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PREHEATING, INTERPASS AND POST-WELD HEAT TREATMENT REQUIREMENTS FOR WELDING LOW ALLOY STEELS

1.0 INTRODUCTION

1.1 Issue: [1-5]

In fusion welding processes (see 2.1), the reason often given to explain the need for preheating, controlling the interpass temperature (in multipass welds), and post-weld heat treatment (PWHT) is to reduce the risk of cold cracking in the heat affected zone (HAZ). Cold cracking is a hydrogen embrittlement phenomenon, often referred to as hydrogen induced cracking or HAZ cracking (see 2.2).

This report examines, in some detail, the preheating, interpass temperature, and PWHT requirements for fusion welding low alloy steels, such as AISI 4130, in order to reduce the risk of cold cracking. Chemistry of AISI 4130 in wt.% is as follows: *C, 0.28-0.33; Mn, 0.4-0.6; Si, 0.15-0.35; Cr, 0.8-1.1; Mo, 0.15-0.25; Ni, 0.25 max.; Cu, 0.35 max*. In what follows, nominal alloy contents will be used in carbon equivalent computations. The Ni and Cu contents will not be considered here, since they are not common to all US specifications for AISI 4130.

1.2 Report Layout:

Section 2 introduces necessary background on fusion welding processes, cold cracking characteristics, single pass vs. multipass welds, and heating & temperature control. Sections 3, 4, and 5, respectively, present comprehensive discussions of preheating, the interpass temperature, and PWHT. The issue of heat treating (hardening and tempering) welded structures is discussed in section 6. Section 7 deals with welding large structures. Some notes on welding AISI 4130 are presented in section 8.

2.0 BACKGROUND

2.1 Fusion Welding Processes:[6]

Fusion welding processes include gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), shielded metal arc welding (SMAW), flux cored arc welding (FCAW), submerged arc welding (SAW), electroslag welding (ESW), and electrogas welding (EGW), as well as the plasma, carbon, and stud arc, plasma-MIG, laser, high frequency, resistance, projection, flash, upset, electron beam, capacitor discharge, thermite, and oxyfuel welding processes. AWS D1.1-2010, however, lists only the GTAW, GMAW, SMAW, SAW, ESW, and EGW processes, suggesting that only these processes are subject to the preheating, interpass, and PWHT provisions listed in that standard. This logic will be adopted here. [a] The processes listed in the AWS are discussed in 2.1.1-2.1.6. It should be noted, however, that ESW and EGW are not commonly used in welding aerospace components.

2.1.1 Gas Tungsten Arc Welding (GTAW):

GTAW is AKA TIG (tungsten-inert gas) and HeliArc welding, and it is used for manual, semi-automatic and fully automatic welding. The arc is struck between a bare non-consumable tungsten electrode and the workpiece, in an inert gas envelope that shields the non-consumable electrode and the workpiece. The shielding gas, usually He, Ar or a mixture of the two, is externally supplied. Bare filler wire, where required, is fed into the joint. GTAW can be manual, semiautomatic, or fully automatic. In manual GTAW, the welder moves the torch along the joint and feeds the filler wire into the joint manually. In fully automatic GTAW, the torch or the workpiece are moved relative to each other and the filler wire is fed into the joint mechanically. Semiautomatic GTAW, which is not widely used, utilizes a hand held torch with an attachment that mechanically feeds the filler wire into the joint.

2.1.2 Gas Metal Arc Welding (GMAW):

GMAW is AKA as MIG (metal-inert gas) welding. The arc is struck between a bare consumable weld electrode (filer wire) and the workpiece. The shielding gas, usually He, Ar or a mixture of the two, is externally supplied.

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[a] *ASM Handbook, vol. 6,[6] however, indicates that preheating is required in electron beam welding of thick sections, and that in some oxyfuel welding applications, preheating and PWHT would also be required. The Handbook further indicates that only PWHT would be required for ESW and EGW.*

The filler wire is continuously fed automatically into the joint. GMAW can be semiautomatic or automatic. In semiautomatic GMAW, the torch is manipulated manually, whereas, in automatic GMAW, the torch or the workpiece is moved relative to the other mechanically; in both cases, the filler wire is continuously fed automatically into the joint.

2.1.3 Shielded Metal Arc Welding (SMAW):

SMAW is commonly called stick or covered electrode welding. It is a manual process, where an arc is struck between a flux-covered consumable electrode (filler wire) and the workpiece. Decomposition of the flux coating generates the shielding gas and provides fluxing elements to protect the molten weld metal.

2.1.4 Flux Cored Arc Welding (FCAW):

In FCAW, the arc is struck between a tubular consumable electrode (filler wire) containing internally packed flux and the workpiece; this type of filler is referred to as cored electrode. The filler wire is continuously fed automatically into the joint. FCAW can be semiautomatic or automatic. In semiautomatic FCAW, the torch is manipulated manually, whereas, in automatic FCAW, the torch or the workpiece is moved relative to the other mechanically; in both cases, the filler wire is continuously fed automatically into the joint. Decomposition of the internal flux generates the shielding gas; here, the process resembles SMAW. In addition to the flux gas, an auxiliary shieling gas, usually CO_2, may be supplied by external source; here, the process resembles GMAW. The former method is preferred for field applications.

2.1.5 Submerged Arc Welding (SAW):

In SAW, the arc is struck between a bare (or cored) consumable metal electrode (filler wire) and the workpiece. The filler is continuously fed automatically into the joint. SAW can be semiautomatic or automatic. In semiautomatic SAW, the torch is manipulated manually, whereas, in automatic SAW, the torch or the workpiece is moved relative to the other mechanically; in both cases, the filler wire is continuously fed automatically into the joint. The arc is shielded by a layer of fusible granular flux, which, upon melting, blankets the joint and nearby regions and protects them from contamination. In addition, the flux may contain alloy ingredients that modify the weld metal. To increase deposition rates, more than one filler wire can be simultaneously fed into the weld pool.

2.1.6 Electroslag & Electrogas Welding (ESW & EGW):

ESW utilizes a granular, electrically conductive slag (flux) to accomplish the joining. The process is used primarily for producing single pass joints [b] in thick (1 ¼-12 in thick) steel plate in the vertical position. The arc is struck between a continuously fed consumable electrode (filler wire) and the workpiece. This arc heats up the granulated slag to a molten pool that covers the area of the joint opening and shields it from contamination. The molten slag is retained by backing shoes on either side of the joint; the joint is usually square groove. The arc is extinguished once the molten slag layer becomes sufficiently thick. Then, further heating is by the electrical current passing through the conductive slag. Weld progression is uphill (moving upward). The high heat inputs associated with ESW generally lead to inferior mechanical properties (lower toughness and strength) compared to other welding processes. However, the high deposition rates obtained make the process economically attractive. EGW is similar to ESW, except that no slag is used for shielding. Rather, shielding gases are provided from an external source (just like GMAW) or through the decomposition of flux (just like FCAW); in the former a solid filler is used, whereas in the latter a tubular cored filler is used. Furthermore, the arc in EGW is not extinguished; it continues through the process. ESW and EGW are used primarily for producing single pass square groove butt and T-joints in thick steel plate, typically < 2 in thick. Both ESW and EGW are automatic processes.

2.2 Cold Cracking: [6]

Cold cracking is a hydrogen embrittlement phenomenon that is prevalent in thick sections. It does not manifest itself until hours, even days, after the weld cools, typically initiating in the HAZ and then propagating transversely across the weld. [c]   The technical community is of the view that cold cracking is brought about by three conditions: a susceptible microstructure; the presence of a threshold level of atomic (diffusible) hydrogen, and; a threshold tensile stress (residual and / or applied). In general, a higher level of hydrogen will require a lower threshold

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[b] *Multipass techniques, however, have been developed.*
[c] *While not of interest here, it is for the sake of completion that mention has to be made of another type of weld cracking. This is hot weld cracking, which occurs at high temperatures, generally above 1000 F. Unlike cold cracking, hot weld cracks appear more or less immediately (though not always visibly) upon solidification of the weld. Hot cracking almost always appears in the longitudinal direction of the weld bead itself or directly adjacent to it. There are two main types of hot cracking, centerline and crater, with the first being further divided into either segregation or bead shape cracking.*

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stress for the onset of cold cracking, and visa-versa. Similarly, a more susceptible microstructure will require a lower threshold stress and / or a lower threshold amount of hydrogen for the onset of cold cracking. There is a fourth condition that is necessary for the onset of cold cracking; viz., a temperature below 600 F. The necessary conditions for the onset of cold cracking are discussed in 2.2.1. The potential sources for hydrogen are presented in 2.2.2. The delay time involved in cold cracking is discussed in 2.2.3.

2.2.1 Necessary Conditions for Cold Cracking: [6]

As indicated above, four conditions are necessary for the occurrence of cold cracking. These are presented in 2.2.1.1-2.2.1.4.

2.2.1.1 Susceptible Microstructure: In steels, it is generally accepted that martensitic microstructures are the most susceptible to cold cracking, and that higher strength makes the steel more susceptible to cold cracking, with untempered martensitic microstructures with medium to high carbon contents being the most susceptible; low carbon martensite (C content below about 0.1%) is generally not susceptible to cold cracking. A more susceptible microstructure will require a lower threshold stress and / or a lower threshold amount of hydrogen for the onset of cold cracking. The literature, however, appears to be devoid of any reliable quantitative data that systematically back up these qualitative statements.

2.2.1.2 Threshold Hydrogen Level: A threshold level of diffusible hydrogen needs to be present for the onset of cold cracking. This threshold level depends on the microstructure and stress level. It is common knowledge that higher levels of hydrogen tend to reduce the threshold stress necessary for the onset of cold cracking, and visa-versa. Similarly, higher levels of hydrogen can lead to the onset of cold cracking in microstructures that are not ordinarily considered to be susceptible to this type of cracking. Again, the literature appears to be devoid of any reliable quantitative data that back up these qualitative statements.

2.2.1.3 Threshold Stress: The stress can be residual and / or applied. Residual stresses encompass those that are thermally-induced (due to cooling) and those that are transformation-induced (due to austenite transformation to martensite). Joint restraint, brought about by section thickness, joint location, and / or joint design, is also a contributor to residual stresses. In general, the higher the stress level is, the more susceptible will be the steel to cold cracking, and the lower will be the threshold hydrogen level necessary for the onset of this cracking, and visa-versa. Similarly, higher stress can lead to the onset of cold cracking in microstructures that are not ordinarily considered to be susceptible to this type of cracking. As was the case above, the literature appears to be devoid of any reliable quantitative data that back up these qualitative statements.

2.2.1.4 Temperature: For cold cracking to occur, hydrogen needs to diffuse to certain defects. The thermodynamic driving force for this diffusion is hydrogen solubility in the steel, which decreases with temperature. The lower the solubility is, the larger the driving force becomes. Thus, thermodynamically speaking, lower temperatures would favor the diffusion of hydrogen, due to the increased driving force for that diffusion. From a dynamic standpoint, however, lower temperatures tend to suppress this diffusion due to the general decrease in diffusion rates at lower temperatures. Accordingly, hydrogen diffusion, hence, cold cracking is not likely to take place at high temperatures (small driving force) or very low temperatures (sluggish diffusion rates). Rather, cold cracking is likely to take place within a certain intermediate temperature range where both the driving force and diffusion rates are sufficiently high. As to exactly what this range is, the literature offers varied expressions: below 600 F, -60 to 300 F, -150 to 390 F, around RT (room temperature, 75 F), and -150 to 400 F, to mention a few.

2.2.2 Sources of Hydrogen: [6]

The hydrogen is derived primarily from decomposition of moisture bearing gases, released during melting of the fluxes present in electrode coatings (e.g., SMAW), electrode cores (e.g., FCAW), or in bulk fluxes (e.g., SAW, ESW), and to a lesser extent from moisture in the inert gas environment surrounding the arcs or from contaminants that may be present at the joint surfaces (moisture, lubricants, paints, etc.). It is generally agreed that the risk of cold cracking is greatly reduced in processes using bare metal electrodes (e.g., GTAW and GMAW), particularly when these electrodes and the joint surfaces are adequately cleaned and dried before welding.

2.2.3 Cold Cracking is Delayed Cracking: [7-10]

There is a certain delay (incubation time) involved for hydrogen embrittlement to manifest itself in the form of detectable cold cracks. This delay is brought about by the rate of hydrogen diffusion (movement), which, in turn,

depends on microstructure, temperature, and hydrogen content. The existence of such delay makes it particularly difficult to schedule weld inspection, to ensure structural integrity. Accordingly, welding standards generally require a certain delay between the completion of welding and performing the NDI (nondestructive inspection), when there is a possibility that martensite could form during cooling to RT after the completion of welding. [d] The required delay times vary from 16-48 hrs, depending on the particular standard, but there is no firm basis for these times. There are recommendations, based on testing, for up to 72 hrs delay, but these have not yet been adopted in standards. In steels where the formation of martensite does not take place during cooling to RT, NDI may proceed immediately after the completion of welding. The same is true where low carbon martensite forms during cooling to RT, as would be the case for low carbon steels (C content below about 0.1%); low carbon martensite is generally not susceptible to cold cracking.

2.3 Single & Multipass Welds:

In single pass welds, we speak of preheating and post-weld heat treatment. In multipass welds, we speak of preheating, controlling the interpass temperature, and post-weld heat treatment.

2.4 Heating and Temperature Control:

Heating for the various operations may be in ovens, by resistance heaters, or by flame (torches). Temperature control may be accomplished by infrared (IR) guns (pyrometers), temperature indicating crayons (e.g., Tempilstiks), or thermocouples.

3.0 PREHEATING:

In general, low alloy steels are required to be preheated to some temperature (T_{PH}), prior to welding. It has been suggested that T_{PH} for any given steel should be about 50 F above the martensite start temperature (M_S) for the particular steel being welded. Most low alloy steels, however, have fairly high M_S temperatures, making welding at or above them somewhat uncomfortable to the welder, thereby potentially compromising weld quality. For such steels, therefore, manufacturers often opt for T_{PH} temperatures below M_S. [11,12] A case in point is AISI 4130 with an M_S of 700 F; refer to Illustration 1. [e] For this steel, federal, military, industry and company specifications typically list T_{PH} temperatures in the 200-600 F range, all below M_S. [f]

3.1 Why Preheat?

Preheating drives moisture and other contaminants off the joint; moisture, lubricants and other contaminants are sources of hydrogen. More importantly, preheating serves to reduce the rate at which the metal cools down from the welding temperature to T_{PH}. This is so whether preheating is above or below M_S. Cooling rate reductions will lead to a general reduction in residual stress magnitudes, and also allow more time for hydrogen removal. Furthermore, cooling rate reductions can affect austenite transformation to products other than martensite, before reaching M_S ($T_{PH} < M_S$) or T_{PH} ($T_{PH} > M_S$). This statement warrants some explanation.

Most low alloy steels that may be susceptible to hydrogen-induced cracking transform from austenite during cooling through the 800-500 C (1470-930 F) temperature range. The length of time, $\tau_{8/5}$ (seconds), a steel spends in this range during cooling, will establish its microstructure and, hence, its susceptibility to cold cracking. To maximize cracking

Illustration 1: TTT Diagram, AISI 4130.

resistance, a microstructure that is free of untempered martensite is desired; [13] that is, the austenite would have transformed to ferrite + carbide [g] and no austenite will be available to transform to martensite upon reaching M_S.
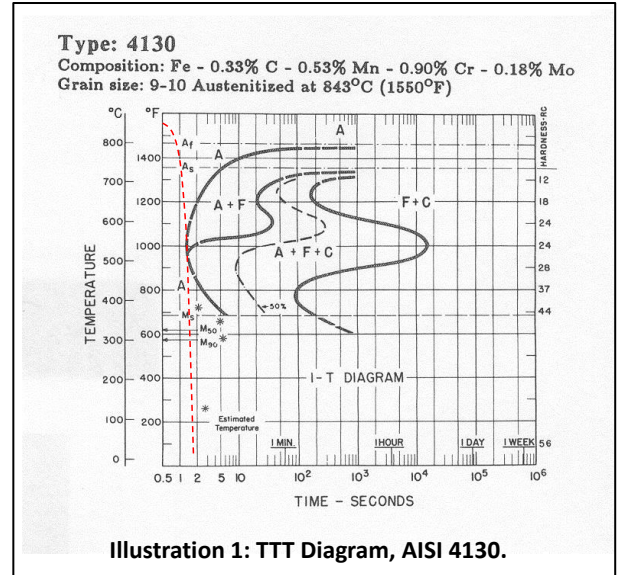
[d] For steels, NDI includes magnetic particle, radiographic, and / or ultrasonic inspections. Occasionally, penetrant inspection maybe required in lieu of, or in addition to, magnetic particle inspection.
[e] Illustration 1 is an isothermal transformation diagram. Weld microstructures, however, are best understood with the aid of continuous cooling transformation (CCT) diagrams. Illustration 1 is presented here for the sake of simplicity.
[f] Mil-STD-2219, Mil-R-5632 and some company specifications, however, indicate that preheating, controlling the interpass temperature, and PWHT are optional or not required for AISI 4130.
[g] Some of, or all, the ferrite and carbide would be in the form of pearlite and / or bainite.

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Using a specifically developed carbon equivalent, CE*, a relationship has been formulated [5] to establish the critical time, $\tau_{8/5}$, for a martensite-free HAZ in low-carbon alloy steels. CE* is defined as:

$$CE^* = \%C^* + \frac{\%Mn}{3.6} + \frac{\%Ni}{9} + \frac{\%Cu}{20} + \frac{\%Cr}{5} + \frac{\%Mo}{4}$$ $Equation\ 1$

$where,$

$\%C^* = \%C\ for\ C \leq 0.3\%\ and\ \%C^* = \dfrac{\%C}{6} + 0.25\ for\ \%C > 0.3\%$

The critical time, $\tau_{8/5}$, is computed from the following equation:

$$\log \tau_{8/5} = 2.69\ CE^* + 0.321$$ $Equation\ 2$

If the carbon equivalent formula (Equation 1) is valid for AISI 4130, [h] a CE* value of 0.68 is obtained for that steel; the corresponding $\tau_{8/5}$ is 141.25 s or 2.4 min. [i] When $\tau_{8/5}$ is known, welding parameters and T_{PH} for a given thickness can be established to produce cooling rates slow enough to avoid martensite formation. A higher T_{PH} would result in slower cooling rate through the transformation range and a larger $\tau_{8/5}$. Thicker sections generally require higher T_{PH} because of the greater heat-sinking capacity of thicker sections; heat sinking increases cooling rates resulting in smaller $\tau_{8/5}$ values.

The intent of controlling cooling rates ($\tau_{8/5}$) is to obtain a martensite-free microstructure at room temperature (RT), by allowing the austenite to transform to ferrite + carbide, as the weldment cools down from the welding temperature to T_{PH}. [j] It is more likely, however, that not all the austenite will transform to these products. Rather, some austenite is likely to remain in the weld metal and the adjacent HAZ regions when these regions reach T_{PH} ($T_{PH} > M_S$) or MS ($T_{PH} < M_S$). In either case, if the weldment is allowed to immediately cool down to RT, this austenite will transform to martensite, with the attendant generation of residual stresses. More martensite will form, and residual stress magnitudes will keep on increasing, as the temperature continues to drop, during cooling. Residual stresses by themselves are not cause for alarm. [k] Rather, it is the combination of these residual stresses, the presence of hydrogen, picked up during welding, and the metallurgical notch, resulting from the presence of a weld, that is cause for alarm. This combination increases the risk of cold weld cracking. Concern over this increased risk of cold weld cracking necessitates imposing PWHT in some applications. The subject of PWHT is discussed in section 5.0.

3.2 Estimating Preheat Temperatures:

There are literally tens of methods, each utilizing a particular carbon equivalent (CE) formula, that can be used to estimate the preheat temperatures required for crack-free welding. Some of these methods are discussed below. It should be noted, however, that all carbon equivalent formulae must be considered as approximations, since they do not consider other factors affecting hardenability, such as section size, mass, restrain, [l] and grain size. Furthermore, these formulae were derived by experimentation on specific sets of steels. Accordingly, a particular carbon equivalent formula derived from a specific set of steels may not be accurate for steels outside the "family" of steels to which that set belongs. The same limitations generally apply to estimates of the preheat temperatures. For weld process qualification, it is wise to use the maximum carbon equivalent value; this value corresponds to the maximum limits of the alloying elements present in the steel. This ensures that all heats of that steel will yield acceptable results.

3.2.1 European Standard EN 1011-2 Method A: [14,15]

Method A of EN 1011-2, referred to as the hardness control method, is based on the assumption that if the CGHAZ (coarse-grained HAZ) hardness is kept below a certain critical value, the risk of cracking is greatly

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[h] *The fact that AISI 4130 is devoid of Ni and Cu seems to suggest that the CE* formula is not really designed for that steel.*
[i] *According to Illustration 1, holding the steel for 141 s isothermally at any temperature within the 1470-930 F range would lead to near complete transformation of the austenite to ferrite + carbide; see footnote e.*
[j] *Note that some martensite will also be present if $T_{PH} < M_S$.*
[k] *Steels are regularly quenched during heat treatment, with the attendant generation of residual stresses. These stresses do not ordinarily lead to cracking if the steel is quenched in an appropriate quenchant and tempered within a set period of time after quenching.*
[l] *Stress, be that residual or a result of constraint, indirectly affects hardenability by influencing the austenite to martensite transformation. This transformation involves a volume expansion of about 4.5%. A compressive stress, therefore, would impede the transformation, in effect making the steel act like one with lower hardenability. A tensile stress would have the opposite effect.*

reduced. This is achieved by controlling the cooling rate below a critical value that depends on the hardenability of the steel. Here, hardenability of steels is represented by the carbon equivalent, CE_{IIW}, adopted by the International Institute of Welding (IIW) in 1967. [16]

$$CE_{IIW} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15} \qquad \textbf{\textit{Equation 3}}$$

The method is based on the further assumption that the critical hardness is independent of carbon equivalent (CE_{IIW}). It has been shown, however, that the critical hardness decreases with decreasing carbon equivalent. Therefore, steels with low carbon equivalents may crack if the hardness control approach is used to estimate the preheat temperature.

The main steps involved in estimating the preheat temperature are: (1) compute CE_{IIW}; (2) find the hydrogen content of the consumable (filler) from the corresponding datasheet; (3) obtain the hydrogen scale from (2), using tables provided in the standard; (4) calculate the combined thickness for the joint (e.g., 2 x thickness for butt joints) as indicated in the standard; (5) compute the heat input using the formula listed in the standard; (6) the information collected in items (1)-(5) is then located on nomograms provided in the standard to determine the minimum preheat temperature. There are "calculators" designed to facilitate the above tasks; see, for example: *http://www.gowelding.com/weld/preheat/preheatcalc.htm*

The standard imposes limits on the alloying elements that can be present in the steel: C, 0.05-0.25; Si, 0.8 max.; Mn, 1.7 max.; Cr, 0.9 max.; Cu, 1.0 max.; Ni, 2.5 max.; Mo, 0.75 max.; V, 0.2 max. The formula cannot be used if any of these elements is present in amounts outside the specified range (C) or exceeding the specified maximum (all other elements). Based on the C and Cr limits, Method A of EN 1011-2 would not be suitable for predicting preheat temperatures for AISI 4130 or for any other conventional US low alloy high strength or ultrahigh strength steel. This, however, should not be construed as implying a restriction on the use of CE_{IIW} in other methods or standards; see 3.2.5.

3.2.2 European Standard EN 1011-2 Method B: [14,17]

The main steps involved in estimating the preheat temperature in Method B of standard EN 1011-2 are essentially the same as those used in Method A (3.2.1), except that a different carbon equivalent, CET, is used in Method B:

$$CET = C + \frac{Mn+Mo}{10} + \frac{Cr+Cu}{20} + \frac{Ni}{40} \qquad \textbf{\textit{Equation 4}}$$

Method B of EN 1011-2 imposes limits on the alloying elements that can be present in the steel: C, 0.05-0.32; Si, 0.8 max.; Mn, 0.5-1.9; Cr, 1.5 max.; Cu, 0.7 max.; Ni, 2.5 max.; Mo, 0.75 max.; V, 0.18 max; Ti, 0.12 max; Nb, 0.06 max.; B, 0.005 max. The formula cannot be used if any of these elements is present in amounts outside the specified range (C and Mn) or exceeding the specified maximum (all other elements). Based on these limits, it appears that the method can be used for AISI 4130 (CET = 0.43). Computing an actual preheat temperature, however, requires knowledge of the weld parameters (heat input), hydrogen content, and material thickness, information that depends on the particular application. This being so, no such computation will be attempted here. It is interesting to note that CET has been referred to as the German carbon equivalent. [18]

3.2.3 AWS D1.1-2000: [19]

In AWS D1.1-2000, a carbon equivalent referred to as the Critical Metal Parameter, [20] P_{cm}, is utilized to define hardenability of steels. The method described in the AWS, AKA the P_{cm} method, has been referred to as the hydrogen control method. [14] It is based on the assumption that cracking will not occur if the average quantity of hydrogen remaining in the joint after it has cooled down to about 120 F (50 C) does not exceed a critical value that depends on steel composition and joint restraint. The P_{cm} formula is based on the work of Ito and Bessyo [21] from Japan. Accordingly, P_{cm} has been referred to as the Japanese Carbon equivalent: [18]

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \qquad \textbf{\textit{Equation 5}}$$

The main steps involved in estimating the preheat temperature by this method are: [14,19] (1) compute P_{cm}; (2) determine the susceptibility index to hydrogen induced cracking from the hydrogen content of the consumable and P_{cm}, using tables provided in the standard; (3) determine thickness of thickest plate in the joint; (4) identify the residual stress / restrain condition for the joint, as instructed in the standard; (5) the information collected in (1)-(4)

is then used to select a preheat temperature from those listed in the standard. The preheat temperatures listed in the standard range from < 20 C (< 65 F) to 160 C (320 F).

This method differs from those of EN 1011-2 in that T_{PH} is determined as a function of residual stress / restrain. Three levels of stress are identified, depending on joint configuration; viz., low, medium, and high. The method works well for short cooling times and root welding applications. It is especially suited for low carbon steels, and, as such, it is not adequate for conventional US high strength and ultrahigh strength steels, such as AISI 4130. A detailed discussion of P_{cm} limits for thick carbon and alloy steel plate is presented elsewhere. [22]

3.2.4 AWS D1.1-2010: [23]

Starting with the 2006 revision, AWS D1.1 incorporated a table (Table 3.2), to be used for prequalified welding processes (SMAW, SAW, GMAW, and FCAW). This table lists the recommended preheat and interpass temperatures (32-300 F, depending on steel grade and stock thickness) for specific steels, mostly carbon, C-Mn, and HSLA steels; conventional US high strength and ultrahigh strength steels, such as AISI 4130, are not listed.

In addition to Table 3.2, the AWS incorporated a new Annex I (Guideline on Alternative Methods for Determining Preheat). This Annex is intended to aid in estimating the preheat temperatures for welding processes that are not considered prequalified; specifically, GTAW, GMAW-S, [m] ESW, and EGW. For both the prequalified and non-prequalified processes, PWHT requirements are per paragraph 5.8 of the AWS. The subject of PWHT is discussed in section 5.0 of this report.

Annex I lists two methods for estimating preheat temperatures; viz., the hardness control and the hydrogen control methods.

3.2.4.1 The Hardness Control Method:

As indicated in conjunction with EN 1011-2 Method A (3.2.1), the hardness control method is based on the assumption that if the HAZ hardness is kept below a certain critical value, the risk of cracking is greatly reduced. This is achieved by controlling the cooling rate below a critical value that depends on the hardenability of the steel. The AWS, however, does not use the carbon equivalent, CE_{IIW} (Equation 3), that is utilized in EN 1011-2 Method A. Rather, use is made of another carbon equivalent, CE, which incorporates a Si/6 term into Equation 3:

$$CE = C + \frac{Mn+Si}{6} + \frac{Cr+Mo+V}{5} + \frac{Cu+Ni}{15} \qquad\qquad Equation\ 6$$

The hardness control method in the AWS is limited to fillet welds. It is used primarily to determine the heat input, hence the weld size, for single pass fillet welds that can be executed without preheat. This being so, no provisions or formulae for computing T_{PH} are provided. [n]

Heat input determination is performed as follows, in the order stated:

(a) Compute CE using equation 6.

(b) Use Figure I.2 of the AWS to determine the cooling rate required for obtaining specific Vickers hardness numbers, HV 350 or 400; the figure depicts the relation between CE and the cooling rates required to obtain the aforementioned hardness values in the HAZ. These hardness values are based on extensive laboratory testing with fillet welds which have shown that HAZ cracking does not occur if the HAZ hardness is less than HV 350, even with high hydrogen electrodes and that, with low hydrogen electrodes, a hardness of HV 400 can be tolerated without cracking.

(c) Use the cooling rate thus determined, together with the thickness to determine the heat input, using Figure I.3 of the AWS.

As can be seen, the hardness control method of AWS D1.1 depends solely on controlling the HAZ hardness. Joint restraint is not considered. The hydrogen level is only mentioned in a
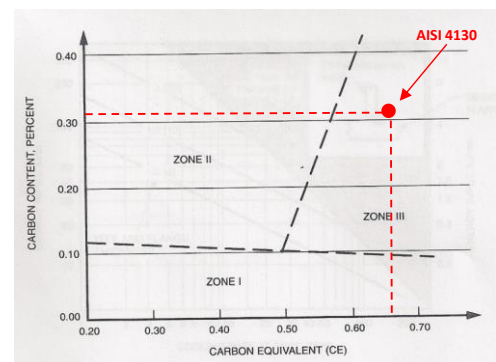

Illustration 2: Figure I.1, Annex I, AWS D1.1-2010. AKA the Graville Diagram. AISI 4130 is located on the figure.

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[m] *S: Short-circuiting metal transfer.*
[n] *One can, therefore, argue that the hardness control method of EN 1011-2 (Method A), discussed in 3.2.1, is more general than its counterpart in AWS D1.1, since the former is not limited to fillet welds and it does require an actual determination of T_{PH}.*

qualitative manner, high and low, without requiring any quantitative assessment. By contrast, the hardness control method of Method A of EN 1101-2 explicitly considers the hydrogen level by defining a hydrogen scale that depends on the hydrogen content of the consumables; see 3.2.1.

3.2.4.2 The Hydrogen Control Method:

The hydrogen control (P_{cm}) method in Annex I of AWS D1.1-2010 remains more or less unchanged from that of AWS D1.1-2000, described in 3.2.3.

The following procedure is recommended as a guide for selecting the method to be used:

(a) Determine CE (Equation 6).

(b) Locate the zone position of the steel in Illustration 2 (Figure
I.1 in the AWS). Three zones are identified,
  ➢ Zone I: Cracking is unlikely, but may occur with high hydrogen or restrain. Use the hydrogen control (P_{CM}) method.
  ➢ Zone II: Use the hardness control method and the selected hardness (HV 350 or 400) to determine the minimum heat input (hence weld size) for single-pass fillet welds without preheat. If the heat input is not practical, or for groove welds, use the hydrogen control method to determine preheat.
  ➢ Zone III: Use the hydrogen control (P_{CM}) method.

It is clear that the AWS recommends that the hydrogen control method be used except for single pass fillet welds where the hardness control method can be used. In essence, then, the 2006-2010 revisions of the AWS are very much the same as the 2000 revision. For AISI 4130, CE is 0.66, using nominal alloy contents: C, 0.31, Mn, 0.5; Si, 0.23; Cr, 0.95, and; Mo, 0.2. The steel is located on Illustration 2, where it is clear that the hydrogen control (P_{CM}) method should be used to determine preheat.

3.2.5 The Skoda Method:

Hinton and Wiswesser [24] referred to a formula used by Skoda (Czechoslovakia), quoted as ref. 10, to estimate T_{PH}, based on CE_{IIW} (Equation 3):

$$T_{PH} = 450 \,°\text{C} \sqrt{CE_{IIW} - 0.42} \qquad\qquad Equation\ 7$$

For AISI 4130, CE_{IIW} = 0.62.

Thus, $T_{PH\text{-}AISI\ 4130}$ = 201 C or 395 F, below the M_S temperature (700 F).

3.2.6 The Winn Method:

ASM Handbook vol. 6 [25] lists the following carbon equivalent (C_{eq}) formula developed by Winn: [26]

$$C_{eq} = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} \qquad\qquad Equation\ 8$$

This Ceq was used to compute T_{PH} from the following formula:

$$T_{PH}\ (°\text{C}) = 210(C_{eq}) - 25 \qquad\qquad Equation\ 9$$

According to Equation 8, C_{eq} = 0.6 for AISI 4130. Thus, from equation 9,

$T_{PH\text{-}AISI\ 4130}$ = 101 C (214 F), below the M_S temperature (700 F).

The following variant of Equation 9 is listed in the ASM Handbook vol. 6: [27]

$$T_{PH}\ (°\text{C}) = 210(C_{eq}) - 25\ ^{+15}_{-45} \qquad\qquad Equation\ 10$$

According to equation 10, the preheating temperature for AISI 4130 is in the 81-141 C (178-286 F) range, also below the M_S temperature (700 F).

3.2.7 Other Methods & Formulae:

A relatively new carbon equivalent formula, CEN, is reported in the literature: [22]

$$CEN = C + A_F \left\{ \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr + Mo + Nb + V}{5} + 5B \right\} \qquad Equation\ 11$$

where A_F is an accomodation factor:

$$A_F = 0.75 + 0.25\ \tanh\{20\ (C - 0.12)\} \qquad\qquad Equation\ 12$$

CEN applies to both the traditional steels covered by CE_{IIW}, and the low carbon steels upon which P_{cm} was developed. This is brought about by the hyperbolic tangent (tanh) term in the accommodation factor, A_F. At higher carbon levels, A_F approaches 1 and CEN approaches CE_{IIW}. Conversely, at lower C levels CEN approaches P_{cm}. A detailed discussion of the methods used to estimate T_{PH} from CEN is presented elsewhere.[22] Other carbon equivalent formulae and the associated methods for computing T_{PH} can be found in numerous publications. A few are cited here. [15,16,18,28-33]

4.0 THE INTERPASS TEMPERATURE [11,34,35]

In multipass welds, the interpass temperature is the temperature of the weld zone between consecutive weld passes. The interpass temperature can be specified as a minimum, a maximum, or both, depending on the material being welded. Unfortunately, however, many publications just list interpass temperatures without indicating whether these are minimum or maximum values.

The minimum specified interpass temperature (T_{IP-Min}) is typically equal to the minimum specified preheating temperature, both < M_S. The purpose of maintaining the weld temperature above T_{IP-Min} between passes is the same as that for preheating; viz., to reduce or eliminate the risk of cold weld cracking.

Apart from specifying a T_{IP-Min}, a maximum interpass temperature (T_{IP-Max}) is sometimes specified to ensure that adequate weld properties are obtained. To illustrate, we consider the case of the 300 series stainless steels. These steels do not harden by heat treatment. This means that no austenite to martensite transformation takes place during cooling from the weld temperature to RT. The absence of martensite transformation obviates the need for preheating and controlling T_{IP-Min}, since there is no risk of cold cracking. It is important, however, to define a temperature that corresponds with the onset of the loss in corrosion resistance (sensitization). This temperature would be specified as the T_{IP-Max}. Weld temperature between passes should then be controlled so as not to exceed T_{IP-Max}, in order to retain the corrosion resistance of the steel. Controlling T_{IP-Max} is also important in quenched and tempered (Q & T) steels. Exceeding T_{IP-Max} in these steels can have adverse effects on strength, toughness and fracture toughness.

In some cases, the interpass temperature is specified in the following manner: $T_{IP} \geq T$. In such cases, T indicates T_{IP-Min}. In other cases, the interpass temperature is specified in the following manner: $T_{IP} \leq T$. In such cases, T indicates T_{IP-Max}., and it is implied that preheating and controlling T_{IP-Min} are not necessary.

It is said[35] that weldments with small cross sectional areas tend to accumulate interpass temperature; that is, part temperature tends to increase with each weld pass. By contrast, weldments with large cross sectional areas tend to dissipate interpass temperature; that is, part temperature tends to decrease with each weld pass, unless an external heating source is used. The undersigned is of the view that this behavior is brought about by the greater heat sink effect associated with the larger mass of parts with larger cross sections.

A note on large (thick section multipass) weldments is in order here. Hinton and Wiswesser[24] note that for large weldments, substantial amounts of austenite may be present at the conclusion of welding if T_{PH} and T_{IP-Min} are significantly higher than M_{90}[o] for the base steel. Upon subsequent cooling, this austenite can transform to martensite thereby increasing the risk of cold cracking. Accordingly, these authors recommend that for large weldments, T_{PH} and T_{IP-Min} should be below M_{90}. [p]

5.0 POST-WELD HEAT TREATMENT (PWHT) [12,24,25,36-44]

PWHT is a collective term referring to the thermal treatments performed after the completion of welding. There are two types of PWHT: postheating and stress relief. In post heating, the weld is not allowed to cool to RT. Rather, it is maintained at some elevated temperature for a period of time, then allowed to cool down to RT. Stress relief, by contrast, is a separate heat treatment that is performed after the weld had cooled to RT. It

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[o] *M_{90} is the temperature where nearly complete (90%) martensite transformation is achieved.*

[p] *The undersigned is of the view that this scenario (T_{PH} and $T_{IP-Min} < M_{90}$) will allow for the tempering of the martensite that had formed between M_S and T_{PH} or T_{IP-Min}, in any given pass, by the heat from the subsequent pass. It is true that in the other scenario (T_{PH} and $T_{IP-Min} \gg M90$), any austenite present can transform to bainite, but this reaction involves more significant times than those involved in the tempering of martensite. Accordingly, the likelihood is that some austenite will be available to transform to martensite.*

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involves heating to some specified temperature (1100-1400 F for steels), soaking for a period of time (2-4 hrs), and then cooling to RT in air. [q]

(a) Postheating:

To understand the need for postheating, one must first identify the microstructural constituents present in the weld metal and adjacent HAZ regions at the conclusion of welding. These are: untransformed austenite; ferrite and carbide (mostly in the form of pearlite and / or bainite) that formed during cooling from the weld temperature to T_{PH} / T_{IP}, and; untempered martensite that formed between T_{PH} / T_{IP} and M_S (only when T_{PH} / $T_{IP} < M_S$).

If the weldment is allowed to immediately cool down from T_{PH} (single pass welds) / T_{IP} (multipass welds) to RT, the untransformed austenite can transform to martensite (untempered). This transformation will generate additional residual stresses, which will be superimposed on those generated earlier during cooling from the weld temperature down to T_{PH} / T_{IP}. The increased magnitudes of residual stresses, the presence of hydrogen, picked up during welding, the general brittleness of untempered martensite, and the metallurgical notch resulting from the presence of a weld will all combine to increase the risk of cold cracking.

Noting that susceptible steels typically experience cold cracking around ambient temperature (RT), it is possible to avoid cracking by allowing the hydrogen to diffuse from the weld before the weld cools to RT. That is, the completed weld should not be allowed to cool to RT, before the hydrogen is given the chance to diffuse out of the weld at some elevated temperature. The following postheating options have been proposed and implemented in welding procedures.

- Option 1: Upon completion of welding, the weldment is maintained (soaked) at T_{PH} / T_{IP} for a period of time. The soak time should be sufficient to allow for hydrogen diffusion, relief of residual stresses, tempering of the martensite that had formed during cooling from the welding temperature to T_{PH} / T_{IP} (only if T_{PH} / $T_{IP} < M_S$), and the transformation of the untransformed austenite to other products, such as bainite. The steel may then be cooled down slowly and uniformly to RT.

T_{PH} and T_{IP}, being typically < 500 F, are not sufficiently high to allow for fast diffusion rates or for effective relief of residual stresses. To shorten the soaking times required for hydrogen removal, and to provide a more complete stress relief, some manufacturers adopt Option 2.

- Option 2: Upon completion of welding, the weldment is heated directly from T_{PH} / T_{IP} to some higher temperature (but below A_{C1}), occasionally as high as 1100-1400 F (the stress relief temperature range for many steels, including AISI 4130) and soaking for a period of time (say 2-4 hrs), and then cooling the steel down to RT.

In the above postheating options, the untransformed austenite would transform to bainite. Noting that tempered martensite is tougher than bainite, Option 3 has been recommended.

- Option 3: Upon completion of welding, the weldment is allowed to cool down from T_{PH} / T_{IP} to just below M_{90}, to affect the transformation of most of the untransformed austenite into martensite. [r] The temperature is then raised to the postheating temperature as indicated in Option 1 or preferably Option 2. By doing so, the newly formed martensite will transform to tempered martensite, as the temperature is raised as indicated above; simultaneously, the martensite that formed between M_S and T_{PH} / T_{IP} (only if T_{PH} / $T_{IP} < M_S$) would also be tempered. The weldment may then be cooled down to RT. This option involves the least risk of cold cracking, compared to the other two options.

Thus, the microstructure of the weld metal and adjacent HAZ regions after the above postheating treatments are performed properly would consist of ferrite plus carbide, mostly in the form of bainite and / or tempered martensite, [s] whereas, elsewhere, the microstructure will gradually transition from those constituents to the constituents present in the initial microstructure of base steel. This arrangement, which will persist after cooling to RT, may be acceptable for some applications. In such applications, the welded assembly may be cooled down to RT, inspected, finished per drawing requirements (paint, plating, etc.), and then placed into service.

(b) Stress Relief:

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[q] *For some steels, cooling rates faster than that of air are required to avoid the onset of embrittlement (not applicable to AISI 4130).*
[r] *This is the same practice proposed by Hinton and Wiswesser [24] for large weldments (see 4.0).*
[s] *Depending on the exact thermal history, some proeutectoid ferrite and / or pearlite may also be present.*

To reduce manufacturing time and cost, some manufacturers adopt short or even no postheating treatments, preferring to cool the weld to RT as soon as possible after the completion of welding. While this arrangement has the benefit of permitting the inspection [t] of the welded assembly soon after welding, it has the drawback of an increased probability of cold cracking, due to the potential presence of untempered martensite. Therefore, inspection must be performed as quickly as possible. If no defects are found, the assembly may be submitted for stress relief. In the event that defects are found, they should be repaired, and then the assembly should be stress relived. Because of the delay time involved in cold cracking (2.2.3), there should be a second inspection after stress relief. It is possible that cold cracks would be detected during this second inspection, after investing time and money in the above processes. This said, it is worthwhile noting that stress relief of welded structures, even in the absence of hydrogen embrittlement concerns, is a desirable practice.

It is important to note that undesirable effects can sometimes occur as a result of PWHT. For instance, the properties of quenched and tempered (Q & T) alloy steels can be adversely affected by PWHT if the temperature exceeds the tempering temperature of the base metal; the same is true for T_{PH} and T_{IP}. Stress relief cracking (2¼Cr-1Mo steel) and temper embrittlement (Cr-Mn steels) can also occur; AISI 4130 is not susceptible to either.

6.0 FULL HEAT TREATMENT

In some applications, it is required that the welded assembly be fully heat treated (hardened and tempered) to higher strength levels. While heat treatment may be considered a PWHT, it is best to deal with it as a separate issue. Needless to say that, if full heat treatment is required, the filler metal selected has to be able to match the properties of the base metal. [u]

When full heat treatment is required, the welded assembly may be taken directly from the postheating temperature [5.0 (a)] to the hardening oven for austenitizing, without allowing it to cool to RT. The austenitized steel is then quenched and tempered, as specified. Situations exist, however, where the heat treat facility for hardening and tempering is not co-located with the weld shop, or is unavailable at the conclusion of the postheating treatment. In such cases, the best course of action is to adopt Option 3 [5.0 (a)] for postheating, since it involves the least risk of cold cracking. After the weldment has cooled down to RT, it is inspected for weld defects. If no defects are found, the assembly may then be dispatched to the heat treat facility for hardening and tempering. In the event that defects are found they should be repaired; preheat, interpass, and postheating requirements for repair are to be as specified. After repair, the assembly should be inspected (for weld repair defects) and then dispatched to the heat treat facility. The heat treated assembly should be inspected one more time, to verify freedom from heat treat defects.

In the event that postheating options other than Option 3 are used, and the weldment had to be cooled down to RT prematurely (i.e., before achieving adequate stress relief and proper hydrogen removal), there can be a risk of cold cracking. The same is true if no postheating at all is used. In such eventuality, the procedures spelled out in [5.0 (b)] should be followed. Specifically, the weldment should be inspected, and the inspection should be carried out as quickly as possible. If no defects are found, the assembly should be submitted for stress relief [v] and then dispatched to the heat treat facility for hardening and tempering. In case defects are found, they are to be repaired, and then the assembly inspected a second time (for weld repair defects), stress relived, and then dispatched to the heat facility for hardening and tempering. The heat treated assembly should be inspected one more time, to verify freedom from heat treat defects.

7.0 WELDING LARGE STRUCTURES

Large structures include aircraft, automobile, and military vehicle body segments, bridges, ships, and buildings. Some of these structures, such as ships, buildings, and bridges are welded on site, and they cannot be moved. Others, such as aircraft, automobile, and military vehicle body segments, while they can be moved from place to place, they are typically too big for the commercially available ovens. Therefore, conventional (i.e., in ovens) stress relief and full heat treatment (hardening and tempering) cannot be carried out. The best that can be done with these large structures is to preheat, control the interpass temperature, and postheat by local means, such as resistance or torch (flame) heating, with temperature control conveniently done via temperature indicating crayons

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[t] *Inspection is possible only at RT.*
[u] *The chemistry of the filler has to match that of the base metal in order for the weldment to develop the same strength as that of the base metal after heat treatment.*
[v] *Some references indicate that stress relief is not necessary if the welded assembly is to be fully heat treated. This, however, is not advisable, unless the assembly is preheated before insertion in the hardening oven.*

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(e.g., Tempilstiks) or infrared (IR) guns (pyrometers). ESW or EGW maybe the most suitable welding processes for large structures.

Due to the difficulty of controlling local heating, it is best that forgiving steels be selected for applications involving large structures. By forgiving steels it is meant steels known to have low or no susceptibility to hydrogen embrittlement, such as low carbon steels (e.g., AISI 1018), or HSLA; stock sizes should be based on the strength of the selected steel relative to the loads that will be encountered in service. It is also wise to use weld metals (fillers) with significantly lower strength than that of the HAZ in the base steels. More importantly, the sequence of welding the various joints should be optimized to reduce constraint, hence the level of residual stresses; this is what had to be done with the Liberty ships during WWII.

8.0 NOTES ON AISI 4130

8.1 The use of ER-70S, ER-80S, or even 300 series stainless, filler metal is acceptable for welding AISI 4130 [45-50] in the annealed or normalized condition, where full heat treatment (hardening and tempering) after welding is not required. In using these filler wire types, preheating, postheating, and controlling the interpass temperature are generally not required. Some manufacturers, however, indicate that preheating and postheating should be applied for products with thickness ≥ 0.125 in. The interpass temperature would have to be controlled for multipass welds. It should be noted that using aforementioned filler wire types involves some sacrifice in weld metal strength compared to the base metal.

8.2 The use of Mil-R-5632 Type I (4130) filler is required in applications where the structure is required to be fully heat treated (austenitize + temper) after welding. [w] Preheating, controlling the interpass temperature, and postheating / full heat treatment requirements apply. Repair of these welds should follow the same rules. This paragraph is based on the undersigned's experience at Ford Aerospace and Communications Corp. in the late 1970 s.

8.3 The use of 17-22 A(S) filler or equivalent is required in applications involving weld repair of heat treated AISI 4130 components that cannot be heat treated (hardened and tempered) after welding. Preheating, interpass and postheating requirements apply. PWHT here is a stress relief at a temperature that is at least 75 F below the original tempering temperature. The same rules apply when welding heat treated AISI 4130. This paragraph is based on the undersigned's experience at Ford Aerospace and Communications Corp. in the late 1970 s.

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[w] *The chemistry of the filler has to match that of the base metal in order for the weldment to develop the same strength as that of the base metal after heat treatment.*

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