Methods for Optimizing the Preheat Temperature in Welding

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Several investigations have developed the principle of the control of the weld cycle cooling rate between 300 and 100°C with the aim of decreasing the preheat temperatures generally applied, while avoiding any risk of cold cracking. This control consists in slowing down sufficiently the cooling above 100°C to favour the elimination of diffusible hydrogen.

The Centre de Recherches Metallurgiques (CRM) has proposed for C-Mn and microalloyed structural steels the use of a cooling time between 300 and 100°C for the actual assembly in addition to the 800 to 500°C cooling time, to optimize the pair of factors "heat input-preheat temperature". A new criterion was developed for this purpose characterizing the sensitivity of the pair of factors "steel to be welded-filler material" which expresses the fact that the critical cooling time between 800 and 500°C is linked to that between 300 and 100°C.

The Institute de Soudure has proposed the use of the concept of critical postheat temperature deduced from postheating diagrams, established by means of the implant test, to determine the minimum preheat temperature as well as the minimum interpass temperature of the actual joint. Those precautions must be coupled with postheating the completed weld at high temperature. A simplified procedure, where the temperature control is limited to the first runs, is also proposed for assemblies whose thickness is less than 30 mm.

This document presents the principles of both these methods, how they complement each other and their preferential fields of utilization as a function of the steel grades used. Their application in welded construction is then described from practical examples communicated by the Belgian Ministry of Public Works.

1. Introduction

The weldability of structural steels has improved in recent years thanks to a reduction in the carbon content, the carbon equivalent and impurity levels. A favourable evolution has also been observed in welding consumables through a decrease in their diffusible hydrogen content. Nevertheless, the risk of cold cracking still exists during fabrication. This risk is still sometimes considerable with very high strength steels, in spite of the considerable advantages brought by the new production processes, and especially with low alloy steels in general which owe their mechanical properties to their composition and for which only a limited improvement can be expected in this regard.

This risk, which can be potentially high, is maintained at an acceptable level by the prescription and the control of a well adapted procedure, which lays down the welding conditions, such as the heat input and the preheating.

Within firms, the welding procedure often give rise to a difference of approach between those who base the preheating conditions to be adopted on old recommendations or on out of date specifications and thus for safety reasons conform to requirements which are often excessively conservative, and the workshop personnel who are reluctant to carry out preheating at high temperature because of the resulting discomfort, and who finally apply the procedure in an unsatisfactory way.

Moreover, preheating contributes significantly to an increase in the fabrication costs and to a reduction in the competitiveness of steel.

These reasons highlight the interest for all parties concerned in having well proven methods to determine the operating conditions which will achieve the best compromise between the safety and the economy of a welding operation. This is why action has been taken to achieve this compromise; it has led to two methods which are briefly presented below.

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2. Review of the factors which govern the cold cracking phenomenon modes of action proposed by both methods

The three main factors which govern cold cracking are shown in Table 1.

The first one is the propensity to brittleness of the micro-structure in the HAZ which depends on the chemical composition of the product and on the cooling rate at high temperatures. This rate which is generally characterized by the cooling time between 800 and 500°C (t8/5).

Then come the specific welding stresses, specially the transverse stresses which generate the cracks in the HAZ. For butt welds these stresses can be evaluated through a mean constraint in relation to the restraint intensity of more precisely a distribution of local stresses deduced from a numerical analysis calculation. Those constraints depend on the joint configuration and thickness, as well as on the environment which creates the restraint.

The last factor is the amount of hydrogen involved in the process, which depends on the potential hydrogen content of the filler product and on the evolution of the hydrogen concentration in the critical areas during cooling. The potential content is appraised conventionally by measuring the diffusible hydrogen on a bead on plate. When examining the possibilities of acting on these three factors through the welding procedure, it appears that:

- o it is hardly possible to modify the stresses which mainly result from the restraint;
- o one may reduce the embrittlement in the HAZ by changing its structure through sufficient decrease of the cooling rate at high temperatures, provided the hardenability of the product is not too high: this is the case for non or very low alloyed steels;
- o one may above all act on hydrogen, first by choosing the filler material with the lowest diffusible hydrogen content, then by drastically slowing down the thermal cycles at moderate temperature before reaching 100°C, because above that temperature hydrogen keeps a mobility in the crystalline lattice which favours its diffusion and reduces the concentrations.

Two ways exist of reducing the cooling rate, increasing the heat input (Fig.1) and raising the preheat temperature (Fig.2).

From a practical point of view, the increase of the heat

Table I Factors governing cold cracking

1. Microstructures in the HAZ (heat affected zone)	Chemical composition t8/5 (temperature 800-500° C)
2. Stresses	Restraint intensity. Geometry and thickness of the joint. Thermo-mechanical effects of the different runs
3. Hydrogen	Diffusible hydrogen content t3/1 (temperature 300-100° C)

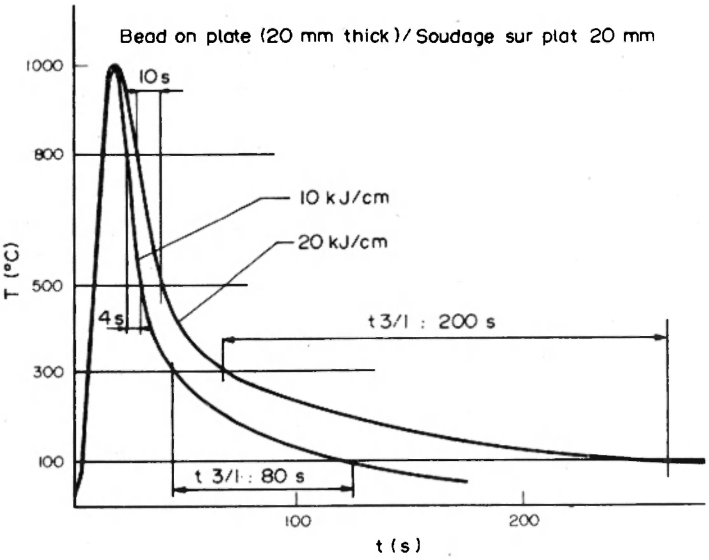


Fig. 1 *Influence of heat input*

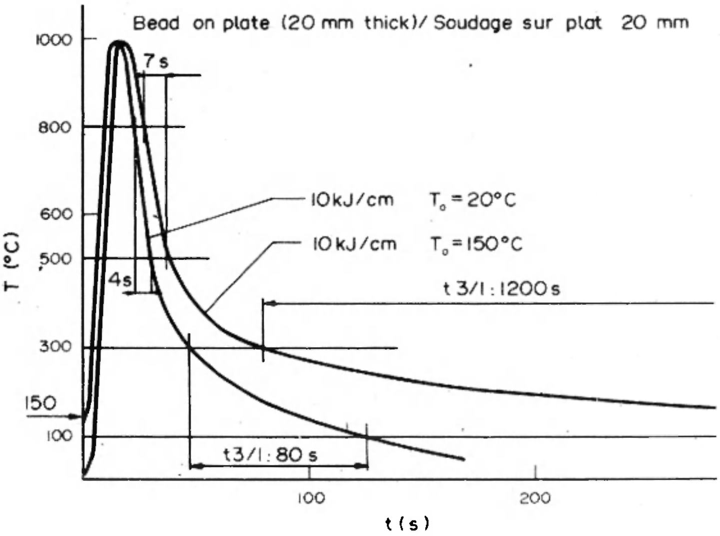


Fig. 2 *Influence of preheating on the decrease of cooling rate*

input can soon be limited by operating impossibilities, so that preheating seems to be the most practical means to reduce the cooling rate and also the most efficient, since it slows down the cooling to a greater extent at medium temperatures than at elevated ones. A more radical cure consists in temporarily stopping cooling at a sufficiently high temperature by means of postheating.

Both methods which we are now going to describe proceed from temperature control at the end of the thermal cycle to master and act on the hydrogen factor.

One, developed by CRM [1], proposes for C-Mn or micro-alloyed structural steels to consider the cooling time between 300 and 100°C (t3/1) of the real assembly in complement to the t8/5 in order to optimize the heat input-preheat temperature factors.The other, developed by the Institute de Soudure [2,3], is specially adapted to multipass welds in low alloy steels and involves the concept of critical postheat temperature to determine the minimal preheat and interpass temperature and to complete these precautions by a final postheating.

Both methods depend upon the characterization of the steel performed by implants fitted with a notch to generate local plastic strains and take into account the criterion of cracking critical stress. Detailed investigations [1,2,4] have in this connection confirmed the accuracy and the safety contributed by implant tests for the prediction of welding conditions on actual joints.

3. The Centre de Recherches Metallurgiques (CRM) method

The CRM method implies on the one hand an original concept to characterize the sensitivity of the factors "steel to be welded-filler material" and on the other hand, the definition of the thermal cycles by both parameters t8/5 and t3/1.

3.1. *Characterization of the factors steel to be welded fillerproduct*

The concept expresses the fact that the value of the critical cooling time between 800 and 500°C (trc) is bound to the cooling duration between 300 and 100°C (t3/1).

It is known that trc corresponds to the point where the implant cracking curve (Fig.3) attains the bae metal yield stress (Re). This parameter trc depends indeed on the cooling rate at moderate temperatures - as is shown by curve 2 in Fig.3 which corresponds to preheating the plate - because of the favourable evolution of hydrogen concentrations mentioned above.

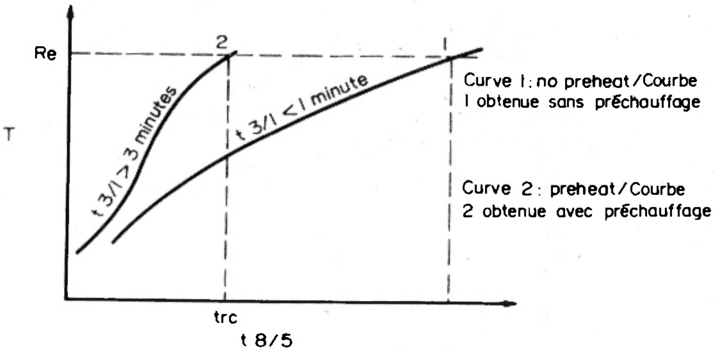


Fig. 3 *Influence of t3/1 on trc (critical cooling time)*

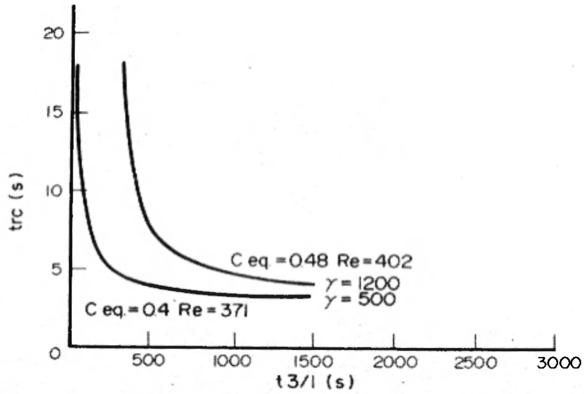


Fig. 4 *Examples of relationships between trc and t3/1*

Gathering such data together, CRM found the relationship which links the trc to the cooling time t3/1 by means of a parameter gamma (of dimension s^2) which in fact assesses the sensitivity of the pair of factors "in steel-filler material" to cold cracking. This law is established for a family of steels and a given potential hydrogen content. As an example, the following relationship applies for C-Mn and microalloyed steels welded with a basic electrode whose diffusible hydrogen content is lower than 6 ml/100 g of deposited metal:

$$[trc - (y/5000 + 3)]\,[t3/1 - (y/3 - 150)] = y.$$

The hyperbola which represents this law in Fig.4 for two gamma values, is symmetrical in the coordinates t8/5 and t3/1. The parameter gamma which ranges from 200 to 3500 for this type of steel as a function, among other things, of the carbon equivalent, may be calculated with this relationship from a couple of values: trc determined in the implant cracking curve of the steel and t3/1 measured during this implant test.

Gamma can also be predetermined from the carbon equivalent and the yield stress of the steel, by means of charts established by CRM (in this case, a statistical value of gamma is obtained, so as to compensate for the imprecision and the scatter of an estimate made on a carbon equivalent concept, for instance the gamma values at a statistical significance of 50% and 95% are available in the model).

3.2.*Characterization of the thermal field in welding*

The method implies that the relationships which link the welding conditions to the cooling parameters t8/5 and t3/1 be established, both for cracking tests which make it possible to lay down the law of behaviour and for real assemblies. As regards t8/5, this relationship has been known for a long time and several models are presently proposed. On the contrary, the parameter t3/1 had not until then been the subject of complete study so that CRM had to develop a mathematical model from direct experimentation. A law of evolution relating t3/1 to the heat input and the preheat temperature was obtained by multiple regression and then proposed for a range of configurations and thicknesses taking equivalent thickness and temperature into account.

Fig.5 shows an example of the evolution of t3/1 as a function of the equivalent thickness for a preheat temperature of 50° C while Fig.6 shows the same evolution for preheat at 200° C. Both examples show that the influence of the thickness on t3/1 is not the same whatever the preheat temperature: when the latter is high, t3/1 increases with the thickness and is practically not influenced by the heat input.

3.3. *Determination of the welding conditions*

The point is to choose a pair of factors "heat input-preheat temperature" which makes it possible to fulfill the conditions:

t8/5 (on actual joint) >= k.trc (of implant) for a same value of t3/1
k being a safety factor.

It is necessary in this regard:

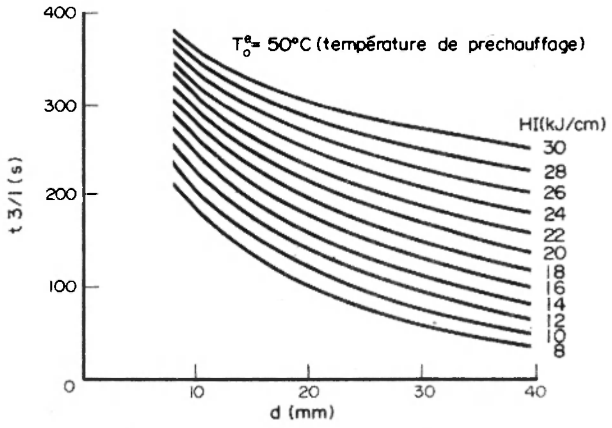


Fig.5 *Diagram for the determination of t3/1*

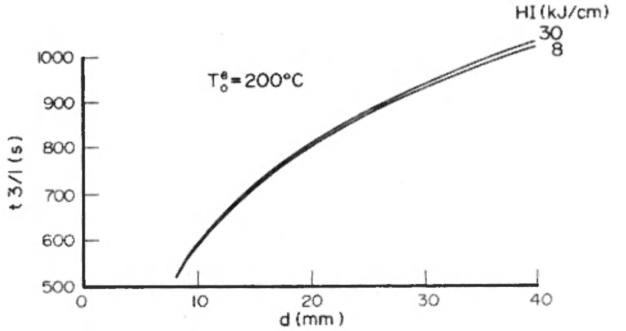


Fig. 6 *Diagram for the determination of t3/1*

(a) to determine the parameter gamma for the pair of factors "base steel-filler material" preferably from direct implant tests or possibly with a chart by means of C_{eq} and R_e.
(b) to determine the cooling times t8/5 and t3/1 in the application concerned by measurement or by predetermination with the proposed model.
(c) to calculate the trc corresponding to the t3/1 determined in (b), using the hyperbolic law of evolution and the parameter gamma.
(d) to compare the trc obtained to t8/5 determined in (b), taking a safety factor into account.

Such a procedure is well suited to a microcomputer treatment. This is proposed by CRM. It is only necessary to feed the program with the data characterizing the pair of factors "steel-filler material", then with those concerning the shape and the thickness of the assembly. The answer takes the form of either the preheating temperature which is necessary for a given heat input or a list of pairs of factors "heat input-preheat temperature" meeting the same criterion and from which the one best suited to the application will be chosen. An example is illustrated in Table 2.

Table 2

What type of material is welded ?
1. Structural steel
2. Pipe steel (X60, X70)
Answer: No. 1

What is the welding process ?
1. Manual metal arc welding with basic electrode
2. Gas shielded metal arc welding (i.e. CO_2)
3. Gas shielded metal arc welding (inert gas)
4. TIG welding
5. Submerged arc welding
Answer: No. 2

What is the type of the assembly ?
1. Butt joint
2. Corner joint
3. T joint
4. Overlap joint
Answer: No. 3

What are the assembled thicknesses ?
A (mm) = 40
B (mm) = 20

How many sides are preheated (2 or 3) ?
Answer: No. 3

What is the relationship between trc and t3/1 ?
Is "gamma" known (Y/N) ? N

Do you wish to compute "gamma" (1) from carbon equivalent or (2) from pairs of t3/1-trc values ?
Answer: No. 1

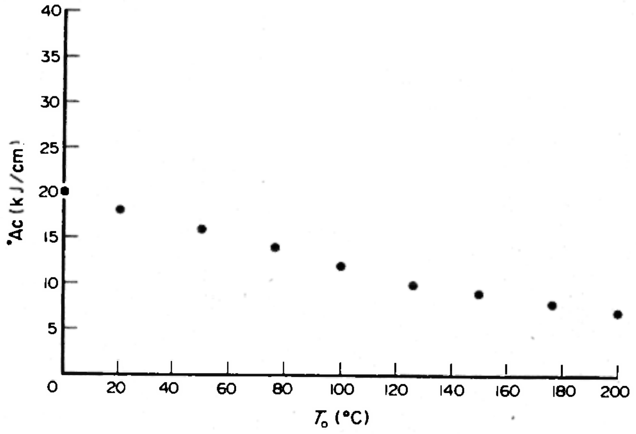
What is the value of the carbon equivalent (IIW) (in %) : 0.38

What is the value of the yield stress (in MPa) : 375

Which is the required degree of safety : t8/5/trc : 1.3

Established welding conditions
D equivalent : 50 mm
Gamma : 154
* Ac (kJ/cm)

Welding of structural steels
Gas shielded metal arc welding (CO_2) T joint
Preheating on : three sides
t8/5 / trc > 1.3



* Heat input

There exist also tables which make it possible to carry out easily the same determinations. Table 3a shows a chart for the determination of gamma starting from C_{eq} (IIW formula). The equivalent thickness which takes the geometry of the joint into account is calculated; and from tables, such as the one reproduced in Table 3b, the possible pairs of factors "heat input-preheat temperature" are obtained.

3.4. *Application of the method - examples*

Different cases in which the method described above was applied have been communicated by the Belgian Ministry of Public Works.

Table 3a Determination of gamma (statistical level: 95%). Manual metal arc welding with basic electrodes

(H_2<=6 cm^3/100 g deposited metal)

R_e/C_{eq}	0.300	0.325	0.350	0.375	0.400	0.425	0.450
300	450	450	450	450	552	651	744
325	450	450	450	493	605	708	806
350	450	450	450	539	655	763	866
375	450	450	450	583	703	816	924
400	450	450	489	626	751	869	982
425	450	450	527	668	797	920	1039
450	450	450	563	708	843	971	1095
475	450	450	598	748	888	1021	1151

Table 3b. Determination of the heat input. Equivalent thickness D = 20

T_v/gamma	450	500	600	700	800	900
20	22	23	26	28	30	33
50	18	20	22	24	26	29
75	16	17	19	21	22	24
100	13	14	15	17	18	20
125	11	12	12	14	15	16
150	9	10	10	11	12	13
175	8	8	9	9	10	10
200	7	7	8	8	8	9

Table 4 describes the chemical composition, the thickness and the mechanical properties of a series of steels which were welded.

T joints were made with these steels under a heat input of 25 kJ/cm. Welding was carried out with a very low hydrogen basic electrode, correctly dried.

The operating parameter to fix in those applications was therefore the preheat temperature.

This was first determined with a method based on a hardness criterion. According to this procedure, the hardness measured in the HAZ must not exceed 420 HVO.5. the preheating level is fixed from a series of hardness measurements performed on test assemblies with the steels to be welded.

The preheating temperature was then evaluated by the CRM method. In this case, the parameter gamma was directly determined from a series of implant tests carried out on the steels. The preheat temperature was then derived from the model.

Ideal conditions are therefore here fulfilled to compare both methods in an objective way, since the predictions of the preheat temperature are in both cases based on characteristic measurements: either the measurement of the underbead hardness in each steel, or the measurement of the sensitivity to cold cracking through the parameter gamma. The comparison illustrated in Fig.7 shows clearly the savings achieved on preheating with the new method. For information purposes, Table 5 lists the values of the gamma coefficient directly determined on each of the steels.

Table 4. Description of the steels

Steel	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Al	Nb	Ceq	t (mm)	R_e* (N/mm^2)	R_m+ (N/mm^2)
1	0.16	1.12	0.017	0.025	0.423	0.285	0.140	0.090	0.024	-	0.022	0.036	0.40	95	374	542
2	0.14	1.17	0.011	0.026	0.437	0.212	0.114	0.051	0.015	-	0.023	-	0.37	15	408	572
3	0.15	1.17	0.024	0.028	0.427	0.235	0.113	0.045	0.021	-	0.021	-	0.38	14	383	578
4	0.15	1.17	0.015	0.021	0.454	0.234	0.132	0.090	0.028	-	0.023	0.029	0.39	30	418	586
5	0.15	1.16	0.018	0.020	0.451	0.250	0.144	0.090	0.020	-	0.029	0.028	0.39	28	396	
6	0.16	1.43	0.016	0.007	0.440	0.020	0.010	0.020	0.020	-	0.044	0.026	0.41	28	383	554
7	0.17	1.27	0.018	0.010	0.431	0.245	0.100	0.030	0.022	-	0.034	0.025	0.41	30	376	547
8	0.17	1.42	0.012	0.002	0.410	0.010	0.020	0.030	0.020	-	0.032	0.030	0.42	20	408	571
9	0.18	1.24	0.014	0.010	0.400	0.210	0.125	0.062	0.016	-	0.029	-	0.42	35	387	548
10	0.17	1.32	0.016	0.011	0.451	0.348	0.160	0.080	0.024	-	0.037	0.032	0.45	30	414	553
11	0.16	1.49	0.027	1.017	0.550	0.050	0.044	0.240	0.008	-	0.031	0.026	0.45	30	395	560
A	0.10	1.11	0.011	0.019	0.270	0.364	0.037	0.626	0.008	0.053	0.050	-	0.45	15	361	498
B	0.10	1.11	0.011	0.019	0.270	0.364	0.037	0.626	0.008	0.053	0.050	-	0.45	30	345	502
C	0.12	0.96	0.029	0.017	0.320	0.410	0.270	0.610	-	-	0.054	0.034	0.45	23	410	542

*Yield strength.

+Tensile strength.

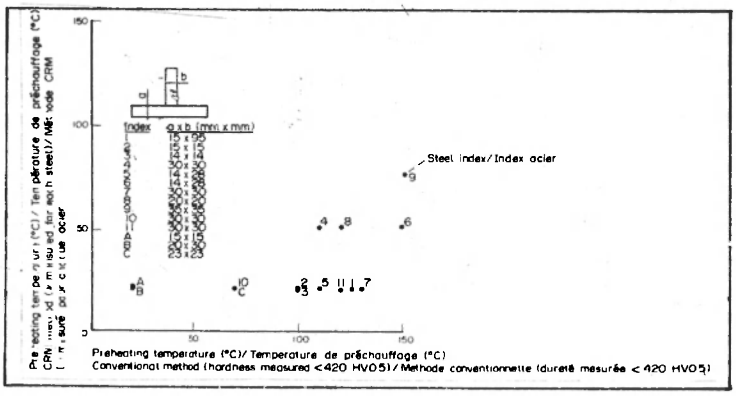


Fig. 7 *Comparison between a conventional method (hardness criterion) and the CRM mode*

Table 5 Gamma values of the steels

Steel	gamma*	Implant test results trc for t3/1 = 20 trc+ trc	t3/1
1	295	5 s	100 s
2	170	4 s	80 s
3	350	5.5 s	110 s
4	400	6 s	120 s
5	350	5.5 s	110 s
6	450	6.5 s	130 s
7	400	6 s	120 s
8	535	7.5 s	150 s
9	575	8 s	160 s
10	170	4 s	80 s
11	170	4 s	80 s
A	400	6 s	120 s
B	170	4 s	120 s
C	300	5 s	100 s

* Hydrogen <= 6 $cm^3/100$ g deposited metal

+ Those cooling conditions (t3/1 = 20 t8/5) correspond to those recorded during an implant test performed without preheat. The dimensions of implant support plate being always the same, one arrives a constant ratio between t3/1 and t8/5 for a given preheat temperature.

Let us add some comments:

The results and the general experience of the Belgian Ministry of Public Works show that the method based on the hardness criterion leads in many cases to uneconomical welding conditions and to scattered results on the same family of steels. Moreover, it is finally costly to apply because of the need for numerous hardness measurements on test pieces.

The method derived from implant tests brings decisive improvements in those regards. The application of the method is in practice very simple since the parameter gamma can be defined once and for all for a family of steels. No more tests are then necessary for its use. The cost savings on tests and on preheating temperature are thus evident. Moreover, a simple and cheap control of the correct application of the welding procedureis achieved by plunging a thermocouple in the weld pool and measuring the cooling times t8/5 and t3/1 on the actual joint. Portable devices exist to carry out easily this non-destructive measure.

A point to highlight is the low sensitivity to cold cracking observed on weathering steels (index A,B,C) in spite of their rather high carbon equivalent. One thus observes once more that the carbon equivalent cannot perfectly quantify every welding phenomenon.

Another application of the method which it is worth mentioning concerns the butt welding of a steel pipeline with cellulosic electrodes at low temperature. The point was to check whether this X60 steel could be welded on site at 0°C. The model indicated that crack free welds could be obtained on this 7.6 mm thick material with a heat input of at least 11 kJ/cm. Verification trials were carried out on actual welds made in a cold room and confirm the validity of the predictions established by the method (see Table 6).

4. Method of the Institute de Soudure for low alloy steels

It is easy to conceive that a limitation to the method described above may result from too high sensitivity in the pair of factors "base metal-filler material" which would lead to excessive preheat temperatures, the drawbacks of which were highlighted in the introduction to this paper. In such a case, the safest way to reduce the preheating to an acceptable level is to maintain this temperature after welding - using additional heating devices - long enough to decrease the hydrogen concentrations to a level low enough to enable cooling to be completed without the risk of cracking.

For 25 years, the Institute de Soudure has recommended the use of postheating to solve the most critical

Table 6 Butt welding on pipeline at 0°C

1. Welded steel : X60
C.E = 0.36%
Wall thickness : 7.57 mm

2. Questions

Is it acceptable to weld with cellulose electrodes at a heat input of 11 kJ/cm?

3. Answer of the model

Crack free welds obtained with 11 kJ/cm at 0°C under established welding regime. Need to preheat at 75°C, the first 100 mm of the firstbead, to avoid critical transient cooling conditions

		Predicted cooling times		Safety against cracking
	T_p	t8/5	t3/1	t8/5 / trc
Established regime	0°C	11 s	195 s	1.2
Transient conditions	0°C	8 s	97 s	0
(first 100 mm first bead)	75°C	12 s	204 s	1.4

4. Results on test weld

Welding was performed at 0°C in a cold room in a Belgian brewery

		Measured cooling times		
	T_p	t8/5	t3/1	Cracks in the assembly
Established regime	0°C	13 s	225 s	No
Transient conditions (at 30 mm first bead)	0°C	8 s	156 s	Some in the first 50 mm of the 1st bead

Heat input : 10.7 kJ/cm

cracking problems. Therefore, the aim of the recent actions reported in this document was just to expand the potentialities of such a treatment by determining the lowest applicable temperatures, and to propose a procedure making use of the control of interpass temperatures during welding. This procedure reinforces the interest of this parameter, whose importance is from another point of view increasingly emphasized as regards the final mechanical properties of a welded assembly.

4.1. *Significance of the critical postheating temperature*

The postheating diagrams are determined thanks to a particular procedure of the implant test, illustrated in Fig.8. A diagram is drawn for a given hydrogen content, that of the filler material used and for a heat given input and nominal stress. The test is itself defined by a pair of factors - "temperature-duration of postheating" - and the minimum durations which make it possible to avoid cracking are determined for different temperatures. A load is applied to the specimen as soon as postheating starts and is maintained for 20 h. Several tests are performed to provide a diagram like the one shown in Fig.9, which separates a safe area and a zone where delayed cracking occurs after postheating and during cooling. The evolution of the duration t is linked to the hydrogen mobility as a function of temperature. By seeking to decrease the temperature while increasing the duration, a criticalpostheating temperature T_{cp} can be defined, below which cracking takes place during postheating. That means that the HAZ is not without risk in this transition period during which the concentr- ation in hydrogen decreases.

A diagram for a high strength low alloy structural steel is shown in Fig.10. It will be noted that those tests involve preheating the plate at the same temperature as for postheating. Although not really necessary, this operation facilitates the application of postheating in practice.

4.2. *Definition of a procedure*

It is proposed to use the critical temperature T_{cp} to specify the minimum interpass temperature. This prescription implies that the temperature of the assembly and its immediate vicinity over a total width of 200 mm must in no case fall below this value before the final postheating is carried out. This treatment can, without drawback for the welding personnel, be conducted at a higher temperature according to the indications of the diagram. Figure 11

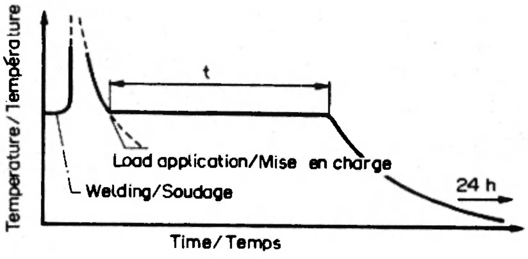


Fig. 8 *Implant procedure test with pre- and postheating*

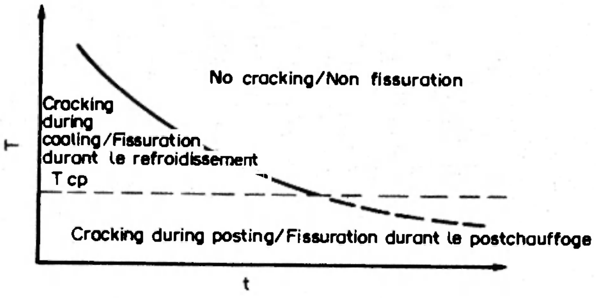


Fig. 9 *Postheating diagram*

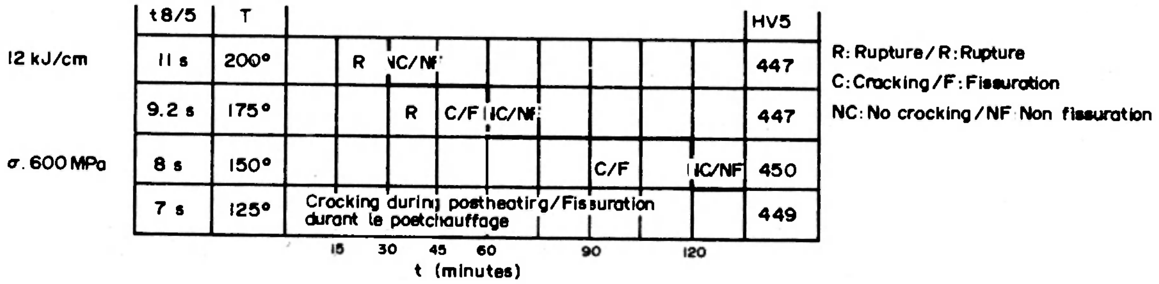


Fig. 10 *Example of preheating diagram for a low alloy HS steel E 690*

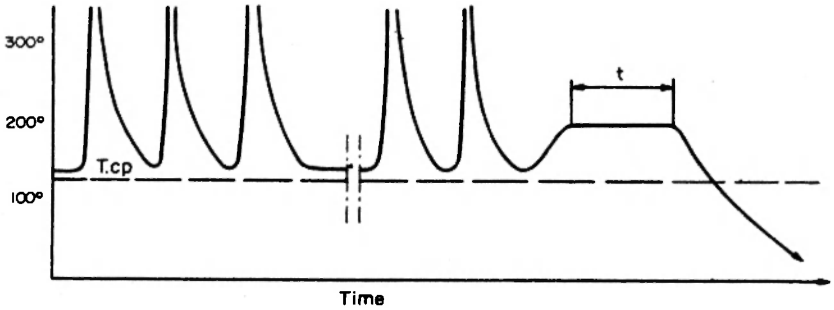


Fig. 11 *Evolution of the temperature in an assembly welded with postheating and respect of the minimum interpass temperature*

represents the evolution of the temperature which should be observed at any point in the assembly.

This procedure is particularly suited to the case of very thick parts, where high stresses may develop as a result of angular distortions of the assembly. It enables complete cooling to be envisaged with more safety and post weld heat treatment, which is sometimes performed immediately after welding when the risk of cracking is high, to be delayed.

A study [3] was aimed at determining whether it was possible to relax the strict control of the thermal regime that this procedure imposes during the whole of the execution of the weld, particularly for the very high strength steels used in structural work. In this field, it is generally more difficult to apply pre- and postheating precautions than in vessel construction. This investigation showed that for butt welds and thicknesses up to 30 mm it was possible to restrict the thermal control to a limited number of runs, which means the three or four first runs; the rest of the assembly can then be fabricated under the sole control of the heat input at much lower temperatures, as

Table 7 **Quenched and tempered microalloyed E690 steel. Determination of the minimum number of runs for which thermal control has to be made. Assembly with restrained transverse contraction (H shaped specimen)**

	Run No.	Interpass temperature	Heat input (kJ/cm)	t8/5	HAZ hardness Max	At the root	Results
E690T	1	-	16.0	5.8	439	429	100% cracks in HAZ and fused metal
	2	100°C	15.6	7.8	429	306	100% cracks in HAZ and fused metal
	3	100°C	14.5 14.7 13.6	6.3	445	314	100% cracks in HAZ and fused metal
	4	100°C	16.2 16.4 14.6 15.6	7.5	423	325	No crack
	Verification						
H e: 30 mm H^2: 322	4 +10	100°C 50°C	15.6 17.5 16.5 16.0	7.0	432	318	

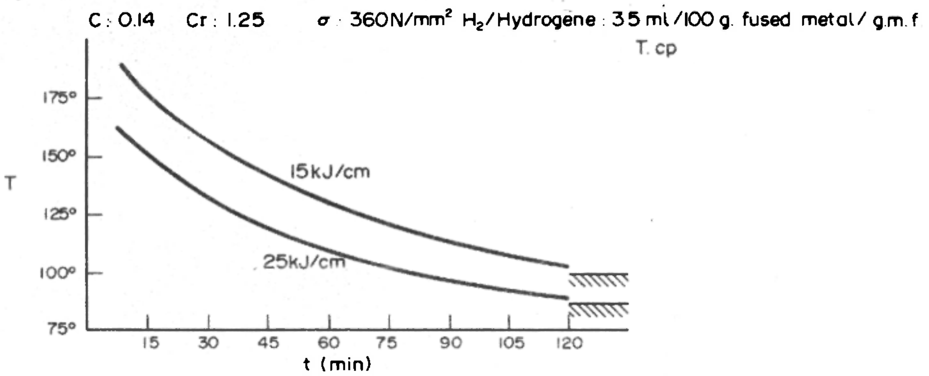


Fig. 12 *Grade 15 CD 4-05: influence of heat input on the postheating diagram*

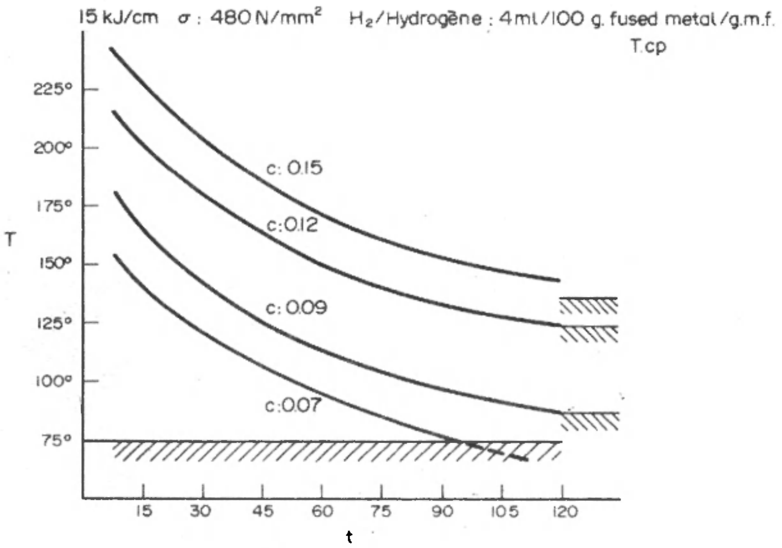


Fig. 13 *Postheating diagram for grade 10 CD9-10 (2.25% Cr-1% Mo)*

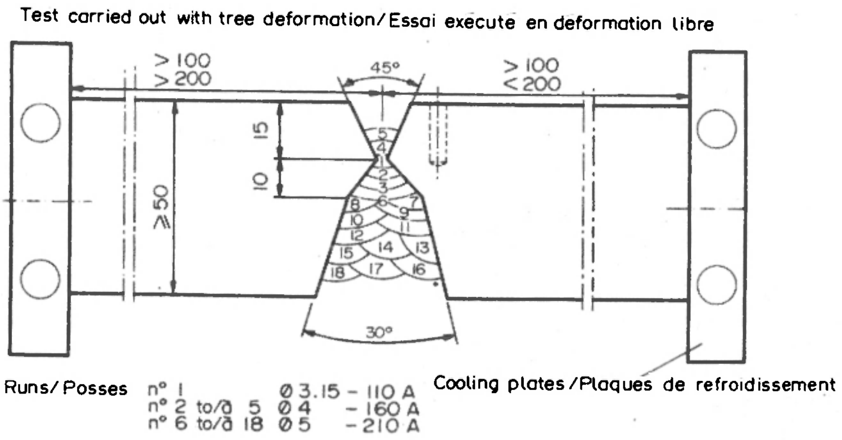


Fig. 14 *Cracking test to verify the efficiency of a minimum interpass temperature control: interpass minimum temperature equal to critical postheat temperature*

shown by the results relating to an E 690 steel listed in Table 7.

4.3. *Justification of the method*

To apply this method, it is necessary to have available the postheating diagram corresponding to the intended applications. Let us recall that this diagram is established for a pair of factors "steel-hydrogen content of the filler material" and for a given applied stress and a given input. The effect of both these parameters on the postheating conditions will be examined. To take the maximum risk into account, the nominal stress usually applied is the yield stress of the steel. Since this practice does not lead to excessive temperatures, it is generally not necessary to modulate this nominal stress as a function of the actual restraint level in the application.

Globally, the effect of postheating reduces the influence of the heat input on the cooling rate. This influence only subsits at elevated temperatures on t8/5. It has often no effect on the microstructure in the HAZ, owing to the self quenching feature of the steel (case of the steel with 2.25% Cr-1% Mo); a single diagram designed for low or medium welding energy is then sufficient. For less quenchable steels, it may be advantageous to use a diagram with an energy close to that really applied. It is worthwhile then to consider two diagrams: one designed for low energy - 12 to 15 kJ/cm, the other for a higher energy of about 25 kJ/cm. Figure 12 shows an example of the gap between both curves for a steel with 1.25% Cr-0.5% Mo.

There remains to be evaluated the influence of variations in the chemical composition so as to know whether it is necessary to adapt the postheating curve to each product. For the steels envisaged in this method, the fluctuations of the carbon content are those who mainly induce changes in the sensitivity to cold cracking. For some grades, this variation may be important and necessitates consideration of a network of curves T = f(t) such as the one shown in Fig. 13 and proposed for the grade 10CD9-10 (2.25% Cr). For other steels, the composition is rather well defined and displays very small fluctuations from one cast to another, so that a single curve can describe the grade.

The efficiency of the method has been verified by means of the specimen represented in Fig.14, on different low alloy steels. This specimen is designed for the execution of a multipass weld in asymmetrical chamfers. When making this weld in free rotation, the high local stress produced near run No.5 is liable to initiate a crack at this location.

5. Conclusions

It is clear that the methods just described are complementary. Both make it possible to determine welding conditions for the group of unalloyed and low alloy steels. Let us underline once again that they ensure the maximum safety at the best price. They are presently currently used and their development is still going on. So, CRM has adapted its method to the pipelines welded with cellulosic electrodes and to the hot tapping operation [1]. Another complementary investigation, relating to gas-shielded welding of structural steels, was reported very recently [5].

The Institute de Soudure extends the determination of the diagrams to new grades and will soon propose a computerized version to make the use of the method easier.

Let us end with an important remark. The behaviour of an assembly with regard to cold cracking is governed not only by the heat affected zone but also by the sensitivity of the weld metal. In most cases, the precautions required by the base metal apply *a fortiori* for the molten zone. In certain circumstances, the reverse situation may be encountered.

From this comes the interest in considering the behaviour of the factors "base metal-weld product" and in establishing the recommendations as a functionof the more sensitive metal.

Acknowledgments

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