mo	V	Cu	CE[(a)]
A	AMS 6414 (AISI 4340[(b)])	0.41	0.27	0.72	1.82	0.85	0.25	0.09	0.12	0.942
B	ASTM A36	0.15	0.33	0.64	0.11	0.13	0.05	—	0.43	0.384
C	ASTM A616 Grade 60[(c)]	0.36	0.25	1.08	0.09	0.12	0.03	0.02	0.35	0.645

(a) Carbon equivalent (CE) = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15.
(b) Modified.
(c) Concrete reinforcing bar specification.

Table 4 — Carbon Equivalents (CE) and Flame-Cut Surface Heat-Affected Zone Maximum Hardnesses of Steels A, B, and C

Steel	Carbon Equivalent (CE)	Max. HRA HAZ Hardness, (BHN)[(a)]
A	0.942	82.0 (679)
B	0.384	62.9 (255)
C	0.645	73.0 (420)

(a) Conversion to Brinell hardness (BHN) from measured Rockwell A (HRA) hardness on the HAZ surface (Ref. 8).

time that the Jominy bar is held in the furnace prior to the water end-quench procedure increases hardenability and maximum hardness by producing larger prior austenite grain size, more complete solid solution of carbides, and a higher cooling rate than those conditions and parameters in an oxygen-cut HAZ.

Steel Composition and Carbon Equivalent

In addition to higher carbon in steel producing higher as-quenched hardness and higher HAZ hardness, other alloying elements in steel, such as, manganese, nickel, chromium, molybdenum, vanadium, and copper produce higher hardness at lower cooling rates in the HAZ shown by all the Jominy bar hardenability and maximum hardness results presented in Ref. 2. Cooling transformation diagrams for a range of carbon steels and low-alloy steels shown in Ref. 9 demonstrate steel's hardenability by showing the lowest cooling rate for a particular grade of steel to transform to martensite. In contrast to the wide range in hardenability, the thermal conductivity of carbon and low-alloy steels that relate to heating and cooling (oxygen cutting) parameters is similar within a narrow range of thermal conductivity. Therefore, higher preheats for welding to promote lower cooling rates and lower hardness in the HAZ are needed for low-alloy steels with medium carbon contents (0.3 to 0.4% carbon), such as SAE or AISI 4130, 4340, and 8630 steels.

Steel's weldability is represented by the carbon content and alloy elements that are combined as a carbon equivalent (CE) in wt-% in Refs. 3 and 4 as follows:

$$\begin{aligned} CE &= C + (Mn + Si)/6 \\ &+ (Cr + Mo + V)/5 + (Ni + Cu)/15 \end{aligned}$$

Carbon Equivalent and Preheat Temperatures

Preheat temperature recommendations for various grades of carbon and low-alloy steel that include joint size, complexity, and hydrogen relief are published in numerous welding codes (Refs. 3–7). Note that if weld repair is to be made on a code-welded component, other strict code welding procedures are required for weld repair, and the following estimates do not apply. Empirical estimates (Ref. 10) of a minimum preheat temperature (PH) for values of CE between 0.47 and 1.0 for a 1-in.-thick weldment are

$$\begin{aligned} PH &= 450^\circ C \sqrt{CE - 0.42} \\ &= 850^\circ F \sqrt{CE - 0.42} + 32^\circ F \end{aligned}$$

The Fahrenheit to Celsius temperature conversion of °F = (°C) 9/5 + 32°F is used.

The CE value of 1.0 is a practical limit for welding low-alloy steels with less than 5% cumulative carbon and alloy contents. This preheat estimate must be adjusted for weldment size and weld joint complexity, i.e., a thicker V-joint or more complex weldment geometry may require a higher preheat.

Martensite Transformation and Preheat Temperatures

Carbon and low-alloy steels with high carbon equivalent (CE) values, high maximum as-quenched hardness, and high HAZ hardness also have relatively low 90% martensite transformation temperatures as listed for comparison in Table 1. The preheat and interpass temperatures should not be above the 90% martensite (M_{90}) transformation temperature of the base steel because in completed large weldments the additional martensite transformation from retained austenite can take place during cooling to increase shrinkage from final welding and promote HAZ or weldment cracking.

A good least-squared straight line (method of determining the best representation) fit of the martensite (M_{90}) transformation temperature vs. the as-quenched maximum Brinell hardness (Max EQ BHN) listed in Table 1 from Ref. 2 is shown in Fig. 1, and the relationship is listed below

$$\begin{aligned} M_{90} &= 510^\circ C - 0.45 \text{ Max EQ BHN} \\ M_{90} &= 950^\circ F - 0.81 \text{ Max EQ BHN} \end{aligned}$$

Major chemical compositions of the steels tested and reported in Ref. 2 are listed in Table 2 and the composition carbon equivalents (CE) are listed in Tables 1 and 2. When the M_{90} vs. the composition CE data points for that steel is plotted in Fig. 2, a least-squared straight-line fit results in a good correlation

$$\begin{aligned} M_{90} &= 464^\circ C - 277 \text{ CE} \\ M_{90} &= 867^\circ F - 499 \text{ CE} \end{aligned}$$

Comparison of Carbon Equivalent and End-Quenched Hardness

When the carbon equivalents (Table 1) estimated from Ref. 2 compositions are plotted vs. the as-water-quenched maximum hardnesses reported in Ref. 2 (Table 1), the good least-squared straight-line fit correlation shown in Fig. 3 resulted in the following relationship:

$$CE = HEQ = (\text{Max EQ BHN} - 44)/667$$

Carbon Equivalent and Maximum Oxygen-Cut Surface HAZ Hardness

In order to validate the proposed methodology, three unidentified steel samples were submitted for oxygen-cutting and maximum surface HAZ BHN hardness determinations. This was part of a blind test for the proper welding of these steels based upon the measured maximum oxygen-cut surface HAZ hardness. The certified chemical compositions and CE of these three steels are listed in Table 3. The maximum oxygen-cut surface HAZ hardnesses determined are listed in Table 4. When the CE from Table 3 is plotted (Fig. 4) vs. the maximum HAZ hardnesses for each steel listed in Table 4, the good ,least-squared straight-line fit is as follows:

$$CE = HE = (HAZ\ BHN + 54)/ 769$$

Note that the maximum oxygen-cut surface HAZ hardness is less than the as-water end-quenched (Jominy test) maximum hardness reported in Ref. 2 for similar grades of steel.

Table 5 — Maximum Hardness of Base Steel Heat-Affected Zone (HAZ) Next to Fusion Line

Steel	Maximum HAZ Hardness, DPH[(a)] (BHN) Next to Weld
A	321 (304)
B	222 (212)
C	242 (230)

(a) Measured diamond pyramid hardness (DPH) or Vickers hardness using a 500-g load on a polished and etched cross section (Refs. 8, 11).

Field or Shop Measurements to Determine Maximum Oxygen-Cut Surface HAZ Hardness

1) Use a portable hardness device for large components or a shop bench hardness device for a smaller component or a ½-in.-thick oxygen-cut section from a larger component, and take measurements on a ground number 100-grit or finer surface. Also, measure the base metal hardness of the failed component or the new weld fabrication.

2) If possible, in field repair, visually determine the cause of failure, such as product quality, corrosion-assisted or wear-assisted overload, or fatigue. Report these observations to the owner-operators before proceeding to weld repair to alleviate, if possible, these conditions in the future.

3) At ambient or room-temperature oxygen cut a 13-mm (½-in.) or thicker section from the base metal using a normal continuous through-thickness oxygen-cutting procedure. Adjust the oxygen flow to produce a smooth, continuous through-thickness oxygen cut of the component section. Avoid checking maximum HAZ surface hardness where there was evidence of either dwell, backup, or weave during the oxygen-cut. The thickness and width of the oxygen-cut area should be at least 13-mm (½-in.) thick to ensure substantial cooling from the oxygen-cut face. Sufficient steel mass on both sides of the oxygen cut, such as 13 mm (½-in.) or more, is required to promote adequate cooling after the flame has passed. The oxygen cut produces HAZ hardness in the base metal that is similar but usually harder than the HAZ next to a weld bead on that same steel.

4) Grind the scale and a small decarburized metal to a depth of approximately 0.1 mm (0.004 in.) from the more massive side of the oxygen-cut surface and measure the maximum hardness on the HAZ on the component with a portable hardness unit. Use the highest hardness value measured. Do not average these values. Alternatively, a substantial size of the oxygen-cut loose piece can be ground flat and parallel on the backside of the oxygen cut to measure its the maximum hardness in a shop hardness tester. The surface preparation for maximum oxygen-cut HAZ hardness should be ground to a number 100-grit or finer finish.

5) Measure and record the individual hardness on three or more locations with either electronic or shop hardness units to produce small and shallow indentations. Lightly regrind the previously ground oxygen-cut surface to remove approximately 0.1 mm (0.004 in.) and repeat the hardness measurements until a single maximum hardness value is identified in the previous surface measurement. Convert the maximum hardness measurement to a Brinell hardness number (BHN) via ASTM E140 (Ref. 8) after the maximum hardness is determined. Only the maximum hardness of the steel's martensitic microstructure is determined by this method of rapid cooling the oxygen-cut HAZ. This procedure is not designed to measure the steel's hardenability or ability to transform to martensite at a minimum cooling rate that is different for different types of steel as shown in Ref. 9.

Discussion with Examples

Welding Procedure Designed from Maximum Oxygen-Cut Surface HAZ Hardness

1) Choose a welding electrode or wire to produce an as-welded deposit of weld metal that is hardness compatible with the measured base metal hardness. Descriptions of hardness tests and the correlation between hardness and tensile strength of carbon and low-alloy steels are found in Ref. 11.

2) Estimate the following welding parameters from the measured maximum hardness (Brinell hardness number) of the oxygen-cut HAZ:

A. Composition carbon equivalent (CE) = Hardness Equivalent (HE):
$HE = (Max\ HAZ\ BHN + 54)/ 769$

B. Estimate from measured maximum oxygen-cut HAZ hardness the 90% martensite (M_{90}) completion transformation temperature
$M_{90} = 510° - 0.45°C$
(Max HAZ BHN)
$M_{90} = 950° - 0.81°F$
(Max HAZ BHN)

C. Estimate minimum preheat temperature (PH) from CE (now HE):
$PH = 450°C\ \sqrt{(HE - 0.42)}$
$PH = 810°F\ \sqrt{(HE - 0.42)}\ + 32°F$

D. Temperature conversion (°F = 9/5 (°C) + 32°F) is used.

Example 1. Estimations from maximum HAZ hardness of 440 BHN are
$HE = (440 + 54)/769 = 0.64$
$M_{90} = 510°C - 0.45\ (440)°F = 312°C\ (594°F)$
$PH = 450°C\ \sqrt{0.64 - 0.42} = 211°C\ (412°F)$

Note that the 211°C (412°F) preheat is acceptable because it is below the 90% martensite (M_{90})completion transformation temperature of 312°C (594°F). The weld interpass temperatures during welding should be kept below this M_{90} martensite completion temperature. Postweld heat treatment of the weldment (component) may be required for higher carbon and medium carbon low-alloy steels with carbon equivalents or hardness equivalents above a value of approximately 0.5. Examples of some AISI grades of steel with higher carbon equivalents are listed in Table 1. Postweld heat treatment reduces the hydrogen content of the welds and HAZs and reduces the maximum hardness of the HAZ. In some cases, postweld heat treatment improves the cyclic stress fatigue strength of weldments by reducing the magnitude of residual tensile stresses across and along the length of weldments.

Caution

When the 90% martensite completion transformation temperature of the base steel is below the preheat temperature and interpass temperature for a large weldment, delayed cracking can occur from the transformation of retained austenite to martensite after the completed weldment has cooled. Therefore, buttering or predepositing first-bead weld metal on the base metal joint surface at a high preheat temperature should be considered on large multibead weldments. After the base metal surface is weld overlaid, cool to below the 90% Martensite transformation temperature of the base steel to complete the weldment.

Example 2. Procedure when the estimated M_{90} temperature is below the preheat temperature for a HAZ hardness of 600 Brinell is as follows:

$HE = (600 + 54)/769 = 0.85$

$M_{90} = 510°C - 0.45\ (600) = 240°C$ (464°F)

$PH = 450°C\ \sqrt{(0.85 - 0.42)} = 295°C$ (563°F)

Use the preheat temperature to make the first-bead weld deposits on the base metal (butter the base metal) and then drop the temperature to below the M_{90} temperature to complete the multibead weldment.

Welding Unknown Steels A, B, and C

Steels A, B, and C were welded in 1-in.-thick single-V multibead joints using the hardness equivalent (HE), the M_{90}, and the preheat temperature (PH) welding procedures determined from the measured maximum oxygen-cut HAZ hardnesses. The A, B, and C compositions and carbon equivalents (CE) are listed in Table 3. During this study, WTTI staff and the welding instructor doing the work did not know the compositions or grades of Steels A, B, and C. Therefore, this welding exercise was a blind test of measuring the proposed oxygen-cut surface maximum HAZ hardnesses and welding to the following welding procedures. Composition carbon equivalents (CE) and oxygen-cut surface maximum HAZ hardnesses are listed in Table 4 for Steels A, B, and C.

The following welding procedures were based upon the measurements of flame-cut surface maximum HAZ hardnesses and the corresponding carbon equivalents of A, B, and C steels. The following welding procedure designs were as follows:

Steel A: (679 BHN HAZ max)

$HE = (679 + 54)/769 = 0.95$

$M_{90} = 510°C - 0.45\ (679) = 204°C$ (399°F)

$PH = 450°C\ \sqrt{(0.95 - 0.42)} = 328°C$ (622°F)

Since a preheat of 622°F would produce excessive radiant heat on the welding personnel located at the weld joint site, Steel A was preheated to 550°F and the base metal joint surface was welded (buttered joint technique). The buttered Steel A was then cooled to below the M_{90} (399°F) temperature and the multibead weldment was completed.

Steel A represents medium-carbon steel with substantial low-alloy content (Table 3) and a hardness equivalent of 0.95. The difficulty in welding this type of steel is demonstrated by the higher preheat temperature requirement compared with the lower M_{90} temperature requirement. In general, a CE or HE value of 1.0 represents the practical maximum of weldability.

Steel B: (255 BHN HAZ max)

$HE = (255 + 54)/769 = 0.40$

$M_{90} = 510°C - 0.45\ (255) = 395°C$ (743°F)

PH: Since HE is less than 0.47, no preheat except moisture removal was required.

The Steel B weld joint base metal surface was heated to above 200°F to remove surface moisture before welding. Interpass temperature was not restricted because the M_{90} temperature was extremely high at 743°F.

Steel C: (420 BHN HAZ max)

$HE = (420 + 54)/769 = 0.62$

$M_{90} = 510°C - 0.45\ (420) = 321°C$ (610°F)

$PH = 450°C\ \sqrt{(0.62 - 0.42)} = 201°C$ (394°F)

Steel C was preheated to 400°F and multibead welded. Maximum interpass temperature was kept below 610°F.

Transverse cross sections of Steels A, B, and C weldments were saw cut, ground, polished, and etched to show the etched structure of the weld metal HAZ and base metal. The maximum hardness of the HAZs next to the weld metal was measured via diamond pyramid hardness (DPH) or Vickers hardness with a 500-g load using the standard load to indentation geometry described in Ref. 11 and converted to Brinell hardness (Ref. 8). The three base metal maximum HAZ hardnesses that were measured next to the weld interface are listed in Table 5.

The multibead weldments of steel samples A, B, and C were all sound and the maximum weld HAZ hardnesses listed in Table 5 were reduced by the preheat temperatures used compared with the oxygen-cut maximum HAZ hardnesses listed in Table 4. The application of this alternative welding procedure design was demonstrated by these results.

Conclusion

In the absence of knowledge of the carbon and low-alloy steel grade or knowledge of a manufacturer's certified composition of the steel to be weld fabricated or weld repaired, a product check of the steel's chemical composition may not be practical. In the absence of a confirmed steel grade identification, a welding procedure can be developed for this unknown steel by measuring the oxygen-cut surface maximum heat-affected zone (HAZ) hardness equivalent (HE), by estimating temperature of the 90% martensite completion transformation (M_{90}) using the same oxygen-cut surface maximum HAZ hardness, and by estimating the minimum preheat temperature (PH) from the hardness equivalent (HE). These welding procedures should not be applied to weld repair code-welded steel components.

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