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Carbon Equivalent (Pcm) Limits for Thick Carbon and Low Alloy Steels

U.S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION,
NAVAL SURFACE WARFARE CENTER

in cooperation with
Halter Marine Group, Inc.
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National Shipbuilding Research Project #7-96-3

FINAL REPORT

**“Carbon Equivalent (P_{CM}) Limits
for Thick Carbon and Low Alloy Steels”**

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ABSTRACT

Experimentally determined preheating/interpass temperatures necessary to prevent hydrogen-assisted cracking of restrained butt welds were established, and compared to the best algorithms available to predict such cracking. Weldability tests on large-size plates of ABS & MIL-S-22698, Grades B, D and DH-36 as well as ASTM A612 steels were conducted at Electric Boat Corporation using three different plate thicknesses, three welding procedures, and two levels of diffusible hydrogen. The plate thicknesses were 25mm (1in), 44mm (1.75in) and 64mm (2.5in). The welding procedures included: FCAW with E71T-1MH8, FCAW with low-hydrogen E71T-12MJH4, and pulsed GMAW with MIL-70S-3 electrodes. Navy-modified WIC tests of sub-size specimens were also performed to determine preheat/interpass temperatures, and to compare them with preheat temperatures obtained from the weldability tests conducted on large-size plates. Factors affecting hydrogen-assisted cracking were also evaluated; such as, (a) the effect of composition of plates produced in integrated mills vs 100% scrap mills, and (b) the effect of fillet joints vs butt joints. The best preheat prediction algorithm to match the experimental results was found. Recommendations to establish Pcm limits to reduce hardenability and possibly reduce the minimum required preheat temperature to 16°C (60°F) for Grades B, D and DH-36 shipbuilding steels are presented.

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OBJECTIVES

- Survey and assess algorithms from the literature to calculate preheating/interpass temperatures necessary to prevent hydrogen-assisted cracking of restrained butt welds and fillet welds.
- Experimentally determine preheating/interpass temperatures necessary to prevent hydrogen-assisted cracking of restrained butt welds deposited on large-size 25mm (1in), 44mm (1.75in) and 64mm (2.5in) thick plates of ABS & MIL-S-22698, Grades B, D and DH-36 as well as ASTM A612 steels using FCAW with E71T-1MH8, low-hydrogen FCAW with E71T-12MJH4, and pulsed GMAW with MIL-70S-3 electrodes.
- Compare the calculated preheating/interpass temperatures with experimental hydrogen-assisted cracking results of welds deposited on large-size plates of Grades B/D, DH-36 and A612 steels conducted at Electric Boat Corporation.
- Perform selected Navy-modified WIC tests using E71T-1MH8 electrodes to determine preheating temperatures to prevent hydrogen-assisted cracking in 25mm (1in) thick DH-36 and A612 steels; and, to compare these results with those found in restrained butt welds deposited large-size plates.
- Select the best preheat algorithm to match the experimental results in order to establish Pcm limits to possibly reduce the minimum required preheat temperature to 16°C (60°F) for Grades B, D and DH-36 shipbuilding steels.
- Develop an economical approach to ensure safety from hydrogen-assisted cracking in carbon steel, HTS and ABS steels over 25mm (1in) thick.

INTRODUCTION

Both U.S. Naval and private shipyards have reported hydrogen-assisted cracking in the heat-affected zone (HAZ) of HTS and ABS grades of steel over 25mm (1in) thick, despite preheating weld joints to the prescribed minimum temperatures specified by MIL-STD-278 and MIL-STD-1689. For example, a preheating temperature of 16°C (60°F) minimum is required when welding ABS Grades B, D or DH-36 plates over 25mm (1in) thick by FCAW with E71T-1 type electrodes. Even though the codes are being followed, hydrogen-assisted cracking still occurs in both butt and fillet welds in the construction of Naval ship structures. Although preheating to temperatures greater than 16°C (60°F) effectively eliminates cracking, the cost of fabrication (in labor and resources) rises significantly. Thus, to improve cost-effectiveness, Pcm limits need to be established to possibly eliminate preheat during welding of Grades B/D, DH-36 and other similar shipbuilding steels.

This goal of reducing preheat temperature to 16°C (60°F) may possibly be achieved by combining theoretical and experimental approaches to determine necessary preheat to prevent hydrogen-assisted cracking. The theoretical approach consisted of selecting (and modifying, if needed) the best hydrogen-assisted cracking prediction algorithm available in the international literature to fit the experimental welding data. The experimental data was obtained from restrained test welds deposited on large-size plates using different welding processes with different diffusible hydrogen levels. Specifically, a matrix of three thicknesses, three levels of carbon equivalent, and three welding procedures with two levels of diffusible hydrogen were evaluated. All large-size plate welding tests were performed at Electric Boat Corporation. Plate thicknesses used in this investigation were:

- 25mm (1in)
- 44mm (1.75in)
- 64mm (2.5in)

The three levels of carbon equivalent (CE) were represented by:

- ABS Grades B/D (Low CE)
- DH-36 (Medium CE)
- ASTM A612 (High CE)

The three welding techniques were:

- FCAW using E71T-1MH8 6-10ml/100g diffusible H
- Low-hydrogen FCAW using E71T-12MJH4 4-5ml/100g diffusible H
- Pulsed GMAW using MIL-70S-3 4-5ml/100g diffusible H

If Pcm limits can be established to reduce preheating, welding fabrication can be achieved more economically with ensured safety from hydrogen-assisted cracking in carbon steel, HTS and ABS shipbuilding steels over 25mm (1in) thick.

CRITICAL REVIEW OF THE LITERATURE

Carbon Equivalents:

In any mathematical algorithm to predict the preheating temperature necessary to prevent hydrogen-assisted cracking in the heat-affected zone (HAZ) of welds, the effect of chemical composition of the weld and/or HAZ material must be taken into consideration. A convenient method to accomplish this is combine the elements of the chemical composition into a single number, equaling the carbon equivalent. Over the years, many formulae for carbon equivalents have been developed for a variety of purposes. However, three primary carbon equivalent formulae have been commonly used in prediction algorithms for hydrogen-assisted cracking of steels. These include: P_{cm}, CE_{I_W} and CEN.

P_{cm} is designed for newer steels with low carbon, low alloy content. The effect of carbon becomes critical to an HAZ containing large amounts of martensite. Thus, P_{cm} is a good indicator of hydrogen-assisted cracking in the HAZ because carbon is a heavily weighted factor in this formula, as shown below:

$$P_{cm} = C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B \quad \text{Equation (1)}$$

The carbon equivalent formula, CE_{I_W}, is one of the most widely used because it is a good measure of the hardenability for conventional steels. CE_{I_W} is preferable for common carbon steels and carbon-manganese steels, while P_{cm} is designed for modern low-carbon low alloy steels. In the CE_{I_W} formula, the alloying elements are heavily weighted compared to carbon, as shown below:

$$CE_{I_{W}} = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15 \quad \text{Equation (2)}$$

In the P_{cm} formula in Equation (1), Ni does not raise the susceptibility to hydrogen-assisted cracking to the degree that it increases hardenability. For example, the factor “Ni/60” is used in the P_{cm} formula, while “Ni/15” is used in the CE_{I_W} formula. Since Cr and Mn increase the susceptibility to hydrogen-assisted cracking and hardenability of the steel, both P_{cm} and CE_{I_W} are strongly influenced by these elements.

The newest carbon equivalent formula, CEN, applies to both traditional steels (covered by CE_{I_W}) and low carbon low alloy steels (covered by P_{cm}) because of the hyperbolic tangent “tanh” term in the accommodation factor, A(C), shown below:

$$CEN = C + A(C) * \{ Si/24 + Mn/6 + Cu/15 + Ni/20 + (Cr+Mo+Nb+V)/5 + 5B \} \quad \text{Equation (3)}$$

where:

$$A(C) = 0.75 + 0.25 \tanh\{20(C-0.12)\}$$

In the higher C range, A(C) approaches 1 and CEN approaches CE_{IIW} . Conversely, at low carbon levels, the CEN approaches Pcm. This behavior of the CEN equation is due to the “tanh” (hyperbolic tangent) function. The three types of steels used in this study illustrate this point. For example, the CEN and CE_{IIW} values for the high carbon A612 steel nearly identical; while, the value of CEN approaches Pcm for the lower carbon DH-36 steel.

Hydrogen-Assisted Cracking in Steel Weldments:

The literature was searched to find methods to calculate preheating temperatures necessary to prevent hydrogen-assisted cracking for butt welds, and to compare those calculated values with experimental test results obtained in this investigation. The literature is replete with algorithms for the calculation of heat-affected zone hardness¹⁻¹⁴ as well as preheating temperatures¹⁵⁻⁵⁰. Preheating temperature predictions for fillet welds are based primarily on the Controlled Thermal Severity (CTS) test, while predictions for butt welds are based on several weldability tests such as the Tekken test per Japanese Standard JIS-Z- 3158⁴⁴.

Preheating the joint prior to welding and maintaining preheat temperature during welding is the best insurance against hydrogen-assisted cracking. The factors responsible for hydrogen-assisted cracking in steels include:

- Diffusible hydrogen,
- Tensile stress,
- Type of microstructure having a critical hardness, and
- Cracking temperature of approximately 20°-150°C (68°F - 302°F).

Preheating mitigates the detrimental factors listed above by allowing diffusible hydrogen to escape from the weld while relaxing the residual tensile stresses throughout the welded joint area. Furthermore, preheating promotes the transformation during cooling to a more ductile microstructure such as ferrite + carbide instead of martensite. The actual preheating temperature necessary to prevent hydrogen-assisted cracking is decreased by:

- Decreasing carbon equivalent of the steel plate and weld metal,
- Increasing heat input,
- Reducing the level of diffusible hydrogen,
- Decreasing hardness of the HAZ,
- Decreasing the degree of restraint,
- Decreasing the plate thickness(es), and
- Reducing the stress concentration factor in groove profile and joint design.

The most successful algorithms are those which address these issues quantitatively producing numerical solutions confirmed by an extensive experimental data base. The method of Yurioka et al⁴³ published in 1985 in their “Welding Note” clearly predicts the required preheat/interpass temperatures for butt welds and fillet welds. This method is the most mathematically rigorous of all the preheating algorithms. To determine the necessary preheat/interpass temperatures to prevent hydrogen-assisted cracking in the HAZ of welds, the cracking index, CI, needs to be calculated:

$$CI = CEN + 0.15 \log H_{JIS} + 0.30 \log (0.017 \kappa_t \sigma_w) \quad \text{Equation (4)}$$

where:

- CEN = Carbon equivalent in Equation (3)
- $H_{IIW} = 1.27H_{JIS} + 2.19$
- H_{IIW} = Standard diffusible hydrogen measurement using IIW method
- H_{JIS} = Diffusible hydrogen using glycerine method per Japanese Specification JIS Z 3113
- κ_t = Joint stress concentration factor. For example, a double V groove has a κ_t value of 3.5.
- σ_w (butt) = $\sigma_y + 0.0025 (R_F - 20 \sigma_y)$ for high restraint welds
- $R_F = 4970 \{ \arctan (0.017h) - (h/400)^2 \}$
- h = plate thickness, mm
- σ_y = yield strength, kg/mm²

The next step is to calculate the critical weld cooling time, $t_{100(cr)}$, to 100°C (212°F). This is the cooling time necessary to just prevent hydrogen-assisted cracking.

$$t_{100(cr)} = \exp(68.05CI^3 - 181.77CI^2 + 163.8CI - 41.65) \quad \text{Equation (5)}$$

The condition required to prevent hydrogen-assisted cracking is given by the following equation:

$$t_{100} \geq t_{100(cr)}$$

Empirically derived relationships between preheat temperature and $t_{100(cr)}$ are given by Yurioka et al⁴³ for different heat input levels, ambient temperatures and width of preheating strips used.

The only problem with the Welding Note by Yurioka et al⁴³ is the complexity of this method. Therefore, in 1995, Yurioka and Kasuya²⁹⁻³⁰ at Nippon Steel developed the Chart Method for calculation of preheating temperatures. This method retains the precision of the Welding Note⁴³ without complex mathematics.

Over the years, the Chart Method of Yurioka and Kasuya²⁹⁻³⁰ has become one of the most commonly used algorithms for the determination of necessary preheat to prevent hydrogen-assisted cracking. Yurioka and Kasuya²⁹⁻³⁰ take into account plate composition, thickness, restraint, heat input, and hydrogen content.

To calculate the preheating temperatures by the chart method²⁹⁻³⁰, the following variables need to be known:

- Plate composition
- Thickness of plate
- Heat input
- Diffusible hydrogen

First, the CEN value for the steel plates are calculated first by substituting the plate compositions into Equation (3). Knowing the CEN values, thickness of each steel plate, heat input, and diffusible hydrogen content of the weld, the necessary preheat temperature is then looked up by the Chart Method directly. Reasonable preheating temperatures in butt welds can be determined using charts. For example, if the diffusible hydrogen level is different than 5ml/100g, a correction chart provides an increment to the CEN value to compensate for the different hydrogen value. Similarly, if the heat input is different from 1.7kJ/mm, another correction chart provides an increment to CEN to compensate for the difference. If the restraint is “ordinary” or high, a chart is available to make that correction.

Uwer and Hohne^{40,41} use the Tekken test to derive their algorithm for predicting preheating temperature necessary to prevent hydrogen-assisted cracking in butt welds. Uwer and Hohne^{40,41} take into account carbon equivalent, hydrogen content, plate thickness and heat input. They state that the preheat temperature in Equation (6) developed for butt welds would apply conservatively for fillet welds. Their equation^{40,41} for the critical preheating temperature (T_{cr}) necessary to prevent hydrogen-assisted cracking for butt welds is:

$$T_{cr} = 700 + 160 \tanh(h/35) + 62 H_{IIW}^{0.35} + (53 \text{ CET} - 32)Q - 330 \quad \text{Equation (6)}$$

where:

$$\begin{aligned} \text{CET} &= C + (\text{Mn}+\text{Mo})/10 + (\text{Cr}+\text{Cu})/20 + \text{Ni}/40 && \text{Equation (7)} \\ Q &= \text{heat input, kJ/mm} \\ h &= \text{plate thickness, mm} \\ H_{IIW} &= \text{Standard diffusible hydrogen using IIW method} \end{aligned}$$

On the basis of results of a similar investigation, Brozda³⁴ asserts that this method of assessing the minimum preheat temperature to prevent cold cracking in welded joints proposed by Uwer and Hohne^{40,41} (above) is appropriate because of its simplicity. The only problem with this method is that the predicted preheating temperatures are too high or too conservative.

The ANSI/AWS D1.1-98 Structural Welding Code⁴² provides preheating temperatures for butt welds and fillet welds for shipbuilding steels including ABS Grades B/D and DH-36 steels.

The preheating temperatures given in Table 3.2 of the D1.1 Structural Welding Code⁴² are based on thickness and the use of low-hydrogen electrodes. For example: for ABS Grades B/D and DH-36, the specified preheating temperatures are:

Up to 19mm (¾ in)	None
Over 19mm (¾ in) thru 38.1mm (1½ in)	10°C (50°F)
Over 38.1mm (1½ in) thru 63.5mm (2½ in)	66°C (150°F)
Over 63.5mm (2½ in)	107°C (225°F)

Optionally, minimum preheat and interpass temperatures may be established on the basis of steel composition in Annex XI D1.1 Structural Welding Code⁴² using the “hydrogen control” method.

The military standard, MIL-STD-278⁴⁶, has been used for many years to determine preheating and interpass temperatures for shipbuilding steels such as ABS & MIL-S-22698 Grades B/D and DH-36. In this document, the minimum specified preheat and interpass temperature (T_{min}) for Grades B/D, DH-36 and even ASTM A612 is:

$$T_{min} = 16^{\circ}\text{C} (60^{\circ}\text{F})$$

However, if both carbon content of the base metal is greater than 0.3% and thickness exceeds 25mm (1in), the minimum specified preheat/interpass temperature necessary to prevent hydrogen-assisted cracking is raised to:

$$T_{min} = 80^{\circ}\text{C} (175^{\circ}\text{F})$$

unless otherwise approved by the welding procedure qualification. Also, MIL-STD-1689⁴⁷ has preheating requirements similar to MIL-STD-278, except that when carbon content exceeds 0.30%, the preheating temperature will be established in procedure qualification tests.

The “Guide for Steel Hull Welding”, ANSI/AWS D3.5⁴⁸, also addresses the preheating issue in a similar manner to MIL-STD-1689. In this document, preheating is advisable on heavy weldments and castings. Although preheating

as high as 200°C (400°F) is considered desirable in some cases, practical considerations usually dictate lower preheat temperatures of approximately 65°C to 90°C (150°F to 200°F) and the use of low-hydrogen welding processes. In higher strength steels, a higher preheat temperature together with low-hydrogen welding processes may be necessary. Sometimes preheating is unnecessary because the use of a high heat input welding process may bring about a sufficient retardation of cooling rate. Continuous welding operations, together with the maintaining of a specified temperature, are highly desirable when heavy units or highly restrained structures are welded. Preheat may be necessary before tack welding when the members to be joined are highly restrained. When higher strength steels are fabricated, the same preheat temperatures specified in the welding procedures should be used when any type of weld or tack is made.

The “Specification of Welding Earth Moving and Construction Equipment”, AWS D14.3⁴⁹, has far more rigorous preheating requirements than do the military specifications. In AWS D14.3, steels are classified according to strength, carbon equivalent, and carbon content. Preheating temperatures are for prequalified welding procedures for ordinary restraint. When exceptionally high restraint is encountered, D14.3 recommends higher preheating temperatures than those predicted above, but, does not specify exact preheating temperatures.

As noted earlier, the “Welding Note” published in 1985 by Yurioka et al⁴³ is the most rigorous mathematical algorithm derived to predict the preheating temperature necessary to prevent hydrogen-assisted cracking in the HAZ of steel welds. Yurioka et al⁴³ take into account stress concentration factor of the butt groove shape, plate thickness, heat input, diffusible hydrogen, stress in the weld, carbon equivalent and ambient temperature. Although Yurioka et al⁴³ provided great flexibility, it was often difficult to choose the correct boundary conditions to use this algorithm correctly.

Consequently, in 1995, Kasuya, Yurioka & Okumura,⁵⁰ and Kasuya & Yurioka³¹ published a final refinement of the Chart Method²⁹⁻³⁰. In this algorithm, not only are all of the difficult calculations of the Welding Note⁴³ replaced by charts, but also the ambient temperature is taken into consideration. Since low ambient temperatures can increase weld cooling rate and subsequent susceptibility to hydrogen-assisted cracking, a “CEN increment” was needed to appropriately increase preheating temperature to prevent cracking. As with the original Chart Method, Kasuya & Yurioka³¹ accounted for ambient temperatures different than the standard 20°C by converting their effect on preheating temperature into increments of CEN. For example:

CEN increment	= +0.02	at -10°C (14°F) ambient temperature
and		
CEN increment	= +0.08	at -30°C (-22°F) ambient temperature

By using these CEN increments, the latest version of the Chart Method can be used to estimate the effects of all significant variables including ambient temperature on the preheating temperature predicted to prevent hydrogen-assisted cracking.

Fillet Welds vs Butt Welds Regarding Crack Susceptibility:

The literature was searched and assessed to find methods to calculate preheating temperatures for fillet welds and butt welds. Only a few articles address the specific differences in preheating temperatures between butt welds and fillet welds in a numerically rigorous manner. Preheating temperature predictions for fillet welds are based primarily on the Controlled Thermal Severity (CTS) test, while predictions for butt welds are based on several weldability tests such as the Tekken test per Japanese Standard⁴⁴ JIS Z 3158. Several articles were selected below to compare preheating calculations for fillet welds and butt welds.

These articles are:

- N. Bailey, F.R. Coe, T.G. Gooch, P.H.M. Hart, N. Jenkins and R.J. Pargeter³⁷
- Tanaka and Kitada³⁸
- Uwer and Hohne^{40,41}
- ANSI/AWS D1.1-98 Structural Welding Code⁴²
- Yurioka et al⁴³

In 1973, Bailey et al³⁷ of The Welding Institute published a book entitled “Welding Steels without Hydrogen Cracking” which contained methods to predict preheating temperatures in both butt and fillet welds. In this early work, they³⁷ based their predictions on the efficiency of heat removal by introducing the concept of the combined thickness of various butt and fillet joint configurations. This combined thickness of a weld joint was defined as the total thickness of the plates meeting at the joint line. The combined thickness parameter described the magnitude of the heat conduction paths leading away from the molten weld pool. For example, the combined thickness (T_{com}) of two 25mm (1in) thick plates in a simple butt weld joint configuration is:

$$T_{com}(\text{butt}) = 2 * 25\text{mm} = 50\text{mm}$$

For a Tee joint of two 25mm thick plates and three heat paths with the two fillets being welded simultaneously, the combined thickness is:

$$T_{com}(\text{double-fillet}) = _ (3*25\text{mm}) = 38\text{mm}$$

But, for a Tee joint where only one fillet is being welded, the combined thickness is:

$$T_{\text{com}}(\text{single fillet}) = 3 \times 25\text{mm} = 75\text{mm}$$

This concept of the combined thickness suggests that the required preheating temperature for the single fillet weld will be greater than that for the butt weld which in turn will be greater than the preheating temperature for the Tee joint with two simultaneously welded fillets³⁷. Two simultaneously welded fillet welds in a Tee joint will always have the lowest preheating temperatures because of doubling the heat input and preventing efficient heat transfer paths away from the welded areas. However, the primary weakness of this early algorithm is the lack of a numerical or quantitative value for restraint in the butt and fillet weld joints. This is the only algorithm that predicts a higher preheating temperature for single fillet welds than butt welds of the same plate thickness and composition. All of the more recent models predict higher preheating temperatures for butt welds than fillet welds, as will be discussed next.

In subsequent algorithms (after the work by Bailey et al³⁷), particularly those from Japan and Germany, the concept of combined thickness was not used. The required preheating temperatures for fillet welds in the more recent algorithms was always lower than those required for butt welds. In the excellent study by Tanaka and Kitada³⁸, fillet welds and butt welds were deposited on the Japanese high strength HT50 steel using low-hydrogen electrodes. They found that hydrogen-assisted cracking in the form of “heal” cracks in single fillet welds in Tee joints were affected by the thickness of the web plate and that the severest cracking occurred in specimens with thicknesses of 8 to 14mm. No hydrogen-assisted cracking occurred in plates 20mm thick. Fillet welding on both sides of the Tee joint simultaneously prevented cracking regardless of thickness. Tanaka and Kitada³⁸ concluded that the cracking was attributable to HAZ hardening and vertical expansion/contraction in the web plate due to the thermal cycle of the weld. The critical preheating temperature, T_{cr} , was calculated for the particular steel in terms of the cracking parameter, P_{H} , for fillet welds:

$$P_{\text{H}}(\text{fillet}) = P_{\text{cm}} + .030 \log H_{\text{IIW}} + .027$$

The critical preheating temperature, T_{cr} , for a fillet weld is:

$$\begin{aligned} T_{\text{cr}}(\text{fillet}) &= 1600 P_{\text{H}}(\text{fillet}) - 408 \\ T_{\text{cr}}(\text{fillet}) &= 1600 P_{\text{cm}} + 48 \log H_{\text{IIW}} - 365 \end{aligned}$$

Assuming a diffusible hydrogen level, H_{IIW} , equal to 4 ml/100g of weld metal:

$$T_{\text{cr}}(\text{fillet}) = 1600 P_{\text{cm}} - 336 \quad \text{Equation (8)}$$

For butt welds with an oblique y-groove:

$$\begin{aligned}
P_H(\text{butt}) &= P_{cm} + .075 \log H_{IIW} + .035 = P_{cm} + .080 \\
T_{cr}(\text{butt}) &= 1600 P_H(\text{butt}) - 408 \\
T_{cr}(\text{butt}) &= 1600 P_{cm} - 280
\end{aligned}
\tag{Equation (9)}$$

Comparing Equations (8) and (9), the following is obtained independently of P_{cm} :

$$T_{cr}(\text{butt}) - T_{cr}(\text{fillet}) = 56^\circ\text{C} \tag{Equation (10)}$$

Thus, according to Tanaka and Kitada³⁸, the preheating temperature for 20mm thick HT-50 steel butt welds is 56°C greater than that for fillet welds.

Similarly, Uwer and Hohne^{40,41} show that a milder state of stress exists in fillet welds compared to butt welds. They claim that the CTS test simulates the conditions in fillet welding and produces lower minimum preheating temperatures than the Tekken test (for butt welds). Even when the stress state of the CTS test is intensified by notching the root region, the minimum preheating temperature of the butt weld in the Tekken test is always higher than that of the CTS fillet weld. The critical preheating temperature for butt welds was given by Equation (6):

$$\begin{aligned}
T_{cr}(\text{butt}) &= 700 + 160 \tanh(h/35) + 62 H_{IIW}^{0.35} \\
&+ (53 \text{ CET} - 32)Q - 330
\end{aligned}$$

Comparing experimental data for fillet welds and butt welds, Uwer and Hohne^{40,41} prepared Tekken and CTS specimens using 30mm thick plates, hydrogen level of 4ml/100g, and 1kJ/mm heat input using the SMAW process. The only variable was the carbon equivalent (CET) of the plate. The critical preheating temperatures to prevent hydrogen-assisted cracking for Tekken and CTS tests are given by:

$$T_{cr}(\text{butt}) = 750 \text{ CET} - 150 \quad (\text{Tekken welds})$$

$$T_{cr}(\text{fillet}) = 745 \text{ CET} - 210 \quad (\text{CTS welds})$$

For a wide variety of steels, experimental results revealed that the butt welds in the Tekken test required 60°C (108°F) higher preheating temperature to prevent cracking than did the CTS test specimens as shown in the above equations. For example, 25mm (1in) thick DH-36 would require the following preheating temperatures according to Uwer and Hohne^{40,41}:

$$\begin{aligned}
\text{CET} &= C + (\text{Mn}+\text{Mo})/10 + (\text{Cr}+\text{Cu})/20+\text{Ni}/40 \\
&= .14 + (1.31+.04)/10 + (.13+.26)/20 + .16/40 \\
&= .30
\end{aligned}$$

$$\begin{aligned}
T_{cr}(\text{butt}) &= 750 \text{ CET} - 150 \\
&= 75^\circ\text{C} (167^\circ\text{F}) \text{ preheat for } \underline{\text{butt}} \text{ welds}
\end{aligned}$$

$$T_{cr}(\text{fillet}) = 745 \text{ CET} - 210$$

$$= 14^{\circ}\text{C} (57^{\circ}\text{F}) \text{ preheat for } \underline{\text{fillet}} \text{ welds}$$

The ANSI/AWS D1.1-98 Structural Welding Code⁴² specifies preheating temperatures for butt welds and fillet welds for shipbuilding steels including ABS Grades B/D and DH-36 steels using Annex XI of the Structural Welding Code⁴².

For example, consider 44mm (1.75in) thick DH-36 with the composition listed below:

C	0.14	Cr	0.16
Mn	1.36	Cu	0.22
Si	0.23		0.036
Ni	.15		

From Equation (1), P_{cm} is 0.24. The Structural Welding Code requires the calculation of another carbon equivalent, CE_{AWS}, for the composition of DH-36 above:

$$CE_{AWS} = C + (Mn+Si)/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$$

$$CE_{AWS} = .46$$

For comparison, preheating temperatures for both fillet and welds will be calculated for 44mm (1.75in) thick DH-36 using 1.6kJ/mm (40kJ/in) and low-hydrogen electrodes as defined by AWS (<10ml/100g diffusible hydrogen). For fillet welds deposited on 44mm (1.75in) DH-36, the Hardness Method⁴² can be used to calculate the heat input required for FCAW and GMAW without the need for added preheat. With CE_{AWS}=0.46, the cooling rate at 540°C (1000°F) is 44°C/s from Figure XI-2 in the Code. For single pass SAW fillet welds with both web and flange thicknesses = 44mm (1.75in), the minimum heat input required by the code is 1.3 kJ/mm (32 kJ/in). For FCAW or GMAW, the minimum heat input required by the code is:

$$Q = 1.3\text{kJ/mm} * 1.25$$

$$Q = 1.6\text{kJ/mm} (40\text{kJ/in})$$

Thus, according to this method, fillet welding 44m (1.75in) thick DH-36 flanges and webs by FCAW or GMAW with no added preheat and a minimum of 1.6kJ/mm (40kJ/in) is acceptable to the code.

For butt welds deposited on 44mm (1.75in) thick DH-36, the Hydrogen Control Method⁴² can be used to calculate the required preheating temperature. Assume the diffusible hydrogen content of welds deposited by GMAW and FCAW-H4 were between 4-5ml/100g for a rating of “low-hydrogen” or H2. Assume the level of restraint was severe for a rating of *high* restraint. In Table

XI-1 in D1.1 Structural Welding Code⁴², the susceptibility index of D is obtained using $0.24P_{cm}$ and H2 level of diffusible hydrogen. Applying the susceptibility index of D , thickness of 44mm (1.75in) and high restraint in Table XI-2 in D1.1 Structural Code⁴², the preheating temperature recommended by AWS D1.1 hydrogen control method is: 130°C (265°F).

The preheat calculations using the Hardness Method⁴² for fillet welds and Hydrogen Control Method⁴² for butt welds are compared in Table 1. Both fillet and butt welds are calculated for FCAW-H4 and GMAW of 44mm (1.75in) thick DH-36 using 1.6kJ/mm (40kJ/in). From this table, the Structural Welding Code⁴² clearly allows lower preheat/interpass temperature requirements for fillet welds than for butt welds.

Finally, the method of Yurioka et al⁴³ clearly shows that fillet welds require lower preheat/interpass temperatures compared to butt welds. This method is probably the most rigorous of all the preheating algorithms. To determine the necessary preheat/interpass temperatures to prevent hydrogen-assisted cracking in fillet welds, the following calculations for butt welds need to be performed. First, the carbon equivalent CEN from Equation (3) must be calculated for the steel base metal.

Table 1

Comparison of predicted preheating temperatures for FCAW and GMAW of 44mm (1.75in) thick DH-36 with low-hydrogen electrodes (4-5ml/100g) by the AWS Hardness Method⁴², AWS Hydrogen Control Method⁴².

	Hardness Method (For Fillet Welds)	Hydrogen Control Method (For Butt Welds)
Minimum Preheat Temperature	No added preheat required with 1.6kJ/mm (40kJ/in) minimum heat input	130°C (265°F)

Next, the cracking index, CI, from Equation (4) is calculated:

$$CI = CEN + 0.15 \log H_{JIS} + 0.30 \log (0.017 \kappa_t \sigma_w \text{ (butt)})$$

However, when Yurioka⁴³ considers fillet welds, the value of stress imposed on the weld metal, σ_w , is substantially relaxed even for highly restrained joints:

$$\sigma_w \text{ (fillet)} = \sigma_w \text{ (butt)} / 2 \quad \text{Equation (11)}$$

Clearly, the stress imposed on a fillet weld in Equation (11) is only half that on a butt weld. Thus, the subsequent calculations to determine a preheating temperature will result in a substantially lower preheating temperature for fillet welds than for butt welds. The next step is to calculate the critical cooling time to 100°C (212°F), $t_{100(cr)}$, using Equation (5). To prevent hydrogen-assisted cracking, the actual cooling time should be greater than $t_{100(cr)}$.

Sub-Size Weldability Tests for Butt and Fillet Welds:

The driving force for using sub-size weldability specimens for determining preheating temperatures to prevent hydrogen-assisted cracking is cost savings. Many sub-size weldability specimens can be tested in the laboratory at the same cost of one weld test on large-size plates. The old tests such as the British CTS test⁵⁰ were based on fillet welds, but all of the new weldability tests and CE equations are based on various types of butt welds with different joint configurations and different levels of restraint. The CTS test was developed in the 1950's with the focus on critical cooling rate at 300°C (572°F). The CTS test provided a bithermal and trithermal fillet weld. The thermal severity number was a total combined plate thickness in 6.4 mm ($\frac{1}{4}$ in) units. Unfortunately, this test was not severe enough to reproduce cracking known to occur in the field. So, in 1990, the CTS test was modified to be more severe by eliminating the slow cooling bithermal weld and introducing a root gap to increase severity. This new version of the test is covered in British Standard BS7363:1990⁵¹.

The window-type cruciform restraint test was developed in Japan⁶⁶ and was designed to test the short transverse direction of a plate. An inserted plate is rigidly welded so that the tensile residual stress acts on the short transverse direction to initiate lamellar tearing around the mid-thickness or toe cracking at the surface.

Since virtually all hydrogen-assisted cracking occurred in the HAZ of the older steels, Granjon developed the Implant test⁵² in 1969. This was essentially a constant load rupture test that was applied to the actual HAZ of a particular steel. A one-pass weld is deposited so that the notch of the cylindrical sample is located in the coarse grained HAZ. When the weld cools to 150° C, a prescribed load level is applied to the sample for up to 72 hours or until the steel cracks. The critical stress at which no rupture occurs or no arrested crack is found is recorded. Because of the difficulty in placing the notch at the correct location, a modified version of the implant test using a spiral notch has been used extensively^{53,54}.

Also, in the 1950's, the Lehigh test for groove butt welds was introduced by Stout et al⁵⁵. In this test, a root crack initiates predominantly in the weld metal and therefore is preferred to assess the susceptibility of the weld metal to hydrogen-assisted cracking. Later, in the 1970's, Stout et al⁵⁶ introduced the slot test which was developed to evaluate pipeline materials. In this test, a cellulosic

electrode is used in the vertical-down position for the only purpose of evaluating the weldability of line pipe steels. The slot test was standardized in API Recommended Practice 4009 in 1977.

In pipeline welding, the WIC (Welding Institute of Canada) test, which has been used extensively in Canada, is reported to be a good indicator of steel weldability in the field⁵⁷. The WIC test was designed to be a highly restrained weldability test for the pipeline industry. It reproduces the stresses incurred in the root pass of a girth weld on a pipeline. It has been applied to pipe thicknesses of 10 to 25 mm (.4 to 1in).

The modern weldability tests from Japan developed the concept of intensity of restraint by using butt welds with highly restrained Y and oblique Y grooves. The most famous of these is the Tekken test (JIS Z3158) developed by Kihara et al^{58,59}. The Y-groove joint geometry primarily tests the HAZ for hydrogen-assisted root cracking occurring in a single pass butt weld. This test is the basis of most of the hydrogen diffusion and hydrogen cracking prediction models developed in Japan. These models predict preheat temperatures better than the older hardenability models for the lower carbon HSLA type steels. When the modern low carbon "clean" steels are tested by the Tekken test, a root crack tends to be initiated and propagated not in the HAZ but in the weld metal. In general, Ito and Bessyo showed that the straight Y groove tends to promote cracking in the weld metal while the oblique Y tends to promotes hydrogen-assisted cracking in the HAZ⁶².

The major problem with sub-size weldability tests is their questionable accuracy in predicting preheating temperatures in a shipyard. While they are cost-effective, sub-sized specimens are still not well received by U.S. shipyards. In this investigation, weldability tests on both large-size and sub-plates will be compared.

Scrap Mills vs Integrated Mills in Production of Shipbuilding Steels:

Although many innovations in steelmaking practice have taken place worldwide, there are basically two major types of steel production: (1) the integrated mill using mostly iron ore as the starting material and (2) the modern mini-mill which uses about 70% to 100% scrap steel. Because the mini-mills do not need to be physically near a blast furnace facility, they are usually located in cities where the demand for steel is highest. Integrated mills can make very large quantities of common steels economically using high-production continuous casting methods, while the mini-mills tend to make shorter runs of steels so that several different grades of steel can be melted in the same day. Because the demand for AH/DH-36 steels is moderate, both mini-mills and integrated mills produce this steel plate. Due to the high cost of shipping steel plate, the mini-mills may be able to provide steel to a particular location more economically than an integrated mill. For example, Oregon Steel Mills (a mini-mill) may be able to

produce steel plate cheaper for a customer in Seattle than could an integrated mill like US Steel in Pittsburgh. In this country, US Steel and Bethlehem Steel produce AH/DH-36 steel plate in their integrated mills, while a large number of small mini-mills produce limited quantities of these same grades of steel.

In an integrated steel mill, iron from the blast furnace is saturated with carbon (C), phosphorus (P) and other impurities. The first stage of refining of steel from the blast furnace is designed to reduce C and virtually eliminate P by blowing oxygen into the melt. Basic oxygen furnace (BOF) steelmaking accounts for the majority of steel production in many parts of the world; for example, over 70% of production in the United Kingdom and the United States is by the BOF practice. The BOF is a tiltable vessel lined with basic refractory material. It is charged with a mixture of 65-75% molten pig iron and the remainder scrap steel and fluxes. A supersonic velocity jet of oxygen is then blown into the top of the furnace. No fuel or electric power is required by the BOF because the decarburizing and dephosphorizing reactions are highly exothermic⁵¹⁻⁵³. Si and Mn are added to reduce the O content (resulting from the O blow). The oxidation reactions are so highly exothermic that approximately 30% of the charge is scrap steel to provide cooling. That is, the scrap steel is added to prevent the temperature of the molten pool from exceeding 1650° C and causing excessive refractory erosion. Since C content decreases linearly with O blow time, the rate of O used in the jets controls the rate of decarburization in the melt⁵¹⁻⁵³.

In the second stage of refining, the development of the Savard-Lee tuyere made it possible to blow oxygen from bottom of the furnace. The quick quiet basic oxygen process (Q-BOP) provides better mixing of the bottom blows of oxygen which in turn results in lower carbon levels (as low as 0.01%) with less FeO in the slag and shorter processing times (14 vs 17 minutes/blow). Stirring by bottom blowing of oxygen provides substantial reductions in inclusion content as well as reduced alloy segregation. The rapid growth of bottom blown processes has led to the argon-oxygen decarburization (AOD) process which uses an inert gas in the outer tuyere and an oxidizing gas in the inner tuyere. This process was once used only for production of stainless steel but is now used for steel alloy grades. AOD is also used extensively in the foundry industry because it offers refining of small heats of a wide variety of steels and alloys⁵².

Mini-mills now provide 40% of U.S. steel production by using the electric arc furnace (EAF) with steel scrap, instead of iron ore, as its primary source of material.

Of those EAF facilities, almost half of them have furnaces with capacities of 55 tons or less. Due to the great effort to recycle steel throughout the world combined with the phenomenal growth of mini-mills, the weldability of such steels has, in some cases, deteriorated. The reason for the diminished weldability is the entrapment of unwanted alloying and tramp elements in recycled steel,

such as zinc (from galvanizing), tin (from tin-plating), chromium, nickel, molybdenum, copper and other inadvertent ingredients. The presence of these ingredients change the hardenability, weldability and cracking resistance of mild and low alloy steels⁵⁴.

Oregon Steel Mills is an example of an efficient mini-mill plate producer using EAF steelmaking practice to provide a variety of steels including ABS Grades A, AH-36, DH-36 and EH-36⁵⁵. The raw materials used to make DH-36 include scrap steel and from 10% to 40% briquetted iron. The briquetted iron contains no residuals and is used as a pure iron additive to the scrap charge in order to control and reduce the amount of residuals in the resulting heat of steel. If a steel plate is needed with low residuals, up to 40% briquetted iron will be added to scrap-charged melt. The fluctuating market prices for scrap and briquetted iron also determine the amount of each ingredient used for a particular heat. A typical heat of molten metal which weighs approximately 80 tons is then poured into a ladle for further refining. Calcium silicide is added to desulfurize the melt and final alloying adjustments are made. Then the ladle is put into a vacuum degasser. During vacuum degassing, argon is bubbled up from the bottom of the ladle while the melt is undergoing electromagnetic stirring. In this way, inclusions and gaseous impurities are minimized. The ladle is then removed from the vacuum degasser and the melt is transported to two 40 ton capacity slab molds. A tube is inserted down to the bottom of the ladle while the top of the melt in the ladle is pressurized forcing the liquid up through the tube and into the slab molds. Each slab can be 100in x 400in x either 6in, 7in or 8in thick. Reoxidation during molten metal transfer is minimized by shrouding.

Ladle refining is a result of the demand for cleaner steels with higher toughness and more restrictive chemical and physical specifications. During the few minutes just before pouring, critical additions or modifications to the melt chemistry can be most effectively made. For example, Sumitomo Metals Industries developed the novel ladle injection refining (IR) process, in which non-metallic inclusions are removed by the presence of lime particles. The ladle is then vacuum degassed by the Ruhrstahl Hereaus (RH) process to reduce dissolved C, O, H, and N while bubbling inert gas from the bottom of the ladle. As a result, typical S, O, N, H and P contents total only about 50 ppm⁵⁶.

Continuous casting of large tonnages of steel is far more cost-effective than conventional ingot casting. The quality of continuous cast steel slabs is uniform, sound and relatively free of macrosegregation. Grain size is simpler to control than ingot castings. Continuous cast plate is more resistant to lamellar tearing than similarly processed ingot cast plate. This is believed to be due to the accelerated cooling which occurs during the continuous casting process resulting in a finer inclusion size as well as an overall reduction in dendrite arm spacing and grain size. In addition, the reduction of sulfur is most effective in eliminating lamellar tearing regardless of the type of steelmaking practice.

Furthermore, with calcium desulfurization, the MnS inclusions become spheroidized so that low-sulfur calcium-treated steels virtually never experience lamellar tearing initiated at MnS inclusions⁵⁷.

Steel Cleanliness and Its Effect on Hydrogen-Assisted Cracking:

Over the years, the cleanliness and thus the performance of structural steels has improved substantially. For example, in 1919, the sulfur level^{58,59} was maintained below 0.04%; in the 1970's the maximum sulfur content was 0.010, and today sulfur levels as low as 0.001% are required for certain applications⁶⁰. Similarly, inclusion control has been a major concern of steel mills for the past 25 years, primarily because of lamellar tearing problems in the heat-affected zones (HAZ) of welded structures.

The mechanical properties, particularly fracture toughness, are extremely sensitive to steel cleanliness and inclusion content as well as inclusion shape^{61,62,63}. The benefits of lower sulfur and lower inclusion content include improvements in:

(a) toughness (particularly upper shelf energy) and ductility, (b) fatigue properties, (c) short transverse tensile properties and greater resistance to lamellar tearing⁶¹. In addition, clean steels reduce the occurrence of lamellar tears caused in part by the presence of weld metal hydrogen^{64,65}.

The only negative aspect of clean steels appears to be the increased risk of hydrogen-assisted cracking in the HAZ. Many investigators^{66,64,67,68-70} have reported the increased susceptibility of very low sulfur (in particular) and low oxygen steels to hydrogen-assisted cracking. Hart^{66,71} reported that decreasing sulfur from 0.025% to 0.005% was equivalent to an increase in CE_{IIV} of about 0.03%. In fact, in Cottrell's carbon equivalent⁷² equation, a sulfur term (+ 0.0001/S) is used to indicate a noticeable increase in the susceptibility of a steel to hydrogen-assisted cracking by reducing sulfur to an ultra low level, as shown below:

$$CE_{\text{Cottrell}} = C + \text{Mn}/6 + \text{Cr}/5 + \text{Mo}/5 + \text{V}/3 + \text{Nb}/4C + 0.0001/S$$

In ultra clean steels, there are three factors believed to increase the risk of hydrogen-assisted cracking in the HAZ of welds;

1. Reducing sulfide inclusions reduces intragranular ferrite nucleation causing an increase in hardenability^{70,73};
2. Reducing the amount of sulfide inclusions results in a loss of hydrogen trapping sites which can effectively decrease the volume of harmful diffusible hydrogen available for cracking;
3. Very low sulfur levels promote hydrogen pick-up on the molten weld metal surface during welding, resulting in an increased diffusible hydrogen content in the weld metal.

Of the three factors listed above, increased hardenability is believed to be the most important cause for increased susceptibility of hydrogen-assisted cracking⁷¹. In the work by Kikuta and Araki⁷⁴, the critical stress needed in the implant test to cause hydrogen-assisted cracking increased with increasing oxygen and sulfur. Thus, the enhanced susceptibility of clean steels to hydrogen-assisted cracking must be taken into account in welding applications.

PROCEDURE

Acquisition of Steel Plates for Test Matrix:

Steel test plates having three different carbon equivalent levels and three different thicknesses were selected, purchased and delivered to Electric Boat Corporation for subsequent welding tests. These plate compositions are listed in Table 2. These steels included:

- ABS & MIL-S-22698 Gr. B & D Low Pcm
- ABS & MIL-S-22698 Gr. DH-36 Medium Pcm
- ASTM A612 Pressure Vessel Steel (for comparison) High Pcm

Each of the steels listed above was purchased in three thicknesses:

- 25mm (1in)
- 44mm (1.75in)
- 64mm (2.5in)

The Grade B and D designations are based on thickness of plate, even though both grades have essentially the same composition. For example, in this investigation, the 25mm (1in) thick plate is Grade B, while the 44mm (1.75in) and 64mm (2.5in) thick plates are Grade D. The steel plates were purchased in the sizes and quantities shown in Table 3. Because the plates were acquired in small quantities, purchases had to be made through the steel service centers listed in Table 3. Although the cost of small quantities of steel plate was high, these service centers did allow the principal investigator to access the entire stock of available compositions of Grade B & D and DH-36 steel plates. The service centers even provided mill certifications for review prior to purchase to facilitate selection of the best Pcm levels for the project. As a result, not only were steel compositions pre-selected to provide the Pcm levels and thicknesses needed in this project, but also, a representative sampling of the compositions for DH-36 and Grades B & D throughout the country was obtained.

By purchasing via a service center, a variety of steel plates produced by both scrap steel mills and integrated mills could be selected. Since DH-36 (made by Lukens) was the focal point of this research, all of the DH-36 in this study was made by Lukens Steel using 100% scrap mill processing (Table 3). These steels were purchased prior to June 1998, when Bethlehem Steel Corporation acquired Lukens Inc.

All steel plates obtained from Oregon Steel Mills as well as Lukens Steel were made from 100% scrap or recycled steel (Table 3). Only the MIL-S-22698 Grade B steel plates were purchased from both integrated mills (Bethlehem Steel and Gulf States Steel) and a 100% scrap steel mill (Lukens), in order to investigate and compare the effects of different steelmaking practices on weldability and hydrogen assisted cracking susceptibility of the weldment.

The carbon equivalent levels of the Grades B & D and DH-36 steels increase slightly with increasing thickness, as shown in Table 2. ABS, MIL-S-22698, and ASTM specifications permit steel mills to increase carbon and alloy contents with increasing thickness in order to compensate for the reduced amount of hot rolling. ASTM 612 (see Table 2) has the same composition for all thicknesses because one heat was rolled for all three thicknesses especially for this project.

Plate Preparation and Welding Consumables:

Prior to initial groove edge preparation, the 81cm x 122cm (32in x 48in) plates were cut into three pieces each 81cm x 41cm (32in x 16in). For each thickness, a double V-groove edge was cut by oxy-fuel into the 81cm x 16cm (32 x 16in) plates as shown in Figure 1. The beveled edges were ground to bare metal. Welding was performed along the 81cm (32in) direction. All welding was carried out in the vertical-up position. Individual pieces of steel were re-used (after cutting out the test weld and surrounding HAZ) until they were no smaller than 23cm (9 in) wide.

Three types of welding consumables were used in this project:

- AWS Class E71T-1MH8 electrodes manufactured by Lincoln Electric as “Outersield 71HYM”,
- AWS Class E71T-12MJH4 electrodes manufactured by ESAB as “Dual Shield II 70T-12H4”, and
- MIL-70S-3 manufactured by Hobart

The welding details for FCAW with E71T-1MH8, FCAW with E71T-12MJH4 and GMAW with MIL-70S-3 are summarized in Table 4. All flux-cored and solid electrodes were drawn to 1.1mm (0.045in) diameter. The E71T-1MH8

flux cored electrode was shipped in hermetically sealed cans. This electrode was purchased from Lincoln Electric as part of a larger order initiated by Newport News Shipbuilding.

The significant difference between the E71T-1MH8 and E71T-12MJH4 electrodes was the resulting weld metal diffusible hydrogen. The normal E71T-1MH8 would be expected to produce welds with up to 8 ml/100g diffusible hydrogen, while the E71T-12MJH4 and the solid MIL-70S-3 electrodes should produce welds with less than 4ml/100g of diffusible hydrogen.

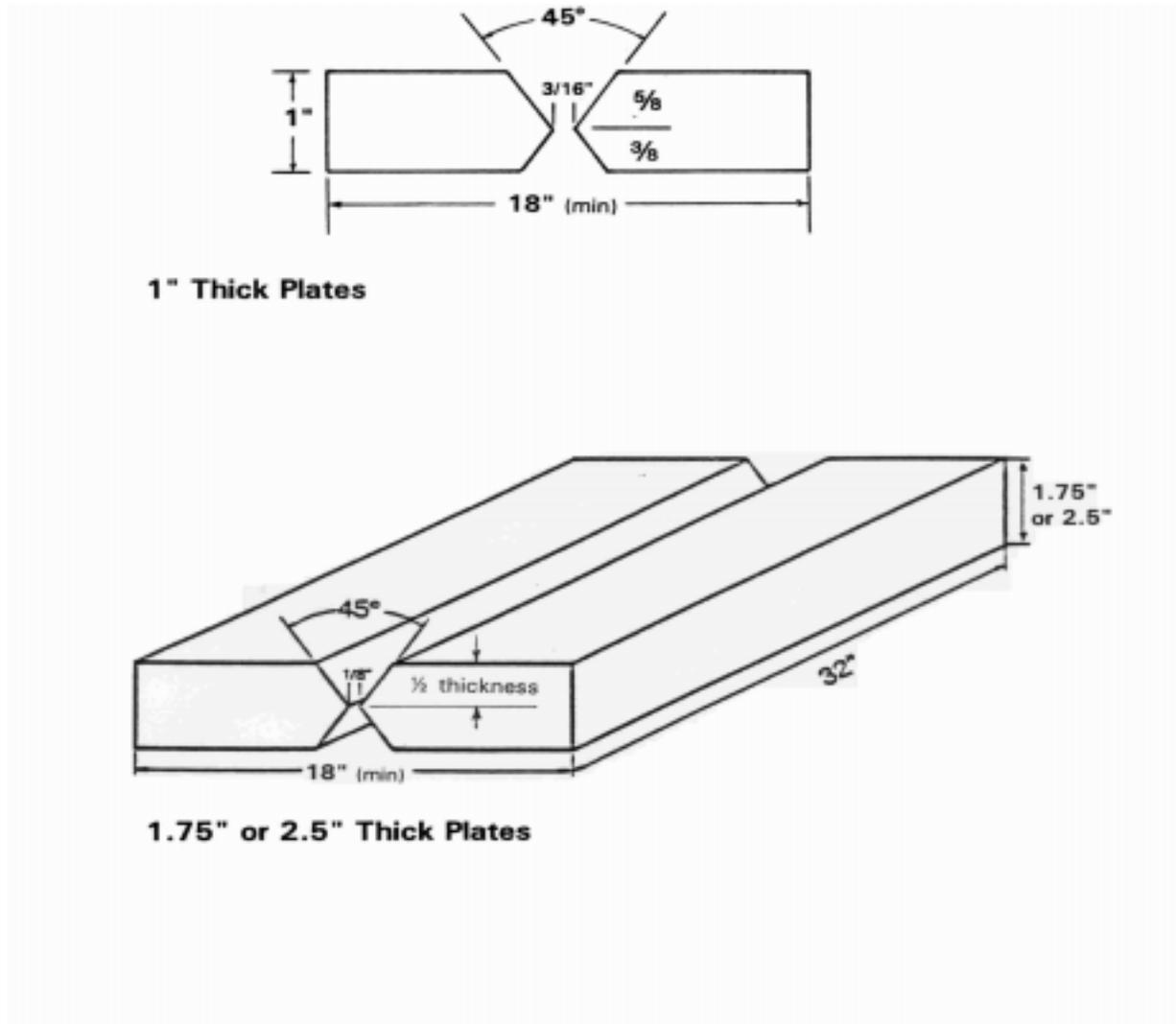


Figure 1 Joint geometry of double V-groove butt welds.

Controlled Environment Test Chamber

All welding was performed in an environmentally controlled test chamber which was set at 16°C (60°F) and 80% humidity. These conditions (16°C and 80%) were selected as representing minimal preheat and moderately high relative humidity. Depending on the shipyard and the time of the year, there is a wide range of conditions present during welding, but the conditions selected were used more as a standard for future test purposes. When preheating/interpass temperatures in excess of 16°C (60°F) were required, plates were heated with electric strip heaters. Regardless of the preheat/interpass temperature, the relative humidity and chamber temperature remained set at 80% and 16°C (60°F), respectively.

Weldability Testing of Large-Size Plates

All welding of large-size plates was performed at Electric Boat Corporation. Test plate details are shown in Figure 1. These plates were clamped in the butt configuration to the rigid test fixture. This fixture was built with reinforced 50mm (2in) thick HY-80 and was designed to provide severe restraint during welding. All welding was performed in the vertical-up position. In general, three sets of weldability tests were performed simultaneously for economy. For example, when welding plates requiring a 16°C (60°F) preheat/interpass temperature, three test welds were performed at the same time so that two sets of plates could be cooling while the third set was being welded. The welding details for FCAW with E71T-1MH8 and E71T-12MJH4 electrodes, and pulsed GMAW with MIL-70S-3 are presented in Table 4. Double V-groove butt joints were used because they (1) represented actual welds in shipbuilding and (2) generated two levels of high restraint; that is, the restraint on second side was approximately 20% greater than that of the first side, according to Yurioka⁴³.

The first set of Grades B, D, DH-36 and ASTM A612 steel plates selected for welding were the medium 44mm (1.75in) thickness plates. The initial set of welding conditions included: 60°F preheat/interpass temperature and 80% relative humidity. When cracking occurred under these conditions, the preheating temperature was increased until cracking was eliminated. This procedure was then repeated for the 25mm (1in) thick and 64mm (2.5in) thick plates of Grades B & D, Grade DH-36 and A612 steels. In addition, when cracking occurred, it was always noted where the cracking originated, for example: HAZ (1st side), HAZ (back side), weld metal (1st side) and/or weld metal (backside).

Inspection of Welds

Inspection of the test welds was critical to determine the presence of cracking in the weld metal and the heat-affected zone. To accomplish this, rigorous non-destructive (NDT) and destructive tests were performed on each test weld.

These NDT methods, which are specified in Table 4, included:

- Magnetic particle (MP) testing,
- Ultrasonic testing (UT),
- Enhanced UT

The destructive tests included:

- Longitudinal metallographic sectioning (Figure 2),
- “House Test” developed by Electric Boat Corporation (Figure 3),
- Transverse metallographic sectioning.

MP inspection would be performed on each test weld (1) each morning, (2) after back-grinding the second side, and (3) after the entire weld joint was completed. Ultrasonic (UT) and enhanced UT tests were performed on the completed weld joints. For each test assembly that did not exhibit visible cracking through magnetic particle testing or visual inspection, longitudinal, transverse and the “House Test” were performed. For most of the test assemblies that exhibited in-process cracking detected by visual or magnetic particle inspection, metallographic sectioning was performed to verify the nature and location of the cracking.

Diffusible Hydrogen Testing

Diffusible hydrogen testing was conducted on the weld metal deposited on DH-36 using E71T-1MH8 and E71T-12MJH4 flux cored electrodes and MIL-70S-3 solid electrode. The procedure for measuring diffusible hydrogen in weld metal was performed in accordance with AWS B4.3 using gas chromatography. All electrodes were tested immediately after opening the package. In the case of the E71T-1MH8, additional diffusible hydrogen tests were performed after several days of exposure to the 80% relative humidity. All diffusible hydrogen testing was performed in the flat position. The shielding gasses for the FCAW and GMAW processes were Ar-25%CO₂ and Ar-5%CO₂, respectively. E71T-1MH8 tests were conducted using both 12mm (½ in) and 19mm (¾ in) contact tip to work distances. The low-hydrogen E71T-12MJH4 tests were conducted using 12mm (½ in) contact tip to work distance. MIL-70S-3 tests were conducted using a 16mm (5/8 in) contact tip to work distance.

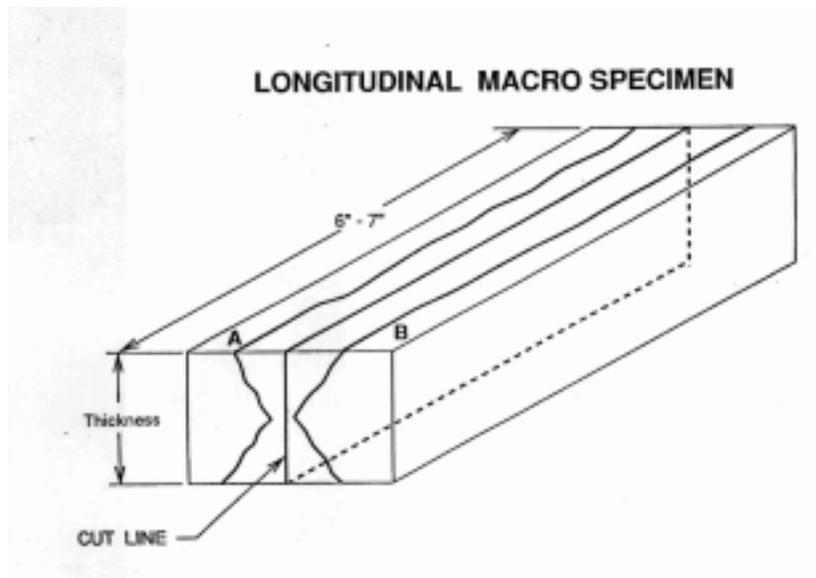


Figure 2 Longitudinal metallographic specimen designed to inspect for flaws in weldments (Electric Boat Corporation).

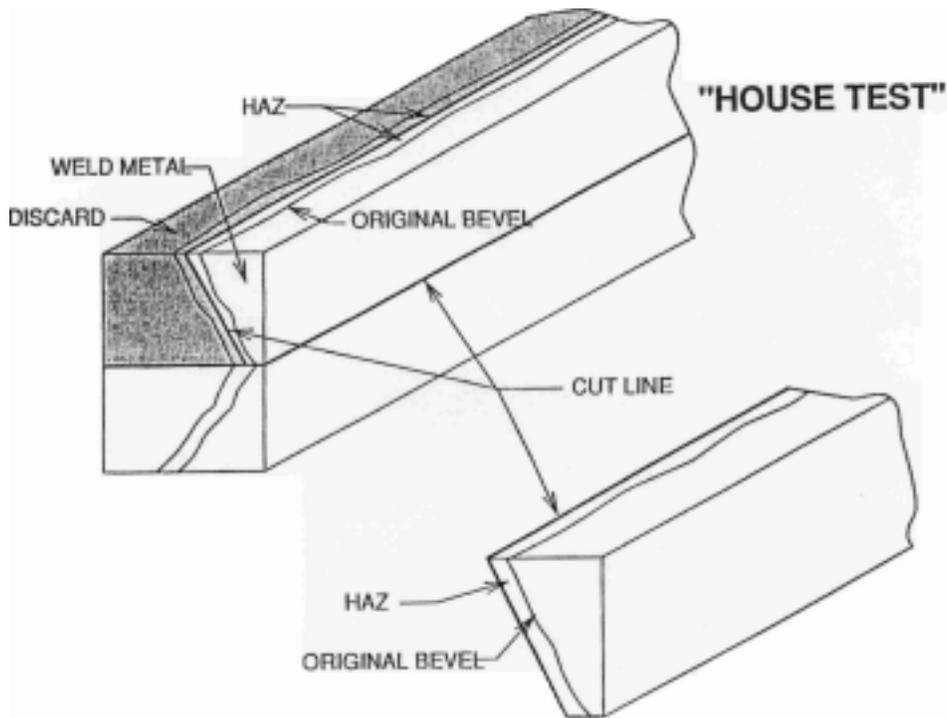


Figure 3 Electric Boat Corporation's "House Test" is a metallographic section test designed to detect small flaws particularly along the heat-affected zone.

Navy-Modified WIC Testing Using Sub-Size Specimens:

The purpose of sub-size weldability tests such as the Navy-Modified WIC test is to determine necessary preheating temperatures without the expense of welding large-size plates. A schematic illustration of the Navy-modified WIC test is shown in Figure 4. In this study, 25mm (1in) thick DH-36 and A612 steel was selected for WIC testing. Briefly, the welding variables used in this test included:

Plate thickness:	25mm (1in)
Welding position:	Flat
Heat input:	35-40 kJ/in
Y-Groove angle:	60°
Root gap:	2mm (.080in)
Root face:	$t/2 = 12.5\text{mm}$ ($\frac{1}{2}\text{in}$); $t = \text{plate thickness}$
Heat input:	35-40 kJ/in
NDT:	MT on weld surface
Electrodes:	E71T-1MH8 and E71T-12MJH4

In this study, duplicate DH-36 specimens and A612 specimens were prepared for each preheat temperature in the Navy-Modified WIC test. To determine whether or not the weld/HAZ was cracked (72 hours after welding), non-destructive testing was performed by magnetic particle testing using a standardized yoke in accordance with the procedure developed by Wong⁷⁵ at CDNSWC.

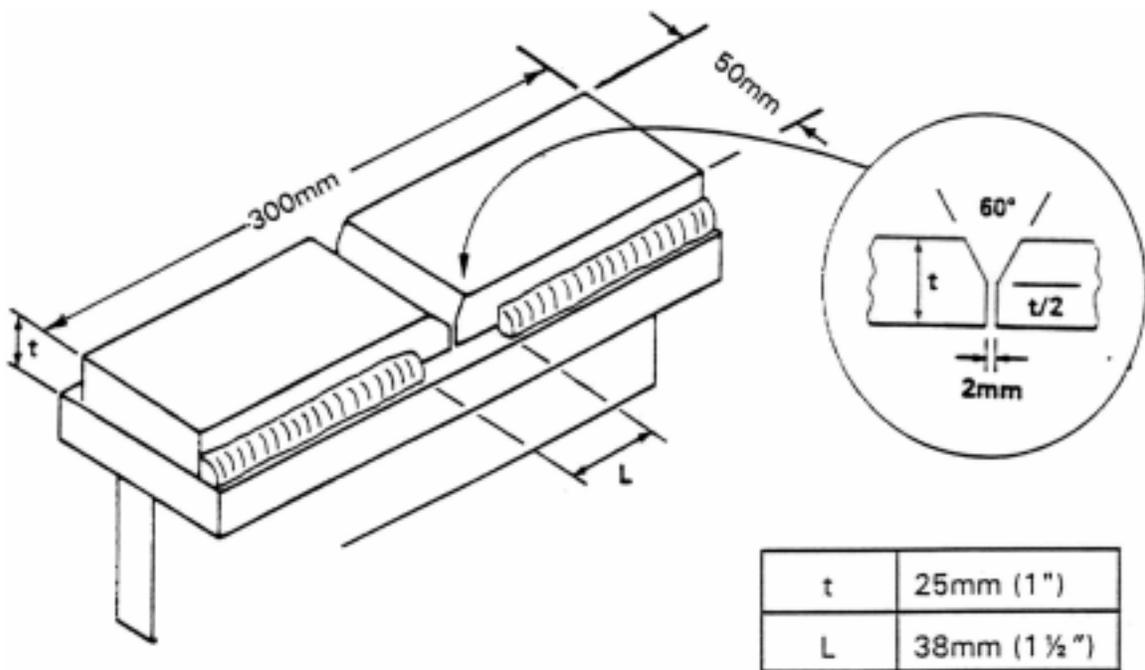


Figure 4 Navy-Modified WIC Test assembly.

The direct current (DC) yoke was calibrated to lift 40 lbs of steel and can detect flaws as deep as about 6mm (¼ in) deep. During magnetic particle inspection, the yoke was in contact with base metal on both sides of the weld. That is, one magnet pole was in contact with base metal on one side of the weld and the other magnet pole was in contact with the base metal on the other side of the weld. With this arrangement, the magnetic field passed through the weld and HAZ. If magnetic particle testing showed an indication of cracking in the weld metal or HAZ, the specimen failed. If magnetic particle testing revealed no indication, the specimen passed.

TABLE 2

Chemical compositions and properties of steel plates obtained from mill certifications

	Grade B & D ABS & MIL-S-22698			DH-36 ABS & MIL-S-22698			A612 ASTM		
	Thickness, mm (in)			Thickness, mm (in)			Thickness, mm (in)		
	25 (1)	44 (1.75)	64 (2.5)	25 (1)	44 (1.75)	64 (2.5)	25 (1)	44 (1.75)	64 (2.5)
C	0.16	0.10	0.15	0.14	0.14	0.15	0.24	0.24	0.24
Mn	0.84	1.00	1.03	1.31	1.36	1.40	1.42	1.42	1.42
Si	0.20	0.22	0.213	0.22	0.23	0.23	0.28	0.28	0.28
Ni	0.02	0.13	0.01	0.16	0.15	0.15	0.19	0.19	0.19
Mo	0.02	0.06	0.006	0.04	0.05	0.06	0.04	0.04	0.04
Cr	0.02	0.17	0.03	0.13	0.16	0.11	0.09	0.09	0.09
Cu	0.03	0.22	0.012	0.26	0.22	0.27	0.22	0.22	0.22
S	0.014	0.013	0.005	0.005	0.018	0.010	0.002	0.002	0.002
P	0.007	0.014	0.016	0.010	0.016	0.008	0.007	0.007	0.007
Nb	-	-	-	0.029	0.036	0.032	-	-	-
V	-	-	-	0.004	0.005	0.002	0.028	0.028	0.028
Al	-	-	0.035	-	-	-	0.025	0.025	0.025
Pcm	.21	.18	.21	.24	.24	.25	.34	.34	.34
CE _{IIW}	.31	.34	.33	.42	.43	.45	.54	.54	.54
Yield Str. (ksi)	38	41	43	60	54	55	64	64	64
Tens. Str. (ksi)	61	67	66	79	76	79	89	89	89
% Elong.	26	29	32	29	31	27	24	24	24

TABLE 3

Description of plates delivered to Electric Boat Corporation for weldability testing.

Steel	Plate Sizes cm (in)	No. of Plates	Steel Mill	Type of Mill (Heat #)	Service Center
<u>MIL-S-22698</u>					
Grade B	2.5x81x122 (1x32x48)	3	Gulf States	Integrated (7448085)	High Strength Steel
Grade B	4.4x81x122 (1.75x32x48)	3	Lukens*	100%Scrap (C5023)	High Strength Steel
Grade D	6.4x81x122 (2.5x32x48)	3	Bethlehem*	Integrated (813M71390)	High Strength Steel
<u>MIL-S-22698</u>					
DH-36	2.5x81x122 (1x32x48)	3	Lukens*	100%Scrap (D0623)	Interstate Steel
DH-36	4.4x81x122 (1.75x32x48)	3	Lukens*	100%Scrap (C7336)	High Strength Steel
DH-36	6.4x81x122 (2.5x32x48)	3	Lukens*	100%Scrap (C8310)	High Strength Steel
<u>ASTM</u>					
A612	2.5x81x122 (1x32x48)	3	Oregon	100%Scrap (375810)	Oregon Steel
A612	4.4x81x122 (1.75x32x48)	3	Oregon	100%Scrap (375810)	Oregon Steel
A612	6.4x81x122 (2.5x32x48)	3	Oregon	100%Scrap (375810)	Oregon Steel

* These steels were purchased prior to June 1998 when Bethlehem Steel Corporation acquired Lukens Incorporated.

Table 4

Welding variables and non-destructive inspection methods.

	FCAW E71T-1MH8	FCAW E71T-12MJH4	GMAW-P MIL-70S-3
<u>WELDING</u>			
Position	Vertical-up	Vertical-up	Vertical-up
Joint Geometry	Double V-groove	Double V-groove	Double V-groove
Plate Thickness, mm	25, 44, & 64	25, 44, & 64	25, 44, & 64
Plate Thickness, (in)	(1, 1.75 & 2.5)	(1, 1.75 & 2.5)	(1, 1.75 & 2.5)
Electrode Type	E71T-1MH8 (Outershield 71HYM)	E71T-12MJH4 (Dual Shield II 70T-12H4)	MIL-70S-3
Electrode Dia, mm (in)	1.1 (.045)	1.1 (.045)	1.1 (.045)
Current, A	160-170	175	115
Voltage, V	23	23	21.5
Contact Tip to Work Distance mm (in)	16 ()	12 ()	16 ()
Heat Input, kJ/mm (kJ/in)	1.6 (40)	1.6 (40)	1.6 (40)
Pulsed Power			
Shielding Gas	No	No	Yes
Preheat/Interpass	Ar-25%CO ₂	Ar-25%CO ₂	Ar-5%CO ₂
Packaging	Variable Hermetically sealed cans	Variable Sealed plastic bags	Variable Boxes
Controlled Humidity	80%	80%	80%
Ambient Temperature, °C (°F)	16° (60°)	16° (60°)	16° (60°)
<u>INSPECTION</u>			
Visual	Continuous	Continuous	Continuous
Magnetic Particle	Each morning Back grind Final weld Final	Each morning Back grind Final weld Final	Each morning Back grind Final weld Final
UT & enhanced UT			
Metallography	Final	Final	Final
Longitudinal	Final	Final	Final
“House Test”	Final	Final	Final
Transverse	Final*	Final*	Final*
<u>OTHER TESTS</u>			
Diffusible Hydrogen	As Needed	As Needed	As Needed
Chemical Analyses	As Needed	As Needed	As Needed

* Several were performed on partially welded test assemblies when in-process magnetic particle inspection revealed an underbead crack.

EXPERIMENTAL RESULTS & ANALYSES

Steel Plate Compositions:

Since shipyard cracking problems involved Lukens DH-36 with high carbon equivalent levels exceeding 0.30P_{cm}, an exhaustive attempt was made to find DH-36 with similarly high P_{cm} values. The results of searching steel service centers nationwide revealed that Lukens DH-36 with P_{cm} > 0.27 could not be found. In fact, none of the domestic steel mills produced DH-36 with P_{cm} levels exceeding 0.27 (at least during the time period when the search was conducted).

The reason for the lower carbon equivalent in modern DH-36 may be because ABS Rules have supplementary requirements in Appendix 2/D.5.2 specifying that P_{cm} must be less than 0.27 for plate thicknesses greater than 45mm (1_ in). However, this P_{cm} limit depends on the contract or shipyard's decision to include such a requirement. Also, a P_{cm} limit on DH-36 enhances the steel's resistance to hydrogen-assisted cracking. Thus, only DH-36 plates with P_{cm} values below 0.27 were found, despite a nation-wide search. The compositions, carbon equivalents and mechanical properties of the nine steels used in this investigation are presented in Table 2. As discussed in the Procedure, this matrix of nine steels represents three different thicknesses and three different levels of carbon equivalent for weldability testing on large size plates conducted at Electric Boat Corporation.

Integrated Mills vs Scrap Mills:

The effect of residual elements (Cu, Ni, Cr, Mo, Nb, V and others) on raising P_{cm} and CE_{I_W} levels in steel is illustrated in Table 5. Steels mills that use 100% scrap as their primary source of material always produce steels with high levels of residual ingredients. The difference in P_{cm} level due to the cumulative presence of residual elements is substantial. For example, from Table 5, the composition of Grade D (produced Lukens Steel) using 100% scrap includes substantial amounts of residual Cu, Ni, Cr, Mo, Nb and V compared to the same steel produced by an integrated mill like Bethlehem Steel using virgin material. Steel mills that utilize 100% scrap can use the residual alloy content to reduce the amount of carbon in the steel as shown in Table 5. The Lukens plate has an increased residual Cu, Ni, Cr and Mo content amounting to an increase of 0.03P_{cm} and 0.07CE_{I_W}. Conversely, the integrated mill plate from Bethlehem gains its strength through an increase in carbon by 0.05%. Although the CE_{I_W} values are nearly the same for both integrated and 100% scrap steels, the P_{cm} values for the 100% scrap steel is substantially lower. Since P_{cm} is a measure of susceptibility to cracking, 100% scrap steel plates may possibly be slightly more resistant to hydrogen-assisted cracking in the HAZ.

Weld Metal Carbon Equivalent

The carbon content and carbon equivalent values (measured by CE_{IIW} and P_{cm}) for welds produced with E71T-1MH8, E71T-12MJH4, and MIL-70S-3 electrodes are substantially lower than those for Grades B & D, DH-36 and A612 base metals as shown in Table 6. This is because the electrodes typically contain only about 0.02-0.06% carbon and about 1.2% Mn. Also, in Table 6, a comparison is presented to illustrate the difference in compositions between 64mm (2.5in) thick DH-36 plate, and weld metal deposited with E71T-1MH8, E71T-12MJH4 and MIL-70S-3. Clearly, the highest carbon content and P_{cm} levels are in the plate. This makes the heat-affected zone of the DH-36 more susceptible to hydrogen-assisted cracking than the weld metal, because increasing the value of P_{cm} in Equation (1) promotes greater susceptibility to hydrogen-assisted cracking. Thus, the advantage of the lower weld metal P_{cm} values (compared to the base metal) is the reduced possibility of hydrogen-assisted cracking in the weld metal.

Joint Design Effect on Restraint

In this study, the double-V groove joint provided a substantial stress concentration factor according to Yurioka et al⁴³. When welding the first side the stress concentration factor was approximately 3.7. If the weld survived the first side, the second side provided a stress concentration of greater than 4.2, since the welded first side provides additional restraint on weld beads deposited on the second side.

Diffusible Hydrogen Analyses of Flux Cored and Solid Electrodes

Diffusible hydrogen analyses were performed using three consumables: (1) E71T-1MH8 flux cored electrode, (2) E71T-12MJH4 flux cored electrode and (3) MIL-70S-3 solid electrode. From Table 7, the diffusible hydrogen content of E71T-1MH8 weld metal is 6-10ml/100g, while those of E71T-12MJH4 and MIL-70S-3 are between 4 and 5 ml/100g. Clearly, there are two levels of hydrogen. The higher level of diffusible hydrogen was provided by the E71T-1MH8 electrode, while the lower hydrogen electrodes were the E71T-12MJH4 and MIL-70S-3. In fact, the E71T-12MJH4 was essentially equivalent to a solid electrode (MIL-70S-3) for low-hydrogen performance. Thus, FCAW with E71T-12MJH4 and GMAW with MIL-70S-3 solid electrode should be equally resistant to hydrogen-assisted cracking in the heat-affected zone of thick carbon and low alloy steels, such as Grades B & D, DH-36 and A612 used in this project.

Hardness Profile of Weld, HAZ and Unaffected Base Metal

Since the P_{cm} values for MIL-S-22698 Grades B & D and DH-36 as well as ASTM A612 plates were always significantly higher than P_{cm} levels of the weld metal, the hardness of the heat-affected zone (HAZ) was always greater

than both the weld metal and the unaffected base metal. For example (see Figure 5) the microhardness profile of weld metal, HAZ and unaffected base metal are plotted for 44mm (1.75in) thick Grade D, DH-36 and A612 using E71T-1MH8 flux cored electrode at a heat input of 1.6 kJ/mm (40 kJ/in) with 16°C (60°F) preheat/interpass temperature. In all cases, the maximum hardness occurred in the heat-affected zone. Thus, the HAZ should be the most susceptible to hydrogen-assisted cracking. Since the peak hardness in the HAZ increased with increasing P_{cm} level of the base plate (Figure 6), the susceptibility to hydrogen-assisted cracking in the HAZ was greatest for the A612 steel and least likely for the Grade D. One of the beneficial effects of preheating is the reduced peak hardness in the heat affected zone (shown in Figure 7), due to the slower cooling rate.

Cracking in Restrained Welds Deposited with E71T-1MH8

Welds were deposited on large-size plates of MIL-S-22698 Grades B & D, DH-36 and A612 by FCAW using E71T-1MH8 (Outershield 71HYM) electrodes producing 6-10ml/100g diffusible hydrogen. Welding variables and inspection methods are presented in Table 4. This flux cored electrode produced the highest level of diffusible hydrogen used in this study. The results of weldability testing of these plates in thicknesses of 25mm (1in), 44mm (1.75in) and 64mm (2.5in) are given in Table 8. In this table, hydrogen-assisted cracking occurred in the heat-affected zones of the DH-36 and A612 plates for all thicknesses tested. No cracking was observed in either the weld metal or the heat-affected zones of the Grade B/D plates.

As plate thickness and carbon equivalent values increased, the susceptibility to cracking in the HAZ also increased. The reason why hydrogen-assisted cracking occurred only in the heat-affected zone was due to the higher carbon content and carbon equivalent levels (P_{cm} and CE_{IW}) of the plates compared to the weld metal as illustrated in Table 6. Clearly, the Grade B & D plates in all thicknesses up to 64mm (2.5in) were crack-free because their carbon equivalent values were low; not exceeding 0.21P_{cm}.

Surprisingly, DH-36 plates in all thicknesses cracked in the heat-affected zone when welded at 16°C (60°F) preheat/interpass temperature. Although the 25mm (1in) thick DH-36 cracked in the heat-affected zone (determined by metallography), cracking was not detected by magnetic particle and UT. A typical hydrogen-assisted crack in the heat-affected zone of 44mm (1.75in) thick DH-36 is shown in Figure 8. These heat-affected zone cracks occurred in the weld joints despite the low carbon equivalent of the DH36 (.24-.25P_{cm}). To prevent hydrogen-assisted cracking in the heat-affected zones of the 25mm (1in) and 44mm (1.75in) thick plates, the preheat/interpass temperature had to be raised to 51°C (125°F). HAZ cracking in the 64mm (2.5in) thick DH-36 plates could only be prevented with a preheating temperature of 106°C (225°F). The results of this work showed that the preheat requirements specified by military

codes MIL-STD-278⁴⁶ and MIL-STD-1689⁴⁷, Structural Welding Code⁴² ANSI/AWS D1.1, and ABS Rules are inadequate to prevent cracking in DH-36, particularly in the 25mm (1in) and 44mm (1.75in) thicknesses.

The A612 pressure vessel steel was used in this analysis for comparison purposes only, because of its high carbon content and high carbon equivalent as shown in Table 2. As expected, the A612 was the most susceptible to hydrogen-assisted cracking in the heat-affected zone as illustrated in Table 8. Due to its 0.34Pcm level and 0.24% carbon content, preheating temperatures of 106°C (225°F), 135°C (275°F), and 135°C (275°F) were needed to prevent hydrogen-assisted cracking in the heat-affected zones of the 25mm (1in) and 44mm (1.75in) and 64mm (2.5in) thick plates, respectively. Clearly, the A612 plates were far more susceptible to hydrogen-assisted cracking in the heat-affected zone than either the Grades B & D and DH-36 shipbuilding steels. Detailed weld cracking data are given in the Appendix.

Cracking in Restrained Welds Deposited with Low-hydrogen E71T-12MJH4

Welds were deposited on large-size plates of MIL-S-22698 Grades B & D, DH-36 and A612 by FCAW using E71T-1MJH4 (Dual Shield II 70T-12H4) electrodes containing 4-5ml/100g diffusible hydrogen. Welding variables and inspection methods are presented in Table 4. The reduction in diffusible hydrogen for the E71T-12MJH4 weld metal to the H4 level had substantially reduced the occurrence of hydrogen-assisted cracking in the shipbuilding steels Grades B & D and DH-36, as shown in Table 9. In fact, no cracks were detected in Grades B & D and DH-36 for all thicknesses. This illustrates the importance of using low-hydrogen flux-cored electrode to reduce the susceptibility to hydrogen-assisted cracking in the heat-affected zones of Grades B & D and DH-36 steels regardless of thickness.

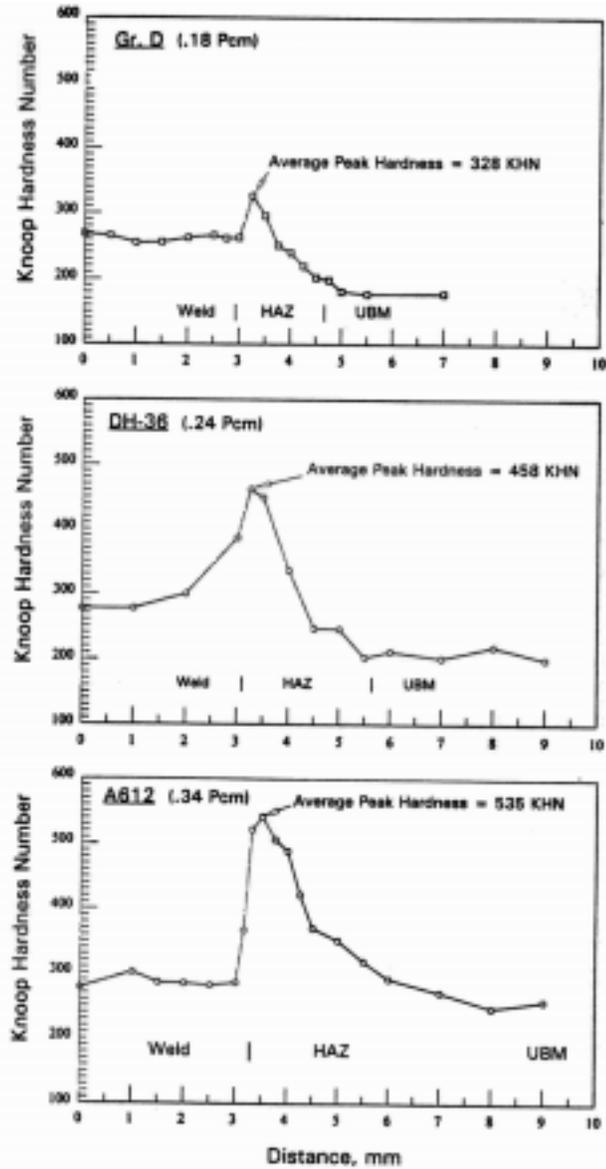


Figure 5 Microhardness profile for butt welds deposited by FCAW at 1.6kJ/mm (40kJ/in) with E71T-1MH8 at 16°C (60°F) preheat/interpass temperature on 44mm (1.75in) thick plates of (A) Grade D, (B) DH-36, and (C) A612 steel.

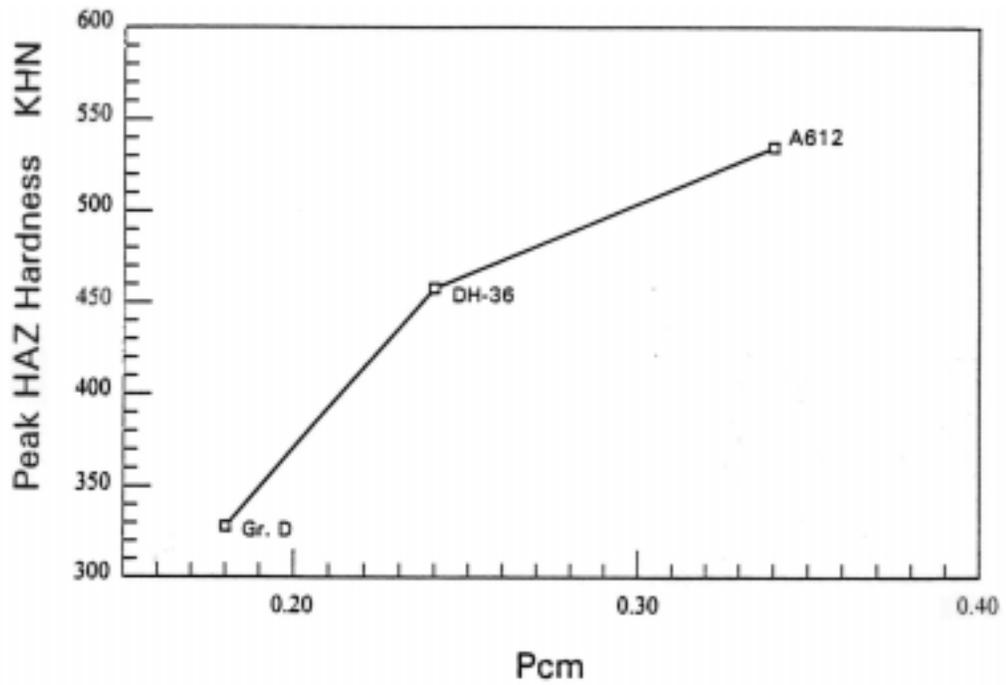


Figure 6 Peak heat-affected zone hardness of butt welds deposited by FCAW at 1.6kJ/mm (40J/in) using E71T-1MH8 electrodes on 44mm (1.75in) thick plates at 16°C (60°F) preheat/interpass temperature.

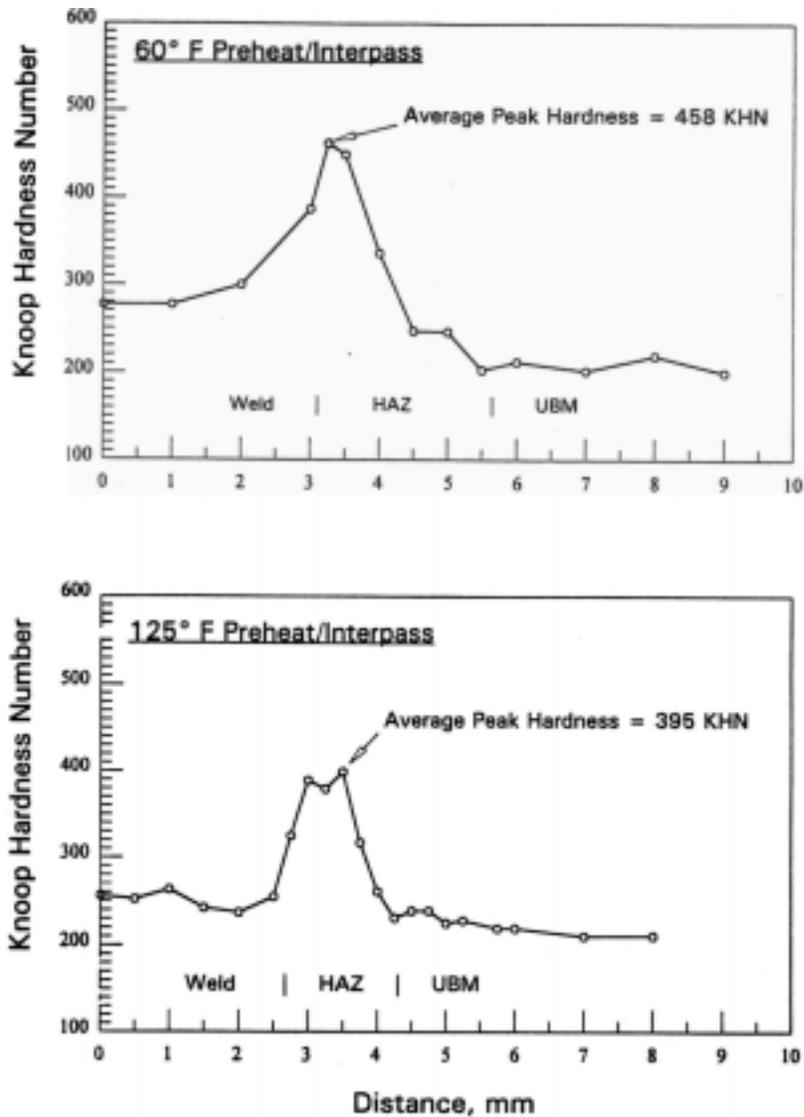


Figure 7 Preheating effect on microhardness profiles and peak heat-affected zone hardness values of butt welds deposited by FCAW at 1.6kJ/mm (40kJ/in) using E71T-1MH8 electrodes on 44mm (1.75in) thick plates of DH-36 steel at: (A) 16°C (60°F) and (B) 52°C (125°F) preheat/interpass temperatures.

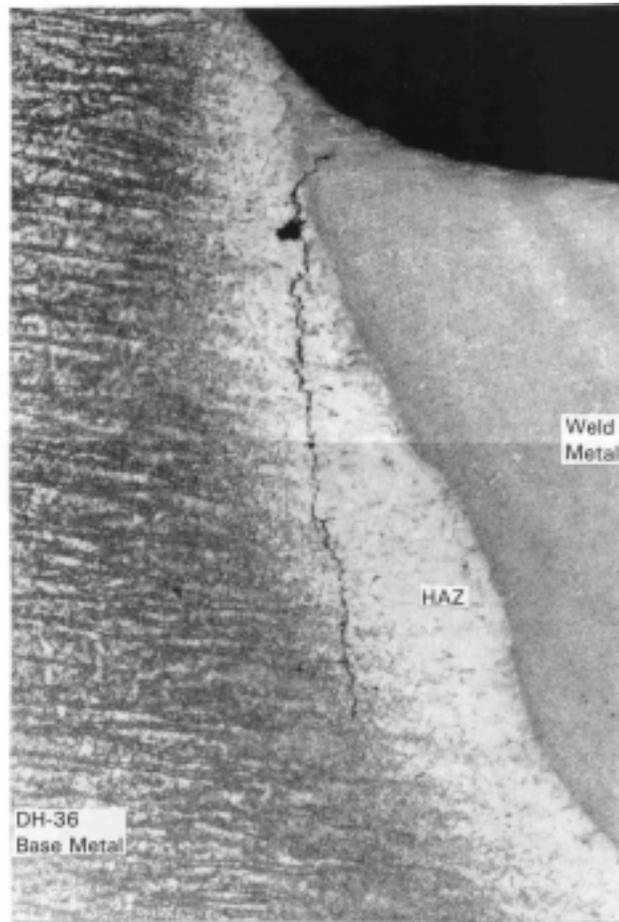
Cracking in Restrained Welds Deposited with MIL-70S-3 (Solid Electrode)

Welds were deposited on large-size plates of MIL-S-22698 Grades B & D, DH-36 by pulsed GMAW using MIL-70S-3 electrodes producing 4-5ml/100g diffusible hydrogen. Welding variables and inspection methods are presented in Table 4. Because the diffusible hydrogen content of the MIL-70S-3 weld metal was very similar to that produced by E71T-12MJH4 flux cored electrode, the cracking resistance for both processes were similar as shown in Tables 9 and 10. In all testing, the E71T-12MJH4 and MIL-70S-3 electrodes provided equally good resistance to hydrogen-assisted cracking in the heat-affected zones of Grades B & D and DH-36. It should be noted that it is not correct to extrapolate the performance of this specific lot of MIL-70S-3 to all lots because MIL-70S-3 electrodes are not conformance tested for diffusible hydrogen.

Navy-Modified WIC Testing of DH-36 and A612 Steels

Welds were deposited at 35-40 kJ/in for the Navy-Modified WIC test to duplicate the welds deposited on large-size plates of 25mm (1in) thick DH-36 and ASTM A612 steels. Results in Table 11 show that the WIC test was not as severe as the large-size restrained welds tested at Electric Boat Corporation. For example, welds deposited by with E71T-1MH8 electrodes producing 6-10ml/100g diffusible hydrogen on 25mm (1in) thick DH-36 (in Table 8) developed HAZ cracking with Electric Boat's test, but, passed the Navy-Modified WIC test. Similarly, welds deposited with E71T-1MH8 electrodes containing 6-10ml/100g hydrogen on 25mm (1in) thick A612 pressure vessel steel required a 107°C (225°F) preheat/interpass temperature to prevent hydrogen-assisted cracking in the HAZ of large-size weldments deposited at Electric Boat Corporation, while the Navy-Modified WIC test required only 79°C (175°F) preheat to prevent cracking. Thus, even though the Navy-Modified WIC test was an extremely economical single pass weldability test, it did not reproduce the cracking developed in the large-size highly restrained welds deposited at Electric Boat Corporation.

Since the maximum restraint in the Navy-Modified WIC test occurs at a 19mm (¾in) to 25mm (1in) thickness⁴⁵, further testing of the 44mm (1.75in) and 64mm (2.5in) thicknesses would not be valid tests. Thickness limitations of small weldability specimens like the WIC specimen and the Tekken specimen are significant drawbacks to these cost-effective tests. The large-size welding tests conducted at Electric Boat Corporation were extremely sensitive to hydrogen-assisted cracking problems; however, they were very costly and time-consuming.



Magnification: X50

Figure 8 Hydrogen-assisted cracking in the heat-affected zone of 44mm (1.75in) thick DH-36 welded by FCAW at 1.6kJ/mm (40kJ/in) using E71T-1MH8 electrodes with 16°C (60°F) preheat/interpass temperature and 80% relative humidity.

Table 5

Comparison of chemical compositions of Grade D steel plate produced by an integrated mill vs 100% scrap mill.

	Grade D ABS & MIL-S-22698	
	Integrated Mill (Bethlehem Steel)	100% Scrap Mill (Lukens Steel)
<u>Specified</u>		
C	0.15	0.10
Mn	1.03	1.00
Si	0.213	0.22
<u>Residuals</u>		
Ni	0.01	
Mo	0.006	0.13
Cr	0.03	0.06
Cu	0.012	0.17
		0.22
Pcm	.21	.18
CE _{IIV}	.33	.34

Table 6

Chemical compositions of weld metal deposited with E71T-1MH8 and E71T-12MJH4 flux cored electrodes and MIL-70S-3 solid electrode on 64mm (2.5in) thick DH-36 using 1.6 kJ/mm (40 kJ/in) heat input.

	DH-36 Base Metal	Weld Metal: MIL-70S-3 (Hobart)	Weld Metal: E71T-1MH8 (Outershield 71-HYM)	Weld Metal: E71T-12MJH4 (Dual Shield II 70T-12H4)
C	0.15	0.088	0.026	0.033
Mn	1.40	1.09	1.30	1.27
Si	0.23	0.5	0.37	0.43
Ni	0.15	0.01	0.44	0.02
Mo	0.06	-	-	-
Cr	0.11	0.02	0.04	0.06
Cu	0.27	0.01	-	0.04
S	0.010	0.009	0.009	0.011
P	0.008	0.012	0.010	0.017
Nb	0.032	0.002	0.019	0.026
V	0.002	-	0.024	0.015
Al	-	0.002	0.017	0.004
Ti	-	-	0.074	0.059
B		0.0006	0.0001	0.0059
Pcm	.25	.16	.12	.12
CE _{IIV}	.45	.28	.29	.27

Table 7

Diffusible Hydrogen assessment per AWS B4.3 for 1.6mm (1/16in) diameter E70T-1MH8 and E71T-12MJH4 flux cored electrodes and MIL-70S-3 electrode.

Electrode	Conditions of Testing	Contact Tip to Work Distance mm (in)	Diffusible H ml/100g	Average Diffusible H ml/100g
E71T-1MH8 (Outershield E71-HYM)	Freshly opened spool; Welded in: 80% Rel. Humidity Preheat: 16°C (60°F)	19 ()	4.8, 4.5, 5.4	4.9
		13 ()	10.0, 10.6, 8.8, 6.9	9.1
	Freshly opened spool; Welded in Lab: No control over humidity; Preheat: RT	19 ()	8.0, 7.8, 7.3, 5.1	7.1
		13 ()	10.8, 9.2, 9.0, 11.2	10.1
	Electrode exposed to 80% Rel. Humidity for one week; Welded in: 80% Rel. Humidity; Preheat: 16°C (60°F)	19 ()	6.7, 6.6, 8.7, 4.8	6.7
		13 ()	6.0, 7.5, 6.1, 6.9	6.6
E71T-12MJH4 (Dual Shield II 70T-12H4)	Freshly opened spool; Welded in: 80% Rel. Humidity Preheat: 16°C (60°F)	13 ()	6.0, 4.0, 3.6, 4.3	4.5
MIL-70S-3 (Hobart)	Freshly opened spool; Welded in: 80% Rel. Humidity Preheat: 16°C (60°F)	16 ()	5.2, 4.0, 5.2, 5.3	4.9

Table 8

FCAW: Weldability testing at 40kJ/in Using E71T-1MH8 (Outershield 71HYM) producing 6-10ml/100g diffusible hydrogen; and, inspected by MP, UT, enhanced UT, and metallographic sectioning

Preheat & Interpass Temperature ° C (° F)	Grades B & D ABS & MIL-S-22698 (Plate Pcm)	DH-36 ABS & MIL-S-22698 (Plate Pcm)	A612 ASTM (Plate Pcm)
<u>25mm (1in) Thick</u> 16 (60) 52 (125) 79 (175) 107 (225)	(0.21 Pcm) Pass	(0.24 Pcm) HAZ Cracking* Pass	(0.34 Pcm) HAZ Cracking HAZ Cracking HAZ Cracking Pass
<u>44mm (1.75in) Thick</u> 16 (60) 52 (125) 79 (175) 107 (225) 135 (275)	(0.18 Pcm) Pass	(0.24 Pcm) HAZ Cracking Pass	(0.34 Pcm) HAZ Cracking HAZ Cracking HAZ Cracking HAZ Cracking Pass
<u>64mm (2.5in) Thick</u> 16 (60) 52 (125) 79 (175) 107 (225) 135 (275)	(0.21 Pcm) Pass	(0.25 Pcm) HAZ Cracking HAZ Cracking HAZ Cracking Pass	(0.34 Pcm) HAZ Cracking HAZ Cracking HAZ Cracking HAZ Cracking Pass

* HAZ cracking found by Electric Boat's "house test", but not detected by UT.

Table 9

Low-hydrogen FCAW: Weldability testing at 40kJ/in using E71T-12MJH4 (Dual Shield II 70T-12H4) producing 4-5 ml/100g diffusible hydrogen; and, inspected by MP, UT, enhanced UT and metallographic sectioning

Preheat & Interpass Temperature °C (°F)	Grades B & D per ABS & MIL-S-22698 (Plate Pcm)	DH-36 per ABS & MIL-S-22698 (Plate Pcm)
<u>25mm (1in) Thick</u> 16 (60) 52 (125)	(0.21 Pcm) Pass	(0.24 Pcm) Pass
<u>44mm (1.75in) Thick</u> 16 (60) 52 (125) 79 (175)	(0.18 Pcm) Pass	(0.24 Pcm) Pass* Pass
<u>64mm (2.5in) Thick</u> 16 (60) 52 (125) 79 (175)	(0.21 Pcm) Pass	(0.25 Pcm) HAZ Cracking Pass
* Detected a single 0.25mm (.01in) HAZ crack in 1 of 4 "House Tests" by EB Corp.		

Table 10

GMAW-P: Weldability testing at 40kJ/in Using MIL-70S-3 (4-5 ml/100g diffusible hydrogen) inspected by MP, UT, enhanced UT and metallographic sectioning

Preheat & Interpass Temperature °C (°F)	Grades B & D per ABS & MIL-S-22698 (Plate Pcm)	DH-36 per ABS & MIL-S-22698 (Plate Pcm)
<u>25mm (1in) Thick</u> 16 (60) 52 (125)	(0.21 Pcm) Pass	(0.24 Pcm) Pass
<u>44mm (1.75in) Thick</u> 16 (60) 52 (125)	(0.18 Pcm) Pass	(0.24 Pcm) Pass
<u>64mm (2.5in) Thick</u> 16 (60) 52 (125) 79 (175)	(0.21 Pcm) Pass	(0.25 Pcm) HAZ Cracking Pass

Table 11

Comparison of preheating temperatures necessary to prevent hydrogen-assisted cracking in flux cored welds deposited on WIC test weldability specimens vs. large-size rigidly-restrained plates welded at Electric Boat Corporation.

Steel	FCAW Electrode	Diff. Hydrogen ml/100g	Thickness mm (in.)	Preheat & Interpass Temp. °C (°F)	WIC Test	Large-size Weld Tests*
DH-36	E71T-1MH8	6-10	25 (1)	16 (60)	Crack-free	HAZ cracking
DH-36	E71T-12MJH4	4-5	25 (1)	16 (60)	Crack-free	Crack-free
A612	E71T-1MH8	6-10	25 (1)	52 (125)	HAZ cracking	HAZ cracking
A612	E71T-1MH8	6-10	25 (1)	79 (175)	Crack-free	HAZ cracking
A612	E71T-1MH8	6-10	25 (1)	107 (225)	Crack-free	Crack-free

* Tests reported in Tables 8 and 9.

COMPARING PREHEAT ALGORITHMS WITH EXPERIMENTAL RESULTS

In this section, several current algorithms will be used to predict the preheating/interpass temperatures for welds deposited on each of the nine plates that were tested for weldability at Electric Boat Corporation (listed in Table 2). In this way, a direct comparison can be made between the calculated and experimentally determined preheating temperatures necessary to prevent hydrogen-assisted cracking.

The first preheat prediction algorithm is that of Yurioka et al⁴³ predicts the required preheat/interpass temperatures for butt welds. To determine the necessary preheat/interpass temperatures for FCAW assuming an average diffusible hydrogen level of 8ml/100g for the large-size steel plates used in this investigation, the carbon equivalent, CEN in Equation (3), is calculated first for each of the nine steel plates (in Table 2). From Equation (4), the cracking index, CI, is calculated:

$$CI = CEN + 0.15 \log H_{JIS} + 0.30 \log(0.017 \kappa_t \sigma_w) \quad \text{Equation (4)}$$

where:

$$\begin{aligned} H_{IIW} &= 1.27H_{JIS} + 2.19 = 8\text{ml}/100\text{g diffusible hydrogen} \\ \kappa_t &= 3.5 \text{ for double V groove} \\ \sigma_w (\text{butt}) &= \sigma_y + 0.0025 (R_F - 20 \sigma_y) \text{ for high restraint welds} \\ R_F &= 4970\{\arctan(0.017h) - (h/400)^2\} \end{aligned}$$

After CI is calculated for each of the nine steels in Table 2, the critical weld cooling times, $t_{100(\text{cr})}$, for each steel can then be calculated using Equation (5):

$$t_{100(\text{cr})} = \exp(68.05CI^3 - 181.77CI^2 + 163.8CI - 41.65) \quad \text{Equation (5)}$$

The condition predicted to prevent hydrogen-assisted cracking is when the actual cooling time to 100°C, t_{100} , is equal to or greater than the critical weld cooling time, as shown below:

$$t_{100} \geq t_{100(\text{cr})}$$

Using the empirical data in the Welding Note⁴³ relating preheat temperature to $t_{100(\text{cr})}$ for different heat input levels, ambient temperatures, and width of strip heaters, the preheating temperatures to prevent hydrogen assisted cracking for all nine steels have been calculated and are presented in Table 12.

Table 12

Calculation of minimum preheating temperature of butt welds in large-size plates (using the “Welding Note” by Yurioka et al⁴³) for different thicknesses, 8ml/100g diffusible hydrogen, using FCAW and GMAW at 1.6kJ/mm (40kJ/in) heat input.

	Grade B & D ABS & MIL-S-22698			DH-36 ABS & MIL-S-22698			A612 (ASTM)		
	1in	1.75in	2.5in	1in	1.75in	2.5in	1in	1.75in	2.5in
C	0.16	0.10	0.15	0.14	0.14	0.15	0.24	0.24	0.24
Mn	0.84	1.00	1.03	1.31	1.36	1.40	1.42	1.42	1.42
Si	0.20	0.22	0.213	0.22	0.23	0.23	0.28	0.28	0.28
Ni	0.02	0.13	0.01	0.16	0.15	0.15	0.19	0.19	0.19
Mo	0.02	0.06	0.006	0.04	0.05	0.06	0.04	0.04	0.04
Cr	0.02	0.17	0.03	0.13	0.16	0.11	0.09	0.09	0.09
Cu	0.03	0.22	0.012	0.26	0.22	0.27	0.22	0.22	0.22
Nb	-	-	-	0.029	0.036	0.032	-	-	-
V	-	-	-	-	0.005	-	0.03	0.03	0.03
CEN	.31	.26	.32	.39	.40	.42	.54	.54	.54
Yield Str. (MPa)	262	283	296	414	372	379	441	441	441
Preheat Temp: °C (°F)									
Normal restraint	<0 (<32)	<0 (<32)	80 (176)	65 (149)	85 (185)	130 (266)	170 (338)	185 (365)	210 (410)
Severe restraint	<0 (<32)	<0 (<32)	105 (221)	80 (176)	110 (230)	145 (293)	195 (383)	205 (400)	220 (428)

The Chart Method of Yurioka and Kasuya²⁹⁻³⁰ of Nippon Steel retains the precision and rigor of the Welding Note⁴³ without complex mathematics. To calculate the minimum preheating temperatures for all nine plates (listed in Table 2) by the chart method²⁹⁻³⁰, the CEN value for each steel plate has to be calculated first by substituting the plate compositions into Equation (3). Knowing the CEN values, heat input (Q), ambient temperature (T_o), and thickness (h) of each steel plate, the necessary preheat temperature can be looked up by the Chart Method directly for:

$$\begin{aligned}
 H_{IIW} &= 5\text{ml}/100\text{g} \text{ and also for } 8\text{ml}/100\text{g} \\
 h &= 25\text{mm (1in)}, 44\text{mm (1.75in)} \text{ and } 64\text{mm (2.5in)} \\
 Q &= 1.7\text{kJ}/\text{mm} \\
 T_o &= 10^\circ\text{C (50}^\circ\text{F)}
 \end{aligned}$$

Reasonable preheating temperatures necessary to prevent hydrogen-assisted cracking in butt welds are predicted by the Chart Method and are presented in Table 13 for two levels of diffusible hydrogen (5 and 8ml/100g). If the H_{IIW} is different than 5ml/100g, a correction chart provides an increment to the CEN value to compensate for the different H_{IIW} value. Similarly, if the heat

input, Q, is different from 1.7kJ/mm, another correction chart provides an increment to CETN to compensate for the difference. If the restraint is “ordinary” or high, the correction chart is available to make that correction. The calculated preheating temperatures (in Table 13) to prevent hydrogen-assisted cracking for the nine large-size plates are in good agreement with the actual welds deposited on large-size plates (in Tables 7-9) at Electric Boat Corporation.

Uwer and Hohne^{40,41} take into account CET carbon equivalent from Equation (7), hydrogen content, plate thickness and heat input to calculate preheating temperatures for butt welds in Equation (6). Their equation^{40,41} for the critical preheating temperature necessary to prevent hydrogen-assisted cracking (T_{cr}) for butt welds is:

$$T_{cr} = 700 + 160 \tanh(h/35) + 62 H_{IIW}^{0.35} + (53 \text{ CET} - 32)Q - 330 \quad \text{Equation (6)}$$

Using Equation (6), the critical preheating temperatures to prevent hydrogen-assisted cracking for each steel composition have been calculated and are presented in Table 14. In this table, welds were deposited by FCAW and GMAW on Grades B/D, DH-36 and ASTM 612 with a diffusible hydrogen level of 4-5ml/100g and 1.6kJ/mm heat input. For example, 25mm (1in) thick DH-36 would require a preheating temperature of 75°C (167°F) according to Uwer and Hohne^{40,41}. This algorithm is clearly too conservative since only the 64mm (2.5in) thick DH-36 was susceptible to cracking at the 4-5ml/100g level of diffusible hydrogen.

Table 13

Chart Method (Yurioka and Kasuya²⁹⁻³⁰) to calculate preheating temperatures of butt welds deposited at 1.6kJ/mm (40kJ/in) using FCAW with E71T-1MH8 electrodes (8ml/100g diffusible hydrogen), and also low-hydrogen FCAW and GMAW with E71T-12MJH4 and MIL-70S-3 electrodes, respectively, with 5ml/100g diffusible hydrogen.

	Grade B & D ABS & MIL-S-22698			DH-36 ABS & MIL-S-22698			A612 (ASTM)		
	1in	1.75in	2.5in	1in	1.75in	2.5in	1in	1.75in	2.5in
CEN	.31	.26	.32	.39	.40	.42	.54	.54	.54
H_{IW} = 8ml/100g:									
Yield Str. (MPa)	262	283	296	414	372	379	441	441	441
Initial T _{cr} (°C)	<0	<0	75	78	124	151	170	182	195
CEN Increments:									
H _{IW} (8ml/100g)	+0.04	+0.04	+0.04	+0.04	+0.04	+0.04	+0.04	+0.04	+0.04
Q	0	0	0	0	0	0	0	0	0
Corrected CEN	.35	.30	.36	.43	.44	.46	.58	.58	.58
Corrected T _{cr} (°C)	40	35	110	110	145	170	185	200	210
Restraint :									
Normal	-75°	-75°	-75°	-62°	-72°	-70°	-60°	-60°	-60°
High	-25°	-25°	-25°	-23°	-24°	-24°	-20°	-20°	-20°
Preheat Temp:									
Ordinary restraint	none	none	35	48	73	100	125	140	150
°C (°F)			(95)	(118)	(163)	(212)	(257)	(284)	(300)
High restraint	15	10	85	87	121	146	165	180	190
°C (°F)	(59)	(50)	(185)	(189)	(250)	(294)	(329)	(356)	(374)
H_{IW} = 5ml/100g:									
Yield Str. (MPa)	262	283	296	414	372	379	441	441	441
Initial T _{cr} (°C)	<0	<0	75	78	124	151	170	182	195
CEN Corrections:									
H _{IW}	0	0	0	0	0	0	0	0	0
Q	0	0	0	0	0	0	0	0	0
Restraint:									
Ordinary	-75	-75	-75	-62	-72	-70	-60	-60	-60
High	-25	-25	-25	-23	-24	-24	-20	-20	-20
Preheat Temp:									
Ordinary restraint	<0	<0	<0	15	51	79	110	122	135
°C (°F)	(<32)	(<32)	(<32)	(59)	(124)	(174)	(230)	(252)	(275)
High restraint	<0	<0	50	55	100	126	150	162	175
°C (°F)	(<32)	(<32)	(122)	(131)	(212)	(259)	(259)	(324)	(347)

Table 14

Calculation of preheating temperatures for butt welds using the method of Uwer and Hohne^{40,41} for different thicknesses, 5ml/100g diffusible hydrogen using FCAW and GMAW at 1.6kJ/mm (40kJ/in) heat input.

	Grade B & D ABS & MIL-S-22698			DH-36 ABS & MIL-S-22698			A612* (ASTM)		
	1in	1.75in	2.5in	1in	1.75in	2.5in	1in	1.75in	2.5in
CET	.25	.23	.26	.30	.30	.32	.41	.41	.41
Preheat/Interpass Temperature, T _{cr} °C (°F) min.	21 (70)	43 (109)	80 (176)	75 (167)	102 (216)	129 (264)	144 (291)	182 (360)	198 (388)
* ASTM 612 is not specifically listed in MIL-STD-278, but, is may be used if quality assurance and inspection.									

Table 15

Preheating temperature calculations for butt welds using the Hydrogen Control Method, D1.1 Structural Welding Code⁴². FCAW at 1.6kJ/mm (40kJ/in) with 6-10ml/100g diffusible hydrogen (assuming 8ml/100g average).

	Grade B & D ABS & MIL-S-22698			DH-36 ABS & MIL-S-22698			A612 (ASTM)		
	1in	1.75in	2.5in	1in	1.75in	2.5in	1in	1.75in	2.5in
Pcm	.21	.18	.21	.24	.24	.25	.34	.34	.34
CE _{AWS}	.35	.37	.37	.46	.47	.48	.58	.58	.58
H _{IHW} (8ml/100g) Index Grouping	H2 C	H2 B	H2 C	H2 D	H2 D	H2 D	H2 F	H2 F	H2 F
Preheat, °C (°F) Restraint:									
Low	18 (65)	18 (65)	38 (100)	79 (175)	93 (200)	93 (200)	138 (280)	138 (280)	138 (280)
Normal	74 (165)	79 (175)	110 (230)	110 (230)	129 (265)	129 (265)	149 (300)	149 (280)	149 (280)
High	116 (240)	129 (265)	149 (300)	138 (280)	149 (300)	149 (300)	160 (320)	160 (280)	160 (280)

Table 16

Calculation of preheating temperatures for butt welds using MIL-STD-278⁴⁶ for different thicknesses, 5ml/100g diffusible hydrogen using FCAW and GMAW at 1.6kJ/mm (40kJ/in).

	Grade B & D ABS & MIL-S-22698			DH-36 ABS & MIL-S-22698			A612* (ASTM)		
	1in	1.75in	2.5in	1in	1.75in	2.5in	1in	1.75in	2.5in
P _{cm}	.21	.18	.21	.24	.24	.25	.34	.34	.34
CEN	.31	.26	.32	.39	.40	.42	.54	.54	.54
CE _{IIW}	.31	.34	.33	.42	.43	.45	.54	.54	.54
Preheat/Interpass Temperature, T _{cr}	16°C (60°F) min.	16°C (60°F) min.	16°C (60°F) min.	16°C (60°F) min.	16°C (60°F) min.	16°C (60°F) min.	16°C (60°F) min.	16°C (60°F) min.	16°C (60°F) min.

ASTM 612 is not specifically listed in MIL-STD-278, but, is may be used if quality assurance and inspection requirements are established by the contractor and submitted to NAVSEA for approval.

The ANSI/AWS D1.1-98 Structural Welding Code⁴² specifies minimum preheating temperatures for butt welds for shipbuilding steels including ABS Grades B/D and DH-36 steels. Using the “hydrogen control” method, the minimum preheating temperatures for all nine steels tested have been calculated and are presented in Table 15 for a diffusible hydrogen level of 6-10ml/100g, according to the hydrogen control method. Clearly, the Hydrogen Control Method is too conservative because of the very high preheating temperatures that are predicted.

The military standard, MIL-STD-278⁴⁶, specifies minimum preheating and interpass temperatures for shipbuilding steels such as ABS & MIL-S-22698 Grades B/D and DH-36. In this document, the minimum required preheat and interpass temperature (T_{cr}) for Grades B/D, DH-36 and even ASTM A612 is:

$$T_{cr} = 16^{\circ}\text{C} (60^{\circ}\text{F}) \text{ minimum}$$

as shown in Table 16 for steels. However, if both carbon content of the base metal is greater than 0.3% and thickness exceeds 25mm (1in), the minimum required preheat/interpass temperature is raised to:

$$T_{cr} = 175^{\circ}\text{F} (80^{\circ}) \text{ minimum}$$

unless otherwise approved by the welding procedure qualification. MIL-STD-1689⁴⁷ has similar preheating requirements to MIL-STD-278, except that when carbon content exceeds 0.30%, the preheating temperature will be established in procedure qualification tests.

The great danger in using either MIL-STD-278 or MIL-STD-1689 is the temptation to avoid preheating in butt and fillet welds. These military codes are not conservative enough. For example, ASTM A612 in thicknesses of 25mm and above has been shown to crack readily without preheating from Table 8. Yet, the minimum preheating temperature allowed in Table 16 is only 16°C, which will likely produce hydrogen-assisted cracking in the HAZ of the A612 plates.

AWS D14.3⁴⁹ has far more rigorous preheating requirements than do the military specifications (MIL-STD-278 and MIL-STD-1689). In AWS D14.3, steels are classified according to strength, carbon equivalent, and carbon content. For example:

ABS Grade B and D are Class II steels because:

- Minimum yield strength is 35-55ksi
- Carbon equivalent $(C+Mn/6+Ni/20+Cr/10-Mo/40-V/10)$ does not exceed 0.48
- C and Mn contents do not exceed 0.30 and 1.35, respectively.

ABS DH-36 is a class III steel because:

- Minimum yield strength is 40-55ksi
- Carbon equivalent $CE_{D14.3}$ does not exceed 0.63
where: $CE_{D14.3} = C+Mn/6+Ni/20+Cr/10-Mo/40-V/10$
- C, Mn, Cr, Ni, Mo & Nb contents do not exceed 0.24, 1.35, 1, 1.25, .25, & .04 respectively.

ASTM A612 pressure vessel steel is a class IV steel because:

- Minimum yield strength is 60-65ksi
- Carbon equivalent $(C+Mn/6+Ni/20+Cr/10-Mo/40-V/10)$ does not exceed 0.63

A612 is not specifically listed in D14.3, but qualifies for a Class IV high strength steel. Preheating temperatures specified in Table 17 are for prequalified welding procedures for ordinary restraint. When exceptionally high restraint is encountered, D14.3 recommends higher preheating temperatures than those specified in Table 17, but, does not specify exact minimum preheating temperatures.

In comparing minimum preheating temperatures predicted by AWS D14.3 in Table 17 with those from experimental welds in Table 8, AWS D14.3 is also too conservative.

For example, D14.3 requires Grades B and D to be preheated for all thicknesses in excess of 25mm (1in), yet corresponding experimental welds did not require preheating above 16°C (60°F) even for diffusible hydrogen levels of 6-10 ml/100g.

Table 17

Calculation of minimum preheating temperature for butt welds tested (using AWS D14.3⁴⁹) for different thicknesses, 5ml/100g diffusible hydrogen using FCAW and GMAW at 1.6kJ/mm (40kJ/in).

	Grade B & D ABS & MIL-S-22698			DH-36 ABS & MIL-S-22698			A612 (ASTM)		
	1in	1.75in	2.5in	1in	1.75in	2.5in	1in	1.75in	2.5in
CE _{D14.3}	.16	.20	.33	.38	.39	.40	.49	.49	.49
D14.3 Weldability Class	II	II	II	III	III	III	IV	IV	IV
Preheat Temp. °C (°F)	10 (50)	65 (150)	65 (150)	10 (50)	65 (150)	65 (150)	65 (150)	105 (225)	105 (225)

NEED FOR CHANGES IN THE MILITARY WELDING CODES

Clearly, there is a need for the military codes MIL-STD-278 and MIL-STD-1689 to reflect the actual cracking susceptibilities of ABS & MIL-S-22698 Grades B/D, DH-36 and other shipbuilding steels. The problem in using either MIL-STD-278 or MIL-STD-1689 is that these codes allow the welding of shipbuilding steels over 25mm (1in) thick in butt or fillet configurations with preheat levels that may be too low. For example, both military codes permit 64mm (2.5in) thick DH-36 to be welded with only 16°C (60°F) preheat (see Table 16), which is inadequate based on the test results reported herein. Based on the results of this investigation, 64mm (2.5in) thick DH-36 would crack when welded by either FCAW or GMAW. In addition, the military codes do not adequately take into account the level of diffusible hydrogen involved in the welding procedure. Thus, the military codes are not conservative enough. There needs to be a minimum preheat table created for these steels over 25mm (1in) thick.

In February 1998, the commander of NAVSEA⁷⁶ addressed this problem by issuing a precautionary letter to the appropriate group(s) at private shipyards, NAVSHIPYDS, SUPSHIPS, SEA and PMS concerning Hydrogen-Related Cracking of High Restraint Welds in Structural Steels. In particular, mandatory preheating temperatures for welding of thick ABS & MIL-S-22698 Grades B/D, DH-36 and other Naval steels were addressed. The letter states that NAVSEA 03M2 will update NAVSEA Technical Publications, MIL-STD-278, MIL-STD-1688 and MIL-STD-1689; and, revise as necessary to assure weld quality and avoid cracking problems in structural steels during ship construction and maintenance. In reference 76, design and welding engineering activities are reminded of the need to recognize and consider specific weld constraint, heat sink, and materials composition conditions in determining structural designs as well as weld and inspection parameters. D1.1-96 Structural Welding Code - Steel was referenced for guidance for preheat based on constraint and carbon equivalent of the base materials, and may be used for additional guidance on welding HSS and MS materials. Typical preheating temperatures for thick ABS & MIL-S-22698 Grades B/D, DH-36 using AWS D1.1-96 (hydrogen control method) is given in Table 15. In this table, preheating for thick section HSS is clearly required. It should also be noted that the two shipyards which weld almost all of the HSS materials over 25mm (1 inch) thick have changed their procedures to require the necessary preheat.

In the next section, the best algorithm for predicting minimum preheat temperatures will be determined based on weldability tests conducted on large-size plates in this study. Using this algorithm, more reasonable preheating temperatures can be predicted than those specified in military codes.

PREDICTION OF HYDROGEN-ASSISTED CRACKING OF EXPERIMENTAL WELDS

In the previous sections, several preheat algorithms were presented, and critical preheat temperatures required to prevent hydrogen-assisted cracking were compared to experimental results from welds deposited on large-size plates of ABS & MIL-S-22698 Grades B/D, DH-36 and ASTM A612 steels. Based on these comparisons, it is now possible to select and/or modify an existing algorithm to best fit the experimental data generated on large-size plates. The Chart Method²⁹⁻³⁰ and its latest revisions^{31&50} provide the best and most efficient method to calculate preheat/interpass temperatures for welding shipbuilding steels.

When the Chart Method is applied to the welds deposited on ABS & MIL-S-22698 Grades B/D, DH-36 and ASTM A612 steels, very good correlation is achieved between the predicted preheating temperatures to prevent hydrogen-assisted cracking and the experimentally determined preheating temperatures. The experimentally determined preheating temperatures are shown in Tables 8, 9 and 10 for FCAW with E71T-1MH8 electrodes, low-hydrogen FCAW with E71T12MJH4 electrodes, and GMAW-P with MIL-70S-3 electrodes, respectively. The predicted preheat temperatures to prevent hydrogen-assisted cracking using the “Welding Note” method and the Chart Method are shown in Tables 12 and 13, respectively. Comparison of Tables 12 and 13 with Tables 8, 9 and 10 shows that there is good correlation between the calculated minimum preheat temperatures and the experimentally determined minimum preheat temperatures.

When using the Chart Method, the “ordinary restraint” chart must always be used. These preheat calculations match very well with the experimental welds deposited on large-size plates. The most severe level of restraint is reserved for repair welding on thick plate. Tables 18, 19 and 20 compare experimentally determined minimum preheat temperatures to those calculated using the Chart Method (using “ordinary restraint”) for FCAW with 6-10ml/100g diffusible hydrogen, FCAW with 4-5ml/100g diffusible hydrogen and GMAW-P with 4-5ml/100g diffusible hydrogen, respectively.

The Chart Method is still slightly conservative, for safety. For example, in Table 18, the Chart Method predicts that the HAZ of 44mm (1.75in) thick DH-36 welded by FCAW with 6-10ml/100g diffusible hydrogen should exhibit hydrogen-assisted cracking at the preheating temperature of 52°C (125°F). However, the experimental welds generated at Electric Boat Corporation did not crack. In a second example; also from Table 18, the Chart Method predicts that the HAZ of 44mm (1.75in) thick A612 welded by FCAW with 6-10ml/100g diffusible hydrogen should exhibit hydrogen-assisted cracking even when preheated to 135°C (275°F).

Table 18

Comparing preheating temperatures necessary to prevent hydrogen-assisted cracking for FCAW with experimental welds performed at Electric Boat Corporation using 40kJ/in and E71T-1MH8 (Outershield 71HYM) containing 6-10ml/100g diffusible hydrogen; and, inspected by MP, UT, enhanced UT, and metallographic sectioning.

Preheat & Interpass Temperature °C (°F)	Grades B & D ABS & MIL-S-22698		DH-36 ABS & MIL-S-22698		A612 ASTM	
	Chart Method	Experiment	Chart Method	Experiment	Chart Method	Experiment
<u>25mm (1in) Thick</u> 16 (60) 52 (125) 79 (175) 107 (225) 135 (275)	(0.21Pcm) Pass Pass		(0.24 Pcm) Crack Crack* Pass Pass		(0.34 Pcm) Crack Crack Crack Crack Crack Crack Crack Pass Pass	
<u>44mm (1.75in) Thick</u> 16 (60) 52 (125) 79 (175) 107 (225) 135 (275) 163 (325)	(0.18 Pcm) Pass Pass		(0.24 Pcm) Crack Crack Crack Pass Pass		(0.34 Pcm) Crack Crack Crack Crack Crack Crack Crack Crack Crack Pass Pass	
<u>64mm (2.5in) Thick</u> 16 (60) 52 (125) 79 (175) 107 (225) 135 (275) 163 (325)	(0.21 Pcm) Crack Pass Pass		(0.25 Pcm) Crack Crack Crack Crack Crack Crack Pass Pass		(0.34 Pcm) Crack Crack Crack Crack Crack Crack Crack Crack Crack Pass Pass	
* HAZ cracking found by Electric Boat's "house test" and not detected by UT.						

Table 19

Comparing preheating temperatures necessary to prevent hydrogen-assisted cracking for low-hydrogen FCAW with experimental welds performed at Electric Boat Corporation using 40kJ/in and E71T-12MJH4 (Dual Shield II 70T-12H4) containing 4-5 ml/100g diffusible hydrogen; and, inspected by MP, UT, enhanced UT and metallographic sectioning.

Preheat & Interpass Temperature °C (°F)	Grades B & D ABS & MIL-S-22698		DH-36 ABS & MIL-S-22698	
	Chart Method	Experiment	Chart Method	Experiment
<u>25mm (1in) Thick</u> 16 (60) 52 (125) 79 (175)	(0.21 Pcm) Pass Pass		(0.24 Pcm) Pass Pass	
<u>44mm (1.75in) Thick</u> 16 (60) 52 (125) 79 (175)	(0.18 Pcm) Pass Pass		(0.24 Pcm) Crack Pass* Pass Pass	
<u>64mm (2.5in) Thick</u> 16 (60) 52 (125) 79 (175)	(0.21 Pcm) Pass Pass		(0.25 Pcm) Crack Crack Crack Pass Pass	
* Detected a single 0.25mm (.01in) HAZ cracking 1 of 4 "House Tests" by EB Corp.				

Table 20

Comparing preheating temperatures necessary to prevent hydrogen-assisted cracking for low-hydrogen GMAW (pulsed) with experimental welds performed at Electric Boat Corporation using 40kJ/in and MIL-70S-3 electrode containing 4-5 ml/100g diffusible hydrogen; and, inspected by MP, UT, enhanced UT and metallographic sectioning

Preheat & Interpass Temperature °C (°F)	Grades B & D ABS & MIL-S-22698		DH-36 ABS & MIL-S-22698	
	Chart Method	Experiment	Chart Method	Experiment
<u>25mm (1in) Thick</u> 16 (60) 52 (125)	(0.21 Pcm) Pass Pass		(0.24 Pcm) Pass Pass	
<u>44mm (1.75in) Thick</u> 16 (60) 52 (125) 79 (175)	(0.18 Pcm) Pass Pass		(0.24 Pcm) Crack Pass Pass	
<u>64mm (2.5in) Thick</u> 16 (60) 52 (125) 79 (175)	(0.21 Pcm) Pass Pass		(0.25 Pcm) Crack Crack Crack Pass Pass	

However, the experimental data generated at Electric Boat Corporation shows no evidence of hydrogen-assisted cracking in the HAZ when preheated at 135°C (275°F). Tables 19 and 20 show additional examples where the Chart Method accurately (although somewhat conservatively) predicts cracking behavior compared to the experimental welds.

Thus, the Chart Method successfully predicts hydrogen-assisted cracking behavior in the HAZ's of highly restrained welds deposited on large-size ABS & MIL-S-22698 Grades B/D and DH-36 and ASTM A612 steel plates as long as "ordinary restraint" charts are used. The model is slightly conservative to allow safety from cracking, but not so conservative that welding becomes too expensive.

METHOD FOR REDUCING PREHEAT FOR GRADES B, D AND DH-36

A major objective of this project was to find a method to eliminate preheating above 16°C (60°F). There are three fundamental approaches to reduce and possibly eliminate preheating above 16°C (60°F) in Grades B, D and DH-36.

- Limit Pcm by lowering carbon, but increasing Mn and/or Mo to maintain specified strength,
- Maintain welding heat input above a critical level, and
- Maintain diffusible hydrogen below a critical level.

Grades B and D per ABS & MIL-S-22698:

Weldability tests on large-size plates show that ABS & MIL-S-22698 Grades B and D are not susceptible to hydrogen-assisted cracking in thicknesses up to 64mm (2.5in) or for any thickness, when:

- Diffusible H does not exceed 6-10ml/100g
- Pcm does not exceed 0.21
- Heat input is 1.6kJ/mm (40kJ/in) or greater.

If ABS & MIL-S-22698 Grades B and D are purchased with Pcm values not-to-exceed 0.21, crack-free heat affected zones are likely in any thickness as long as a reasonable low-hydrogen welding procedures are used.

DH-36 per ABS & MIL-S-22698:

DH-36 can be welded without additional preheating above 16°C (60°F), if:

- Pcm is lowered by reducing carbon, but increasing Mn and/or Mo to maintain the specified strength of DH-36 (51ksi yield strength),
- Heat input is maintained above a critical level, and
- Diffusible hydrogen does not exceed H4 level.

Regarding the composition of DH-36, ABS Rules specifies the following ranges:

C	.18max
Mn	.90 - 1.60
Nb	.02 - .05
Cr	.2max
Ni	.4
Mo	.08
Cu	.35

If the Pcm value for DH-36 is lowered from the 0.24-0.25 (Table 2) used in this investigation to a level of 0.21, DH-36 should be as resistant to hydrogen-assisted cracking as Grades B and D. For example, the composition of 25mm (1in) thick DH-36 in Table 2 contains .14C-1.31Mn-.029Nb-residuals. In review of the Pcm equation (below), reducing carbon to 0.10% and adding sufficient Mn +Cr+ Mo to retain required strength can result in a substantial reduction in Pcm value.

$$P_{cm} = C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B \quad \text{Equation (1)}$$

While this approach is valid, the cost of DH-36 would certainly increase because alloying elements are more expensive than carbon.

Heat input augmentation can also eliminate preheat above 16°C (60°F) even with the 0.24-0.25 Pcm levels, according to the Chart Method. For example, increasing the heat input from the 40kJ/in to above 70kJ/in would be equivalent to reducing Pcm to approximately 0.21(similar to Grades B and D) making DH-36 weldable without preheat above 16°C (60°F) for all thicknesses. However, welding at higher minimum heat input levels is not always practical in shipyard welding, because of the large variety of position/thickness/groove geometry/accessibility combinations. In addition, specification of a minimum heat input requirement in place of the traditional “no minimum” heat input requirement imposes an additional process control on welding which might be challenging and costly to implement and maintain.

Diffusible hydrogen reduction can greatly lower required preheat, according to the Chart Method. For example, reduction of diffusible hydrogen from 8 to less than 4ml/100g is equivalent to reducing Pcm of DH-36 to 0.21 (similar to Grades B and D). If GMAW with solid electrodes can produce weld deposits with less than 4ml/100g diffusible hydrogen, it is likely that crack-free welds can be made in all thicknesses with DH-36. However, it must be recognized that diffusible hydrogen is not a material property but a characteristic that is highly dependent on the cleanliness of the materials used, the welding conditions, technique applied, and the prevailing atmospheric conditions. Therefore, depending on a certain maximum diffusible hydrogen content in a production weld to assure crack-free welding is not guaranteed. The recommended minimum preheat temperatures should be on the conservative side to account for actual diffusible hydrogen in production welds possibly being higher than in laboratory welds.

The practical solution to welding DH-36 without preheat above 16°C (60°F) may be a compromise using all three approaches. For example, by limiting Pcm to 0.23, limiting diffusible hydrogen to less than 4ml/100g (as in GMAW

with minimal lubricant on the electrode), and augmenting heat input to not less than 50kJ/in, DH-36 would be weldable without preheat in excess of 16°C (60°F) for any thickness.

Preheat Tables for the Shipyards:

Using the Chart Method combined with the data generated in this investigation, quick-reference preheating tables can be created for practical use by shipyards. These simple tables can be created by the welding engineer for use by shop personnel. Possible example of a preheat table for ABS Grades B and D is given in Table 21. The possible preheat table for ABS Grade DH-36 is given in Table 22. The purpose of these tables is to provide a simple means for welding shop personnel to look up preheat/interpass temperatures for the steel and welding process being used. The Pcm limits for Grades B, D and DH-36 would be the responsibility of the procurement engineer. For example, all DH-36 could be purchased to a Pcm limit such as 0.25. Then, the welding shop personnel need only to use a simple table like that shown in Table 22 to weld DH-36. Since the welder will know the thickness, electrode type, heat input and ambient temperature, he/she will be able to selected the correct preheating temperature, if needed. All of the values shown in Tables 21 and 22 meet the requirements of MIL-STD-278 and MIL-STD-1689.

Table 21

Possible example of a quick-reference preheat/interpass temperature table for welding ABS Grades B and D by shop personnel in a shipyard. Welding engineer must make certain that incoming plates of Grades B and D meet a Pcm limit of 0.21 maximum; and, heat input and diffusible hydrogen are considered.

	ABS Gr. B & D		
Process and Electrode(s)	FCAW & GMAW: E71T-1H4 E71T-12H4 MIL-70S-3	FCAW: E71T-1H8	FCAW: E71T-1H8
Thickness	Unlimited	up to 1.75in	>1.75in
Minimum Preheat/Interpass Requirement	16°C (60°F)	None	125F

Table 22

Possible example of a quick-reference preheat/interpass temperature table for welding ABS Grade DH-36 by shop personnel in a shipyard. Welding engineer must make certain that incoming plates of DH-36 meet a Pcm limit of 0.25 maximum; and, heat input and diffusible hydrogen are considered.

	ABS Grade DH-36		
Process and Electrode(s)	FCAW & GMAW: E71T-1H4 E71T-12H4 MIL-70S-3	FCAW: E71T-1H8	FCAW: E71T-1H8
Thickness	up to 1in	>1in to 1.75in	>1.75in
Minimum Preheat/Interpass Requirement	16°C (60°F)	52°C (125°F)	79°C (175°F)

CONCLUSIONS

In comparing predicted (from the literature) and experimentally-determined preheat/interpass temperatures necessary to prevent hydrogen-assisted cracking in the HAZ of butt welds deposited by FCAW with E71T-1MH8, FCAW with low-hydrogen E71T-12MJH4, and pulsed GMAW with MIL-70S-3 electrodes on large-size 25mm (1in), 44mm (1.75in) and 64mm (2.5in) thick ABS & MIL-S-22698, Grades B/D, DH-36 and ASTM A612, the following can be concluded:

- Current military welding codes, such as MIL-STD-278 and MIL-STD-1689, do not specify adequate minimum preheat temperatures for the above steels. There is no question that revised minimum preheat tables or charts need to replace current military code requirements.
- The Chart Method developed by Yurioka and Kasuya with the latest 1995 revisions provides the best prediction for hydrogen-assisted cracking in shipbuilding steels, such as DH-36. Reasonable preheating temperatures necessary to prevent hydrogen-assisted cracking in the HAZ's of welds can be determined using charts instead of complex mathematics, if the following are known: heat input, plate thickness, plate composition, and diffusible hydrogen.
- Pcm limits can be established to eliminate additional preheating above 16°C (60°F) for Grades B, D and DH-36 using the Chart Method, provided the diffusible hydrogen, plate thickness, and heat input are taken into account.
- Quick-reference preheating tables can be created for practical use by shipyards, by using the Chart Method combined with the data generated in this investigation.
- Generally, preheat/interpass temperatures to prevent hydrogen-assisted cracking in the HAZ are higher for butt welds than they are for fillet welds. Preheat/interpass temperatures calculated for butt welds can be conservatively used for fillet welds.
- WIC weldability tests with sub-size specimens do not need as high a minimum required preheat to prevent hydrogen-assisted cracking as restrained welds deposited on large-size plates.
- Steel plates produced by an integrated steel mill are likely to contain higher carbon and Pcm levels than similar plates produced in a 100% scrap mill.

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APPENDIX

Table A1. Welding Cracking Data provided by Electric Boat Corporation

Summary of Lincoln Electric E71-T1-HYM FCAW Results on CE Limits Study, 6/29/98

Plate Type	Thickness (in.)	PH/TP Temp. (°F)	Assembly Number	MT- In Process	MT - Backgrind	MT - Final	UT - Standard	UT - Enhanced	Transverse Macro	Longitudinal Macro	House Tests	Cracked? (Y / N)
Grade D	1.75	60	PD21456	NC	NC	NC	NC	NC	NC	NC (note 1)	NC	No
Grade D	2.50	60	PD21470	NC	NC	NC	NC	NC	NC (note 5)	NC (note 5)	NC	No
DH-36	1.00	60	PD21469	NC	NC	NC	NC	NC	HAZ cracking (photos 45687 and 45688)	HAZ cracks (note 3)	Extensive HAZ cracks in root area	Yes
DH-36	1.00	125	PD21480	NC	NC	NC	NC	NC	NC	NC	NC	No
DH-36	1.75	60	PD21457	Longitudinal fusion line cracking approximately 6 in. long after 4 beads deposited on side 1	---	---	---	---	HAZ cracking, (photos 45652-45653)	---	---	Yes
DH-36	1.75	125	PD21459	NC	NC	NC	NC	NC	NC	NC (note 2)	NC	No
DH-36	2.50	125	PD21478	Longitudinal fusion line crack approximately 27 in. long after depositing 3 beads on side 2.	NC	---	---	---	HAZ Cracking, (photos 45701, 45702, 45703)	---	---	Yes
DH-36	2.50	175	PD21490	NC	NC	NC	NC	NC	NC	NC	HAZ cracking (note 4)	Yes
A612	1.00	125	PD21475	NC	NC	NC	NC	NC	NC	NC	Extensive HAZ cracking	Yes
A612	1.00	175	PD21487	NC	NC	NC	NC	NC	NC	HAZ crack (note 6)	NC	Yes
A612	1.75	60	PD21455	Longitudinal fusion line cracking entire 32 in. length after 4 beads deposited on side 1	---	---	---	---	HAZ cracking, (photos 45646, 45655)	---	---	Yes
A612	1.75	125	PD21458	NC	Longitudinal HAZ cracking entire 32 in. of backgrind	---	---	---	HAZ cracking, (photo 45654)	HAZ root crack	---	Yes
A612	1.75	175	PD21462	NC	Longitudinal HAZ cracking over approximately 17 in. of backgrind	---	---	---	---	---	---	Yes
A612	1.75	225	PD21468	After welding about one-half of side 2, found HAZ crack about 5" long	NC	---	---	---	HAZ cracking, (photo 45689)	---	---	Yes
A612	1.75	275	PD21472	NC	NC	NC	NC	NC	NC	NC	NC	No
A612	2.50	275	PD21479	NC	NC	NC	NC	NC	NC	NC	NC	No

NC = No Cracking
 Np = not performed
 ip = in progress
 --- = not necessary
 Bold = met lab action
 Italics = Weld lab action

NOTES:

- On 1 of 2 longitudinal macros, one 0.020" crack-like defect in weld, one 0.020" crack in weld, and one 0.010" crack in weld. All appeared to be associated with a slag line. Not considered hydrogen assisted cracking.
- Several very small crack-like indications associated with a slag line. Not considered hydrogen assisted cracking.
- Several HAZ cracks with many crack-like indications which appear to be related to base metal slag and "dirt" with tearing in between. See photo numbers 45684, 45685, and 45686.
- One of 8 "House" tests had HAZ cracking. 7 cracks in HAZ root area approximately 0.040" long on average. Also, 3 HAZ cracks about 0.3" up from side 2 root approximately 0.160" long each.
- Several areas of small crack-like indications associated with slag and "dirt." Not considered hydrogen assisted cracking.
- Single 0.020" HAZ crack in side 1 of one longitudinal macro.

Chemistries Done
 1.75" A612, DH-36, and Grade D
 1.00" DH-36, A612
 2.50" Grade D

CE Limits Study, Final Results, Lincoln Electric E71-T1-HYM FCAW, 3/24/99

- All welding was conducted in the vertical up position using 0.045 in. diameter Lincoln MIL-71T-1-HYM FCAW electrode (MIL-E-24403/1D and MIL-E-24403A Am. 1), Lot No. 467H. 25% CO₂ / 75% Ar was used for shielding.
- When not being used, FCAW electrode was stored in a sealed plastic bag with fresh desiccant packages.
- Nominal welding parameters were 246 to 254 in/min wire feed speed, 160 to 170 amperes, 22.5 to 23 arc volts (21 to 22 for side 1 root pass), 5/8 to 3/4 in. contact tip-to-work and gas cup-to-work distances, and 40 ± 5 kJ/in heat input (except for the side 1 root pass which was "as necessary" to successfully close the root).
- Power Supply = Linde VI-600, constant potential.
- All welding was conducted using a 45° Included angle double-V balanced joint design (except the 1 in. thick assemblies were unbalanced 5/8 in. on side 1 and 3/8 in. on side 2). The root gap was a nominal 3/16 in.
- All assemblies were fully restrained using large clamps to a heavily strong-backed fixture.
- All test assemblies were 32 in. long by 16 to 32 in. wide.
- The nominal atmospheric condition in the room where all welding was performed was 60°F temperature and 80% relative humidity. This condition was automatically controlled and monitored on a regular basis.
- Test assemblies which utilized a 60°F preheat/interpass temperature were typically forced air cooled between beads.
- The typical welding and inspection progression was as follows: 1) fit-up plates and tack weld. 2) Clamp assembly into vertical fixture. 3) Cool assembly down to 60°F temperature or apply preheat, as appropriate. 4) Deposit side 1 root pass using the heat input necessary to successfully close the root. 5) Continue welding side 1 to completion. Perform magnetic particle inspection ("MT - In-Process") before the start of welding each morning. 6) Remove assembly from fixture and excavate the backside using grinding. Perform magnetic particle inspection ("MT - Backgrind"). 7) Continue welding side 2 to completion. Perform magnetic particle inspection ("MT - In-Process") before the start of welding each morning. 8) Remove assembly from fixture and flush grind the weld on side 2. Magnetic particle inspect final weld layer on both sides welded ("MT - Final"). Perform standard and "Enhanced" ultrasonic inspection from the flush ground side.
- Detection of suspected welding defects or cracking by visual or magnetic particle inspections ("In-Process" or on the "Backgrind" inspection) resulted in an "on the spot" evaluation. This may have included examination under magnification, light grinding or burring followed by additional inspection and examination, more extensive grinding followed by additional inspection and examination, polishing of the indication with a small grinding wheel and a Scotch Brite wheel followed by Nital etch to determine location of indication relative to fusion line, etc. If the conclusion reached was that cracking was probable, the assembly was removed from the fixture and appropriate macro sections were cut from the weld and heat affected zone and polished and etched for examination. Photos were generally taken.
- Final destructive testing (on fully completed welds) consisted of transverse macro sections (principally to evaluate longitudinal indications and cracks), longitudinal macros through the approximate transverse centerline of the weld joint (principally to look for and/or evaluate transverse weld metal indications and cracking), and "House Tests" (longitudinal macro sections cut parallel to the fusion line in the heat affected zone) to examine for heat affected zone cracking.

CE Limits Study, Final Results, Hobart MIL-70S-3 PGMW, 3/24/99

Plate Type	Thickness (in.)	PH/IP Temp. (°F)	Assembly Number	MT - In Process	MT - Backgrind	MT - Final	UT - Standard	UT - Enhanced	Transverse Macro	Longitudinal Macro	House Tests	Cracked ? (Y / N)
Grade D	2.50	60	PD21499	NC (Note 1)	---	---	---	---	NC (note 1)	---	---	---
Grade D	2.50	60	PD21504	NC (Notes 4 and 6)	NC (Note 5)	NC	NC (Note 8)	NC (Note 9)	NC	NC	NC	No
DH-36	1.75	60	PD21505	NC (Notes 3 and 7)	NC	NC	NC (Note 8)	NC	NC	NC	NC	No
DH-36	2.50	60	PD21500	One 2" HAZ crack detected after 3 beads deposited on side 1. See note 2.	---	---	---	---	HAZ cracking (see photo 45721)	---	---	Yes
DH-36	2.50	125	PD21506	NC	NC	NC	NC (Note 8)	NC (Note 10)	NC	NC	NC	No
A612	2.50	60	PD21501	3 HAZ cracks (total length 3.25") detected after 3 beads deposited on side 1. See Note 2.	---	---	---	---	HAZ cracking	---	---	Yes

NOTES:

- In-process MT showed crack-like sidewall indications after 5 beads were deposited. Removed plate from fixture and did Nital etch in polished groove. Still observed crack-like indications (total indication length was 1.75"). Cut 2 transverse macros. Macros showed lack of fusion at HAZ fusion line and interbead lack of fusion. Re-beveled the plate members and re-welded using the same preheat/interpass temperature (plate number PD21504).
- Verified by transverse macro sections taken on the partially welded test plate.
- After 2 beads deposited on side 1, had MT indications 4.75 to 6" from the finish end of the assembly. Found to be lack of fusion and slag by macro examination of finished weld.
- After 2 beads deposited on side 1, had MT indications 1 to 1.75" from the start end of the assembly. Transverse macros on final weld did not reveal any cracking, just lack of fusion and slag.
- On the backgrind, found crack-like indications 2.25 to 3.75" from the start end of the assembly. Macro exam of final weld did not reveal any cracking, just lack of fusion and slag.
- In-process MT after several beads deposited on side 2 revealed 2 areas of sidewall lack of fusion (verified by etching in place). Locations are 0 to 2.5" from the top and 0 to 6.25" from the bottom.
- In-process MT after several beads deposited on side 2 revealed 2 areas of sidewall lack of fusion (verified by etching in place). Locations are 1.5 to 4.75" from the top and 0 to 4.75" from the bottom.

NC = No Cracking np = not performed --- = not necessary

10. Numerous longitudinal root area indications found to be lack of fusion and slag by macro examination.

Three transverse indications were found to be slag and lack of fusion by macro examination.

A single transverse indication was found to be slag and lack of fusion by macro examination.

CE Limits Study, Final Results, Hobart MIL-70S-3 PGMW, 3/24/99

- All welding was conducted in the vertical up position using 0.045 in. diameter Hobart MIL-70S-3 electrode (MIL-E-23765/1E Am. 1), S304612M-L22. 5% CO₂ / 95% Ar was used for shielding.
- Nominal welding parameters were 168 to 180 in/min wire feed speed, 110 to 115 amperes, 21 to 22 arc volts (25 for side 1 root pass), 5/8 in. contact tip-to-work distance, 1/2 in. gas cup-to-work distance, and 40 ± 5 kJ/in heat input.
- Power Supply = Gilliland CV-600FI, 120 Hz Pulse Arc Mode.
- All welding was conducted using a 45° Included angle double-V balanced joint design. The root gap was a nominal 1/8 in.
- All assemblies were fully restrained using large clamps to a heavily strong-backed fixture.
- All test assemblies were 32 in. long by 16 to 32 in. wide.
- The nominal atmospheric condition in the room where all welding was performed was 60°F temperature and 80% relative humidity. This condition was automatically controlled and monitored on a regular basis.
- Test assemblies which utilized a 60°F preheat/interpass temperature were typically forced air cooled between beads.
- The typical welding and inspection progression was as follows: 1) fit-up plates and tack weld. 2) Clamp assembly into vertical fixture. 3) Cool assembly down to 60°F temperature or apply preheat, as appropriate. 4) Deposit side 1 root pass using the heat input necessary to successfully close the root. 5) Continue welding side 1 to completion. Perform magnetic particle inspection ("MT - In-Process") before the start of welding each morning. 6) Remove assembly from fixture and excavate the backside using grinding. Perform magnetic particle inspection ("MT - Backgrind"). 7) Continue welding side 2 to completion. Perform magnetic particle inspection ("MT - In-Process") before the start of welding each morning. 8) Remove assembly from fixture and flush grind the weld on side 2. Magnetic particle inspect final weld layer on both sides welded ("MT - Final"). Perform standard and "Enhanced" ultrasonic inspection from the flush ground side.
- Detection of suspected welding defects or cracking by visual or magnetic particle inspections ("In-Process" or on the "Backgrind" inspection) resulted in an "on the spot" evaluation. This may have included examination under magnification, light grinding or burring followed by additional inspection and examination, more extensive grinding followed by additional inspection and examination, polishing of the indication with a small grinding wheel and a Scotch Brite wheel followed by Nital etch to determine location of indication relative to fusion line, etc. If the conclusion reached was that cracking was probable, the assembly was removed from the fixture and appropriate macro sections were cut from the weld and heat affected zone and polished and etched for examination. Photos were generally taken.
- Final destructive testing (on fully completed welds) consisted of transverse macro sections (principally to evaluate longitudinal indications and cracks), longitudinal macros through the approximate transverse centerline of the weld joint (principally to look for and/or evaluate transverse weld metal indications and cracking), and "House Tests" (longitudinal macro sections cut parallel to the fusion line in the heat affected zone) to examine for heat affected zone cracking.

CE Limits Study, Final Results, ESAB Dual Shield II E70T-12H4 FCAW, 3/24/99

Plate Type	Thickness (in.)	PH/IP Temp. (°F)	Assembly Number	MT- In Process	MT - Backgrind	MT - Final	UT - Standard	UT - Enhanced	Transverse Macro	Longitudinal Macro	House Tests	Cracked? (Y / N)
DH-36	1.00	60	PD21515	NC	NC	NC	NC	NC	NC	NC	NC	No
DH-36	1.75	60	PD21516	See Note 1	NC	NC	NC	NC	NC	NC	One 0.010" HAZ crack (see Notes 1 and 2)	Yes
DH-36	1.75	125	PD21517	NC	NC	NC	NC	NC	NC	NC	NC	No

NOTES:

- Noted centerline cracking on side 1 root pass (1.4" to 1.8" from finish end, 4.0" to 5.4" from finish end, and 10.5" to 11.3" from finish end). Did not appear to be hydrogen assisted cracking. Removed root pass down to 12.4" from finish end and re-rooted. After bead 2 on side 1, had additional centerline type MT indications 6.3" and 13.5" from finish end. Removed by grinding and burring. Longitudinal macro and House tests removed from these areas did not show any cracking. Before bead 21 on side 2, had an MT indication 9.1" from start end. Looked to be lack of fusion at sidewall under bead 18. Length was _". Longitudinal macro and House test removed from this area revealed a single 0.010" HAZ crack (see Note 2).
- First grind on one of four House tests shows a single ~0.010" long HAZ crack. This MICRO crack appears to be hydrogen assisted. Additional grind (0.020") on this House specimen did not reveal any additional cracks.

NC = No Cracking np = not performed --- = not necessary

CE Limits Study, Final Results, ESAB Dual Shield II E70T-12H4 FCAW, 3/24/99

- All welding was conducted in the vertical up position using 0.045 in. diameter ESAB Dual Shield II E70T-12H4 FCAW electrode (AWS A5.20 E71T-12MJH4), Lot No. 54850. 25% CO₂ / 75% Ar was used for shielding.
- When not being used, FCAW electrode was stored in a sealed plastic bag with fresh desiccant packages.
- Nominal welding parameters were 237 to 250 in/min wire feed speed, 160 to 175 amperes, 23 arc volts (21 for side 1 root pass), 1/2 to 5/8 in. contact tip-to-work and gas cup-to-work distances, and 40 ± 5 kJ/in heat input (except for the side 1 root pass which was "as necessary" to successfully close the root).
- Power Supply = Linde VI-600, constant potential.
- All welding was conducted using a 45° Included angle double-V balanced joint design (except the 1 in. thick assemblies were unbalanced 5/8 in. on side 1 and 3/8 in. on side 2). The root gap was a nominal 3/16 in.
- All assemblies were fully restrained using large clamps to a heavily strong-backed fixture.
- All test assemblies were 32 in. long by 16 to 32 in. wide.
- The nominal atmospheric condition in the room where all welding was performed was 60°F temperature and 80% relative humidity. This condition was automatically controlled and monitored on a regular basis.
- Test assemblies which utilized a 60°F preheat/interpass temperature were typically forced air cooled between beads.
- The typical welding and inspection progression was as follows: 1) fit-up plates and tack weld. 2) Clamp assembly into vertical fixture. 3) Cool assembly down to 60°F temperature or apply preheat, as appropriate. 4) Deposit side 1 root pass using the heat input necessary to successfully close the root. 5) Continue welding side 1 to completion. Perform magnetic particle inspection ("MT - In-Process") before the start of welding each morning. 6) Remove assembly from fixture and excavate the backside using grinding. Perform magnetic particle inspection ("MT - Backgrind"). 7) Continue welding side 2 to completion. Perform magnetic particle inspection ("MT - In-Process") before the start of welding each morning. 8) Remove assembly from fixture and flush grind the weld on side 2. Magnetic particle inspect final weld layer on both sides welded ("MT - Final"). Perform standard and "Enhanced" ultrasonic inspection from the flush ground side.
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