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ESSENTIAL WELDING ASPECTS FOR HIGH STRENGTH LINEPIPE

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Abstract

The exploration and exploitation of remote natural gas fields results in pipeline designers facing challenging conditions, and materials have to be tailored to the needs of these conditions. Challenges include - thick wall, high strength, deep sea locations, corrosion resistance against sour gas, low temperature toughness for arctic use, and crack arrest toughness. As well as the technical challenges noted above, operating gas pipelines are expected to perform safely over long time periods and be built as economically as possibly to minimize costs to consumers.

Consequently the applied technologies from steel making to pipe production are continuously being improved in order to increase the pipe quality level and also the productivity by reducing non-quality critical costs. In this paper special attention is paid to the control of the welding process for the longitudinal seam as this is of essential importance for the intrinsic pipeline safety. Various quality requirements are defined by customer specifications for the weld seam with respect to mechanical properties, shape and allowable size of imperfections. Sometimes these requirements work in opposing directions and measures chosen to fulfill one requirement can prevent achieving another target. The key factors to guarantee high weld seam quality are tight control of welding parameters and optimized selection of welding consumables. In the first part of this paper, it will be shown how the weld seam quality can be improved by use of modern welding technology and process control. Furthermore, it will be discussed how unbalanced requirements for the weld bead profile can lead to the unnecessary use of high heat inputs. In the second part, the role of the welding consumables will be discussed. The different types of welding fluxes and the most common welding wire types are presented and compared with regard to their properties.

Introduction

The steady increase in the operating pressures of oil and gas pipelines, pipe laying and service under extreme conditions in offshore regions has led to increasingly severe property requirements for pipeline steels. Today, not only greater wall thicknesses but also higher strengths are needed. Further requirements are excellent toughness, good weldability and pipe geometry within narrow tolerances. In the case of sour service applications the linepipe steel has in addition to withstand the aggression of a corrosive environment.

Even though produced in bulk orders, large diameter linepipes for high pressure gas supply are anything but commodities. Comprehensive and challenging requirements are usually project specific. Some of these requirements work partly in opposed directions. Measures which support one property can harm the other. This situation in principle applies to all linepipe grades, but is well controlled for conventional grades up to X80. In the case of high strength linepipes, this scenario is changing as higher and additional requirements are imposed by the designers.

In Figure 1 the main properties that are relevant for high strength linepipe steels are presented. For trouble-free weldability with low preheat temperatures and a low cold cracking susceptibility, a well adapted chemical composition with low carbon and limited alloying content is required. On the other hand high requirements on strength and toughness require a certain amount of alloying. Furthermore the pipe should exhibit a nearly round shape with low ovality which requires high deformation during the forming and expansion process. However, mitigation of ageing during coating or enhanced resistance against collapse due to external pressure requires low deformation by mechanical expansion.

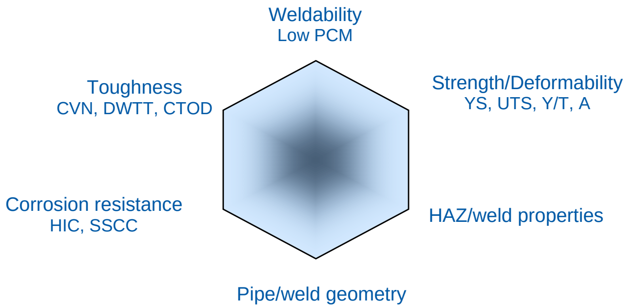


Figure 1. General property profile for linepipes.

An analogous picture can be drawn specifically for the seam weld as shown in Figure 2. For productivity reasons the heat input and the welding speed must be set as high as possible, however a high heat input has a detrimental effect on the HAZ toughness and must therefore be controlled. Furthermore a high weld speed can promote the presence of welding defects like undercuts or lack of penetration. In the case of high toughness requirements, specific alloying of the weld seam is necessary. On the other hand, this adapted alloying content will increase the hardness and the weld strength overmatching. As discussed above, in general, for the overall linepipe quality different requirements are partly competing and require a well defined setting of all parameters.

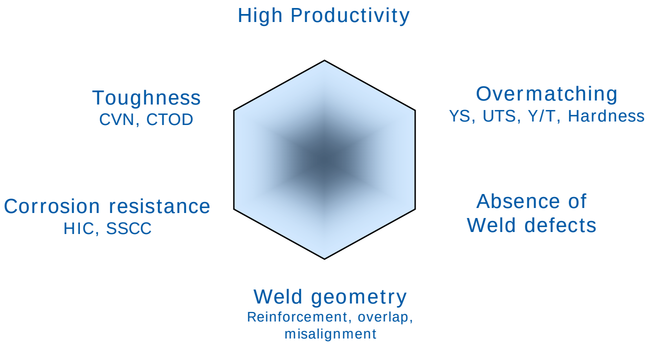


Figure 2. General requirements for weld seam quality.

Welding Technology

The most economic production method for linepipes fulfilling such high quality requirements is the UOE manufacturing route with a two pass submerged arc welding process for the seam weld. Whereas the mechanical properties and corrosion resistance are predominantly defined by the selection of appropriate welding consumables, the weld shape and the occurrence of imperfections or defects is strongly influenced by the welding parameters.

A wide range of different quality requirements have to be achieved reliably and under economic conditions. The production of a weld seam suitable for the purpose of high pressure linepipe is more than just joining two plate edges. The following Table I summarizes the most important quality aspects of a submerged arc welded longitudinal seam:

Table I. Quality Aspects for SAW Seams

SAW quality aspects		
Mechanical Properties **Corrosion Resistance**	**Weld shape**	**Imperfections/Defects**
Strength Matching ratio Toughness Hardness HIC/SSCC resistance	Misalignment Radial offset Weld bead height Weld contact angle Weld bead width Interpenetration Weld linearity	Undercuts Slag inclusions Porosities Lack of fusion/interpenetration Cracks
Key factors: (Welding parameters) Consumables, Base metal	**Key factors:** Welding parameters (Consumables)	**Key factors:** Welding parameters (Consumables)

In the EUROPIPE Mill in Muelheim an der Ruhr, up to 15 km of weld seam can be manufactured per day. Stable welding processes are mandatory to guarantee the lowest repair and rejection rates. To further improve the process, EUROPIPE invested in the latest technology of digital power sources. Seven inside and seven outside welding machines are equipped with the most modern digital power sources, Figure 3.

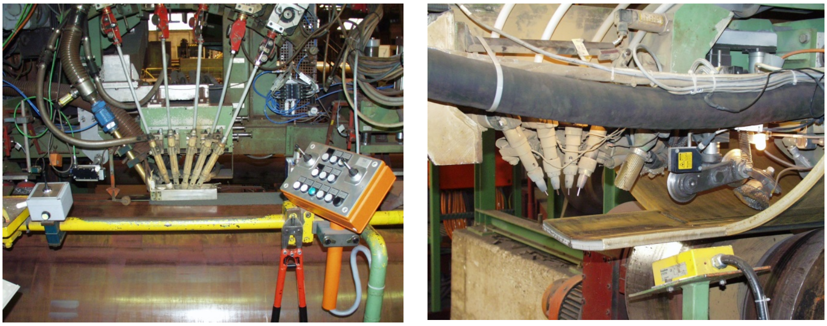


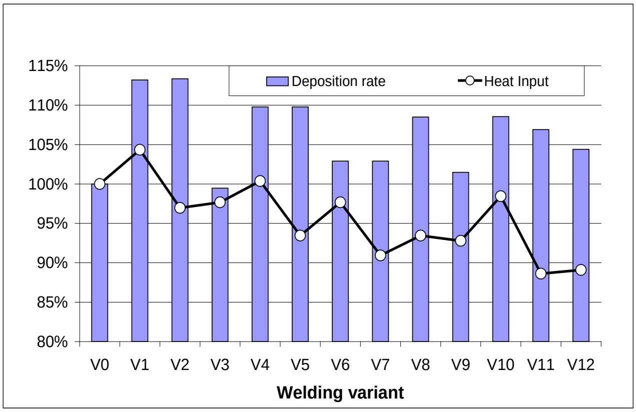
Figure 3. View of the welding heads for outside welding (left) and inside welding (right).

These power sources offer a wide range of additional possibilities compared to conventional equipment, see Table II. Main features are:

Table II. Features of the Power Wave Sources

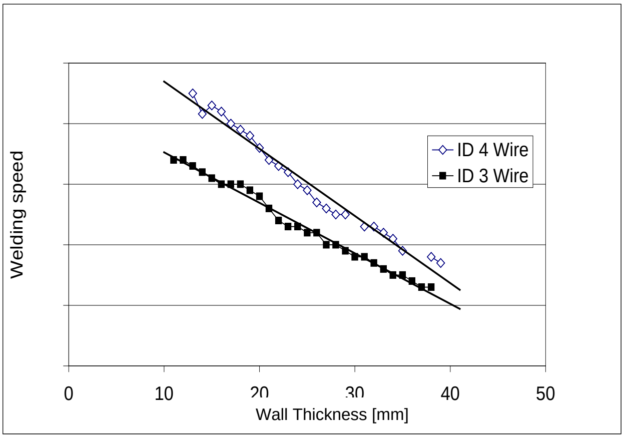
Feature	Power Waves (PW)
Net compensation ± 10%	E
Power source presets	E
Adjustable ramp function	E
AC and DC Mode	E
Frequency control	E
CC-Mode	E
CV-Mode	E
Phase angle control	E
Wave Designer	E

The advantages are based on the new digital design. The Power Wave uses the inverter technique. As these inverters are primary and secondary switched and they allow a wide range of parameter settings. The process can be adapted to the special requirements of pipe production. Once a perfect set of parameters is designed, it can be stored in presets. The use of presets allows a fast setting of the power source which is well adapted to the wall thickness being welded. A preset contains all the necessary information for a single welding head such as wire diameter, stop-/start-parameters, and so on. This allows narrow tolerances for the welding parameters leading to a stable process. Welding speed can be improved to attain high productivity and low heat input without the risk of increasing defect rates. Figure 4 shows as an example, the optimisation of the heat input while increasing the deposition rates at a given wall thickness. A reduction of 11% heat input with a parallel increase of deposition rate by 4% was realised by using the technical options of the digital power sources.



(a)

Figure 4(a). Optimization of deposition rate, heat input.



(b)

Figure 4b. Optimization of deposition rate, welding speed.

Linepipes are generally welded by using the two-pass SAW process. Although this process can be optimised over a wide range it reaches its limits for high wall thickness and/or high toughness requirements. While the alternative multipass welding with its low heat inputs guarantees the mechanical properties of the weld seam and of the heat affected zone, it considerably reduces the cost effectiveness of the pipe mill. The total manufacturing costs rise multi fold depending on the number of necessary layers. These areas of conflict as shown in Figure 5 can only be solved by searching for the best compromise for all partners.

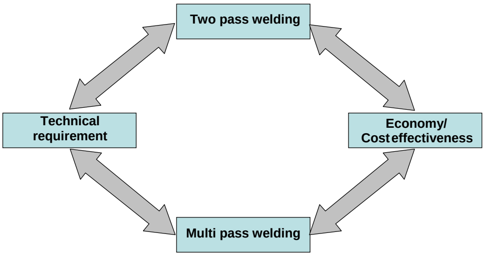


Figure 5. Conflict field for welding.

Frequently defined restrictions for width and depth of interpenetration of the inside and outside weld bead is one typical example for such controversial requirements. On the one hand these specifications guarantee a safe overlap of the inside and outside weld by avoiding lack of penetration. On the other hand they can only be achieved by increasing the energy on the first welding heads resulting in higher heat inputs with negative effects on mechanical toughness properties. Figure 6 shows a 32 mm wall thickness weld macrograph. The penetration E of the outside weld is 18.6 mm (ca. 60% wt) with an interpenetration depth I of 5.3 mm (ca. 15% wt) and a intersection width F of 8.6 mm (ca. 25% wt). The width/depth ratio of 1.7 ensures a favourable dendrite growth to avoid hot cracks. Weld overlap is sufficient to guarantee full penetration even with a seam misalignment of 4 mm. Typical requirements for interpenetration of one quarter of the nominal wall thickness and/or one third of wall thickness for the narrowest point of the weld bead would require an unreasonable increase of heat input by approximately 10% in this example of a thick wall pipe. It is recommended that this weld quality requirement is defined in a balanced way which guarantees full penetration without lack of fusion, but does not cause excessive heat input. These goals could be reached by setting one stepwise requirement for the intersection width of minimum 4 mm up to 16 mm wall thickness, one quarter of nominal wall thickness up to 28 mm and minimum 8 mm above 28 mm nominal wall thickness.

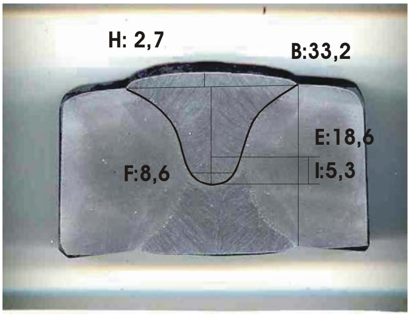
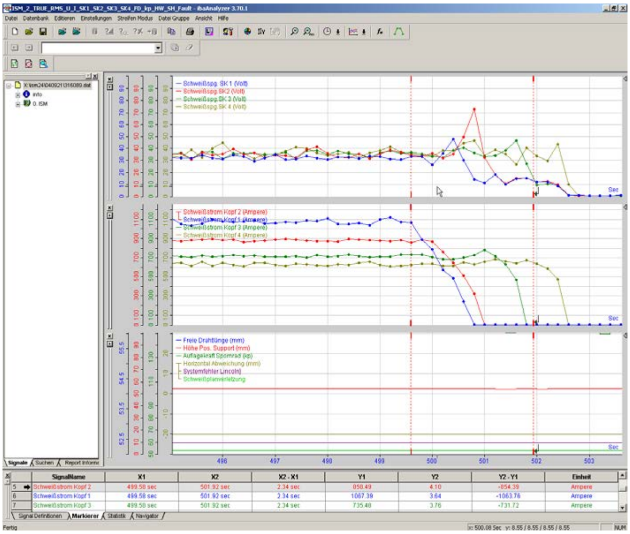


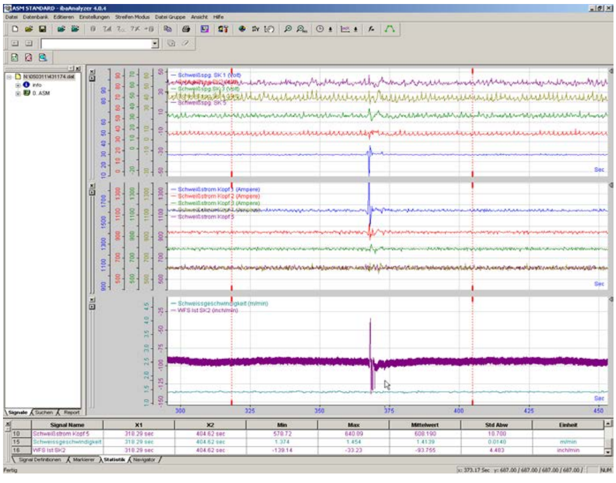
Figure 6. Macrograph of a typical weld seam for 32 mm wall thickness.

Besides the weld properties, the performance and the economy of the process is a main focus of the welding technicians. To maintain a constant production flow in a high throughput pipe mill, a low rate of rework is mandatory. The continuous improvement of quality by reducing the weld defect rate is a permanent task. Reliable and stable welding processes and machines are necessary to reach this goal.

Analyzer software connected to the welding equipment provides the possibility to evaluate the welding process, Figure 7. This leads to a systematic improvement and deeper understanding of the measures required to avoid defects.



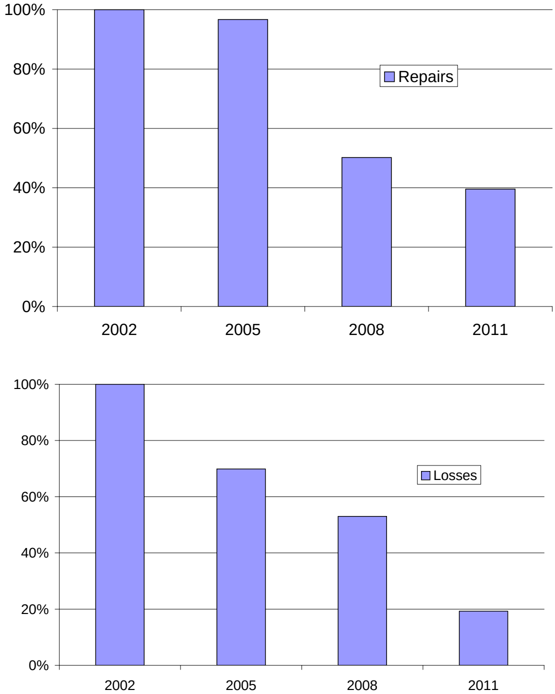
(a)



(b)

Figure 7. Analyzer Tool: Improvement of weld stop on the run-off tab ends (a), welding parameters leading to a slag inclusion (b).

An intensive in-house NDT system with automated ultrasonic testing (AUT) and X-Ray completes the quality process. The resultant process control in combination with fast access to the essential information at any time and any place in the mill has led to a permanent reduction of rework and losses due to weld defects, Figure 8.



(a)

(b)

Figure 8. Improvement of repair rate (a) and pipe losses (b).

Welding Consumables and Weld Seam Properties

To fulfill the various quality requirements while maintaining high productivity and process robustness, great care must be taken to select and develop optimised welding consumables such as welding flux and wire. The most important aspects with regard to welding consumables will be discussed in the following section.

When submerged arc welding, the welding flux has not only the purpose to shield the solidifying welds from the atmosphere, by creating a slag, but it has moreover several additional goals to achieve:

- to prevent the weld material from excessive cooling
- to influence weld bead shape and surface finish
- to pick up or burn out essential alloying elements like manganese or silicon
- to stabilise the arc and control the drop-transition
- to control the oxygen content and hence the inclusion volume fraction and size distribution

In Figure 9 the process zone during SA welding is schematically described for one-wire welding. In the case of multi-wire welding, the process zone is correspondingly enlarged. Welding fluxes must be developed with specific characteristics to cope with the high welding speed and productivity.

Fluxes consist of minerals such as oxides from aluminum, manganese, calcium and other elements. Furthermore they contain fluorspar, ferro-alloys and deoxidizers like ferro-silicon. These components are obtained from natural sources and have to be well defined and specified. Referring to the manufacturing process, there are two main flux types – Fused and Agglomerated.

Fused fluxes are produced by simultaneously melting all ingredients in an electric arc furnace or a cupola-furnace at temperatures between 1200 and 1400 °C. After the pouring of the melt and solidification, the material is crushed to grains, which are dried and sieved. Due to this melting process, fused flux grains are chemically homogeneous. Also the grain strength of fused fluxes is higher than agglomerated fluxes. This can be beneficial when long flux feeding distances have to be overcome by pneumatic transport or mechanical conveyors. Fused fluxes are non-hygroscopic by nature and therefore do not need to be re-dried prior to use.

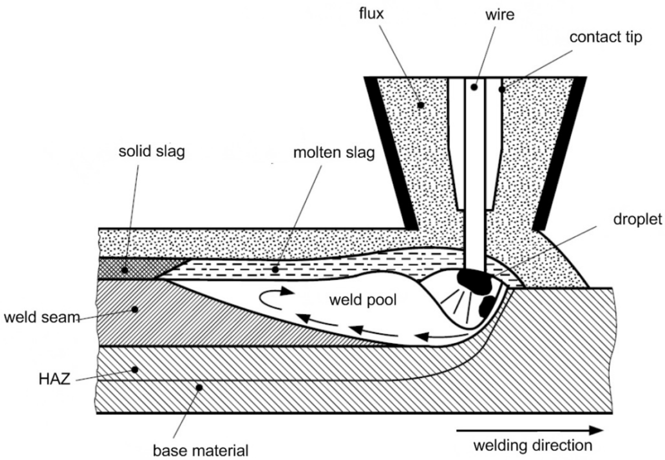


Figure 9. Process zone during submerged arc welding.

Despite the advantages of the fused flux, the agglomerated flux is the predominant type used for linepipe welding. It is manufactured by “rolling” the different components with the addition of silicates. For this, the raw materials are first milled to small particles. These small particles are pelletised to grains which contain the correct proportion of each component. These grains are dried and baked at temperatures between 600 °C and 850 °C. Like all agglomerated products these grains are chemically heterogeneous. Since these fluxes have not reacted during manufacturing, metallic de-oxidants or alloying elements can be added. This is one of the major advantages over fused fluxes, because the weld metal is more efficiently de-oxidized. By this, the oxygen content is well controlled and consequently the inclusion volume fraction and size distribution. As a result the toughness values achieved at sub-zero-temperatures are higher than those from fused fluxes. During welding the flux consumption is lower because the density is lower. Since these fluxes are hygroscopic, it is either recommended to re-dry the flux, prior to use, or to use fluxes with limited moisture pick up kinetics [1].

In the pipe mills of EUROPIPE, only agglomerated fluxes are used. Various quality control steps are implemented over the whole process from initial flux development to final procurement, income inspection and production. These include tight definitions for the main flux components and regular control of the following factors:

- grain size and distribution
- abrasion resistance (grain strength)
- moisture content
- Basicity index (BI)

The flux density and the grain size and distribution are important characteristics for weld shape control and surface quality. If the flux layer is too thick or dense, the weld bead will have a rough and irregular surface as the welding gases cannot escape. On the other hand, in the case of too thin a flux layer, the weld pool is not sufficiently shielded and arc flashing and spattering will cause a bad weld bead appearance.

Typically aluminate-basic type fluxes with a BI in the range of 1 to 1.5 are used in order to optimise deoxidization and hence toughness, productivity and weld surface finish, Figure 10. Fluxes with lower basicity allow for higher welding speed and excellent slag detachability, but toughness is reduced due to the higher oxygen content. Fluxes of the fluoride-basic type with a high basicity index are, on the other hand used for multi-pass welding, with the main goal to reach excellent low temperature toughness down to -60 °C or even lower.

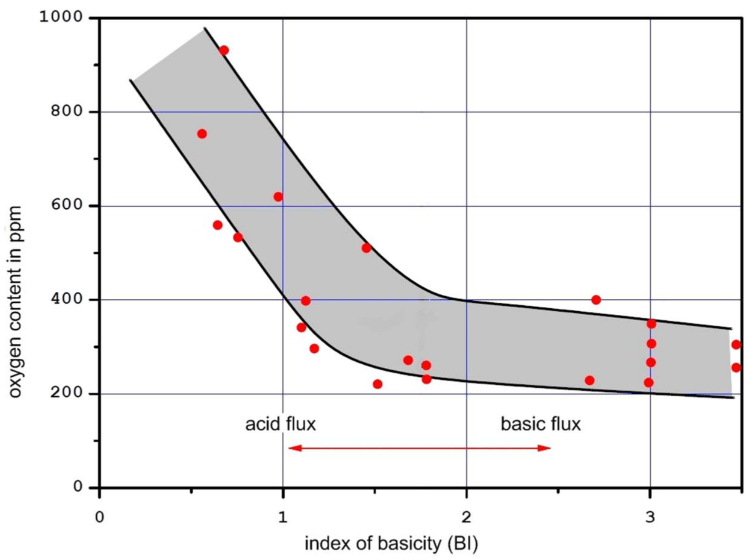


Figure 10. Weld seam oxygen content as a function of flux basicity.

Oxygen content in the range of 300 ppm ± 100 is considered to be the optimum for double layer seam welds. Oxides control the weld seam microstructure as they influence both the austenite grain size, the austenite transformation and the formation of fine acicular ferrite [2].

The already mentioned principal disadvantage of agglomerated fluxes being hygroscopic requires handling and storage procedures specifically adapted to the individual mill and its environment. More and more standards and specifications for SAW linepipe allow a maximum diffusible hydrogen content (HD) of 5ml/100g weld metal [3]. In addition, these specifications define a maximum moisture content of 0.03% for agglomerated fluxes. In EUROPIPE's experience with major suppliers of agglomerated flux, this value can, if ever, only be reached after re-drying and seems to be rather arbitrarily set. As an alternative, it is possible to provide comparative data of diffusible hydrogen versus flux moisture content in order to prove that a maximum HD, diffusible hydrogen, value of 5ml/100g can be guaranteed even for higher moisture levels.

The determination of the flux moisture has to be performed in accordance with AWS standard A4.4M [4]. This standard defines two different methods capable of measuring low quantities of water: Karl-Fischer (KF) method or Infrared detection (IR) method. Both analysing methods differ in the test set-up and measuring process. In compliance with this standard, an extraction temperature of 980 °C (± 10 °C) and carrier gas oxygen or dried, bottled air is mandatory. Both determination methods reveal similar results, although the Karl-Fischer method tends to measure lower values, however with a bigger scatter and higher standard deviation. Independent from the applied method and the determined values, the most important aspect with regard to moisture content in welding consumables is, in terms of the cold cracking sensitivity, the correlating diffusible hydrogen content.

In order to establish this correlation of moisture content vs. HD value, a test series was performed on an aluminate-basic flux in the as-delivered condition and after storage in a climate chamber, to investigate the moisture pick up and its impact on the HD value. Flux samples were exposed in a climate chamber for different time periods to a relative humidity of 95% at 25 °C. It has to be mentioned, that a relative humidity of 95% reflects extreme conditions (very wet climate) and can be considered as very extreme for a mill in Western Europe. Before storing in the climate chamber, the flux samples were re-dried according to the manufacturer's instructions at 300-350 °C for 2 hours to guarantee comparable initial moisture values. The artificially moistened samples were subsequently evaluated by the IR method, to the specified extraction conditions stated in the standard AWS A4.4M. Eventually the samples were used to investigate the influence of the different flux moisture contents on the corresponding HD content. The HD measurements were performed in accordance with the standard DIN EN ISO 3690 by the carrier gas hot (CGH) extraction method (extraction temperature 400 °C, carrier gas: nitrogen).

The resulting HD contents of the flux samples obtained during the investigation for the different conditions are given in Figure 11. The individual values, given in this diagram, are mean values of two measurements.

The investigated aluminate-basic flux exhibits weld metal hydrogen contents of less than 5ml/100g both in the as received state and after re-drying, which are in line with values stated by the manufacturer data sheet and the normative description "H5" (max. hydrogen content 5ml/100g weld metal). After artificially moisturising the hydrogen values increase corresponding to the total moisture content, which depends on the exposure time.

Within the EUROPIPE quality assurance for welding consumables, flux samples are regularly taken immediately after delivery, but also at the individual welding heads in order to check that the actual moisture content is below the internally set limit of 0.06%. In addition air humidity and temperature are recorded both in the flux storage room and in the pipe mill itself.

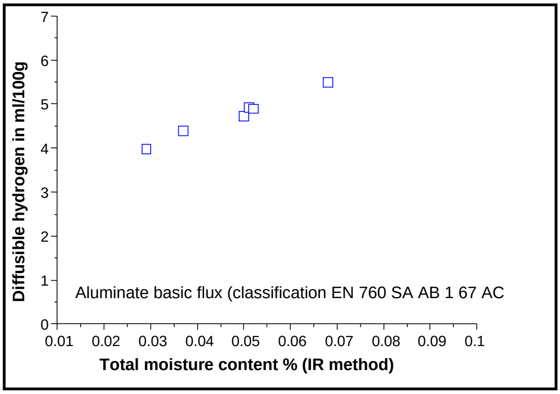


Figure 11. Diffusible Hydrogen (HD) as a function of total moisture content at 980 °C.

As shown in Figure 9 chemical reactions between the welding flux and the melting welding wire are occurring in the electric arc. This requires that, besides the welding parameters and the welding flux, the welding wires have to be correctly designed in order to achieve the best weld seam. With regard to the mechanical properties of the weld metal it is commonly understood that toughness needs to reach a sufficiently high level depending on service conditions and design criteria, whereas the weld metal strength should generally show a moderate overmatching of up to 25% compared to the base metal strength.

As for double seam longitudinal SAW large diameter linepipes the possibilities to influence the weld metal properties by reduced heat input and lowered cooling time are limited. The microstructure of the weld metal is the key to the desired toughness and strength. The formation of a fine acicular ferrite is recognized to be the best solution for this goal and can be influenced by the alloying content of the weld metal. Acicular ferrite reveals a very fine grain size and a high dislocation density. The chemical composition of the base material to be welded has to be taken into account as the dilution of the weld bead can reach up to 70%.

The influence of the most relevant alloying elements on toughness and hardness (strength) of submerged arc weld seams is shown in Figure 12. Besides the oxygen content and its influence on the inclusions, the alloy content is of great importance as it significantly affects the weld metal microstructure and thereby the mechanical properties. Elements like molybdenum and boron delay the transformations from austenite grain boundaries whereas manganese and titanium promote the intragranular transformation to acicular ferrite. In contrast to acicular ferrite, pro-eutectoid ferrite, as a product of austenite phase change during solidification and crystallization should be minimized. Pro-eutectoid ferrite is characterised by low angle boundaries leading to coarse and directional grain growth, which is unfavourable for good impact toughness.

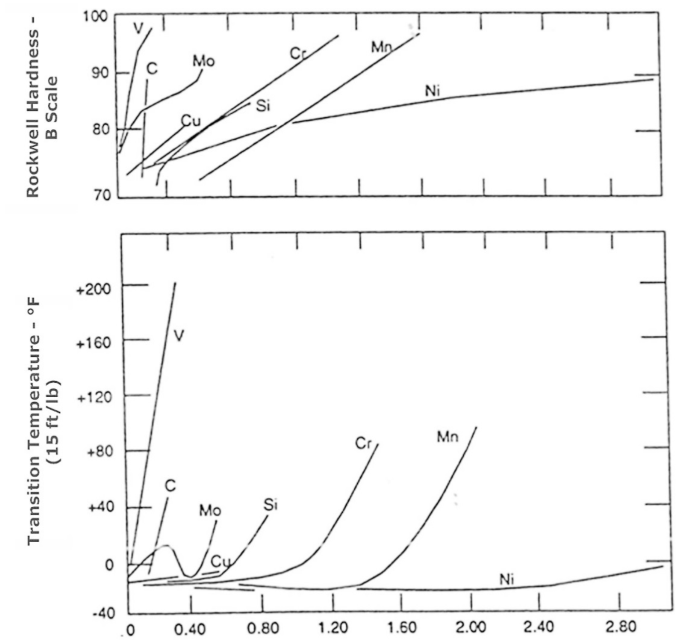
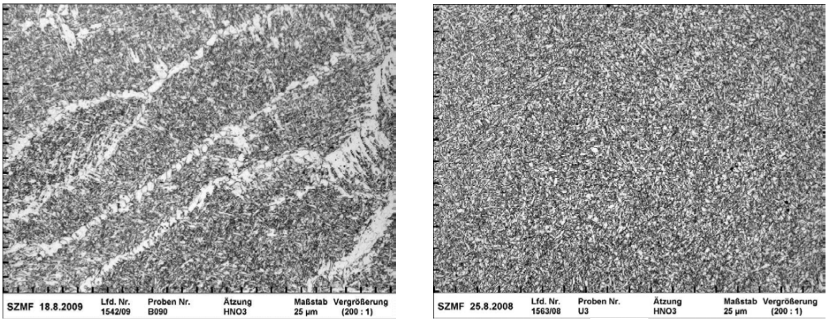


Figure 12. Effect of alloy additions (wt%) on notch toughness and hardness of submerged arc weld metals [5].

In Figure 13 two typical weld metal microstructure examples are shown. Whereas in Figure 13(a) a coarse acicular ferrite with major fractions of pro-eutectoid ferrite at the former austenite grain boundaries serves as an example for an unfavourable microstructure, Figure 13(b) presents a very fine grain acicular ferrite representing high toughness properties and sufficient strength overmatching.



(a) (b)

Figure 13. (a) Coarse acicular ferrite with pro-eutectoid ferrite (b) Fine acicular ferrite (x80).

In Figure 14 Charpy-V transition curves for three basic welding wire alloy concepts are summarised. The highest upper shelf toughness combined with the lowest transition temperature are achieved with a MnMoTiB-alloy system which guarantees a high volume fraction of very fine grain acicular ferrite provided the nitrogen content is low. In TiB-weld metal the boron atoms, segregated along austenite grain boundaries, inhibit the formation of grain boundary ferrite and facilitate acicular ferrite formation inside austenite grains with finely dispersed titanium-oxides as nuclei. Titanium has, in this system, the function of protecting the boron from oxidation and it also prevents boron from forming nitrides, which can suppress the grain refining effect. Compared with this, the results obtained with manganese and/or molybdenum alloyed welding wires reveal significantly lower values, however still sufficient for most onshore applications up to X70 and down to test temperatures of -20 °C as the minimum.

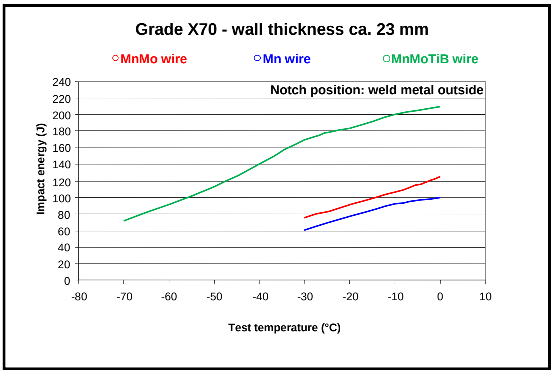
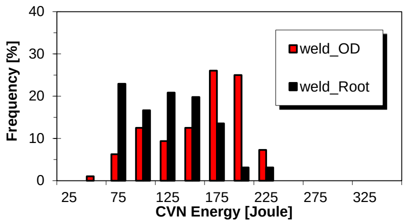
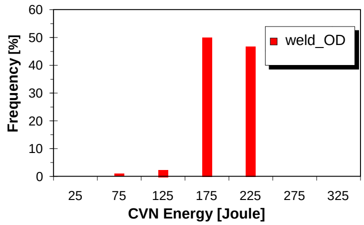


Figure 14. Typical CVN transition curves for different welding wires combinations.

In Figures 15 (a) and (b) actual Charpy-V test results for X70 and X80 (or the Russian equivalent K65) are presented respectively for thick wall linepipe for a test temperature of -40 °C. In both cases MnMoTiB-alloyed welding wires have been used. The results underline the superior behaviour of this welding wire type with a consistently high toughness level even at very low temperatures.



(a)



(b)

Figure 15. (a) Weld metal CVN results at -40 °C for X70 with 29.3 mm wall thickness.
(b) Weld metal CVN results at -40 °C for K65 with 27.7 mm wall thickness.

Weld seam strength generally should have a moderate overmatching compared to the base metal. As shown in Figure 16, both the all-weld-metal yield and tensile strength increase with increasing carbon equivalent as expected. These results have been achieved using various commercially available welding wires. The all-weld-metal strength properties were determined using round bar tensile specimens. Whereas the increase of yield strength for double-layer welding by increased alloying content (mainly Mo, Ni, Cr) is limited to nearly 700 MPa, the tensile strength can reach values above 1000 MPa. It is obvious from these results that the required overmatching can be achieved up to X80 with moderate alloying content allowing the weld metal carbon equivalent to stay below 0.47. In the case of double-layer welding, a further yield strength increase up to X100 is only possible with extremely high additions of alloying elements.

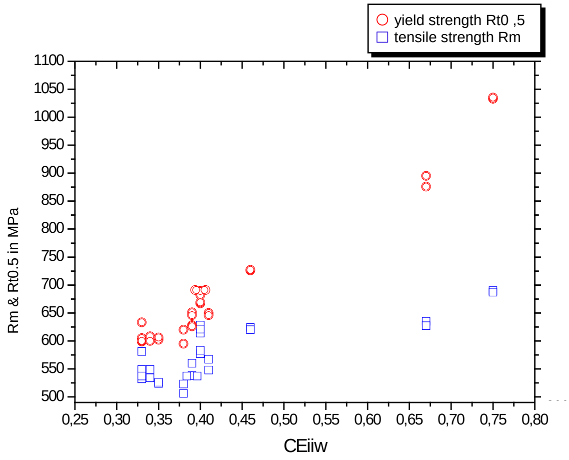


Figure 16. All-weld metal strength as a function of carbon equivalent (IIW).

Such high alloying content will significantly increase hardness and reduce toughness accordingly. It is therefore reasonable that specifications, on the one hand require a sufficient overmatching but also, control it by setting an upper limit. In defining this upper limit the required weld metal toughness plays an important role. As discussed above the best low temperature toughness values can be achieved using MnMoTiB-welding wires as they guarantee a fine grain acicular ferrite. However such enhanced weld metal alloying, unavoidable in order to fulfil the high toughness requirements, accordingly increases the strength level. This might lead to problems when the upper limit for the weld metal strength is set equal to or only slightly above the upper limit of the base metal. It is therefore important, especially for grades with moderate strength levels in the range of X60 up to X70, not to be overly restrictive on the upper limit of the weld metal overmatching and to consider that high toughness requirements can only be achieved with an enriched weld metal deposit.

Conclusions

In order to ensure adequate quality in the weld seam of linepipes for more and more challenging service conditions, modern technology is required for the welding process and the production of welding consumables. Furthermore a stringent control of the SAW process is a prerequisite for low defect rate and high quality. Modern digital welding power sources offer a wide range of enhanced parameter control which allows improved productivity and quality concurrently. As for the linepipe properties in general, quality requirements for the weld seam need to be defined in a balanced way, as some requirements are partly set in opposing directions. As an example, interpenetration of the internal and external weld must be safely achieved, however a too restrictive requirement here will require excessive heat input which is harmful to the heat affected zone toughness.

The second set of factors influencing the weld seam quality is set by appropriate selection of welding consumables. It is very important that agglomerated welding fluxes are developed, manufactured and handled in a way that guarantees a low content of diffusible hydrogen in the weld seam. The control of the moisture content is therefore a necessary quality control measure for agglomerated flux as this value correlates with the diffusible hydrogen content.

In order to achieve the required mechanical properties, it is important to choose a welding flux with a basicity index in the neutral or slightly basic range to control the oxygen content. Furthermore the wires need to be sufficiently alloyed in order that the strength and toughness properties are achieved, but too high hardness is avoided. As generally the weld seam strength should overmatch the base material, the limits for the weld seam need to be defined at a correspondingly higher level.

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