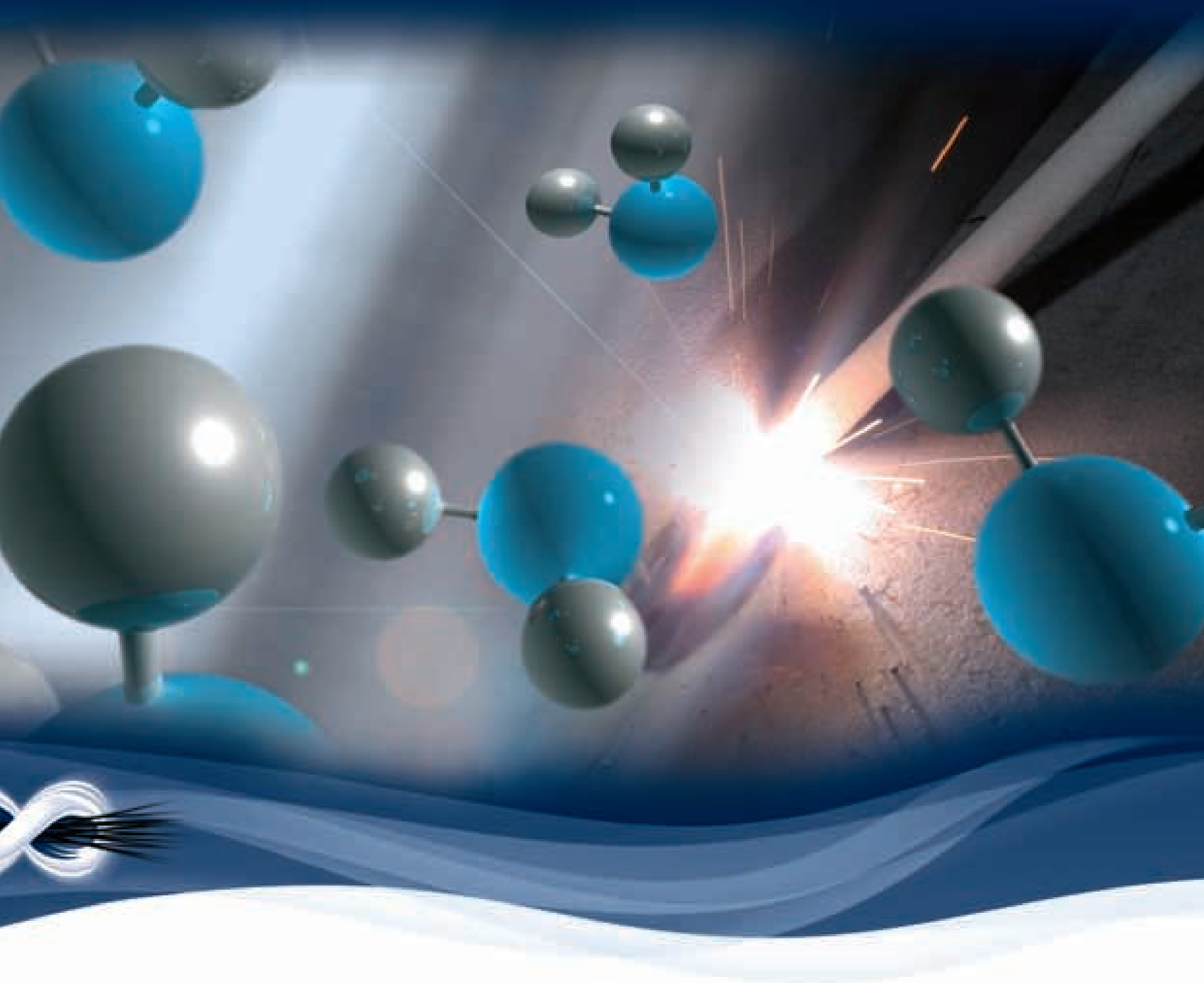
Böhler
WELDING



THE DANGERS POSED BY HYDROGEN IN WELDING UN- AND LOW ALLOYED STEELS

The danger posed by “Hydrogen” in welding un- and low alloyed steels

Overview

This publication will address the problem of hydrogen assisted crack formation in the welding of un- and low alloyed steels. The avoidance of this through appropriate measures will be explained, such as the use of selected welding procedures and the proper handling of electrodes.

PART 1 Describes hydrogen input in weld metals when using stick electrodes. In particular, the subjects of electrode handling prior to welding, ambient atmosphere during welding and the employing of different electrodes are discussed, and their effect on the hydrogen input in the weld metal described based on measurement results.

PART 2 Concerns itself with the hydrogen effusion that occurs after welding is completed. The fundamental relationship of temperature and time will be shown, as well as the influence of various preheating or interpass temperatures, different energy inputs and number of weld beads on the effusion behaviour of hydrogen in practical welds.

PART 3 Discusses a practical measuring method for evaluating the susceptibility of hydrogen assisted cracks (HAC) in multi-layer welds. Testing methods based on practical joint welds will be presented, and the relationships between weld metal strength, diffusible hydrogen content, joint thickness and interpass temperature will be deduced.

PART 1

Influence of welding conditions and electrode treatment on hydrogen input in the weld metal when using stick electrodes

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It was recognised very early on that welds with greater available hydrogen, in combination with greater tensile stresses and critical joint microstructures, are subject to crack formation, especially at temperatures under 200 °C [1, 2]. Above all, moisture arising from various sources was found to play an essential role in increasing the available hydrogen.

Figure 1 shows the sources of moisture or hydrogen when welding with stick electrodes. A distinction is made between the main sources:

- Specimen
- Ambient atmosphere and
- Electrodes

The individual sources of moisture or hydrogen are discussed individually below and the effect of hydrogen input in the weld metal is shown.

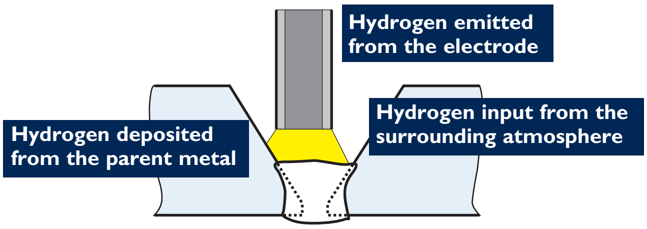


Figure 1: Sources of moisture or hydrogen when welding with stick electrodes

1. Source of moisture: specimen

Primary sources of moisture are most notably surface layers, such as primers, which have not been subject to any heat treatment for drying the seam edges prior to welding. As secondary, the residual – better known as non-diffusible – hydrogen content of the parent metal can be considered, which is already kept at a very low level by high-quality steel manufacturing processes. By means of an appropriate low-hydrogen annealing treatment, as is generally specified for the manufacture of the specimen carrier when testing the diffusible hydrogen content in weld metals, this hydrogen input can be further reduced.

2. Source of moisture: ambient air

A factor not to be underestimated in hydrogen input in the weld metal is the effect of the ambient air during arc welding. The intense energy of the arc can cause the moisture in the ambient air, which is to a certain extent dissociated or ionised in the arc into atomic hydrogen, to be absorbed by the weld metal and may subsequently lead to damages such as cracking. The ambient air, which can be defined by the two parameters

- Relative humidity and
- Air temperature,

can, according to the information of the DVS (German Welding Society) data sheet 0944 [3] or according to Dickehut [4, 5], be described by the water vapour partial pressure. Figure 2 shows the influence of air temperature and relative humidity on the water vapour partial pressure; equation 1 can be used as a formula for calculation [3].

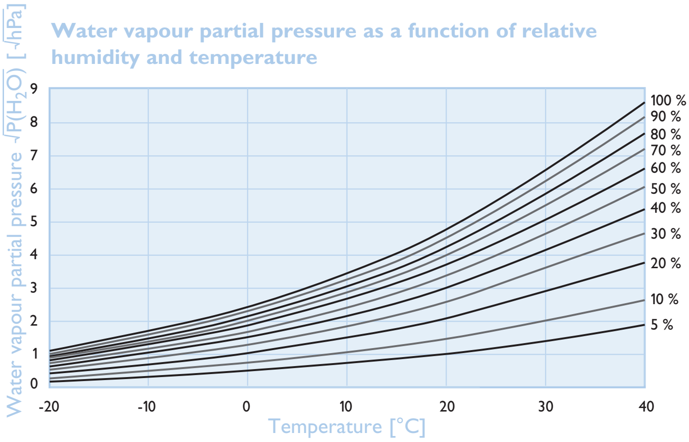


Figure 2: Description of the ambient atmosphere through relative humidity and temperature

$$\sqrt{P(H_2O)} = \sqrt{\frac{rel.RH}{100} \times 10^{\left(-\frac{2313}{273.15 + temp.} + 9.259\right)}}$$

Equation 1: Calculation of the water vapour partial pressure

It can be seen from Figure 2 that high temperatures in combination with high relative humidities generates a high water vapour partial pressure which has an effect upon the weld.

Resistance to the high water vapour pressure can only be maintained through suitable welding procedures and by the electrode itself. It is especially important when welding in humid ambient air that an arc that is as short as possible be maintained.

Figure 3 shows as an example the relationship of diffusible hydrogen content to arc length when welding a basic electrode in humid ambient air. Due to the increase of arc length, the arc surface and thus the absorption surface for hydrogen is increased. Of course, interactions between the individual mechanisms are also to be considered here. With an increase in the arc length, the arc voltage also increases depending upon the current source characteristics, which in turn leads to a higher energy input per unit length and improved effusion capabilities of the hydrogen out of the specimen. Furthermore, an increase of the arc voltage also exhibits changed dissociation and ionisation relationships in the arc, which leads to changes in the hydrogen absorption. It is to be additionally noted that the moisture content or the moisture absorption of the electrode covering changes the hydrogen absorption from the ambient air, since with higher moisture in the coating, relatively less ambient humidity is absorbed. The totality of all mechanisms can, when welding in humid air, lead to a decrease, but for unalloyed basic electrodes usually to an increase of the hydrogen absorption and the diffusible hydrogen content when there is an increase in the arc length.

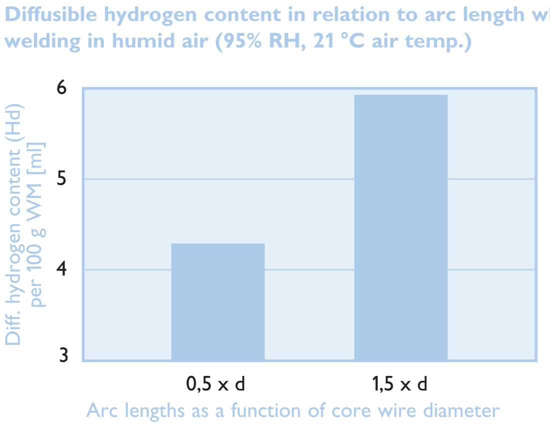


Figure 3: Diffusible hydrogen content per 100 g weld metal in relation to arc length, using the example of a basic electrode; d = core wire diameter of the electrode

The relation of absolute humidity during welding to hydrogen input in weld metals has long since been recognised and thoroughly investigated. From these findings, it is possible today to predict the diffusible hydrogen content (hydrogen input) in the weld metals for different ambient atmospheres [4, 5].

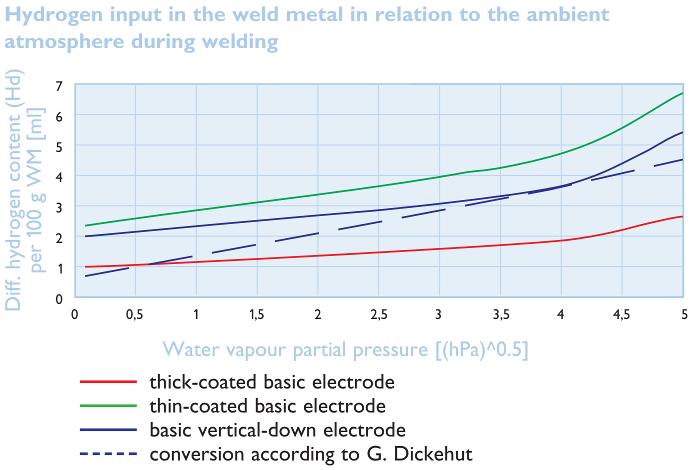


Figure 4: Effect of the ambient atmosphere on hydrogen input in the weld metal when welding various basic stick electrodes

For unalloyed basic stick electrodes from BÖHLER WELDING, distinctions were made between the individual types of basic stick electrode. Figure 4 shows as an example the diffusible hydrogen content in relation to air humidity for various basic stick electrodes. These relationships can be adopted for electrodes which are taken directly from the package or are welded after rebaking. For the example of the basic vertical-down electrode, the conversion developed by G. Dickehut for various ambient atmospheres is shown.

3. Source of moisture: electrodes

3.1. The relation of hydrogen content to base coating type

For the welding of non-alloy steels, a variety of electrodes can be employed. Each electrode type exhibits application-specific characteristics, whereby rough distinctions between the covering types can be made with regard to hydrogen input. Figure 5 shows the spectrum of diffusible hydrogen content in the weld metal, depending on the covering type, for a 4 mm diameter electrode. Cellulosic electrodes exhibit the highest hydrogen content due to the high proportion of hydroxyl groups in the electrode covering and a specifically set residual moisture. In rutile electrodes as well, the moisture content in the electrode covering is adapted or set in order to achieve a particular characteristic profile. For basic electrodes, one of the main objectives is achieving the lowest possible hydrogen content in the weld metal to ensure crack-free seams even when welding increased-strength and extremely high-strength steels.

When using these electrodes, a rebaking process is usually recommended by the electrode manufacturer.

Hydrogen input in the weld metal when using various electrode types

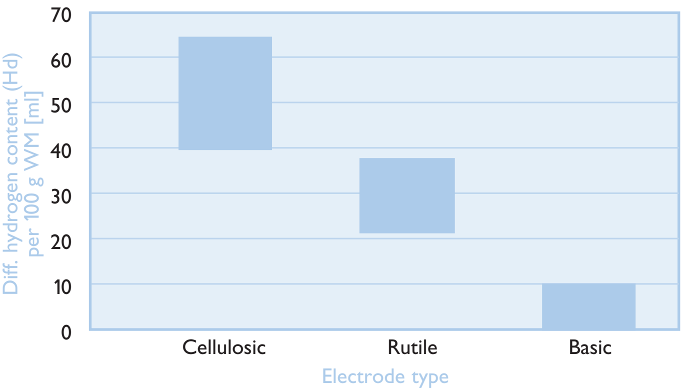


Figure 5: Diffusible hydrogen content per 100 g weld metal according to standard testing methods in relation to type of electrode covering

For these products, greater effort is required to achieve the desired results, whereby the work of the developer can be subdivided into the following main points:

- Reduction of the moisture absorption of the electrode covering with removal from storage into humid air
- High protective function of the electrode covering in a humid atmosphere (tropical regions with relative humidity of 90% or greater and high temperatures)

3.2. The relation of hydrogen content to electrode storage

BÖHLER WELDING was one of the first manufacturers to begin supplying stick electrodes in hermetically sealed tins. This allows the risk of moisture absorption during transport and storage on-site to be excluded up to the moment of welding. The absolutely water- and vapour-proof tin ensures ready-to-use electrodes, which can be reliably welded without rebaking.

As shown in Figure 5, basic electrodes normally exhibit a hydrogen content of 1–10 ml per 100 g weld metal, depending on the composition of their coverings.
This hydrogen content can certainly be substantially increased by improper storage of electrodes, since the electrode covering absorbs moisture from the surrounding air. To create a better picture of the actual effects of electrode storage, a laboratory electrode without moisture absorption-inhibiting agents was manufactured and then stored in various ambient atmospheres.

The exposure time of these basic laboratory electrodes (with a low proportion of iron powder in the electrode covering) was various. This treatment reproduces a period of storage in various climatic zones, whereby the moisture absorption of the electrode covering was measured through the increase of weight. Figure 6 shows the moisture absorption of the electrode covering in relation to water vapour partial pressure and exposure time. With low absolute humidity (water vapour partial pressure), little moisture is absorbed from the surrounding air even with long removal from storage times. With high humidity however, the moisture content increases greatly even with a very brief exposure time. It must be pointed out here that the moisture absorption depends heavily on the electrode coating design, basic composition and diameter, whereby even slight changes in coating composition can lead to considerable differences in moisture absorption behaviour.

Moisture absorption of the electrode covering in relation to absolute humidity and removal from storage time (laboratory electrode without moisture absorption-inhibiting additives)

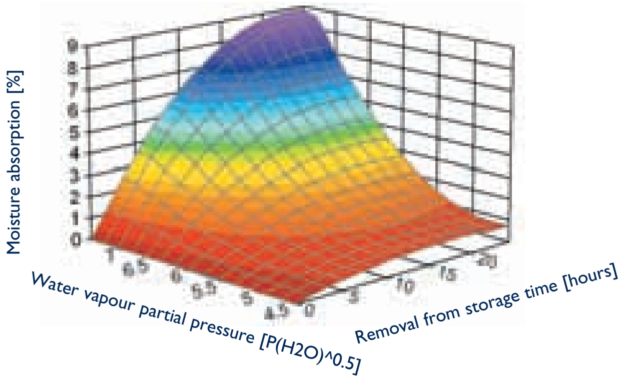


Figure 6: Moisture absorption of the electrode covering

Hydrogen input in the weld metal in relation to the electrode's coating moisture absorption and the ambient atmosphere during welding (laboratory electrodes without moisture absorption-inhibiting additives)

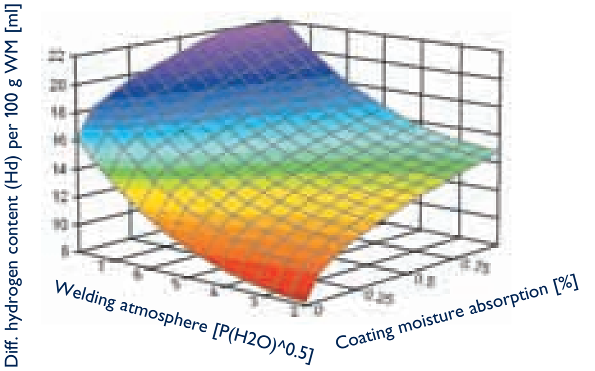


Figure 7: Effect of water vapour partial pressure during welding (welding atmosphere) and coating moisture absorption on hydrogen input when welding a basic laboratory stick electrode

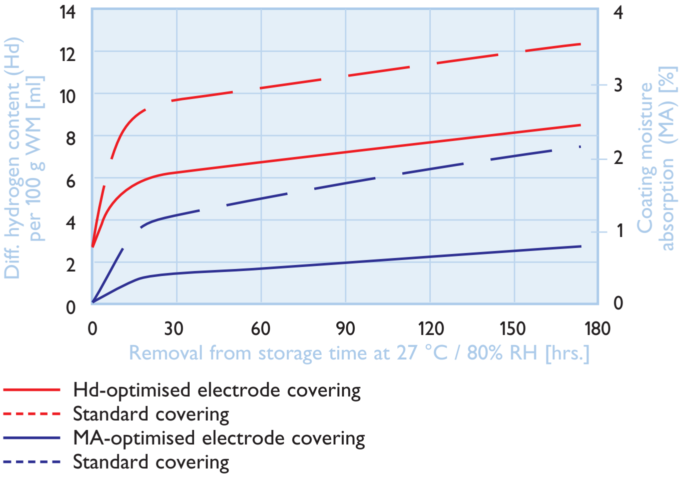
In the development of stick electrodes, the engineers at BÖHLER WELDING therefore pay special attention to the susceptibility to moisture absorption and the relationship of coating moisture and diffusible hydrogen content in the weld metal. Figure 7 shows the relationships for the above-mentioned basic laboratory electrode.

Also shown in this diagram is the effect of welding in differing ambient atmospheres. Notable is the increase in diffusible hydrogen content with removal from storage and welding in a humid atmosphere, which in this case can be attributed to the lack of suitable coating components for reducing the hydrogen input.

3.3. Reduction of the hydrogen input in weld metals through innovative electrode cover designs

The diffusible hydrogen content represents, especially for the welding of high-strength joints, a criteria in regard to the formation of hydrogen assisted cracks. The reduction of coating moisture absorption and of the diffusible hydrogen content of covered stick electrodes is and therefore remains a high-priority development goal. Figure 8 illustrates the know-how of BÖHLER WELDING: Clearly improved hydrogen values through optimised coating designs. Through modification of the coating composition, the moisture absorption, the basic hydrogen content as well as the diffusible hydrogen content could be substantially lowered after removal from storage. Most notably, the susceptibility to moisture absorption with a briefer exposure time (welding of electrodes within a work shift) was considerably improved.

Reduction of the hydrogen input in weld metals through optimisation of electrode coverings



Hd…diffusible hydrogen content
MA...moisture absorption of the electrode covering

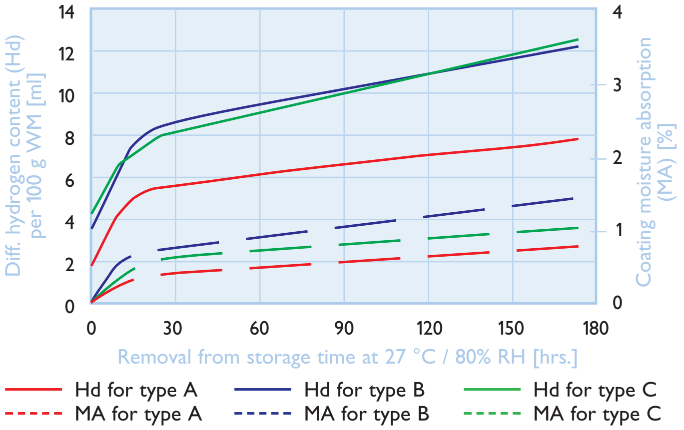
Figure 8: Optimisation of the electrode covering in regard to hydrogen input and coating moisture absorption; ambient atmosphere during welding: 23 °C / 45% rel. humidity

In the development of stick electrodes for high-strength joints, it is particularly useful to reduce the moisture absorption of the electrode covering and the susceptibility in regard to hydrogen assisted cracking. In regard to this, the lowering of the potential risk through the use of such welding consumables should certainly be mentioned.

The moisture absorption of the electrode covering and the effect of water or hydrogen essentially depend on the coating design.

Figure 9 shows the relationship of coating moisture absorption and hydrogen input in the weld metal for various basic stick electrode types.

Relationship of coating moisture absorption and hydrogen input when using various electrodes



Hd…diffusible hydrogen content
MA...moisture absorption of the electrode covering

Figure 9: Relationship of coating moisture absorption and diffusible hydrogen content for various basic stick electrodes (welding atmosphere: 21 °C / 60% RH)

Type A behaves relatively non-critically for removal from storage into a humid atmosphere or exhibits only a minimal increase in the diffusible hydrogen content. Type B and C generally exhibit a higher hydrogen content in the rebaked condition. Removal from storage can additionally result in greater hydrogen input. The differences depend on the design of the electrode coverings and the manufacturing technology. The description of the complex physical and chemical processes that occur during removal from storage and welding would, however, exceed the scope of this report.

3.5. Effect of electrode heating during welding on the hydrogen input in the weld metal

The diffusible hydrogen content is normatively measured by welding a specimen consisting of the starting, centre and ending piece. Unused electrodes are employed for this, which heat up during the welding of the specimen according to the set welding current, the coating moisture and other factors.

The primary reason for the temperature increase of the electrode is the “Joule” heating through the current load of the core wire. The heat transfer depends on the square of the welding current and on the welding time. Hydrogen input in the weld metal changes if electrodes with a certain coating moisture are welded, regardless of whether the moisture arose during production or entered the coating after removal from storage. Figure 10 shows as an example the diffusible hydrogen content of a basic electrode with and without electrode heating. Electrode heating was achieved through an aforegoing weld of half the electrode's length with average current. This heating results in a “self-drying effect” on the electrode coating, causing residual or even later absorbed moisture to then be given off again. Here it should be noted that the cohesive force of the moisture on or in the coating also depends on the storage time in a humid atmosphere.

Hydrogen input in the weld metal when using various electrode types

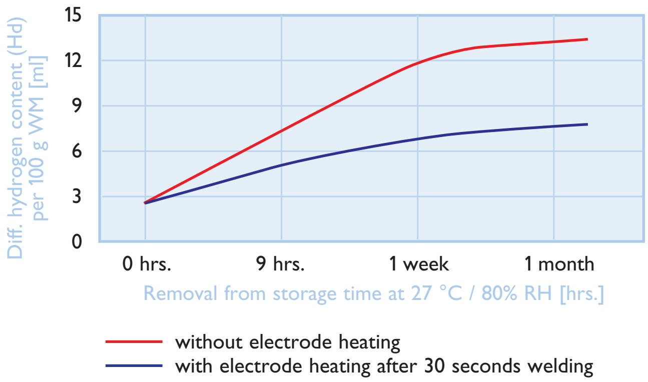


Figure 10: Reduction of hydrogen input through electrode heating during welding, weld atmosphere: 21 °C / 60% RH

Summary

Part 1 shows the possibilities of damaging H_2 absorption and how this can be minimised by appropriate packaging as well as through the expertise provided by development engineers of BÖHLER welding technology. In principle, the welding process can be subdivided into the partial systems of parent metal, electrode and ambient air, whereby each partial system can be a source of hydrogen. For the overall assessment, the individual hydrogen inputs cannot however be added, since the complex physical and chemical processes lead to interactions in the welding process and the diffusible hydrogen content is thereby affected.
The arguably most underestimated hydrogen sources, which ultimately lead to high diffusible hydrogen contents in the weld metal and in critical instances could lead to cracks, are most certainly humid ambient atmospheres, welding with long arcs in humid air and the electrodes being removed from storage into a humid atmosphere. Examples were presented and the focus of development engineers in this field of work was highlighted. Due to the innovative covered electrode design, it is possible to achieve low hydrogen contents in weld metals and thus to substantially lower the potential risk of hydrogen assisted crack formation.

BÖHLER WELDING would like to help sensitise welding engineers, welding supervisors and welders in this area and, through suitable welding processes, electrode treatments and welding preparations, contribute to keeping the hydrogen input in the weld metal as low as possible.

PART 2
Effects on hydrogen diffusion in weld metals when using stick electrodes

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Part 2 describes the options in the manufacture of the electrodes for keeping the diffusible hydrogen content in the weld metal as low as possible [1, 2, 3].

Appropriate welding practices usually seek to improve effusion conditions, but are also directed at minimising damage-contingent factors, such as residual stresses and joint microstructures. It should of course be noted, that constructive solutions can also substantially lower the potential risks in regard to hydrogen assisted crack formation.

This test is concerned with the various influences on the diffusion conditions of hydrogen in weld metals. Particular attention is given here to a practical examination and presentation of the measured results. The diffusion process, which can first of all be understood as a process controlled by temperature, concentration and time, is additionally influenced by various absorption rates, cracking and other mechanisms in weld metals. Alone the evaluation of hydrogen "instances", and their effect on the diffusion conditions in complex weld metals with greatly diversified joint, alloy, inclusion and exclusion characteristics, makes theoretical deduction of the hydrogen behaviour difficult [11–16].

Important when considering the potential danger of hydrogen is, among other things, estimating the effusion under different conditions in order to be able to introduce countermeasures if hydrogen assisted cracking occurs.

The carrying out of practical tests with different welding consumables enables a more accurate description of all these effects.

1. Effect of various removal from age hardening temperature on the effusion behaviour of hydrogen

As a basis for attempting to determine the effusion behaviour, the set regulations, preparations of the specimens and other conditions contained in the appropriate standards can be applied [8, 9]. In particular, the specimen dimensions proposed in the American standard AWS A 4.3 were used. Through the welding of "blind seams" on specimen blocks of a certain size and then quenching in ice water (within 3 seconds), the diffusion of hydrogen from the specimen is substantially inhibited up until the actual measurement – the added hydrogen is "frozen". After performing slag detachment and removal of the starting and ending piece of the specimen, the diffusible hydrogen can be determined with suitable hydrogen analysers and applied calculation algorithms.

Time-dependent hydrogen effusion: Optimised basic stick electrode – age hardening temperature: 400 °C, applied temperature on specimen

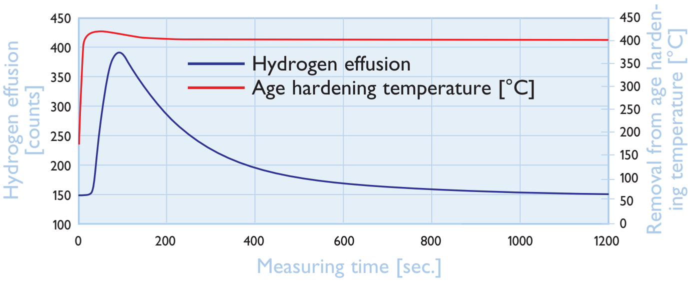
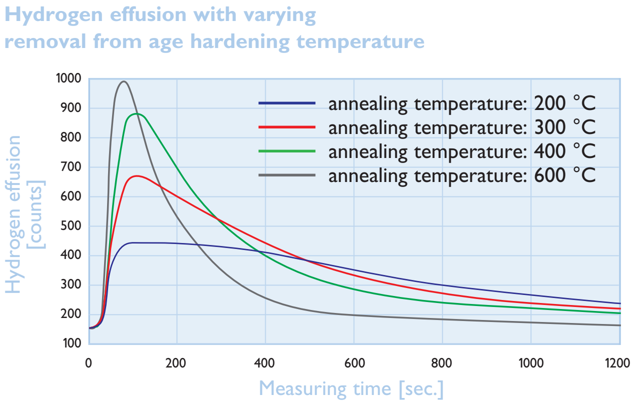


Figure 11: Time-dependent measured hydrogen diffusing from a specimen, using the example of a basic stick electrode and an age hardening temperature of 400 °C

Figure 11 shows the effusion behaviour of hydrogen in relation to the time of measurement for testing a basic electrode at an age hardening temperature of 400 °C. After applying the age hardening temperature, the diffusion conditions are generally speaking positively affected and hydrogen escapes from the specimen. According to the thermically-dependent activation of diffusion processes and differences in concentration, different effusion behaviours can be observed.

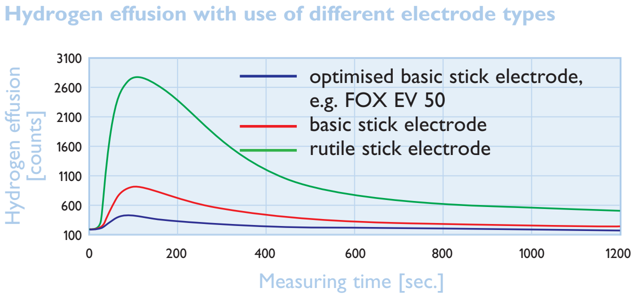
Figure 12 shows this behaviour for different age hardening temperatures. It can be seen that at a higher temperature, the hydrogen diffuses more quickly from the specimen, which is illustrated by a high maximum peak and the steeply declining curve after achieving this highest emission of hydrogen. Of course, it should be discussed in this context to what degree a higher age hardening temperature affects the activation of the overall hydrogen and thus can be recommended for the measurement of the diffusible hydrogen.



Hydrogen effusion with varying removal from age hardening temperature

Figure 12: Behaviour of hydrogen effusion with varying removal from age hardening temperature – example of basic stick electrode

Figure 13 shows the hydrogen that escapes from the specimen with the use of different types of stick electrodes. For rutile electrodes, the electrode design results in a relatively higher hydrogen input in the weld metal; accordingly, a high maximum effusion peak can be expected due to the high concentration differences – high diffusible hydrogen contents are detected.



Hydrogen effusion with use of different electrode types

Figure 13: Hydrogen effusion with use of different stick electrode types; removal from age hardening temperatures 400°C

Basic research such as this is an important part of our ongoing development work at BÖHLER WELDING.
It contributes to keeping our products always up-to-date.

BÖHLER FOX EV 50 – An electrode with a fine tradition and always state-of-the-art

2. Effect of various cooling conditions on the effusion behaviour of hydrogen after welding

When determining the diffusible hydrogen content in weld metals, a swift cooling after finishing welding should normally be performed in order to achieve homogenous conditions, but above all in order to determine the maximum diffusible hydrogen content that has been brought into the weld metal. In contrast to this procedure, and in most cases under practical welding conditions, the specimen is only cooled gradually. In particular with high-strength welds, a certain preheating and interpass temperature also needs to be maintained. To evaluate these different conditions and obtain an estimate of the diffusion behaviour in practical welding, trial welds with different preheating temperatures were carried out and the remaining diffusible hydrogen content was measured in the specimens after various cooling times.

2.1. Hydrogen effusion in relation to preheating temperature and cooling time after end of welding

Figure 14 shows the determined diffusible hydrogen content when using different preheating temperatures and cooling times after end of welding until quenching in ice water. Generally, air-cooling of the specimen can lead to a higher proportion of hydrogen effusion. For the thickly wrapped rutile stick electrode shown, only 20-40% (depending on the preheating temperature) of the initially present hydrogen content was detected after a ten-minute period of cooling. Of note, however, was the measured diffusible hydrogen content in relation to the preheating temperature after a 3-second period of cooling. With a higher preheating temperature, a higher proportion of added hydrogen enters the area surrounding the weld, which, with rapid cooling up until the measurement, is “saved”. This means that at higher preheating temperatures, the changed diffusion relationships cause higher diffusible hydrogen contents – arising from the parent metal - to be measured.

With a longer cooling time until quenching in ice water however, preheating is for certain electrode types advantageous for preserving low hydrogen contents. The weld then cools more slowly due to the higher temperature of the parent metal, whereby the effusion conditions are improved and low diffusible hydrogen contents are the result. Figure 15 shows this situation for an optimised basic stick electrode.

2.2. Diffusible hydrogen content when using different stick electrode types

When welding different electrode types, it is of note that the resulting diffusible hydrogen contents, in addition to the hydrogen input, is also influenced by the preheating and the cooling time until quenching in ice water. Due to the difference in concentration between the input hydrogen (primarily dependent upon electrode type) and hydrogen content in the parent metal, the use of welding filler materials with higher hydrogen inputs at higher preheating temperatures also results in a relatively higher hydrogen content added into the parent metal. Thus, as can be seen in Figures 14 and 15, a considerably higher amount of hydrogen enters the parent metal when using a rutile stick electrode.

In the case described above, the difference between a preheating of 25 °C and 200 °C amounts to 40% after a 3-second cooling period. For basic stick electrodes with lower hydrogen inputs, the difference only amounts to 15%. Accordingly, a longer cooling period and higher preheating or interpass temperature during welding of rutile (or cellulosic) stick electrodes cannot compensate for the difference, and thus high hydrogen contents remain in the weld (see Figures 14 and 15; cooling period of 600 seconds). When looking at rutile stick electrodes, similar hydrogen contents can therefore be predicted with a longer cooling time, regardless of the preheating temperature. Although a higher proportion of hydrogen does effuse due to the higher preheating temperature, a higher hydrogen content is also brought into the weld. For the optimised basic stick electrode shown, higher preheating temperatures with longer cooling periods bring advantages for achieving lower hydrogen contents. Relatively less hydrogen is input due to higher preheating temperatures; accordingly, lower hydrogen contents are also observed with a longer cooling period. In summary, it can be said that a higher preheating or interpass temperature only conditionally appears suitable for achieving low hydrogen contents in welds, since this is essentially dependent upon the added hydrogen content. Nevertheless, hydrogen assisted cracking factors such as residual stress level, joint microstructure and strength are generally speaking positively affected – in terms of preventing cracks – by higher preheating and interpass temperatures.

Effused hydrogen under application of different conditions, rutile stick electrodes

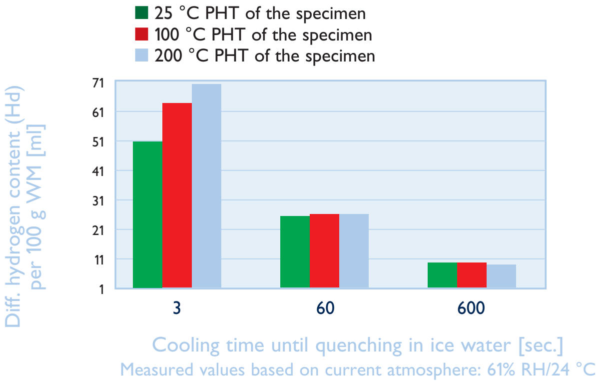


Figure 14: Measured diffusible hydrogen content under application of differing cooling times and preheating temperatures (PHT) using the example of a thickly wrapped, rutile stick electrode

Effused hydrogen under application of different conditions, optimised basic stick electrodes

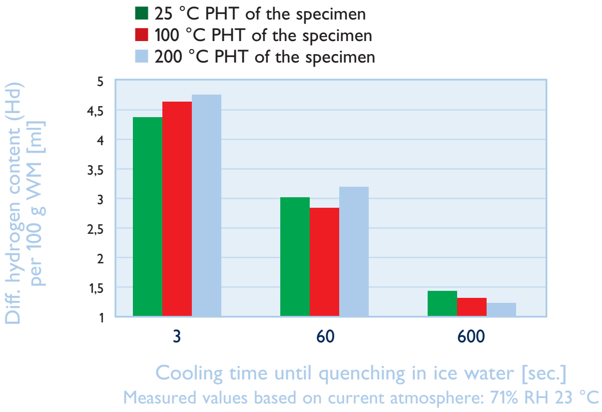


Figure 15: Measured diffusible hydrogen content under application of differing cooling times and preheating temperatures (PHT) using the example of an optimised, basic stick electrode

Effect of post-welding cooling time on diffusible hydrogen content when using different electrode types

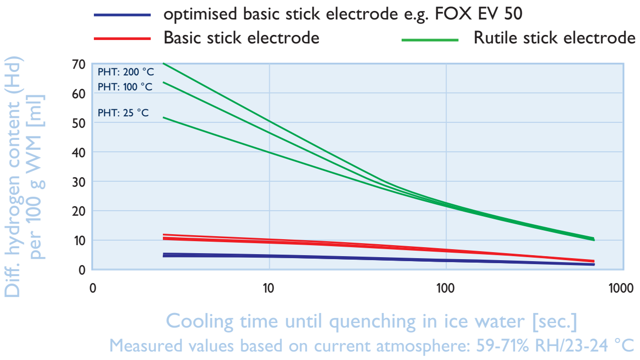


Figure 16: Diffusible hydrogen content in relation to cooling time when welding with different stick electrode types

Figure 16 shows the diffusible hydrogen content in relation to cooling time after end of welding until quenching in ice water when welding with different stick electrode types. After only a brief cooling time, depending on the difference in concentration, only more limited proportions of added hydrogen content are detected.

3. Effect of multi-layer welds on the effusion behaviour of hydrogen

In practical welding, in particular for thick-walled connections having a high potential risk of hydrogen assisted cracking, multi-layer welds are predominant as ever. Positve effects for avoidance of cracking can be achieved not only through the thermically activated increased hydrogen effusion, but also through the recrystallization of the joint of the deposited layers (beads). To better show the actual hydrogen effusion in multi-layer welds, corresponding trials were carried out.

Figure 17 thus shows the seam structures when welding with varying numbers of beads.

Figure 17: Seam structure when welding with different numbers of beads

3.1. Diffusible hydrogen content in weld metals, dependent upon number of beads and preheating or interpass temperature

Particularly in pipeline construction, the question repeatedly arises as to what hydrogen contents can be expected in the finished seams during and after the completion of the weld. In many cases, after application of root pass welding, partial or complete welding of the hot pass layer, the centring device for centring the ends of the pipe becomes detached, and the additional stresses induced by deformation can cause cracking. These welds are often, for economic reasons, performed with cellulosic stick electrodes.

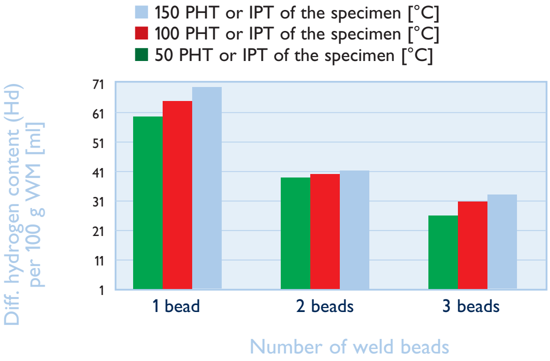
The high hydrogen input due to the use of this type of electrode combined with the usual heavy gauge pipe work connections requires special measures, such as the correct observance of the required interpass temperature, in order to produce crack-free seams. Of particular interest therefore, is knowing the diffusible hydrogen contents or the hydrogen effusion when using cellulosic electrodes with varying number of beads and varying preheating or interpass temperatures.

Figure 18 describes the above-mentioned relationship. In doing so, great importance was attached to ensuring that the following bead was applied only after the interpass temperature of 50, 100 or 150 °C was reached. After completion of the last weld bead, the specimen was quenched in ice water within 3 seconds. The single-layer welds correspond to the relationships shown in Chapter 2. Even when using cellulosic electrodes, higher hydrogen contents for higher preheating temperatures could be determined due to the high hydrogen input. When welding a second or third bead, relatively lower diffusible hydrogen values could be determined based on 100 g of melted weld metal due to

- The cooling of the first or second weld bead and
- Additional temperature treatment during depositing.

Furthermore, higher hydrogen contents are on the other hand predominant for higher preheating or interpass temperatures even with increased number of beads.

Diffusible hydrogen content for single- and multi-layer (multiple-bead) welds, cellulosic stick electrodes



Measured values based on current atmosphere: 72% RH/23 °C

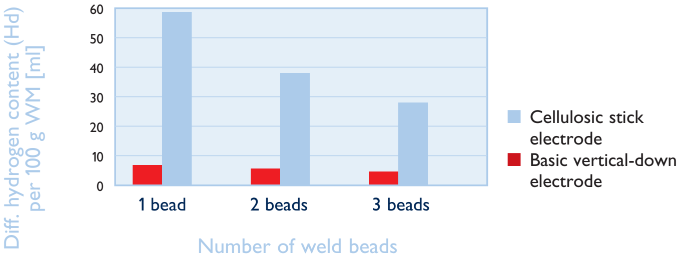
Figure 18: Diffusible hydrogen content in relation to number of beads and preheating or interpass temperature when using cellusosic electrodes; PHT... preheating temperature; IPT... interpass temperature

3.2. Diffusible hydrogen content in weld metals depending on number of beads and type of electrode used

Of course, high hydrogen inputs can, in principle, be modified or under certain circumstances reduced by selecting a different welding filler material. Thus, when using basic vertical-down electrodes as opposed to the cellulosic stick electrodes shown, substantially lower diffusible hydrogen contents are the result, whether for single- or multi-layer welds.

Figure 19 shows the diffusible hydrogen content based on 100 g of melted weld metal for the electrode types specified. Even when welding multiple beads, a hydrogen concentration-dependent behaviour leading to increased effusion of hydrogen with relatively higher hydrogen input could be observed for different electrodes.

Hydrogen effusion in relation to electrode covering type when welding multiple beads



Measured values based on current atmosphere:
70-72% RH/22-23 °C

Figure 19: Hydrogen effusion during welding with differing stick electrode types, dependent upon number of beads; cooling time after end of welding until quenching in ice water: 3 seconds; preheating or interpass temperature 50 °C

$$
\begin{aligned}
&H_d = (HIt) \cdot x^B \text{ with}\\
&HIt = HI + A \cdot t\\
&A = f_{(HI)}\\
&B = f_{(HIt)}
\end{aligned}
$$

Equation 2: Diffusible hydrogen content in relation to hydrogen input for multi-layer (multiple-bead) welds (dependent upon electrode), preheating or interpass temperature, number of beads and electrode-dependent hydrogen effusion

H_d … diffusible hydrogen content [ml/100g]
HIt … hydrogen input in relation to filler material and preheating or interpass temperature [ml/100g]
x … number of weld beads [ ]
B … layer exponent [ ]
HI … hydrogen input in relation to filler material [ml/100g]
t … preheating or interpass temperature over 20 °C [K]
A … filler material-dependent factor [ml/K] based on 100 g of weld metal

In principle, the formula shown in equation 2 can be used in estimating the diffusible hydrogen content (Hd) for the diffusion behaviour in multi-layer (multiple-bead) welding with different preheating or interpass temperature. Thus, the diffusible hydrogen content can primarily be derived from the introduced hydrogen content. Part 1 describes in detail the influence of hydrogen input (HI) in weld metals. Furthermore, this current section could provide pointers for hydrogen input when using diverse stick electrode types (Figures 14, 15, 16, 18). It should be noted of course, that these values can to some extent vary considerably in relation to manufacturer and electrode diameter.

For higher preheating or interpass temperatures of 20 °C or above, an electrode-dependent (hydrogen input-dependent) increase of diffusible hydrogen should also be expected. The corresponding factor A can, as derived from the numerous trials, be estimated according to equation 3 for different electrodes and extends over a relatively large range. The lowest added hydrogen contents can be expected from optimised basic electrodes.
For filler materials with higher hydrogen inputs, e.g. a rutile or cellulosic stick electrode, the greater disparity in concentration between filler and parent metal at a temperature increase of 100 °C can definitely result in 10 ml/100 g weld metal being additionally measured.

$$A = 0.0017 \ x \ HI$$

Equation 3: Factor A for taking into account increased preheating or interpass temperatures – depending on hydrogen input (in turn dependent on electrode)

The hydrogen diffusion in multi-layer (multiple-bead) welding is essentially dependent upon the hydrogen input (HIt). Equation 4 can thus serve as an estimate of the “layer (bead) exponent” (B) and denotes the factor dependent on electrode and preheating or interpass temperature for hydrogen effusion when welding multiple layers (beads), which appears largely due to the difference in concentration.

$$B = -0.53 - 0.0031 \ x \ HIt$$

Equation 4: Layer (bead) exponent B for taking into account increased preheating or interpass temperatures and the filler material-dependent hydrogen input

Summary

Part 2 of the lecture series for investigating the potential risk of hydrogen when welding un- and lowalloyed steels describes the hydrogen effusion in weld joints based on measurements of diffusible hydrogen. Special emphasis was placed on transferring theoretically known basic principles to practical application in order to make estimates of hydrogen effusion based on examples when using different stick electrode types, preheating or interpass temperatures, cooling times and number of beads in multi-layer welding.

The following points appeared essential for practical application:

- Through increased preheating or interpass temperatures, depending on the filler material used, different hydrogen quantities are introduced through improved diffusion conditions in the weld joint (surrounding area of the welded seam).
- The hydrogen effusion correlates to the concentration-related differences and thus the quantity of hydrogen introduced
- Increased preheating and interpass temperatures are thus only conditionally suitable for achieving lower resulting hydrogen contents.
- The lowest hydrogen values or hydrogen damage can be achieved by using specially optimised basic electrodes (see Part 1).

PART 3
Test for hydrogen assisted cracking susceptibility of multi-layer weld joints with the "bead bend test"
Test methods and examples

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In Part 3 of this paper, we discuss the testing methods and used examples to show how the risks can be minimised through correct application [1, 2]. Hydrogen assisted cracks occur in the heat-affected zone (HAZ) primarily as longitudinal cracks and are known as underbead cracks. In particular with high-strength welds, hydrogen assisted cracking (HAC) could however also be detected in weld metals in the form of brittle fractures in tensile specimens or as cracks seen when examining a longitudinal cut of the weld [17]. Figure 20 shows the appearance of hydrogen damage in the weld metal transversally and longitudinally in relation to the welding direction. In the illustration, the preferred point of occurrence of this damage can be seen in the upper third of the V-welds, which can be explained by the localised increased tensile stress and the thereby greater amount of embedded hydrogen.

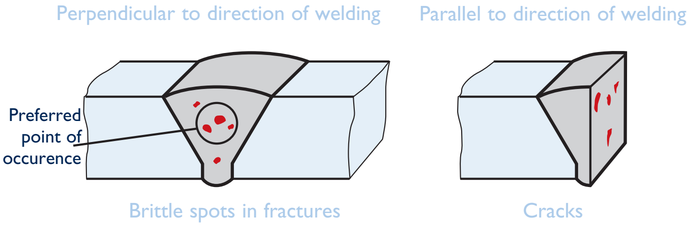


Figure 20: Appearance of hydrogen damage in the weld metal

Since in welded joints, not only the parent metal but also the weld is at greater risk due to these "hydrogen assisted cracks", special efforts in testing these cracks have been made by the most diverse institutions. Over the course of time, many different tests have been developed which are now in use worldwide. These tests can be roughly subdivided into tests with an externally stressed specimen, such as the "implant" test, or those testing the specimen's residual stress [18–21]. Tests assessing the specimen's residual stress are the following [18, 22–27]:

- TEKKEN
- U-GROOVE WELD CRACKING / LEGHIGH
- CTS (Controlled Thermal Severity)
- RRC (Rigid Restraint Cracking) / IRC (Instrumented Restraint Cracking)
- GBOP (Gapped Bead-On-Plate)
- RGW
- CRUCIFORM
- WIC (Welding Institute of Canada)
- TRC (Tensile Restraint Cracking)

Residual stress tests generally have the advantage that they reflect more practical situations, whereas allocating the targeted results to the actual weld is however only conditionally possible. In order to achieve full equivalence of the testing methods with welds created in actual practice, identical joint or specimen welds must be produced [23]. To suitably deal with this requirement, BÖHLER Schweißtechnik Austria has endeavored to develop a testing method which, for the testing of critical joint welds, delivers results that are as transferable as possible to practical on-site conditions.
This test is described below and two examples from the series of numerous investigations will be shown.

Test method – "Bead bend test"

The "BEAD BEND TEST" is a method for determining the hydrogen assisted cracking susceptibility of weld joints. Special emphasis was placed on designing the most simple yet comprehensive test for welds made under the most varied practical conditions. Originally this test was developed for comparative investigations of circumferential joints in pipeline construction. From these experiences a general testing procedure was then developed for examining hydrogen assisted cracking.

Figure 21 shows the design for the welding of test joints and the conventionally used specimen dimensions. For this test, sheets of the parent metal are fastened to a rigid base plate which should be about four times as thick as the sheets.

Since the bead bend test correlates well with the RRC or IRC tests, where "self-restraint" specimens are also used, the stress on the weld can be controlled through the restraint length. The restraint length is defined as the distance of the weld to the clamping of the parent metal.

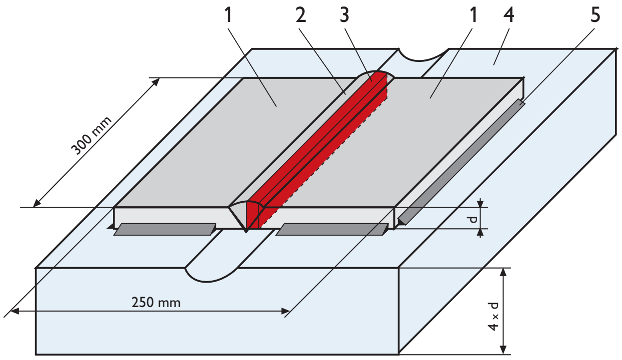


Figure 21: Structure of test: 1…Parent metal, 2…Weld seam, 3… Test specimen, 4… Rigid base plate, 5… Anchored welds; d… Wall thickness of parent metal

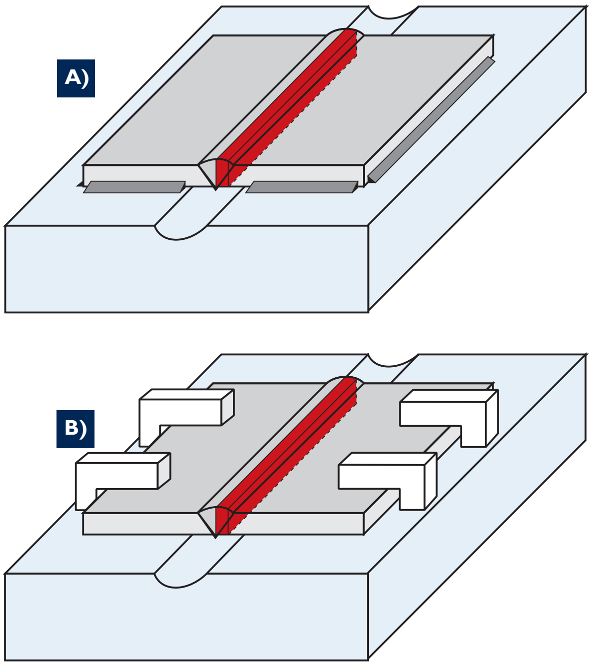


Figure 22: Different restraint variations for bead bend test;
A... transversal and angular contraction fully prevented
B... transversal contraction possible – angular deformation prevented

In Figure 22, clamping options are shown which are of interest for practical tests. In the first clamping type (version A), sheets are attached to the base plate using anchored welds. This results in a short restraint length which induces greater tension in the weld. The second option (version B) differs from this rigid clamping in that it allows contraction of the sheets transversally in relation to the weld seam. Angular deformations however, which occur primarily during welding of V-joints, are prevented. This version is used foremost for tests in which transversal contraction of the weld metal can be permitted. This stress situation typically occurs in the welding of circumferential joints in pipeline construction.

After clamping the plates, the weld can be performed with parameters in step with those in actual practice. To also allow for the effects of delayed crack formation, which is very well described in the literature [1, 28], the specimen is extricated from the base plate approximately 24 hours after the completion of welding. The specimen is extricated from the welded joint and the examination surface is polished. Figure 23 shows the specimen in which its thickness Y is held constant at 10 mm and X corresponds to the thickness of the joint weld. As examination surface, the rectangular cross-section of the weld from the centre of the seam is generally used, since this area is where, according to J. B. Roelens, the localised tensions are highest and the greatest susceptibility to cracking can be expected (Figure 24).

To make the hydrogen assisted cracks in the weld visible, the specimen is deformed through bending. The micro-cracks are thereby expanded and achieve a size that is visible to the observer for subsequent evaluation of the specimen. In this connection, it is especially important that the specimen be subject to a heat treatment for hydrogen effusion at 250 °C for 16 hours prior to bending. This ensures that the micro-crack formation, which occurs during or after welding, does not superimpose fish-eye effects on the test (bending). The heat treatment allows the embedded hydrogen to effuse so that it is not activated by the bending stress to cause fish-eye effects during the test.

Figure 25 shows the bending device with a moderate bending radius of 90 mm. The relatively large examination surface allows a good evaluation of the cracking susceptibility even when testing only a single specimen per parameter setting.

Figure 26 shows the examination surfaces including cracks from tested weld seams.

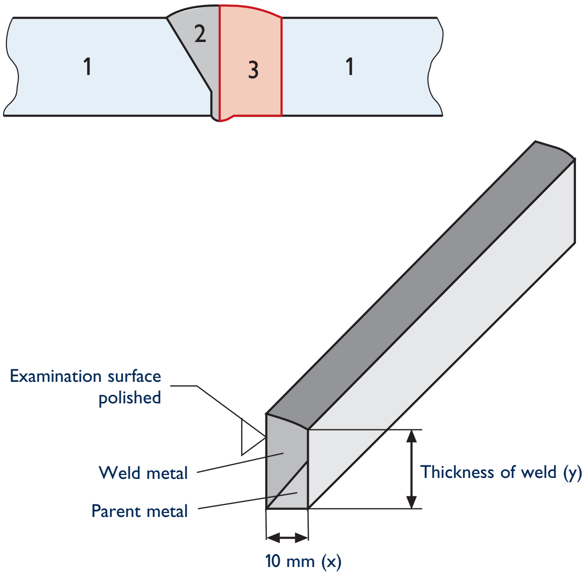


Figure 23: Specimen extricated from the weld joint; 1…Parent metal, 2…Weld seam, 3…Test specimen

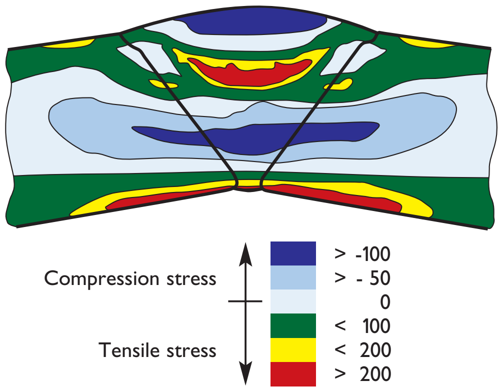


Figure 24: Distribution of stress in a V-joint according to J.B. Roelens with transversal and angular contraction inhibited (values in MPa)

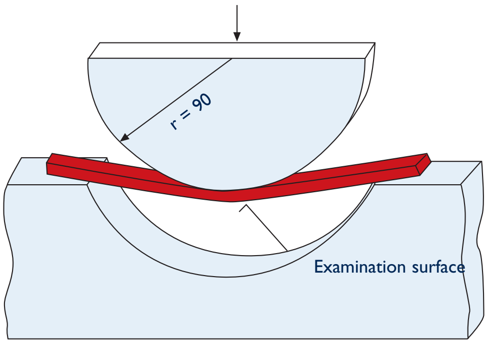


Figure 25: Bending device for bead bend test

Figure 26: Bent specimens with widened cracks

Due the simple and inexpensive implementation of this test, it is especially well suited for the research and development of high-strength and hydrogen-laden weld metals. Moreover, the practical application makes this test also suitable for comparison studies, since combination welds with differing electrode types, such as joint welds with cellulosic and basic vertical-down electrodes, can also be tested.

EXAMPLE 1: Determination of the required interpass temperature for cellulosic weld metal connections

Cellulosic covered electrodes are primarily used for the economical welding of circumferential joints in pipeline construction. The Böhler name of these electrodes is derived from the coating structure, which is comprised to a large extent of organic materials (cellulose). The special coating construction is responsible for a high hydrogen input in the weld metal, which lies at around 40–50 ml/100 g weld metal according to AWS A 4.3 (measured by Ø 4 mm electrodes). This high hydrogen input means that for the welding of this type of electrode, preheating and the maintaining of an appropriate interpass temperature is essential.
In a series of trials, the minimum interpass temperature for achieving crack-free welds in cellulosic weld metals was determined with the aid of the bead bend test. The testing targeted practical welding procedures with various pipe wall thicknesses and weld metal strengths. The following electrode types were tested

- E 6010 (BÖHLER FOX CEL)
- E 7010 (BÖHLER FOX CEL 75, BÖHLER FOX CEL 70-P)
- E 8010 (BÖHLER FOX CEL 85, BÖHLER FOX CEL 80-P)
- E 9010 (BÖHLER FOX CEL 90)

Pipe steels with wall thicknesses of 5, 10, 15, 20 and 25 mm were used for the tests. The preparation of the weld is shown in Figure 27. As the clamping version for the test plate weld, version A (see Figure 22) was selected. The welding of the root and hot pass layers was performed with Ø 4 mm electrodes; for the fill and cap layers Ø 5 mm electrodes were used.
The experiment was performed at interpass temperatures of +20, 50, 80, 100, 120 and 140 °C, using plate of 5, 10, 15, 20 and 25 mm thicknesses, so that in determining the minimum temperature in relation to pipe wall thickness a total of 30 specimens were welded (for each strength level).

**Figure 27:
Weld preparation when welding with Cellusoic electrodes**

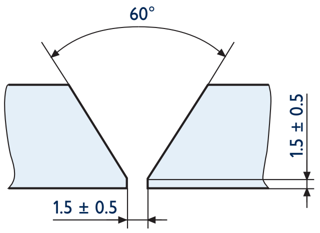


Figure 28 shows the crack evaluation of the specimens in the bead bend test for the high-strength electrode type E 9010 with 3 different interpass temperatures (20 °C, 80 °C and 120 °C) for a 15 mm weld seam. It can be seen that when welding at 120 °C, no cracks occurred on the bent specimen. At 80 °C some cracks are already visible, which occur to an even greater extent at an interpass temperature of 20 °C.

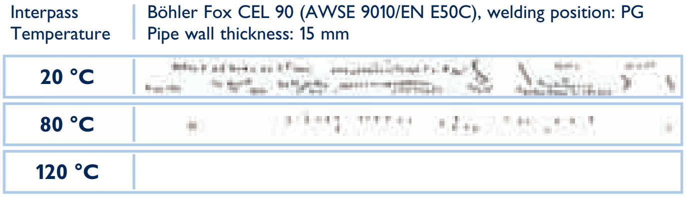


Figure 28: Examination surfaces with cracks in relation to interpass temperature for 15 mm thick welds – electrode used: AWS E 9010

Fox CEL 90 electrode (AWSE 9010/EN E50C)

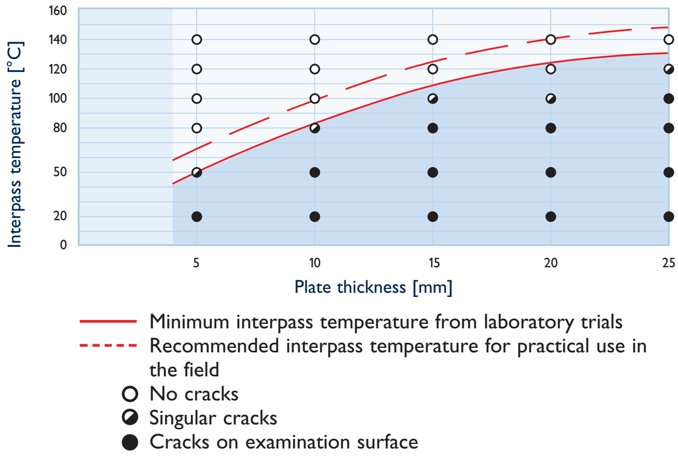


Figure 29: hydrogen assisted cracks in relation to interpass temperature and pipe wall thickness when using BÖHLER FOX CEL-90 electrodes.

Recommended interpass temperature for cellulosic weld metals, depending on weld metal strength and joint thickness. Bead bend test: transversal and longitudinal contraction inhibited

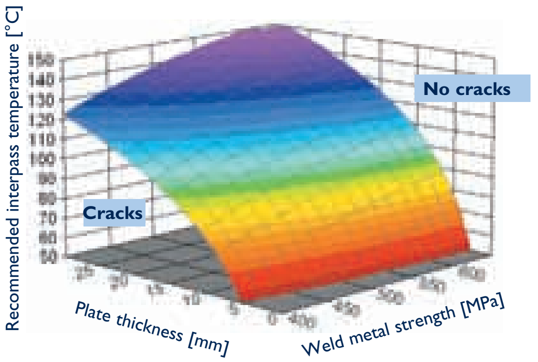


Figure 30: Recommended interpass temperature for creating crack-free joints (applies to cellulosic electrodes)

Figure 29 shows the relationship of crack formation to plate thickness for electrodes of strength class E 9010. The minimum interpass temperature is specified as the temperature just above which negligible crack formation occurs on the examination surface. To ensure within an adequate margin of safety that the joint weld is completely crack-free, a temperature should be selected that is 20 °C above the minimum. Figure 30 shows the interpass temperature, depending on weld metal strength and pipe wall thickness, for achieving completely crack-free joints with cellulosic electrodes. From this diagram, the following equation can be derived for the recommended interpass temperature:

$$rec.\ IPT = 58 + 42 \times \ln(s) - \frac{31413}{YS_{,\ weld\ metal}}$$

Equation 5:
rec. IPT…recommended interpass temperature in °C
s…thickness of weld in mm
YS, weld metal…yield strength of weld metal in N/mm^2

The diffusible hydrogen content was not taken into account in equation 5, since it is generally very high for welds with cellulosic electrodes and also cannot be changed through treatment of the electrodes. Thus, the hydrogen input in the weld metal is not substantially increased by removal from storage or welding of the electrodes in a humid atmosphere. Neither, however, can it be reduced, since rebaking of the electrodes is not permitted.

EXAMPLE 2: Crack susceptibility in relation to diffusible hydrogen content and weld metal strength for combined application of cellulosic and basic vertical-down electrodes

Example 2 presents an application with very high practical relevance for joint welding in pipeline construction. Specifically, the combined use of electrodes with various covering types is discussed. For the root passes and generally also for the hot pass welding of the circumferential joints, cellulosic electrodes are used, which ensure a high efficiency when constructing the pipelines due to the higher welding speeds. For the welding of the fill and cap layers, the lower hydrogen content and generally greater toughness of the weld metal recommend the use of basic vertical-down electrodes. To test the effect of the weld metal strength in combination with the diffusible hydrogen content on the susceptibility to hydrogen assisted cracking in this type of joint, basic electrodes with seven different strength classes (1–7) were produced in the laboratory through a simple Mn alloying process. The yield strengths of the individual weld metals were set between 670 and 814 N/mm^2 for this. To set the diffusible hydrogen content, the basic electrodes were assigned to three groups (I–III) per strength class. Each group was stored in the climate exposure test cabinet at 80% relative humidity and 27 °C.

Through different storage times, the diffusible hydrogen content was variously set in accordance with AWS A 4.3 (Table 1).

Hydrogen group	Diffusible hydrogen content per 100 g weld metal
Group I	**6**
Group II	**9**
Group III	**12**

Table 1: Diffusible hydrogen content of pure weld metal according to ASW A 4.3 for basic electrodes of strength classes 1–7

In all, this investigation covered 21 different conditions in the seven strength classes and three hydrogen groups. These electrodes were then welded in the fill and cap layers of the joint. As the parent metal for the experiment, X80 pipeline steel according to API 5L with a yield strength of at least 550 N/mm^2 was used. The plate thickness was held constant at 18.3 mm. The weld was performed in the PA position (horizontal). The preheating and interpass temperature was set at 100 °C. The clamping version B of Figure 22 was selected, since a transversal contraction in relation to the weld seam is normal in pipe connection welds and can therefore be permitted. Figure 31 shows the layer structure of the joint weld.

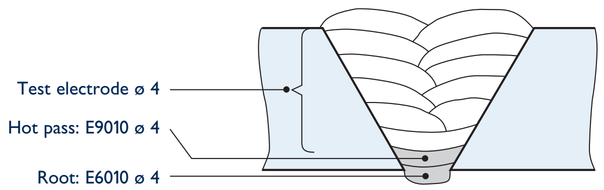
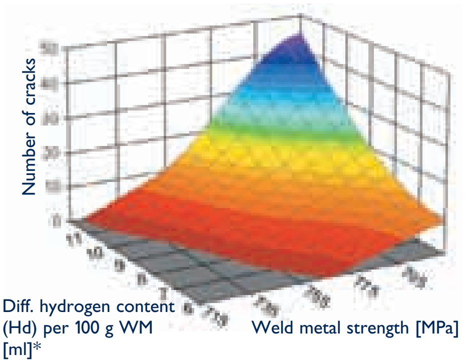


Figure 31: Selected layer structure for combined welding with cellulosic and basic vertical-down test electrodes



Hydrogen-based proneness to cracking in relation to weld metal strength and the diffusible hydrogen content when using combined methods. Bead bend test: unrestricted transversal contraction; steel type: X80; IPT: 100 °C; root pass: E 6010; hot pass: E 9010; fill and cap layers: basic electrodes of differing coating moisture and strength

Figure 32: Hydrogen assisted cracking susceptibility for combined welding with cellulosic and basic vertical-down electrodes*

Figure 32 shows the summarised results of the bead bend test. The hydrogen content in the joint weld metal will, despite the welding of a root pass and the hot pass layers with cellulosic electrodes, be substantially less than that of the standard measurement due to the rapid effusion of the hydrogen. The fundamental relationship of weld metal strength and hydrogen content should, however, be pointed out here. This graphic rendition also appears more relevant for practical application, since it is easier to measure electrodes with the standard approach than to measure the hydrogen content of the actual joint. In addition, it is also possible to predict the diffusible hydrogen values when welding electrodes in certain atmospheres and exposure states based on the welding consumable manufacturer. It has been shown that through a higher moisture content in the electrode coverings and the resulting higher hydrogen content in the weld metal, the danger of hydrogen assisted cracking is considerably increased. Furthermore, there is also evidence that with an increase of the weld metal strength, special attention should be given to the use of electrodes with the lowest hydrogen content possible.

Summary

1. For the most accurate predictions regarding susceptibility to hydrogen assisted cracking in welded joints, it is necessary to develop testing procedures that allow connections in step with actual practice to be examined. In addition, testing methods must be created that are simple yet which supply meaningful results. With the bead bend test, these criteria for testing of weld metals could be fulfilled. For many applications, it is possible to create identical test welds and then evaluate them in regard to their susceptibility to hydrogen assisted cracking.
2. The degree of restraint can be modified by variations in clamping. A rigid clamping can be employed for the theoretically highest stresses.
It is also possible, however, to simulate stress situations encountered in actual practice.
3. The relatively large examination surface of the bead bend test provides meaningful results.
4. For the welding of pipelines with cellulosic electrodes, the susceptibility to hydrogen assisted cracking in relation to weld metal strength and joint thickness (pipe wall thickness) was determined with the aid of the bead bend test. This enabled recommendations to be made regarding the interpass temperature to be used.
5. In modern pipeline construction, the combination method is often used of cellulosic electrodes for the root and hot pass layers, and basic electrodes for the fill and cap layers. The bead bend test enables testing of this type of connection for susceptibility to hydrogen assisted cracking. By varying critical parameters in the production of these connections, such as the moisture content of the electrode coverings, the susceptibility of the weld metal to cracking is changed.
6. By increasing the hydrogen content and the weld metal strength, cracking susceptibility increases.
7. By increasing the wall thickness of the weld joints, susceptibility to hydrogen assisted cracking is increased due to the unfavourable stress distribution in the weld.

---

* The diffusible hydrogen content refers to the weld metals of the basic vertical-down electrodes and was measured using standard testing methods in accordance with AWS A 4.3.

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Acknowledgements

The authors would especially like to thank all employees of the welding laboratory of Böhler Schweißtechnik Austria for their friendly assistance in compiling this publication.

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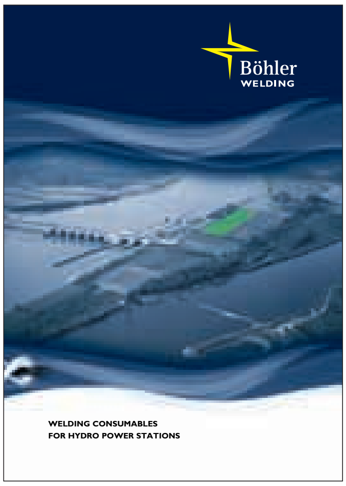
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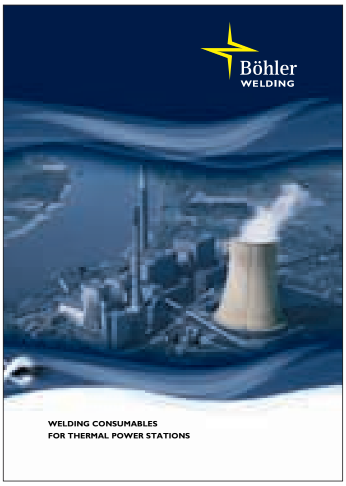
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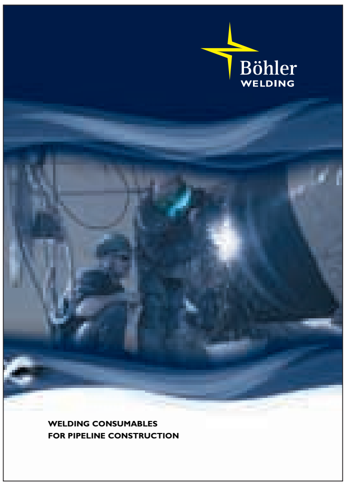
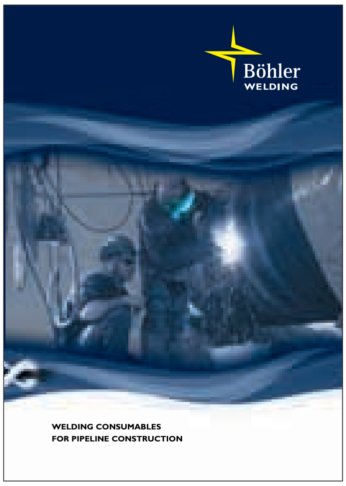
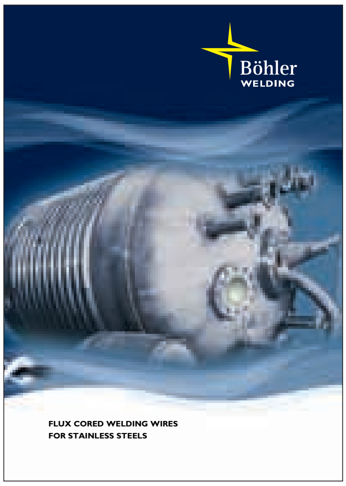
FOR THERMAL POWER STATIONS


Böhler
WELDING

WELDING CONSUMABLES
FOR PIPELINE CONSTRUCTION


Böhler
WELDING

WELDING CONSUMABLES
FOR PIPELINE CONSTRUCTION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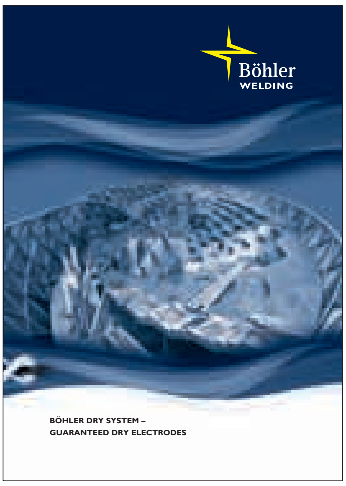
FLUX CORED WELDING WIRES
FOR STAINLESS STEELS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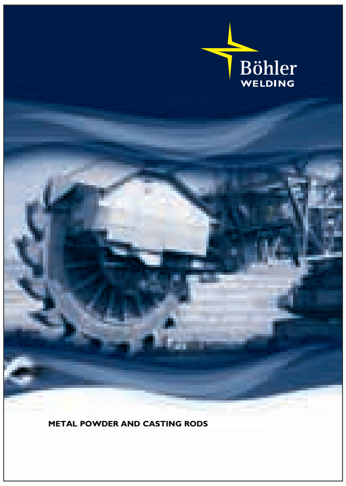
BÖHLER DRY SYSTEM –
GUARANTEED DRY ELECTRODES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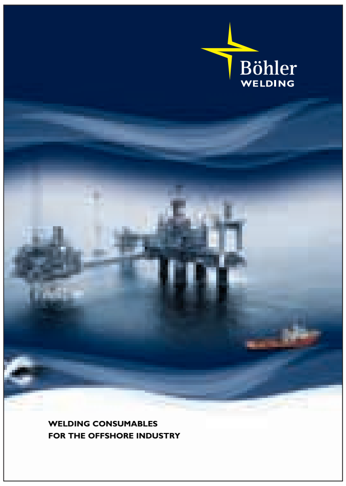
METAL POWDER AND CASTING RODS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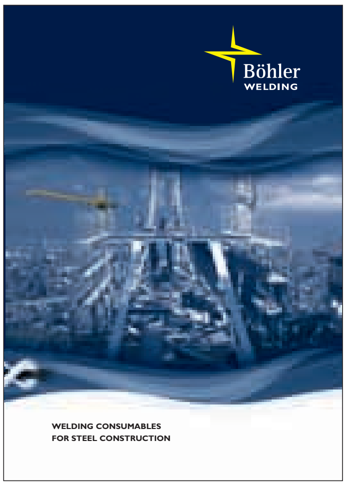
WELDING CONSUMABLES
FOR THE OFFSHORE INDUSTRY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WELDING CONSUMABLES
FOR STEEL CONSTRUCTION

The specifications in regard to the type and application of our products are only for the user's information. The data specified for the mechanical properties always refer to the weld metal alone under observance of the applicable standards. In the weld joint, the weld metal properties are influenced, among other factors, by the parent metal, the welding position and the welding parameters. A guarantee of suitability for a certain type of application requires an explicit written agreement in each individual case.

Subject to modifications.

Published by BÖHLER WELDING

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