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Additional Destructive and Non-destructive Tests, Performed Before Welding of Steel, with Variable Parameter Values Near the WPQR Tolerance Limits

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Abstract
The welding standards and codes define different tolerances of the essential and non-essential welding parameters and conditions, *viz.* variables, influencing the properties of the welded seams. Defining the limits of the actual welding parameters and conditions is responsibility of the welding technologists, supervisors or coordinators, based on the results of destructive tests and non-destructive tests, performed after welding of qualification test-pieces, performed before actual welding works, as well as based on their knowledge and experience. In many cases the welding variables are outside of the limits, actually tested during the qualifications, and the experience could not be used due to technological developments or extreme conditions. This paper evaluates the cases when additional activities to ensure the quality of the welded seams and heat affected zone could be undertaken.

Keywords: welding, variable limits, destructive tests, non-destructive tests, welding qualification

1. Introduction

The welding is a special process [1], as the resulted joint properties could not be readily assessed after completion. The improved knowledge of the materials and the developments in the manufacturing technologies resulted in wider range of applications as well as improved safety of the products. The predominant share of welding applications utilise materials and techniques that are save within wide tolerance limits of the variables, influencing the process. The work processes could be qualified on the base of previous experience, welding consumables tests or standard procedures [2]. When the welding products could represent increased risk in case of failure, due to significant consequences, service conditions or materials utilised, specific tests must be performed to qualify the welding procedures before the start of works [6]. Such cases include steel structures, bridges, transport vehicles, load-lifting devices, pressurised and/or process equipment *etc.* Due to the significant number of variables and the complex nature of their influence, a limited number of scientific models were validated to allow calculative evaluation. Product standards and codes were issued to set up requirements, regarding the welding variable limits and the actual tests to be fulfilled. While the general principles applied in the different codes are similar, the actual value limits differ significantly. In all cases it is a responsibility of the manufacturer's engineering personnel to evaluate the necessity and perform additional tests when some of the variable values are close to the limits within the regulatory requirements.

2. Properties of the welded joints

The mechanical properties of the welds, determining their ability to sustain structural integrity include tensile strength, impact toughness and ductility of the weld metal, and additionally the hardness of the heat affected zone (*HAZ*). The properties of the welded joints depend on two groups of factors, as described in Table 1, together with the variables influencing them.

The first group include the chemical composition and the internal structure of the base material, filler materials and in the transition zone between them, before and after the end of the welding process. The properties of the actual joints could not be measured nor tested after completion of the weld, but advance test procedures should be applied.
The second group of factors (geometrical and volumetric) could influence increase or reduction of the capacity of the joint to fulfil required purposes. For example, increased capacity may be achieved by increase of the size of the welded joint above the required minimum (increased safety factor of the joint). The reduction of the properties values may be result of imperfections within the weld metal, in the transition zone between the base and filler material or on the surface of the welds.

Table 1

	Factors	**Influence on properties of the joint**
1.	Chemical and structural composition of: Base material, Joint filler material, Transition zone material, Dissimilar layers (*e.g.* surface material)	Tensile strength, Impact toughness, Ductility, Resistance to additional load (*e.g.* fatigue, abrasion, corrosion etc.)
2.	Geometrical and volumetric, incl.: Weld design, Size and location of the weld, Shape of the weld, Non-continuities (imperfections)	Increase or reduction of the properties values

The geometrical and volumetric factors could be evaluated after the completion of the weld, by means of inspection, measurement or non-destructive tests. These factors depend on the product design and on the qualification of the welding personnel, which are not considered as variable during the execution of the project.
The chemical composition of the base and filler materials is defined by the respective standards and by the project design. It is measured and described in the certificates by the manufacturer, or by third party inspectors, present during the controls performed by the manufacturer.
The structure of the weld metal and of the base material in the *HAZ* undergoes significant changes during the welding process. The nature of the process is such that the welded metals change their physical state from solid to liquid and back to solid. During a short period of time the temperature of the material is increasing sharply and decreasing from the melting point to the temperature of the base material unaffected by the process. The processes within the weld and in the adjacent zone determine their mechanical properties.

2. Weld metal and *HAZ* cooling rate

Phase transformations and grain formation processes are strongly influenced by the cooling rate of materials with same chemical composition. The cooling time in the temperature range may vary depending on different variable conditions and parameters, Fig. 1.
The cooling models were developed and verified, describing the time and place of the thermal field, during welding and when the heat source was removed [11]. The shape of the cooling curve included fast decrease in the area of the highest temperature and slow equalisation with the temperature of the base material. The $\angle \alpha'$ and $\angle \alpha''$ reflect the cooling rate in case of faster and slower cooling rate, respectively. The $\angle \alpha$ could be measured between the temperature value line and the tangent to the cooling line, progressing from 90 to 0 degrees.

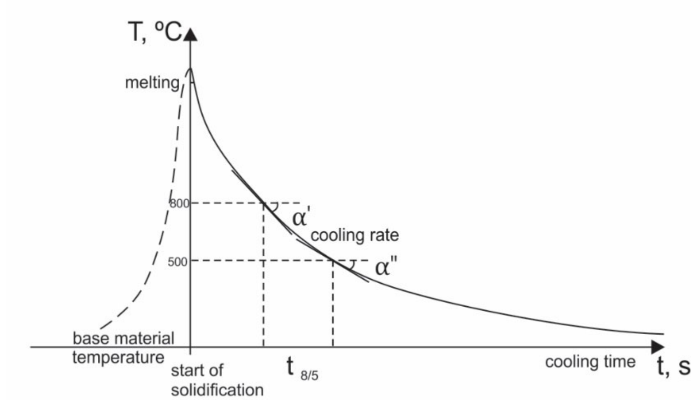

Fig 1. The cooling rate is a sophisticated function of the process variables (parameters and conditions). In normal conditions the cooling rate at lower temperatures is lower than the cooling rate at higher temperatures, α' > α'', as a result of the higher temperature gradient ΔT.

The cooling models were developed and verified, describing the time and place of the thermal field, during welding and when the heat source was removed [11]. The shape of the cooling curve in all cases included fast decrease in the area of the highest temperature and slow equalisation with the temperature of the base material. The ∠ α' and ∠ α'' reflect the cooling rate in case of faster and slower cooling rate, respectively. The ∠ α could be measured between the temperature value line and the tangent to the cooling line, progressing from 90 to 0 degrees. The cooling rate decreases with lowering the temperature.
The absolute value of ∠ α have no physical sense, as it depends on the time and temperature scales, but it is used to evaluate changes to the cooling rate under different conditions.
In case of too fast cooling of the weld metal and of the *HAZ,* hard brittle structure may be formed, increasing the risk of cold cracking and brittle fracture. The maximum admissible hardness limits the minimum cooling time in the temperature range from 800 to 500 °C [5], $t_{8/5\ min}$, Fig. 2.1. In many cases the cooling rate has to be controlled in wider temperature range, down to 100 °C [8], in order to limit the hardness of the *HAZ*.
In case of too slow cooling, coarse grain structure could be formed, reducing the strength and toughness. The required minimum impact energy limits the maximum cooling time in the temperature range from 800 to 500 °C [5], $t_{8/5\ max}$, Fig 2.2.

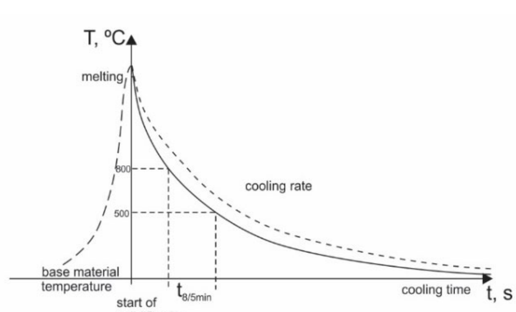

Fig 2.1.

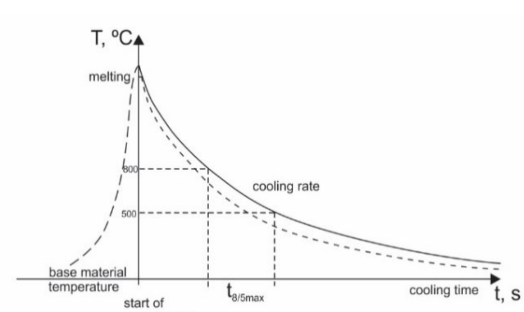

Fig 2.2.

Depending on the material chemical composition or on the application requirements, the impact toughness or the hardness might not be a property to be considered, when it could be esteemed that these do not represent risk to the welded joint. In cases when both hardness and impact strength have to be considered, the actual cooling rate of the weld metal and in the *HAZ* should be within safe zone limits.

3. Welding process variables

In most cases it is not practical to control the cooling rate during the manufacturing process. Instead, variable parameters and conditions, influencing the cooling rate, are defined and controlled. Depending on their influence, in some codes these variables are described as essential, non-essential or supplementary essential [7]. EN 15614-1 sets defined limits to the variables, regarded as essential, or describes some of the variables as non-essential. The defining of some variables as essential or non-essential depend on the level of qualification of the welding procedure [3], based on the application risk evaluation of the welded product. In the different product codes variables described as non-essential acc. to [3] could be regarded as essential or vice versa. It is responsibility of the manufacturer to evaluate the essence of each variable and decide which of these have only to be controlled, and which could be manipulated during manufacturing.

Some of the variables increase the cooling rate and other variables decrease it, according to complex dependencies that are not fully described. In general case the functional dependence of the cooling rate on the variables could be defined by the following relation:

$$\alpha = \frac{f_1(d) \times f_2(q) \times f_3(q) \times f_4(\Delta T)}{f_5(T_{0/i}) \times f_6(Q)}$$

where f_1 to f_6 represent the functions of different nature and significance, on the variables, as in Table 2.

Table 2.

	Variables	Dependencies and limits
f1	d – Material thickness and shape	There are limits set on the materials thickness range qualified by a single test and depending on the type of joint and the test piece thickness.
f2	λ – Thermal conductivity	The thermal conductivity is a property of the base material, but it is influenced by the actual temperature of the material, the structure and structural borders as well as on the presence of internal stresses [9].
f3	q – Energy transfer to adjacent media	The media surrounding the weld metal could be of different shielding gases, slag layers and air. Different materials influencing the transfer of energy and the cooling rate (e.g. insulation) could be utilized. The ambient conditions like temperature, wind, rain, etc. influence the energy transfer. The slag systems and the shielding gases are regarded as essential variables and requalification is required in case of change [3].
f4	ΔT – Temperature gradient	The difference between the weld temperature and the temperature of the base material. In the different standards the minimum ambient temperature and the base material temperature vary. In [5] the minimum ambient temperature is presumed as 0°C and the base metal temperature as 20°C, but the research shows that welding at much lower temperatures is executed successfully [10].
f5	$T_{0/i}$ – Preheating temperature / Interpass temperature	Comprehensive guidance on the preheating temperature T_0 calculation is presented in [5], as well as conditions that may require more stringent procedures or may permit relaxation. In multi-run apart from the preheat temperature, the inter-pass temperature T_i should be considered for each respective weld run, instead of T_0.
f6	Q – Heat input	$Q = k \frac{U \cdot I}{v} \cdot 10^{-3}$ in kJ/mm [4],

		where: k is the welding process efficiency U is the arc voltage, I is the welding current, V is the welding speed, in mm/s In [5] there is a permitted limit of 25% higher or lower heat input, but it is also required two test pieces to be qualified, from the highest and lowest heat input welding positions.

Further variables could be considered, to represent technological measures, in the cases when the actual cooling rate after welding may not be within the safe range, tested during qualification. Such measures could include post weld heat treatment; prolonged cooling time in the temperature range 300 to 100°C (allowing hydrogen diffusion out of the weld); use of extra-low hydrogen welding consumables *etc*.

4. Welding variables limits

4.1. Welding variable limits determination

The welding procedures are tested in order to verify the properties of the joint produced under the conditions, specified in preliminary welding procedure specification (WPS). The test WPS describe the actual values of the different variables measured during the tests in detail, and the WPQ-records include the limits of the variables, considered as essential by the respective code or standard.

Depending on the material properties and the application requirements, one test or more tests could be performed:

- When the impact toughness is a requirement, the test should be performed at the highest heat input conditions. The test is setting the upper limit (± tolerance, depending on the standard) of the variables.
- When the maximum hardness is a requirement, the test should be performed at lowest heat input conditions and would set the lower limit of the variables (± tolerance).
- When both impact toughness and the hardness should be controlled, two sets of tests should be performed, with the highest and the lowest heat input conditions, determining the upper and the lower limit of the variables (± tolerance).

4.2. Welding variable limits interpretation

In the welding codes and standards there is no common approach about the tolerance limits of the different variables. Apart from the applied product standard/code requirements, different interpretation of the requirements is possible, as in Table 3.

Table 3

Tolerance limit requirement interpretation	Minimum value measured	Mean value, kJ/mm	Maximum value measured	Minimum value – tolerance, kJ/mm	Maximum value + tolerance, kJ/mm
Min to Max ± 25%	0.8	1	1.2	0.60	1.51
Mean ± 25%				0.75	1.25
Min to Max				0.80	1.20
Max only defined				not limited	1.20
Difference in the required limits:				25%	20%

The difference of up to 25% of the defined minimum and maximum limits for same application is possible and significant, even if the weldability of the material is excellent. For some thermomechanically rolled steels the cooling speed limits were obtained by targeted research [12] as on Fig.3. The material properties deteriorated sharply when border values of the cooling time were exceeded. In such cases excessive increase of the variable limits could result in hardness or impact energy decrease outside the product and the joint safety limits, as shown on Fig 3.

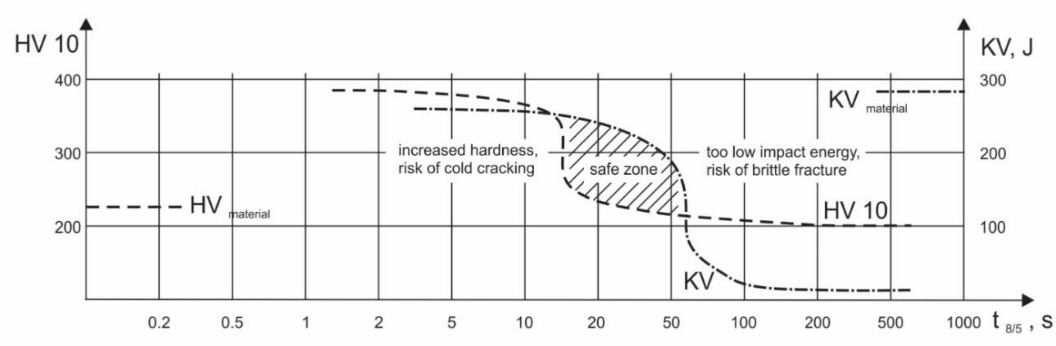

Fig 3.

4.3. Welding variables influence multiplication

The standards set limits on the individual variables. In certain cases the values of more than one variable could close to their limits simultaneously, e.g. high heat input welding parameters could be used on material close to the minimum thickness limit. In such cases the influence of both variables is to lower the cooling time. There is significant risk that the cooling rate would exceed the safety values:

$$d''_{(min)} < d'_{(tested)},$$
$$Q''_{(max)} > Q'_{(tested)}$$
$$\Downarrow$$
$$\alpha'' >> \alpha_{(max)}$$

where:

$\alpha_{(max)}$ is the maximum allowed cooling rate,

α'' is the cooling rate influenced by the heat input $Q''_{(max)}$ and the material thickness $d''_{(min)}$.

4.4. Excessive process variable values range

In specific cases the range of a variable values could be very wide. For example the heat input values range during tests of mechanised PQR of a single weld in PJ position, with welding process 135, could well include:

$Q_{(min.\ tested)}$ = 0.25 KJ/mm in the root pass,
$Q_{(max.\ tested)}$ = 1.50 KJ/mm in the cap pass.

In case of applying tolerances determined by the standard, (Q_{min} – 25%) to (Q_{max} + 25%), the variable limits could result in exceeded cooling rate safety limits (or $t_{8/5}$ cooling time safe limits, if recommended by the manufacturers of the base materials). Restrictive values of the welding parameters could be set or additional tests to be performed in case of necessity.

5. Welding procedure tests to be performed

The welding procedure test types and extend are required by the different standards and codes. The compulsory tests, according to EN ISO 15614-1 include non-destructive, as well as destructive tests [3]:

- Visual testing,
- Surface crack detection,
- Radiographic testing,
- Ultrasonic testing,
- Transverse tensile test,
- Transverse bend test,
- Macroscopic examination,
- Impact test,
- Hardness test.

While the destructive tests result in direct values of the material properties in simulated conditions, non-destructive tests may be employed to evaluate the actual joints of the manufactured products. In case of necessity of additional tests, the same tests used for the WPQR qualification could be used, or additional tests could be employed in order to evaluate certain property in deeper detail.

6. Conclusions

The cooling speed of the weld metal and in the HAZ in the temperature range from 800 to 500°C has highest influence on the structural formation of the welded joints. Measurable welding variables are used for indirect evaluation of the process parameters and conditions, influencing directly the impact toughness and the hardness values. The limits of the measurable variables are determined according to the requirements set in the different standards and codes. There are significant differences in the limits of the welding variables, as well as in the considerations of the different variables as essential or non-essential. Additional influence on the limits of the variable values is exerted by different interpretation of the standard requirements, multiplication of several variable values near the limits or excessive range of values measured during the WPQR tests.

Additional tests could be performed in order to enable or restrict the use of welding parameters nearly within of the allowed limits, as well as to enable informed decisions about the necessity of costly technological arrangements. Advance testing is justifiable as the most appropriate way to ensure the safety of the joints, and the functionality of the products.

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