QUANTITATIVE AND QUALITATIVE COMPARISONS BETWEEN NECESSARY METHODS, APPLICABLE TO WELDING STEEL 13CrMo4-5, TO ESTABLISH THE PREHEATING TEMPERATURE

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Abstract: *The paper presents and compares a series of standardized and non-standardized methods for determining the pre-heating temperature (T_{pr}) applied to reduce or eliminate negative effects resulting from the use of the welding process, such as cold cracking. The results of quantitative and qualitative comparisons of the various T_{pr} calculating/setting methodologies are presented, but the preheat temperature values obtained for a case study referring to 13CrMo4-5 steel welding, a heat-resistant steel used in the case of the pressure-generating products in the energy industry.*

Keywords: *preheating, welding, heat-resistant, steel, cold cracking, methodologies*

1.INTRODUCTION

In steel melting welding there are important changes in the mechanical characteristics, which result in a change in joint elasticity and sometimes, and in some cases occur macro and micro cracking phenomena [1, 2, 3].

In [1, 2, 3] it is stated that the maximum hardness in the thermo-mechanically influenced area (ZITM) depends to a great extent on: the cooling rate, the thermo-physical properties of the welding material, the geometrical characteristics of the welded structure, welding mode used.

The magnitude of the average cooling velocity can be highlighted from the thermal field equations in the case of the thermal source acting on the welding of the two plates in a single pass, using the ratio 1 [4]:

$$v_{T_c} = 2\pi\lambda c\gamma \frac{(T-T_0)^3}{\left(\frac{E_l}{\delta}\right)^2} \; [^0\text{C/sec}] \qquad (1)$$

In which: δ - the thickness of the sheet, in cm; c - the specific heat in J / g^{0}C; cγ - the specific heat of the unit of volume, in J / cm^3 degree, γ - the specific density, in g / cm^3, T - the maximum temperature at which cooling is carried out at ^{0}C, T_0 - the ambient temperature in ^{0}C; E_l - the linear energy used for welding, in J / cm; λ - heat transmission coefficient in J /

cm s ^{0}C.

To control the cooling rate according to ratio 1, it is possible to resort to [5, 6]:

- changing the initial temperature T_0 by performing a preheating (T_{pr}) which leads to a decrease in the cooling rate;

- Modification of the linear energy (E_l) by means of the main parameters of the welding mode: the intensity of the welding current (I_s), the electric arc voltage (U_a) and the welding speed (v_s).

The factors under discussion in the T_{pr} pricing methods are dependent on: the basic material, the adduct, the complexity of the welded structure, the welding process, etc., as exemplified in Figure 1. The major difference between these methods is related to the importance which each method allocates to a certain factor of those listed above.

As a primary effect, preheating causes the removal of hydrogen from the welded joint, thereby reducing the risk of cold cracking [7, 8].

Cold cracking is influenced by several factors such as the chemical composition of the steel, the nature of the base material or its thickness, the amount of diffusible hydrogen in the welded joint, the energy of the electric spring, the deposition limit of the deposited metal (residual stresses), the constraints of the joints , the shape of the joint, the temperature of the environment, the type of joint (single or multilayer), the preheating method (by the heating rate, the type of preheating, local or total) etc. [5, 8, 10].

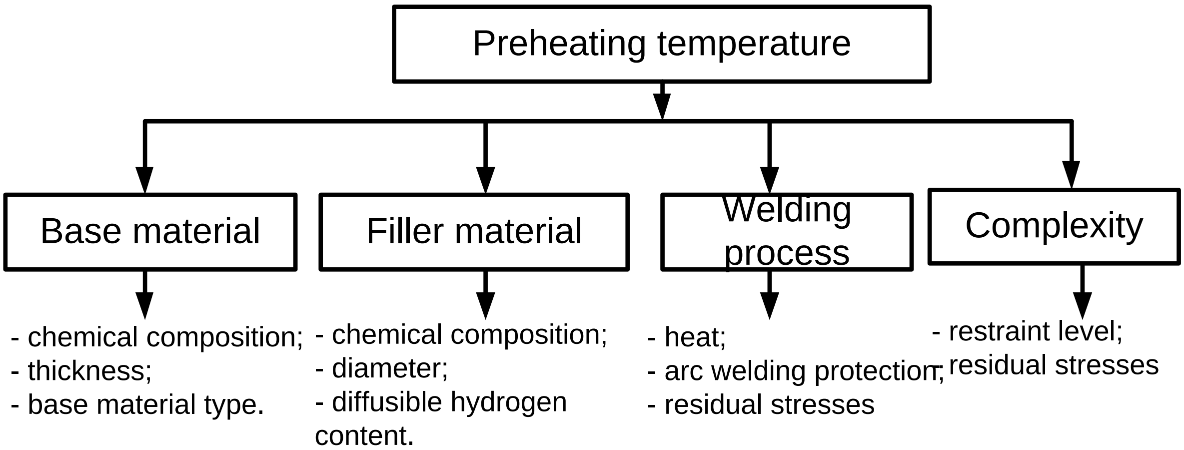

Figure. 1. Factors underlying the setting of the preheating temperature

In national, European and international standards, the pre-heating temperature is indicated as an essential variable of the welding process, which is why selection or setting of the preheating temperature must be in accordance with the rules in force.

It is noted that T_{pr} can modify the structure of the ZITM, the bonding zone and seam, also influencing the state of its own stresses, the concentration of the diffusible hydrogen, thus leading to changes in the properties of the welded joint, including the occurrence of some defects, type of cold cracks.

2. METHODS OF CALCULATING T_{pr}

Methods used in industrial practice to reduce the cold cracking tendency to determine the Tpr value to be applied in the welding technology approval process and subsequently to the welding process itself are inconsistent with the: “SR EN 1011-2: 2002 Standard. Welding. Recommendations for welding metallic materials. Part 2: Electric Ferritic Arc Welding”, COE Nomogram, Florian’s Criterion, DÜREN Criterion, ITO Y BESSYO Criterion SUZUKI

Criterion SUZUKI Y YURIOKA's Criterion, SEFERIAN's Ratio, Methodology proposed by the International Institute of Technology Welding (IIW); "Temperature Control" Methodology; American Standard ANSI / AWSD1.1 / 2015. "Structured weldingcode-steel, Annex H (Normative): Guideline on Alternative Methods for Determining Preheat"; Mathematical Ratios Based on CEN Equivalent Carbon; A series of mathematical formulas; Method established by R. W. Hintonand R. K. Wiswesser, Methodology proposed in ASM Handbook Volume 6 "Welding, Brazing, and Soldering".

The methods listed above differ by considering, in the T_{pr} calculation, the following:
- Parameters of welding technology such as I_s, U_a, v_s, E_l, etc.;
- Chemical elements, as well as their multiplication factors;
- Geometric configuration of the parts subject to welding operation;
- Mechanical features such as breaking limit (R_m), flow limit ($R_{p0.2}$), etc.;
- Addition material used in the welding process (chemical composition, maximum amount of diffusible hydrogen introduced during welding, etc.).

2.1 . Standardized methods

In the standardized methods, the above-mentioned methodologies are included in/by:

- Standard SR EN 1011-2;- International Welding Institute (IIW);- "Temperature Control" methodology;- American Standard ANSI / AWS D1.1 / 2015 - Structural welding code-steel, Annex H (Normative): Guideline on Alternative Methods for Determining Preheat;- ASM Handbook Volume 6: Welding, Brazing, andSoldering.

2.2. Non-standardized methods

In the methods of determining the preheating temperature, non-standard are included:
- The COE nomenclature, presented in [11];- The ratio established by Florian presented in [1, 12, 13]; - DÜREN's criterion, presented in [1];- Criterion of ITO Y BESSYO, presented in [14];- Criteria proposed by SUZUKI;- The criterion of SUZUKI Y YURIOKA, presented in [15];- A series of mathematical formulas;- Mathematical ratios based on equivalent carbon values; - The method of R. W. Hintonand R. K. Wiswesser, presented in [16].

2.3. Brief description of some methods for determining T_{pr} values

The methods outlined above, chosen for a brief description and applied in the case study, are:
- the FLORIAN ratio;ANSI / AWS D1.1 / 2015 - Structural welding code-steel, Annex H (Normative): Guideline on Alternative Methods for Determining Preheat; - SR EN 1011-2 / 2004; - ITO Y BESSYO's Criterion; - SEFERIAN ratio;the methodology developed by the International Welding Institute (IIS);- The methodology proposed in the ASM Handbook Volume 6 [17];
-The method developed by R. W. Hinton and R. K. Wiswesser;

To determine the preheat temperature, *Florian* proposed the following ratio:

$$T_p = 0.25 \times R_m + 62 \times H_{IIW}^{0.35} - 154 \, [^0C] \quad (2)$$

In which: R_m = the breaking strength of the deposited metal in [MPa]; H_{IIW} = diffusible hydrogen concentration in [ml / 100 grams of deposited metal]

From the analysis of the above ratio it can be noticed that the following variables are not taken into consideration: the parameters of the welding regime, the influence of the chemical elements and the type of joint.

Under AWS D1.1, two methods are provided for establishing the minimum value of

T_{pr} as follows:
- method based on hardness control in ZIT;
- method based on diffusible hydrogen control.

The first method is used for corner joints and is based on a critical value of ZIT hardness and the second method is based on the hypothesis that hydrogen-cooled crash cracking occurs if the average hydrogen concentration in the joint drops below a critical value after the welded joint cooled below 50 ^{0}C.

When determining the T_{pr} by the diffusible hydrogen control method, the factors to be consideredare the chemical composition through the Pcm parameter, the diffusible hydrogen concentration, the component thickness and the bridging intensity.

AWS D1.1.Standard provides for the establishment of the susceptibility index against the fracture I, calculated with ratio (3) [18].

$$I = 12 \ x \ P_{cm} + log_{10}H \quad (3)$$

The standard SR EN 1011-2 describes the methodology for setting the preheating temperature to avoid cold cracking, methodology that considers: the chemical composition of the base metal, the dependence between the heat input of the electric arc and the preheating temperature.

In the SR EN 1011/2 standard two methods are indicated: method A, applicable to fine grain steels and low-alloy steels and method B, which is applied to prevent the cracking, due to hydrogen, of non-alloy steels with fine grain and low alloy.

The steps required to determine T_{pr}, according to Method A, specified in SR EN 1011/2 are [19]:

- Making comparisons between the values of the chemical elements of the parent material and the limit values indicated in the standard to determine whether or not the method can be applied;
- Establishing the hydrogen class;
- Determining the combined thickness;
- Standard identification of the nomogram meeting the requirements for the hydrogen class, equivalent carbon value and combined thickness;
- The nomogram sets the pair of values “preheating temperature - linear energy”

The steps required to determine T_{pr} according to Method B of SR EN 1011/2 are:

- Making a comparison of the chemical element values for the base material and the limit values indicated in the standard to determine whether the method can be applied;
- Applying ratio 4 for calculating the preheat temperature:

$$T_p = T_{pCET} + T_{pd} + T_{pHD} + T_{pQ} [^0\text{C}] \quad (4)$$

in which: T_{pCET} - the influence of the chemical composition on T_{pr}, calculated with ratio 5; T_{pd}-influence of the thickness of the weld material on T_{pr}, calculated with ratio 6; T_{pHD}-represents the influence of the diffusible hydrogen introduced by the adduct on T_{pr}, calculated with ratio 7. T_{pQ}- represents the influence of the linear energy (i.e. the parameters of the welding technology) on the T_{pr}, established based on nomograms presented in the standard SR EN 1011/2.

$$T_{pCET} = 750 \times CET - 150 \ [^0\text{C}] \quad (5)$$

$$T_{pd} = 160 \times \tanh\left(\frac{d}{35}\right) - 110 \ [^0\text{C}] \quad (6)$$

In ratio 6, we noted with d, the thickness of the material, in mm;

$$T_{pHD} = 62 \times HD^{0,35} - 100 \, [^0\text{C}] \quad (7)$$

In ratio 7, with HD, the amount of diffusible hydrogen introduced by the addition material was recorded in cm^3 /100 grams of deposited material.
According to the methodology presented in SR EN 1011/2, method B, the preheating temperature can be established with ratio 8 if the following conditions are met:
- The basic material flow limit is up to 1000 [N / mm^2];
- The CET value is between 0.2 and 0.5 [%];
- The base material subjected to the welding operation has a thickness of between 10 and 90 [mm];
- The amount of diffusible hydrogen introduced by the feed additive in the joint is between 1 and 20 [ml / 100g m.d.), the unit of measurement was noted with: g - grams, m.d. - deposited material;
- The linear energy used during welding is between 0.5 and 4.0 [KJ / mm].

$$T_p = 679xCET + 160xtan\left(\frac{d}{35}\right) + 62xHD^{0.35} + (53xCET - 32)xQ - 328\ [^0C] \quad (8)$$

According to the ITO Y BESSYO criterion presented in [14], the analysis of susceptibility to cold cracking of steels with a C content between 0.07 and 0.22 [%] and R_m ranging from 400 to 900 [N / mm^2] can be done through the ratio 9:

$$T_{pr} = 1440xP_w - 392[^0C] \quad (9)$$

Where P_W is calculated with the ratio 10:

$$P_W = Pcm + \frac{H}{60} + \frac{K}{4000} \quad (10)$$

Where: Pcm is the cold cracking index calculated with ratio 11, H - the amount of diffusible hydrogen in [ml / 100 gm d.], K - the restriction factor, calculated with ratio 12 in which t represents the thickness of the components, in cm.

$$Pcm = C + \frac{Si}{30} + \frac{Mn+Cu+Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5xB \quad (11)$$

$$K = 66\ x\ t \quad (12)$$

SEFERIAN proposes the ratio 13 for setting the preheat temperature:

$$T_p = 350\sqrt{C_T - 0.25}[^0C] \quad (13)$$

Where: CT is the equivalent content of C calculated with ratio 14, in which s is the thickness of the material, in mm.

$$C_T = C_q + C_e = C_q\ (1 + 0.005xs)[\%] \quad (14)$$

$$C_q = C + \frac{Mn+Cr}{9} + \frac{Ni}{18} + \frac{7Mo}{90} \quad [\%] \quad (15)$$

$$C_e = C + \frac{Mn+Si}{4}, \text{ for carbon steels} \quad (16)$$

$$C_e = C + \frac{Mn}{20} + \frac{Ni}{15} + \frac{Cr+Mo+V}{5} + \frac{Si}{4}, \text{ for low alloy steels.} \quad (17)$$

Establishing T_{pr} by IIW is done through the following steps:
- Determination of the equivalent carbon value calculated with ratio 17;
- Determination of the weldability index L_s which considers the component thickness, the number of the heat exits, nc = 2 for the joining of the heads;
- Determination of the IST thermal index, calculated with ratio 18;
- Determination of preheat temperature;

$$C_e = C + \frac{Mn}{20} + \frac{Cr+Mo+V}{5} + \frac{Ni}{15} + \frac{Si}{4} \quad (17)$$

$$IST = nc\ \ x\ \frac{S}{6} \quad (18)$$

According to the *ASM Handbook*, Vol. 6, T_{pr} is calculated with the ratio 19 based on the equivalent carbon, determined by the ratio 20.

$$T_{pH} = 210\, x C_{eq} - 25\ [^0C] \quad (19)$$

$$C_{eq} = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} [\%] \quad (20)$$

The method established and presented in [16] by R. W. Hintonand R. K. Wiswesser involves the application of the ratio 21.

$$T_{pH} = 450\, x \sqrt{CE_{IIW} - 0.42} [^0C] \quad (21)$$

In which CE_{IIW} is calculated with ratio 22.

$$CE_{IIW} = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}\ [\%] \quad (22)$$

Table 1 lists the parameters based on the T_{pr} calculation using the methods outlined above.

Table 1. Parameters underlying the T_{pr} value calculation

Method / Parameter	1	2	3	4	5	6	7	8
Chemical composition	x	-	x	x	x	x	x	x
Ways to evacuate the heat	x	-	-	-	-	-	-	-
Characteristics of the additive material	x	-	-	-	-	-	-	-
Tensions (due to bridles)	-	-	x	-	-	-	-	-
Thermal severity index	x	-	-	-	-	-	-	-
Thickness of the material	x	-	x	x	x	-	-	x
Hydrogen diffusible	-	x	x	x	-	-	-	x
Pcm index	-	-	-	x	-	-	-	-
Linear energy	-	-	-	x	-	-	-	-
Susceptibility indicator	-	-	x	-	-	-	-	-
The breaking limit	-	x	-	-	-	-	-	-
Nomograms / graphs / centralizing tables	-	-	-	x	-	-	-	-

In which: 1 - method IIW; 2- Florian's ratio; 3 - The method specified in AWS D1.1.; 4 - The method specified in SR EN 1011-2; 5 - The method proposed by Seferian; 6 - The method outlined in the ASM Handbook; 7 - The ratio proposed by HintonandWiswesser; 8 - ITO Y BESSYO's Criterion; X - the method / ratio / methodology takes account of the parameter; - The method / ratio / methodology does not take into account the parameter.

3. CASE STUDY

3.1. Base material used

In order to establish the T_{pr} values, by the methods outlined in the second point, an application was chosen having the base material 13CrMo4-5 steel with the chemical composition indicated in Table 2 and the mechanical characteristics of Table 3.

Table 2. Standardized chemical composition of steel 13CrMo4-5 [20]

Chemical element	C	Si	Mn	P	S	Cr	Mo	N	Cu
Value [%]	0.08 – 0.18	Max. 0.35	0.4 – 1	Max. 0.025	Max. 0.01	0.7 – 1.15	0.4 – 0.6	Max. 0.012	Max. 0.3

Table 3. Mechanical characteristics of steel 13CrMo4-5 [20]

Nominal thickness [mm]	Up to 16	16 - 60	60 - 100	100 - 150	150 - 250
Breaking limit Rm [MPa]	450-600		440-590	430-580	420-570
Drip limmitReH [MPa]	290-300	290	270	255	245
Breaking energy KV (J)	Transversal: 27 to + 20 ^{0}C Longitudinal: 40-44 to + 20 ^{0}C				
Minimum elongation A (%)	19-22				

3.2. Selected addition material

The addition material is in the form of a coated electrode, the brand E Cr Mo1 B 42 H5 according to SR EN with the chemical composition specified in Table 4.

Table 4. Electrode composition ECrMo1B42H5 [21]

Chemical element	C	Si	Mn	P	S	Cr	Mo
The value [%]	≤ 0.12	≤ 0.80	0.7 – 0.90	≤ 0.015	≤ 0.020	1.00 – 1.50	0.45 – 0.65

This brand of electrode is designed for pressure equipment, pipe welding, welding of components used in the chemical and petrochemical industry. The electrode has a base coat used to weld heat-resistant steels, such as 13CrMo4-5, or 25CrMo4, required at temperatures up to 550 ^{0}C. The electrode, after application of the calcination operation at 250-350 ^{0}C, introduces the maximum hydrogel content up to 5 cm^3 / 100g and has an effective nominal efficiency of RE = 110% [21]. For the use of this electrode, the manufacturer recommends for different diameters the values of the welding current, I_s, given in Table 5.

Table 5. Values I_s recommended by the electrode manufacturer ECrMo1B42H5 [21]

Diameter of electrode [mm]	2.5	3.25	4	5
Welding current I_s [A]	60 - 90	110 - 135	140 – 190	200 - 240

3.3. Case study conditions

In the case study, the following input data were considered:

- The base material is supplied as a sheet of 12 mm thick and the welding process used is manual electrode welding (SMEI);

- The electrode diameter ECrMo1B42H5 is 3.25 mm;

-The amount of diffusible hydrogen introduced by the manufacturer by the ECrMo1B42H5 electrode is maximum 5 [ml / 100 g m.d.];

- The welded joint is of the butt welding;

- The joint type is in Y with the opening angle of 60^0, the distance between components b = 1 mm, the height of the root c = 2 mm;

- The joint is multi-layered on one side;

- Joining is achieved by using a single process (one-process);

- The joint refers to the welding of a 1000 mm diameter spindle and a 2000 mm length for a pressure tank used in the chemical industry;

3.4. Calculations

Obtained values are presented in table 6.

Table 6. Centralization of results

Method / Value T_{pr}	IIW	Florian	AWS	SR EN 1011-2	Seferian	ASM Handbook	HintonandWis wesser	Criteriullui ITO Y BESSYO
Minimum value [^{0}C]	150	68	<20	It can not be established	-	48	-	246
Maximum value [^{0}C]	-	105	<100	T_{pr} = 175^{0}C for E_l= aprox. 0.65KJ/mm;T_{pr} = 150^{0}C for E_l= aprox.0.75KJ/mm;T_{pr} = 125^{0}C for	136	117	238	504

				E_l= aprox.1.10 KJ/mm;T_{pr} = 100^0C for E_l= aprox. 1.15KJ/mm; T_{pr} = 75^0C for E_l= aprox. 1.25KJ/mm;T_{pr} = 50^0C for E_l= aprox. 1.45KJ/mm;T_{pr} = 20^0C for E_l= aprox.1.60 KJ/mm.				

From the analysis of the data presented in the above table we can see:

- The SR EN 1011/2 method provides several T_{pr} values and the choice of an E_l-T_{pr} value torque falls under the responsibility of the welding engineer;
- The values obtained by applying the ITO Y BESSYO criterion can not be applied in industrial practice, being very high, which implies very high production costs and times;
- There are certain methods that, although suitable for the case study analysed, do not lead to T_{pr} values.

4. CONCLUSIONS

After analysing the results obtained by applying the T_{pr} determination parameters studied in the paper, the following conclusions can be drawn:

- There is no single method of determining the T_{pr} that can be applied to all categories of steels undergoing the welding operation;
- Table 1 shows that there is no common parameter for all analysed methods;
- Irrespective of the method chosen and the resulting T_{pr} value, it must be verified by the welding technology approval process.

From the case study analysed in the paper, the following conclusions can be drawn:

- The obtained results of T_{pr} are different, applying different ratios/methods;
- There are methods, which, even if they are suitable for the application, lead to the obtaining of values of T_{pr}, which can not be applied;
- There are methods, which, even if they are suitable for the application, do not lead to T_{pr} values;
- The method presented in SR EN 1011/2 has the advantage that, for a specific case, a set of values for T_{pr} and E_l results, allowing the design engineer to correlate T_{pr} and E_l with the capability of the organization.
- It is very important that the method/methodology that will be applied to the assignation of T_{pr} is established by the contract between the beneficiary and the producer.

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