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Second edition

Welding — Best practices for specification and measurement of ferrite in stainless steel weld metal

PROOF/ÉPREUVE

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Foreword

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This document was prepared by Technical Committee IIW, *International Institute of Welding*, Commission II, *Arc welding and Filler Metals*.

This second edition cancels and replaces the first edition (ISO/TR 22824:2003), which has been technically revised.

The main changes compared to the previous edition are that as follows:

- the metallurgical phenomenon of ferrite has been addressed;
- methods of ferrite measurement have been addressed;
- best practice for reasonable and effective specifications for ferrite has addressed;
- best practice for dealing with outliers in ferrite measurement has been addressed;
- the list of references has been significantly expanded.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document was prepared by the International Institute of Welding, Commission II, through its Subcommission II-C, Arc Welding and Filler Metals, in cooperation with Commission IX through its Subcommission IX-H, Welding of Stainless Steels and Nickel Base Alloys, on behalf of ISO/TC 44/SC 3. It constitutes the considered judgement of the experts on measurement and specification of ferrite in nominally austenitic and duplex ferritic-austenitic stainless steel weld metals.

Welding — Best practices for specification and measurement of ferrite in stainless steel weld metal

1 Scope

This document describes best practices, based on the experience of experts, for setting appropriate requirements, in specifications and other standards and contract documents, on ferrite content of nominally austenitic or duplex ferritic-austenitic stainless steel weld metals. It also describes a best practice on measurement and measurement reproducibility, and deals with outliers in measurement. It considers ferrite in the weld heat-affected zone of duplex stainless steel. It does not consider specification or measurement of ferrite in ferritic stainless steels nor in martensitic stainless steels.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at https://www.electropedia.org/

3.1
stainless steel
any member of a diverse family of alloys containing at least 10,5 % chromium (the minimum chromium content which provides for rust free service in ordinary ambient air free of salt), and often but not always containing substantial nickel, in which the iron content exceeds that of any other element when all other elements are taken at the specification minima for the alloy

3.2
austenite
face-centred cubic crystal structure of iron base alloys that is not ferro-magnetic at ambient temperatures

3.3
duplex ferritic-austenitic stainless steel
stainless steel base metal or weld metal consisting of a microstructure of approximately equal parts ferrite and austenite,

Note 1 to entry: The ranges of the two phases can be quite broad – often shortened to duplex stainless steel.

3.4
ferrite
body-centred cubic crystal structure of iron base alloys that is ferro-magnetic at ambient temperatures

3.5

Ferrite Number

FN

magnetically determined measure of ferrite content made using an instrument calibrated according to ISO 8249[1]

Note 1 to entry: The term is always capitalized to signify conformance with the ISO standard.

3.6

ferrite percent

volumetric content of ferrite which can be determined metallographically, by a magnetic instrument, by x-ray diffraction, or by other means

3.7

martensite

body-centred tetragonal crystal structure of iron base alloys that is ferro-magnetic at ambient temperatures and is formed by a shear transformation from austenite without diffusion

3.8

nominally austenitic stainless steel

stainless steel base metal or weld metal which consists predominately of austenite but contains a small amount of ferrite when it reaches ambient temperature directly after solidification

Note 1 to entry: This ferrite can transform in whole or in part to austenite during hot working and/or annealing, but will reappear in some form if the steel is once again melted (e.g., by gas tungsten arc welding without filler metal).

4 Metallurgical phenomena of ferrite in stainless steel weld metal

4.1 General

The ferrite observed in stainless steel weld metal of a given chemical composition at ambient temperature is the end result of its solidification mode, solid state phase transformations during cooling from solidification temperature, and further solid state phase transformations during reheating cycles caused by deposition of subsequent weld passes and/or by postweld heat treatment.

In pure iron, solidification takes place at 1 538 °C as ferrite, commonly called “delta ferrite”. Upon cooling, this ferrite transforms to austenite at 1 394 °C. On further cooling to 912 °C, the austenite transforms back to ferrite, this time commonly termed “alpha ferrite”. Certain alloying elements when added to iron promote the austenite phase during solidification. Notable austenite promoters commonly found in stainless steels are nickel, carbon, nitrogen and copper. The addition of about 4,6 % nickel, or more, to pure iron changes the result of solidification from ferrite to austenite.

Certain other alloying elements when added to iron promote the ferrite phase during solidification. Notable ferrite promoters commonly found in stainless steels are chromium, molybdenum and niobium. Less common ferrite promoting elements occasionally found in stainless steels include aluminium, titanium, vanadium and tungsten.

At one time, manganese was thought to be an austenite promoter during solidification. More recently, it has been proven that manganese, at least up to 12 %, is neutral with respect to promoting ferrite or austenite during solidification[2] does, however, stabilize austenite with respect to transformation to martensite at much lower temperatures[3].

At one time, silicon was thought to be a ferrite promoter during solidification. The role of silicon is less clear than that of manganese. Experimental work involving weld metal of essentially constant composition except that silicon was varied from 0,34 % to 1,38 % found negligible effect of silicon on weld metal ferrite content[4]. However, still higher levels of silicon do appear to promote ferrite.

4.2 Solidification mode

4.2.1 General

In stainless steels, two metallurgical phases are possible at temperatures just below the solidus. These two phases are austenite and ferrite. A particular stainless steel can solidify entirely as austenite (A solidification mode), entirely as ferrite (F solidification mode), or as a mixture of austenite and ferrite. The mixed solidification can occur as austenite first, ferrite last (primary austenite or AF solidification mode) or as ferrite first, austenite last (primary ferrite or FA solidification mode).

The solidification mode is important with regard to weldability of a given stainless steel because it has a profound effect on the tendency for solidification cracking. Solidification cracking can be readily visible in the weld crater or along the weld centreline. But it also can be hidden as longitudinal cracking along the root.

4.2.2 A solidification mode (austenitic)

Stainless steel weld metal that freezes in the A solidification mode generally contains no ferrite at the end of solidification and generally has the highest tendency towards solidification cracking of the four possible solidification modes. Successful welding when this solidification mode is expected can require selection of filler metal with unusually low levels of sulphur, phosphorus and other trace elements. It can also or alternately require special welding techniques including deposition of weld metal as small convex runs with low heat input, and overfilling of the crater at the end of each run. In the extreme, grinding of convex runs and crater overfill after each weld run can be required to obtain sound weld metal.

Austenitic stainless steel base metals and their corresponding weld metals that are high in nickel content generally exhibit the A solidification mode. Examples of weld metals which can be expected to exhibit A solidification mode include 25 20 (310), 18 36 H (330), 27 31 4 Cu L (383), and 20 25 5 Cu L (385).

Some improvement in solidification cracking resistance can also be observed if filler metal of abnormally high manganese content is available. Normal manganese content would be typically in the 1 % to 2 % range, while abnormally high manganese would typically be in the 3 % to 9 % range. Examples of A solidification mode filler metals of abnormally high manganese content include 25 20 Mn and 20 16 3 Mn L (316LMn).

4.2.3 AF solidification mode (primary austenite)

Stainless steel weld metal that freezes in the AF solidification mode generally forms a small amount of ferrite in the interdendritic spaces between columnar austenite crystals in the last stages of solidification. Some partitioning of alloy elements generally takes place, with ferrite-promoting elements chromium and molybdenum (if the latter is present) concentrating more in the ferrite, and austenite-promoting elements nickel, carbon and nitrogen (if the latter is present) concentrating more in the austenite. Weld metal that solidifies in the AF mode generally has only slightly less tendency for solidification cracking than weld metal that solidifies in the A mode. The same welding techniques and weld metal composition modifications that are beneficial for the A solidification mode are also beneficial for the AF solidification mode.

At times, AF solidification mode can be found in 19 12 3 L (316L), 25 20 (310) and 20 16 3 Mn L (316LMn) weld metals. AF solidification mode can also be found in diluted weld metals used in cladding and/or dissimilar metal joining when one or more of the base metals is carbon steel or low alloy steel, and filler metal such as 23 12 L (309L) is deposited.

4.2.4 FA solidification mode (primary ferrite)

Stainless steel weld metal that solidifies in the FA solidification mode generally forms columnar ferrite grains with a small amount of austenite that forms in the interdendritic spaces during the last stages of solidification. Some partitioning of alloy elements generally takes place, with ferrite-promoting elements chromium and molybdenum (if the latter is present) concentrating more in the ferrite, and austenite-promoting elements nickel, carbon and nitrogen (if the latter is present) concentrating more in the austenite. Weld metal that solidifies in the FA mode generally has the highest resistance to solidification cracking of all solidification modes. Such weld metals can generally be deposited without fear of solidification cracking. No special welding techniques or composition modifications are needed to obtain sound weld metal.

Most common nominally austenitic stainless steels and their corresponding filler metals are generally designed to solidify in the FA mode. This includes 19 9 L (308L), 23 12 L (309L), 19 12 3 L (316L) and 19 9 Nb (347). Although ferrite might not be detected in the corresponding base metals, due to solid state phase transformation during hot working and annealing of the base metal, ferrite generally reappears when these base metals are autogenously welded. This is due to the steel mills manipulating the base metal composition to obtain FA solidification which improves yield of quality steel during hot working.

Many nominally martensitic stainless steel weld metals, and their corresponding base metals, solidify as FA, including 13 (410), 13 4 (410NiMo), 420 and 17-4PH, but these are outside the scope of this document.

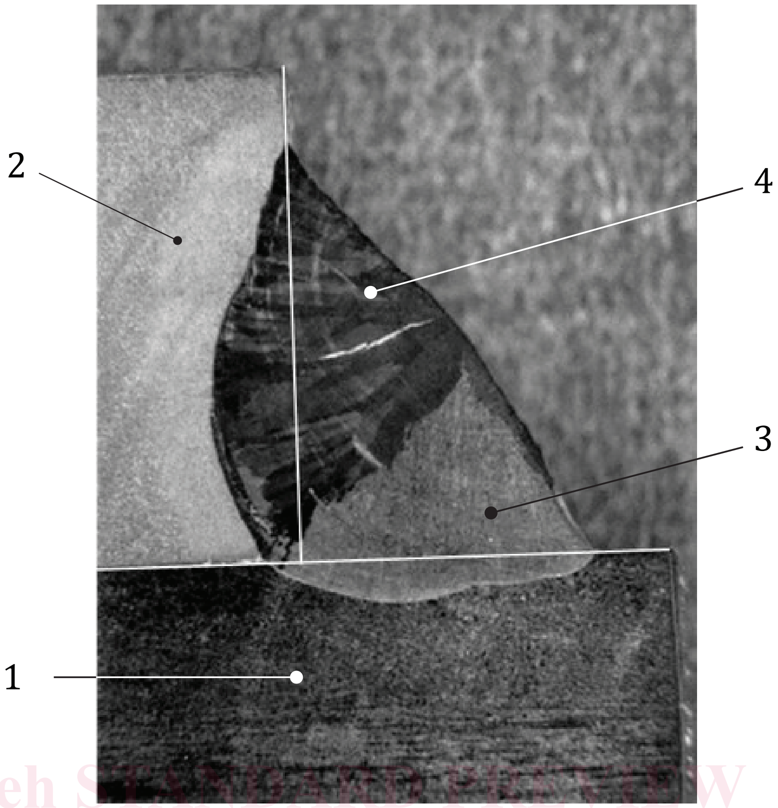
4.2.5 F solidification mode (ferritic)

Stainless steel weld metal that solidifies in the F solidification mode contains no austenite when solidification is complete and is generally much more resistant to solidification cracking than weld metal of the A or AF solidification mode, but not as resistant as weld metal of the FA solidification mode. With F mode compositions, if solidification cracking is encountered, the welding techniques mentioned under the A solidification mode will generally cure the problem.

Examples of stainless steels and their corresponding weld metals that solidify in F mode include duplex, lean duplex, and super duplex stainless steels such as 2205 base metal and its 22 9 3 N L (2209) filler metal; 2101 and its normal filler metal 23 7 N L (2307); and 2507 and its corresponding filler metal 25 9 4 N L (2594). Other base metals and filler metals that solidify as F mode include 29 9 (312), 17 (430) and 18 L Nb. Any austenite found in these steels and weld metals at ambient temperatures results from solid state phase transformation of some ferrite to austenite, as discussed in 4.3. Steels and weld metals such as 17 (430) and 18 L Nb are outside of the scope of this document, but 29 9 (312) is within the scope.

4.2.6 Mixed solidification modes

When a weld metal composition is very close to one of the boundaries between solidification modes, mixed solidification modes can occur. These can be A/AF, AF/FA, or FA/F. From the point of view of resistance to solidification cracking, it makes little difference if the solidification modes are mixed A/AF (similar likelihood of solidification cracking) or if the solidification modes are mixed FA/F (similar solidification cracking resistance). But mixed AF/FA solidification can be significant because AF mode has a significantly greater tendency for solidification cracking than FA mode. Mixed mode solidification can happen on a microscopic scale or on a macroscopic scale. Figure 1 shows a submerged arc single run fillet weld exhibiting macroscopic mixed solidification mode, with solidification cracking in the AF solidification mode region.



Key

1	stainless steel plate	3	FA solidification mode area of weld
2	carbon steel plate	4	AF solidification mode area of weld

NOTE The difference in etching – the region of the weld close to the 304 stainless steel solidified in FA mode, while that close to the structural carbon steel solidified in AF mode. Scribe lines indicate the original metal surfaces before welding. The 304 stainless steel helped to promote FA solidification, while the structural carbon steel helped to promote AF solidification. A solidification crack can be seen in the AF solidification mode region.

Figure 1 — SAW weld joining 304 stainless steel (bottom) to structural carbon steel (top)using 309L filler metal

4.3 Solid state phase transformation of ferrite to austenite

4.3.1 General

When ferrite and austenite coexist in stainless steel and its weld metal, the two phases differ in composition. Lyman[5] showed in 19 9 L (304L) weld metal, FA solidification mode, that ferrite contained about 25 % Cr, 4 % Ni, while the adjacent austenite contained 18 % Cr, 11 % Ni. Ogawa and Koseki[6] showed in 2205 duplex stainless steel (22 % Cr, 6 % Ni, 3 % Mo, 0,12 % N nominal composition) that ferrite in annealed and hot rolled metal contained over 25 % Cr. about 5 % Ni, about 4 % Mo and almost 0 % N, while the adjacent austenite contained less than 21 % Cr, over 7 % Ni, about 2,5 % Mo and nearly 0,30 % N. However, in the as-welded condition, the Cr, Ni and Mo did not vary appreciably between the two phases but the ferrite contained almost 0 % N while the adjacent austenite contained nearly 0,30 % N, and there was much more ferrite in the as-welded condition than in the annealed and hot rolled condition. This illustrates that under weld cooling conditions, only nitrogen diffuses appreciably in this steel to allow austenite formation in the solid state. Carbon in 29 9 (312) weld metal plays the same role as nitrogen in 2205 and its weld metal.

4.3.2 A solidification mode alloys

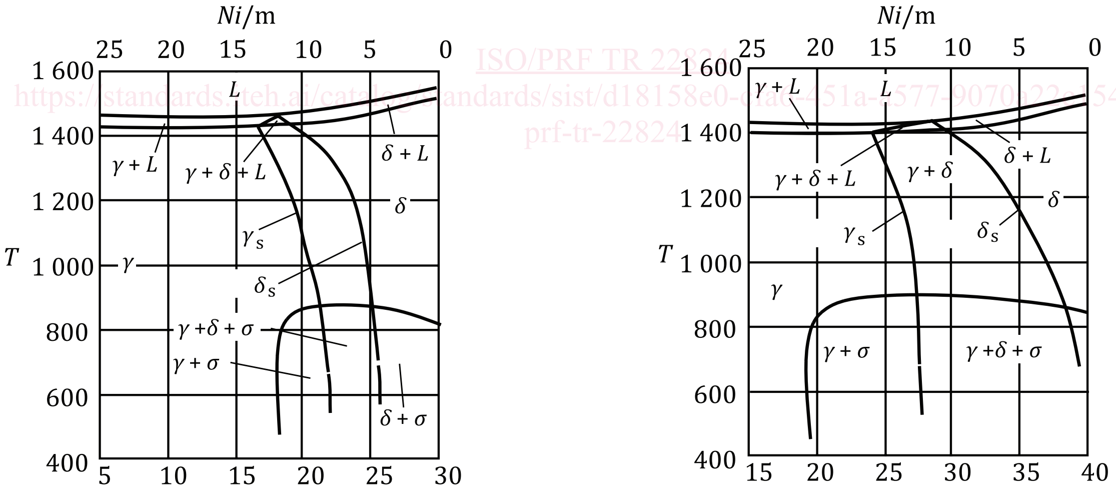
After A solidification mode takes place, the weld metal is already austenite and no transformation of ferrite to austenite takes place.

4.3.3 AF solidification mode alloys

After AF solidification mode takes place, some ferrite can transform to austenite during cooling. Subsequent annealing in the temperature range of about 800 °C to 1 200 °C, or hot working in this temperature range, can cause some or all of the ferrite to transform to austenite as some nickel and other austenite promoting elements diffuse into the ferrite and some chromium (and molybdenum if present) diffuse out of the ferrite.

4.3.4 FA solidification mode alloys

After FA solidification mode takes place, a large amount of the ferrite originally present at the end of solidification transforms to austenite in part because the ferrite becomes thermodynamically less stable and in part as some nickel and other austenite promoting elements diffuse into the ferrite while some chromium (and molybdenum if present) diffuse out of the ferrite. As a result, the ferrite seen at ambient temperatures is much less than what was present at the end of solidification. Subsequent annealing in the temperature range of about 800 °C to 1 200 °C, or hot working in this temperature range, generally causes more of the ferrite to transform to austenite. This transformation behaviour of ferrite to austenite can be understood more fully by reference to Figure 2[7] where it can be seen that the range of compositions over which the two phases, austenite and ferrite, coexist shifts to higher chromium content with falling temperature. Annealing and hot working can cause all of the ferrite to disappear in some alloys such as 19 9 L (308L or 304L) and 19 12 3 L (316L). However, remelting, as in autogenous GTA welding, will cause the ferrite to reform during solidification.



a) 70 % Fe

b) 60 % Fe

Key

T	temperature
m/%	percent by mass
L	liquid
γ	austenite
δ	delta ferrite
σ	sigma
γ_s	austenite solvus
δ_s	delta ferrite solvus

Figure 2 — Pseudobinary sections of the Fe-Cr-Ni ternary phase diagram[7]

Some higher carbon martensitic stainless steels also solidify in FA mode. These generally transform entirely to austenite on cooling through the temperature range of about 1 200 °C to about 800 °C, which in turn transforms to martensite at temperatures generally below about 300 °C. Ferrite is unlikely to be found in such steels at ambient temperature unless an extended tempering is subsequently performed at about 600 °C to 700 °C to precipitate and spheroidize carbides and allow martensite to recrystallize as ferrite.

4.3.5 F solidification mode alloys

After F solidification mode in duplex stainless steels, as the weld metal cools through the temperature range of about 1 200 °C to about 800 °C, diffusion, primarily of nitrogen but also carbon if present, permits some transformation of ferrite to austenite. This transformation begins at the ferrite grain boundaries so that, in the early stages, the ferrite grains become largely enveloped by austenite. Nitrogen and carbon tend to concentrate in this grain boundary austenite by diffusion out of the adjacent ferrite, which in turn slows or stops further transformation along the grain boundaries. Then further transformation of ferrite to austenite must proceed either by nucleation of austenite within the original ferrite grains or by a Widmanstätten-like growth of austenite platelets from favourably oriented locations in the grain boundary austenite.

The lower carbon martensitic stainless steels, such as 13 (410), 13 4 (410NiMo), 17-4PH and 15 5 PH also generally solidify as F mode. These transform largely or entirely to austenite on cooling through the temperature range of about 1 200 °C to about 800 °C. Normally complete transformation to austenite is desired because transformation of austenite to martensite at temperatures below about 300 °C is the aim. However, some residual ferrite can be found in very low carbon versions of alloys such as 13 (410), 13 4 (410NiMo) and 17-4PH.

4.4 Constitution diagrams

Prediction of the ferrite content at ambient temperatures of stainless steels in the as-solidified condition has been of considerable interest for about one hundred years. In 1920, Strauss and Maurer[8] offered a constitution diagram to predict microstructures in wrought chromium-nickel stainless steels. A modified version of this diagram was offered by Scherer et al[9] and seemed applicable to weld metal as well as wrought stainless steels.

Schaeffler, concentrating on weld metal deposited by MMA (SMAW), developed several versions of a constitution diagram, the last of which[10] became very popular and is still referenced today despite its known shortcomings. This Schaeffler Diagram is shown in Figure 3. It makes reasonable predictions of ferrite content in common nominally austenitic stainless steel weld metals such as 19 9 L (308L), 23 12 L (309L, 19 12 3 L (316L) and 19 9 Nb (347). The shortcomings of the Schaeffler Diagram include failure to take into account the important role of nitrogen in promoting austenite, mischaracterizing the role of manganese both with regards to ferrite content and martensite formation, and mischaracterizing the role of silicon in promoting ferrite. As a result of these shortcomings, the Schaeffler Diagram predicts considerably more ferrite than is actually found in high nitrogen weld metals, predicts no ferrite in 18 8 Mn weld metal when significant ferrite is actually found, and predicts martensite in diluted high manganese weld metal such as 18 8 Mn when no martensite is actually found.