“Modern design criteria for stainless steel welding consumables”

by

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Abstract:
The development of welding consumables for stainless steels has been reviewed in respect of the various product types and their chemical composition. The typical position of commercial grades has been projected in the leading weld metal structure diagrams as published by the Welding Research Council (WRC) and Schaeffler. The relation between the composition of slag forming components in the stick electrode covering and in flux cored wires has been linked to the specific welding characteristics of the finished welding consumables. Examples of applications and welding procedures are presented.

1. Introduction

Most welding processes can be applied for welding stainless steel. Each of the main arc welding processes such as SMAW, FCAW, GTAW, GMAW and SAW require consumable products with specific properties and chemical compositions. The weld deposits obtained with these consumables have to fulfil the requirements that are common for all weldments in stainless steel constructions:

- free of cracks, porosity and spatter as well as a very smooth bead appearance.

The weld metal chemical composition must meet at least that of the base material or may be “overmatching” in alloying elements when technically appropriate and/or required. In addition to the above the metallurgical structure shall have a controlled ferrite content and shall be free of detrimental phases such as chromium carbides (Cr23C6) or sigma phase (FeCr). The most important alloying elements used are Cr, Ni, Mo, Mn, Cu, Nb, Ti, W and N. These elements in combination with carbon (C) and silicon (Si) determine to a great extend the solidification structure, considering a cooling rate that is typical and practical for welding stainless steel. A most recent diagram for the determination of the metallurgical microstructure is the Welding Research Council’s WRC 1992 Constitution Diagram /1/.

Welding consumable products for stainless steel are:

- Covered/coated stick electrodes for SMAW
- Bare welding wire, shielded with a slightly oxidizing gas in gas metal arc welding (GMAW) or with an active or neutral flux in submerged arc welding (SAW).
- Bare rods for gas tungsten arc welding (GTAW), with an inert gas shielding.
- Flux or metal cored wires, shielded either by CO₂, Ar/CO₂ or a three component Ar/He/CO₂ mixed gas, applied with the flux cored arc welding process (FCAW).

In this paper emphasis has been put on the position of the weld metal grades adapted for the various base material grades in stainless steel. Their differences in composition lead to a variety of metallurgical microstructures that can be predicted by means of structure diagrams. A further factor in determining the welding characteristic is the interaction of slag forming components from the electrode covering, the fill of cored wires and the flux as used in submerged arc welding.

2. Weld metal grades
The requirements for the various typical weld metal compositions are primarily determined by the application of the final structure or component and the base material applied. Figure 1 shows the development in corrosion resistant base materials and the associated weld metal grades over the last 4 decades.
In the 1950’s, the industrial stainless steel grades AISI 304/DIN X5CrNi 18 10 and the Mo-alloyed companion AISI 316/X5CrNiMo 17 12 2 where improved and converted to the low carbon versions. Earlier, the sensitivity to intergranular corrosion (weld decay) had been limited by stabilizing carbon with Nb or Ti additions in the base material. From grade AISI 316L or nowadays X2CrNiMo 17 12 2 in accordance with EN 10088, the development of commercially successful new grades could be observed.
Elements such as Mo, Cu, W and N all contributed to and increased corrosion resistance and mechanical strength. Such benefits provide superior grades of stainless steel.
The European Norm, EN, classifies steel grades and includes regular grades as X2CrNi19 9 and X2CrNiMo17 12 2, the N-alloyed variations X2CrNiN18 10 and X2CrNiMoN17 11 2, the fully austenitic and super austenitic grades as well as the increasingly more important austenitic-ferritic duplex stainless steel X2 CrNiMoN22 5 3 and superduplex grades such as X2CrNiMoCuWN25 7 4. The duplex and super duplex grades have proved their benefits in strength and corrosion resistance in major on- and offshore installations in the oil & gas industry.
Also the 12%Cr supermartensitic stainless steel grades are now available with a very low C, N and O content /2,9/. These so-called “supermartensitic” stainless steels have become most interesting for transport pipelines such as subsea flow lines. Matching weld metal grades still may not provide adequate toughness and elongation. For this reason superduplex stainless steel welding consumables are being predominantly applied for longitudinal as well as for girth welds. These weldments have a proven track record of providing reliable strength and toughness properties.
The welding consumable grades have been designated using the commonly used standard abbreviations that include covered electrodes, flux cored welding wires as well as wires for GTAW, GMAW and SAW. The position of these grades in the structural diagrams of figures 2 and 3 has been indicated with the letters A, B, etc from figure 1.
3. Weld metal structural diagrams

The WRC 1992 Constitution Diagram from figure 2 is the latest published diagram for the determination of the amount of weld metal ferrite by means of calculation. The ferrite content is expressed as Ferrite Number FN and is based on collective data from various laboratories throughout the world. All these laboratories analyzed the all weld metal chemical composition and determined the ferrite content (FN) according the standard ISO 8249 and further developments co-ordinated by the International Institute of Welding (IIW)/3, 4/. When showing the various possibilities of microstructures in weldments, reference is often made to the earlier developed Schaeffler Diagram /5/. Combining the two diagrams provides a means to show the interaction between the two diagrams. The WRC 92 diagram has a valid indication in a limited area and uses an empirical formula for determination of the Cr and Ni equivalent. Beyond the WRC 92 range, the co-ordinates are based on the earlier formulas as presented by Schaeffler.

4. Design of covered electrodes and flux cored wires

In order to obtain the required mechanical and corrosion resistance properties the correct weld metal chemical composition is of extreme importance. The chemical composition of the core wire used for a stainless steel covered electrode is therefore the starting point for the design of total product. The alloying elements may be provided completely, partly or not at all through the core wire used. In all cases the covering, in addition to other contributions such as the formation of slag protection, arc stabilisation etc. has to provide additional or compensate alloying elements. Compensation for alloying elements that burn-off is always needed because a reaction of alloying elements with the slag cannot be prevented completely. Also, the core wire may not be available in the exact chemical composition required to obtain a certain all weld metal chemical composition.

The variation of the alloying elements such as Cr, Ni and Mo depends on the nominal level, the reactivity and the difference between the supply in the covering and the core wire. Table 1 shows indications for grade EN1600: E CrNiMo19 12 3LR:

<table>
<thead>
<tr>
<th>Element</th>
<th>Core wire type 19 9L</th>
<th>Core wire Mo alloyed, type 19 12 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Core wire</td>
<td>Weld Deposit</td>
</tr>
<tr>
<td></td>
<td>%Cr</td>
<td>20,0</td>
</tr>
<tr>
<td>%Ni</td>
<td>10,0</td>
<td>11,6</td>
</tr>
<tr>
<td>%Mo</td>
<td>0,05</td>
<td>2,8</td>
</tr>
<tr>
<td>%N</td>
<td>0,05</td>
<td>0,065</td>
</tr>
<tr>
<td>FN</td>
<td>9</td>
<td>5 –12</td>
</tr>
<tr>
<td>PREN</td>
<td>28,6</td>
<td>26,1-29,2</td>
</tr>
</tbody>
</table>

Table 1: Variation in alloying elements and Ferrite Number, depending on type of core wire

The acceptability of this variation in the chemical composition of the weld deposit depends on the application of the weld metal. For general purposes the variation of, for example
Molybdenum, will not cause any significant reduction in corrosion resistance. The chemical composition is still within the limits of the requirements according most international standards. However, for more demanding applications a variation with a minimum Molybdenum content of 2,4% would cause a serious risk of preferred weld metal corrosion attack. This type of corrosion “pitting” occurs when the larger surface area of the plate material shows a higher electrochemical potential (higher corrosion resistance) as opposed to the relatively smaller surface area of the less noble weld in a corrosive environment. In this kind of applications the weld metal Pitting Resistance Equivalent,

\[ \text{PREN} = \text{Cr} + 3,3*\text{Mo} + 16*\text{N}, \]

must be higher than that of the plate. To meet this requirement a minimum Molybdenum content of 2,75% is often required. Wide variations in Cr and Mo make it difficult to assure compliance with this requirement.

5. Flux (slag forming) minerals

Established covered electrodes and flux cored wires are not only for use in the downhand welding position. Most common weld metal grades have been designed with various types of covering or core composition. They offer a suitable variety of welding characteristics, with specific advantages in different welding positions. With the type of coating or core composition the weld metal properties are also influenced. Related to the main minerals used in the electrode coating, tubular wire core and submerged arc welding fluxes, standards distinguish rutile, basic and mixed types. Additional reference is made to the recovery of weld metal from alloying or other metallic constituents such as ferromanganese, ferrochrome, Ni and Fe powder etc. A more describing classification would include subclasses such as rutile/basic and rutile/silicate. **Table 2** shows the mass percentage of the slag forming constituents, normalised to 100% of typical classes of covered electrodes, flux cored wires and welding fluxes.

<table>
<thead>
<tr>
<th>Consumable type</th>
<th>Type of slag system</th>
<th>TiO₂</th>
<th>SiO₂</th>
<th>CaCO₃</th>
<th>CaF₂</th>
<th>Na₂AlF₆</th>
<th>Al₂O₃ + MgO</th>
<th>Alloy metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covered electrodes</td>
<td>Rutile</td>
<td>55-65</td>
<td>20-25</td>
<td>5-10</td>
<td>5-10</td>
<td>-</td>
<td>-</td>
<td>Cr</td>
</tr>
<tr>
<td></td>
<td>Rutile / silicate</td>
<td>50-55</td>
<td>25-30</td>
<td>5-10</td>
<td>5-10</td>
<td>-</td>
<td>-</td>
<td>Cr</td>
</tr>
<tr>
<td></td>
<td>Rutile / basic</td>
<td>50-55</td>
<td>20-25</td>
<td>10-15</td>
<td>5-10</td>
<td>-</td>
<td>-</td>
<td>Cr</td>
</tr>
<tr>
<td></td>
<td>Basic</td>
<td>Fluorspar</td>
<td>5-10</td>
<td>&lt;5</td>
<td>30-40</td>
<td>40-50</td>
<td>5-15</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cryolite</td>
<td>5-10</td>
<td>&lt;5</td>
<td>30-40</td>
<td>5-15</td>
<td>40-50</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Combined</td>
<td>5-10</td>
<td>&lt;5</td>
<td>25-35</td>
<td>20-25</td>
<td>30-40</td>
<td>-</td>
</tr>
<tr>
<td>Flux Cored Wire</td>
<td>Rutile</td>
<td>85</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Fe,Cr, Ni,Mo</td>
</tr>
<tr>
<td></td>
<td>Rutile / silicate</td>
<td>60</td>
<td>40</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Fe,Cr, Ni,Mo</td>
</tr>
<tr>
<td>SAW flux</td>
<td>Silicate</td>
<td>-</td>
<td>30</td>
<td>-</td>
<td>20</td>
<td>-</td>
<td>50</td>
<td>(Cr)</td>
</tr>
<tr>
<td></td>
<td>Basic</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>50</td>
<td>-</td>
<td>40</td>
<td>(Cr)</td>
</tr>
</tbody>
</table>

**Table 2**: Flux composition of stainless steel welding consumables (X2CrNi18 9) in mass %.
The position of these slag systems, with the basic minerals combined, can be schematically illustrated in a ternary constitution diagram as shown in figure 4. The essential design parameters for covered electrodes are the slag system and the relative quantity of slag, the mass ratio slag/metal. A small variation in slag composition, together with a significantly different mass ratio, leads to different welding characteristics and consequently to another electrode type.

The appreciation of the welding characteristics of commercial electrode types in butt and fillet welds in the downhand (PA) and vertical (PF and PG) welding positions are shown in figure 5 which has the rating for suitability from low to high on the vertical axis. With flux cored wires one will observe that the more fluid slag from a rutile wire will not allow to maintain sufficient control over the weld pool when welding vertical up. Consumables with a dominating basic composition lead to less wetting action and a lower oxygen level in the weld deposit. This implies better mechanical and corrosion resistance properties versus a less favourable but still acceptable weldability.

Flux cored wires are available for either downhand only or for all position (except vertical down) welding. The difference in slag forming constituents in the core is remarkable. The suitability for welding in vertical position requires a certain amount of rutile to make the slag sufficiently fast freezing in order to maintain control over the weld pool. Silicates improve the wetting action and the smooth bead appearance in the downhand position. Basic minerals are not used due to the fact that they reduce the arc stability too much. In contrast, welding fluxes are often produced on a silicate base or have a mainly basic (fluoride + the amphoteric aluminium oxide) character. Where toughness at low temperature and also easy slag detachability is required, basic fluxes are most successful.

6. Conclusions
Properties of welding consumables and weld metal deposits depend on the major components such as the core wire and coating composition for covered electrodes and similarly on the components as strip and core for flux cored wires and wire / flux combinations in submerged arc welding. The main elements that contribute to the corrosion resistance are Cr, Ni, Mo and N. The vital elements should preferably be present in the core wire of covered electrodes in order to assure the correct and required weld metal chemical composition.

The weld metal usually has a composition compatible with that of the base material but also dissimilar weldments such as in 12%Cr supermartensitic stainless steel proved to be fully adequate for the purpose of the construction. The weld metal composition has been tuned to optimize the structure, this to assure the required balance in austenite and ferrite and to be relatively insensitive for the formation of undesired phases such as carbides and sigma phase. The WRC 1992 constitution diagram, incorporated in the well known original Schaeffler Diagram, provides a tool to estimate and predict weld metal structures, i.e. the weld metal Ferrite Number. The weld metal can be deposited by means of various product forms, adapted to the specific welding process. In welding processes, working with the flux support, slag forming minerals
determine to a great extend the welding characteristics. The electrode coating or the cored wire core composition with mainly rutile or basic minerals provide the capability to weld in vertical positions, whereas products with a high silicate content show smooth weld beads in the downhand position.

7. References
   pp28-31
3. AWS A4.2-74, up-dated by AWS A4.2-91
4. IIW Document II-904-79 and update II-1345-98
5. Schaeffler A.L., Metal Progress (1949), pp680-680B
Fig. 1 Corrosion resistant CrNiMo-steel base materials and weld metal grades
Fig. 2  WRC 1992 Diagram, incorporated in the Schaeffler Diagram;
With the positions of the Lincoln Smitweld welding consumables
Fig. 3 WRC '92 Constitution Diagram

Cr Equiv. = %Cr + %Mo + 0.7(%Nb)

Ni Equiv. = %Ni + 35(%C) + 20(%N) + 0.25(%Cu)

Fig 4 Ternary diagram of flux constituents in stainless steel welding consumables

% basic comp.

basic components

% SiO₂

basic /silicate

covered electrodes

flux coated wires

welding fluxes

% TiO₂

SiO₂

rutile

rutile /basic

rutile /silicate
Fig. 5 Ranking of electrode types in various welding positions