Technical
Report

ISO/TR 22824

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

Soudage — Bonnes pratiques pour la spécification et le mesurage de la ferrite dans le métal fondu des aciers inoxydables

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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*, in collaboration with ISO/TC 44, *Welding and allied processes*, Subcommittee SC 3,*Welding consumables*.

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

The main changes are 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 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.

Official interpretations of ISO/TC 44 documents, where they exist, are available from this page: https://committee.iso.org/sites/tc44/home/interpretation.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* (3.4) and *austenite* (3.2)

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* (3.4) 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* (3.4) 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* (3.2) without diffusion

3.8
nominally austenitic stainless steel
stainless steel base metal or weld metal which consists predominately of *austenite* (3.2) but contains a small amount of *ferrite* (3.4) when it reaches ambient temperature directly after solidification

Note 1 to entry: This *ferrite* (3.4) can transform in whole or in part to *austenite* (3.2) 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. Manganese,[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 below the surface and 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.

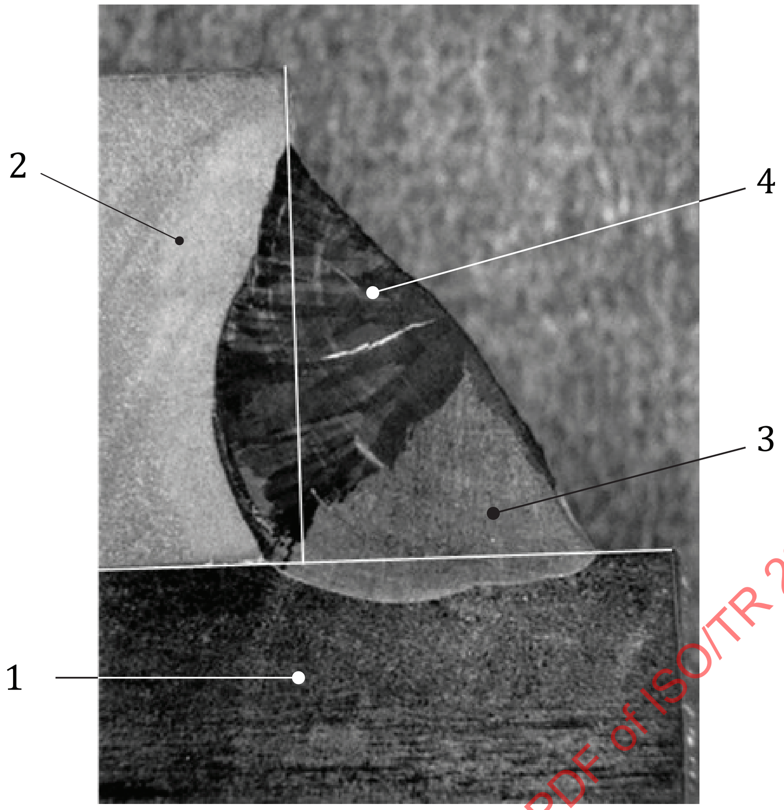
4.2.5 F solidification mode (ferritic)

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

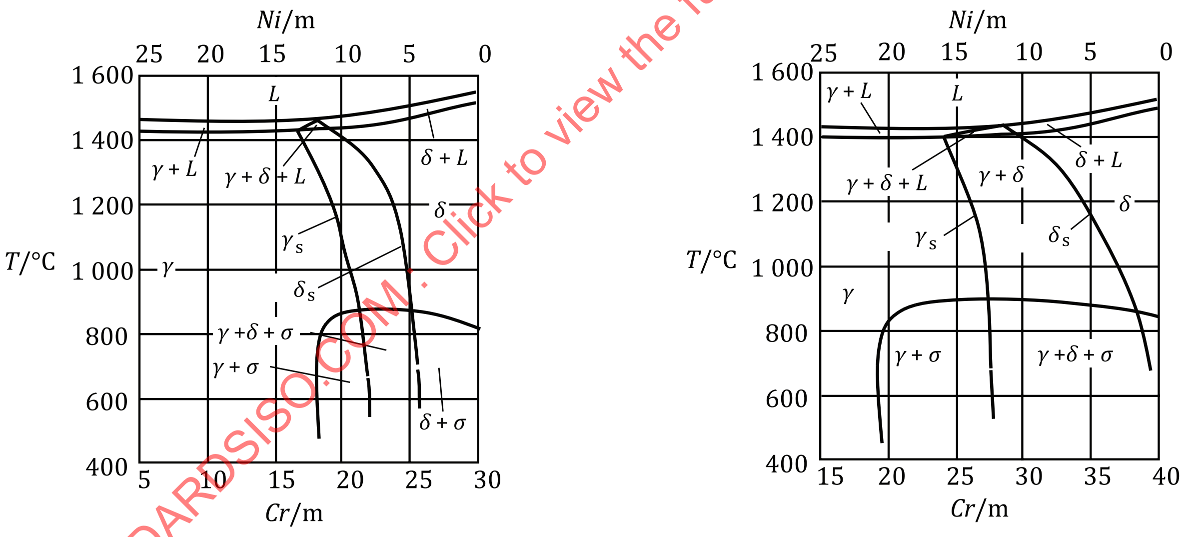
After A solidification mode takes place, the weld metal is already austenite and no transformation of ferrite to austenite takes place.

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

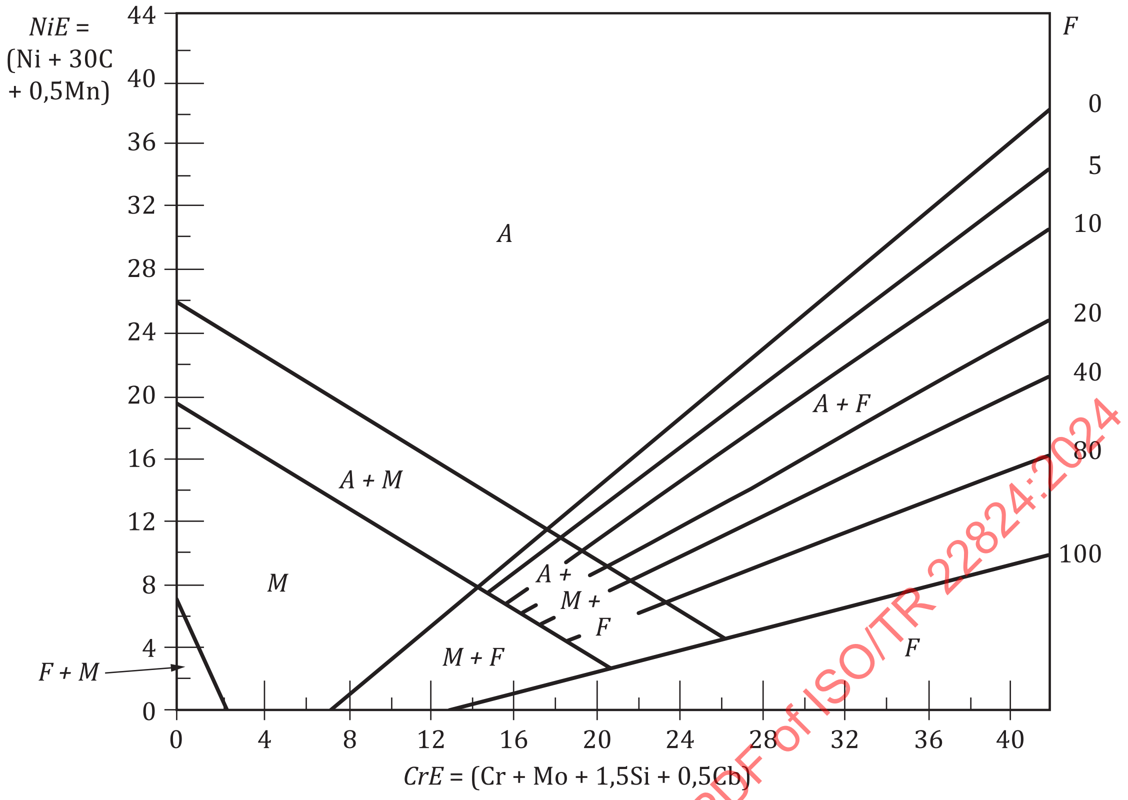
After F solidification mode in duplex stainless steels, as the weld metal cools through the temperature range of about 1 200 °C to about 800 °C, diffusion, primarily of nitrogen but also carbon if present, permits some transformation of ferrite to austenite. This transformation begins at the ferrite 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.

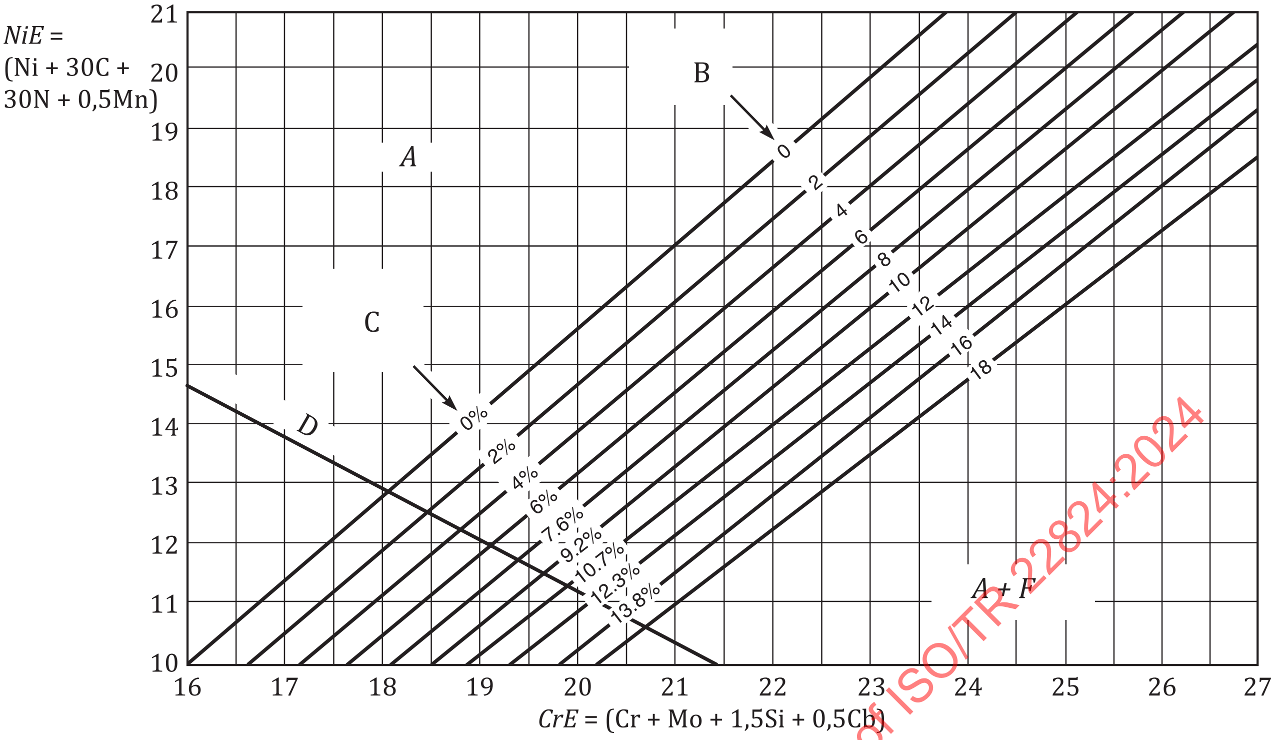


Key

NiE	nickel equivalent
A	austenite
F	ferrite
CrE	chromium equivalent
M	martensite

Figure 3 — Schaeffler Diagram[10]

DeLong led the effort in the USA Welding Research Council to develop a magnetic system for ferrite measurement[11]. This magnetic Ferrite Number measurement system became the AWS A4.2 standard in 1974[12] and was adopted into the ASME Code shortly thereafter. DeLong also developed a revision of the centre portion of the Schaeffler Diagram to address the nominally austenitic stainless steel weld metals to take into account the austenite promoting effect of nitrogen while using the magnetic system of ferrite measurement, resulting in a diagram of more limited range than that of Schaeffler, as shown in Figure 4[13]. Except for the addition of a nitrogen factor in the nickel equivalent, the nickel equivalent and the chromium equivalent of the DeLong Diagram are identical to those of the Schaeffler Diagram, and DeLong retained the martensite boundary as given by Schaeffler. As a result, the DeLong Diagram makes similar prediction errors to those from the Schaeffler Diagram with high manganese weld metals.



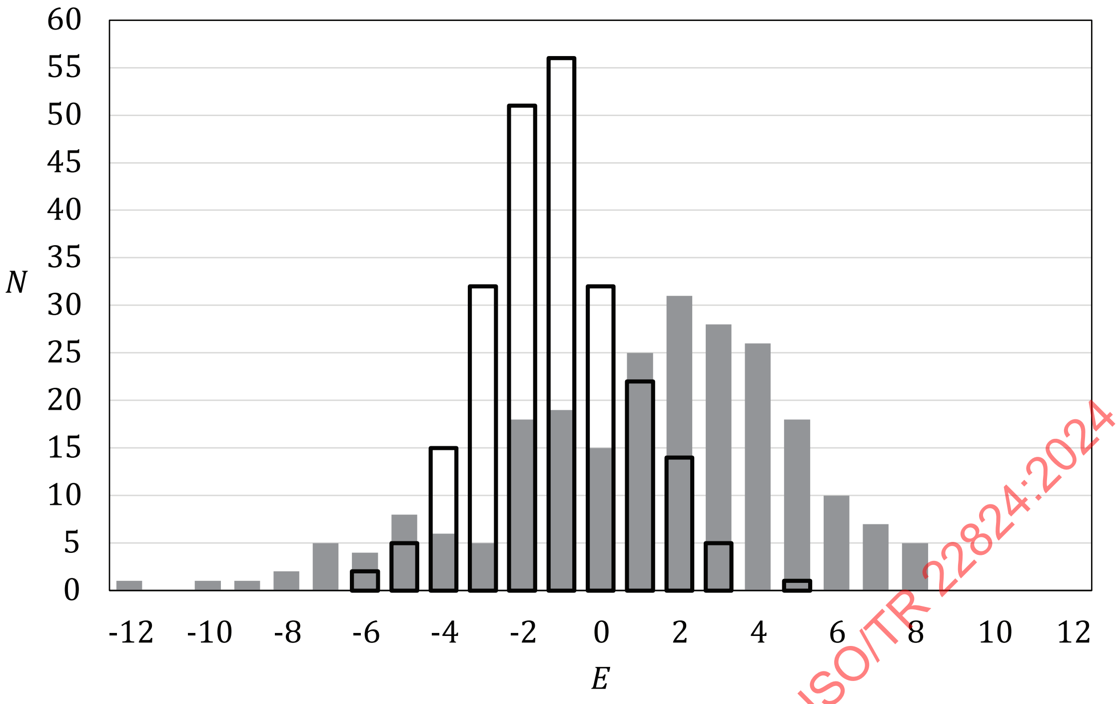
Key

NiE	nickel equivalent	*CrE*	chromium equivalent
A	austenite	B	WRC Ferrite Number
C	prior magnetic percent ferrite	D	Schaeffler A + M line
F	ferrite		

Figure 4 — DeLong Diagram[13]

Under the auspices of the USA Welding Research Council, McCowan et al[14] collected over nine hundred weld metal compositions and corresponding Ferrite Numbers, and applied linear regression analysis and computer mapping to the data to provide revised chromium and nickel equivalents and a revised constitution diagram that became known as the WRC-1988 Diagram because a short form of the report[15] was published before the complete report. This diagram eliminated the shortcoming of the Schaeffler Diagram and the DeLong Diagram with respect to manganese not promoting austenite. It also eliminated the shortcoming of the earlier diagrams with respect to silicon not promoting ferrite, at least up to 1,4 % Si. Further, the WRC-1988 Diagram incorporated the solidification mode data of Suutala[16] to divide the diagram into the four solidification modes (A, AF, FA and F) described earlier. The WRC-1988 Diagram greatly enlarged the range of compositions for which ferrite predictions can be made as compared to that of the DeLong Diagram. The predictions of the WRC-1988 Diagram versus those of the DeLong Diagram over the range of 0 to 18 FN were compared by Kotecki[17] using an independent data set of actual compositions and measured Ferrite Numbers. The errors (measured FN versus predicted FN) were found to be markedly reduced with the WRC-1988 Diagram, as can be seen in Figure 5.

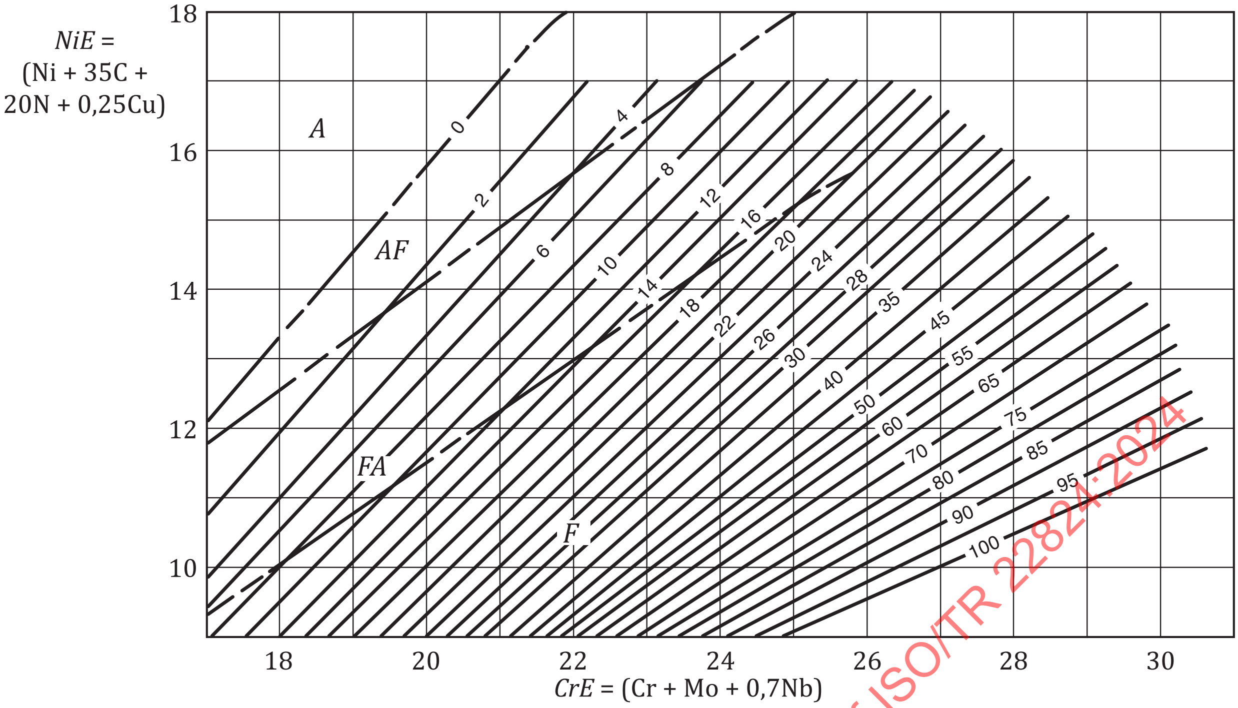
A minor adjustment was made to the WRC-1988 Diagram by Kotecki and Siewert[18] to include a coefficient for copper in the nickel equivalent, and in this form but without the solidification mode boundaries, it was incorporated into the ASME Code to replace the DeLong Diagram in 1994. The WRC-1992 Diagram is shown with the solidification mode boundaries in Figure 6. A more significant modification of the WRC-1992 Diagram was made by Kotecki[19] in adding boundaries below which martensite is predicted to appear in the weld metal. This version of the WRC-1992 Diagram is shown in Figure 7.



Key

N	number of cases within 0,5 FN	*E*	error = measured FN minus calculated FN
■	DeLong	□	WRC

Figure 5 — Comparison of the Measured FN with the FN Predicted by the DeLong Diagram versus the FN Predicted by the WRC-1988 Diagram[17]



Key

NiE	nickel equivalent
A	austenite
AF	austenite/ferrite
CrE	chromium equivalent
FA	ferrite/austenite
F	ferrite

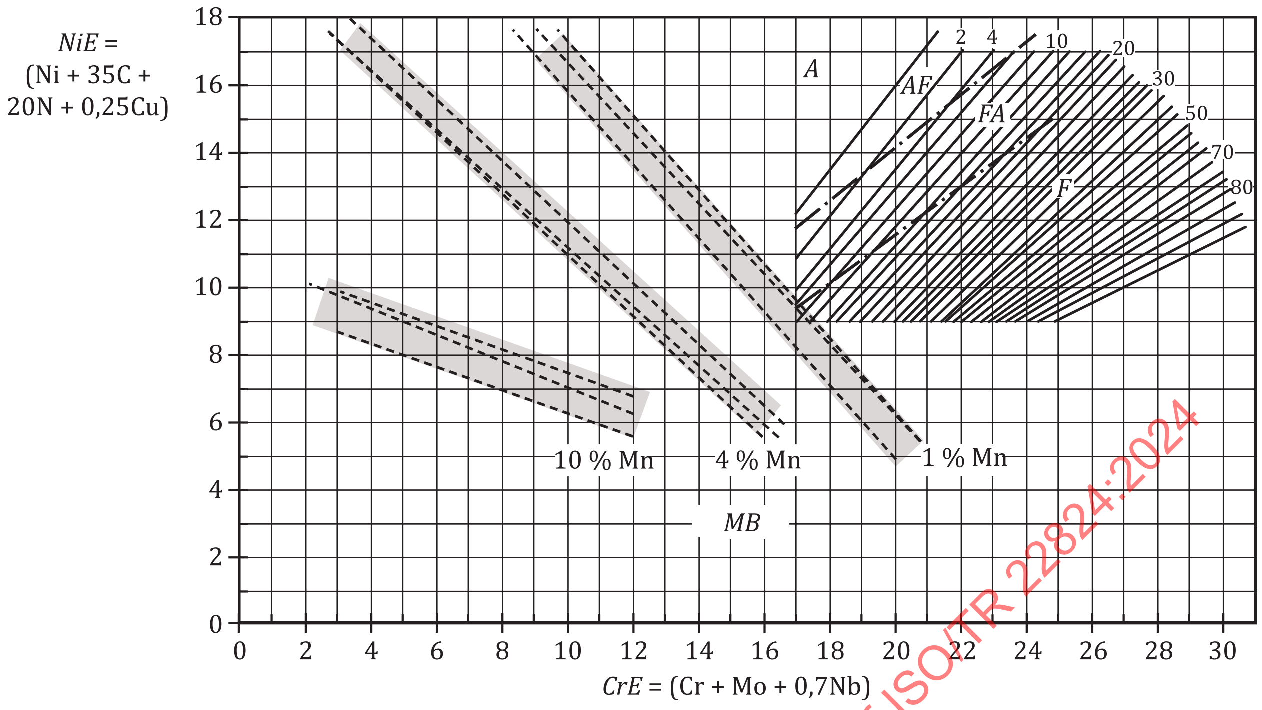
Figure 6 — WRC-1992 Diagram with solidification mode boundaries[18]

Other methods of predicting Ferrite Number in stainless steel weld metals have been developed using neural networks, but they do not lend themselves to visual presentation in the form of a constitution diagram. Vitek et al[20],[21] provided such a neural network online, but it is no longer available online.

4.5 Effects of welding conditions on ferrite

4.5.1 General

There are two ways in which welding conditions can affect weld metal ferrite content. One way is that welding conditions can affect weld metal chemical composition. The second way is that welding conditions can affect the cooling rate through the temperature range in which ferrite transforms in part to austenite.



Key

NiE nickel equivalent

A austenite

AF austenite/ferrite

FA ferrite /austenite

CrE chromium equivalent

F ferrite

MB martensite boundaries

Figure 7 — WRC-1992 Diagram with martensite boundaries for 1 % Mn, 4 % Mn and 10 % Mn[19]

4.5.2 Welding conditions which affect chemical composition

4.5.2.1 Dilution

When the weld metal is diluted by melting of the base metal(s) or by melting of previously deposited weld metal, either or both of which mixes with the molten filler metal, the weld metal will have a different chemical composition from that of the undiluted weld deposit from that filler metal. As a result, the diluted weld metal cannot be expected to contain the same amount of ferrite as the weld metal from the undiluted filler metal. The extent of this change in chemical composition can be estimated by estimating the amount of dilution combined with the composition(s) of the substrate(s) on which the filler metal is deposited and the undiluted composition of the weld metal from the filler metal. This is commonly done on a constitution diagram such as the WRC-1992 Diagram by connecting the two or more compositions by tie-lines and proceeding along the tie-lines in proportion to the estimated amount of dilution. This procedure for estimating ferrite content of diluted weld metal is detailed by Kotecki[22],[23].

4.5.2.2 Without dilution

The most common compositional change that can occur without dilution is pickup or loss of nitrogen from the weld pool. Protection of the welding arc from air incursion is often imperfect. If air enters the welding arc, nitrogen molecules can be disassociated to produce monatomic nitrogen ions which readily dissolve into the weld pool. Since nitrogen is a very strong austenite promoter, nitrogen incursion tends to reduce the weld metal ferrite content as compared to that of more completely shielded weld metal from the same filler metal. Drawing an abnormally long arc with covered electrodes in MMA (SMAW) or disturbance of the shielding gas in gas shielded arc welding are welding conditions which can cause nitrogen incursion and ferrite reduction in the weld metal as compared to properly shielded weld metal. This is explained in more detail by Lefebvre.[24] See also Long and DeLong[13] for effects in GMAW.

Conversely, in the case of filler metal which is designed to contain high nitrogen, loss of nitrogen can occur, particularly when using GTAW (TIG). This mainly affects duplex stainless steel weld metal. Accordingly, shielding gas of argon plus one to three percent nitrogen is commonly used for GTAW and plasma arc welding to prevent formation of excessive ferrite.[25] Root purging with nitrogen or nitrogen-bearing gas is also generally used for this purpose.

4.5.3 Welding conditions which don't affect chemical composition

In stainless steel weld metals which solidify in FA mode, transformation of some part of the ferrite begins almost immediately after solidification is complete, in the vicinity of 1 400 °C under normal weld cooling conditions. Between about 1 400 °C and 1 200 °C, diffusion of both substitutional alloying elements (Cr, Ni, Mo, Nb and others if present) and interstitial alloy elements (C, N) can take place. Figure 1 indicates that some portion of the austenite promoting elements (Ni, C, N and Cu if present) will diffuse from the ferrite towards the austenite, causing the austenite portion of the microstructure to grow. At the same time, some portion of the ferrite promoting elements (Cr, Mo, Nb and others if present) will diffuse from the austenite towards the ferrite. Diffusion of the substitutional alloy elements slows markedly below about 1 200 °C, while the interstitial elements C and N remain mobile to as low as 800 °C.

In stainless steel weld metals which solidify in the F mode, such as duplex alloys, austenite formation generally doesn't begin until about 1 200 °C or even lower, so there is less time for diffusion, and the substitutional alloy elements do not diffuse greatly. Ogawa and Koseki[6] showed that the substitutional alloying elements, especially nickel, scarcely diffuse to any appreciable extent in a 22 % Cr duplex weld metal. Low heat input welding (rapid cooling) can result in very high weld metal ferrite content in such alloys[24].

If the cooling rate is slower through the temperature ranges in which diffusion is appreciable, the alloy elements have more time for diffusion. But if the cooling rate is slower, then solidification is also slower, so that the as-solidified microstructure is coarser and therefore the distances over which the alloy elements must diffuse are greater. As a result, ferrite variation with cooling rate is relatively minor for the cooling rates that accompany most arc welding processes including MMA (SMAW), GTAW (TIG), GMAW (MIG) and even SAW.

Extremely slow cooling rates, as in strip cladding with submerged arc welding or electroslag welding, can produce significantly lower ferrite content than the composition of the weld metal would suggest[24].

Rapid cooling rates in the case of duplex stainless steels, such as during laser welding, laser hybrid welding or resistance welding, can largely prevent significant nitrogen diffusion and result in much higher ferrite content than would be otherwise expected[26],[27].

Extremely rapid cooling rates, as in pulsed laser welding, can dramatically change the solidification mode of weld metals that would normally solidify in FA mode and contain ferrite at ambient temperatures to A mode and contain no ferrite at ambient temperature[28],[29]. The end result can be that compositions which would normally be very resistant to solidification cracking become severely susceptible to solidification cracking.

4.6 Alpha prime and intermetallic phase formation

In addition to ferrite transformation to austenite at high temperatures in stainless steels and weld metals, other phases can precipitate or form within ferrite, and these other phases are generally undesirable. In the temperature range of about 280 °C to about 540 °C, a chromium-rich body-centred cubic phase can form by spinodal decomposition of the ferrite over hundreds to thousands of hours. It forms most rapidly at about 475 °C and seriously embrittles the ferrite, so the embrittlement is commonly referred to as 475 °C embrittlement. Because this chromium-rich phase has the same crystal structure as the ferrite and is generally coherent with the ferrite, it is commonly called alpha prime. This phenomenon is common to ferritic stainless steels, austenitic stainless steel weld metals containing ferrite, and duplex ferritic austenitic stainless steels and weld metals. Alpha prime formation is accompanied also by a marked increase in hardness[30]-[33].

A number of intermetallic phases can also form within ferrite in stainless steels and stainless steel weld metals with long time exposure to elevated temperatures. These intermetallic phases are commonly mentioned lumped together under the term sigma phase which is the most common of these phases. Sigma phase consists of approximately equal amounts of chromium and iron. There are many more phases including chi phase (an iron-chromium-molybdenum phase), R-phase, G-phase, tau-phase and Laves-phase. All of them embrittle the ferrite[34],[35].

Alpha prime and intermetallic phases are not normally found in the as-welded condition of nominally austenitic stainless steel weld metal nor of the lower alloyed duplex stainless steels and weld metals. However, in the 25 % chromium duplex stainless steel weld metals and heat-affected zones, small amounts of intermetallic phases can sometimes be found[34],[35].

4.7 Chromium nitrides and secondary austenite

With falling temperature, nitrogen has very limited solubility in ferrite. This can lead to precipitation of chromium nitrides in duplex stainless steel weld metal and HAZ below about 900 °C if the cooling rate is too rapid to permit the nitrogen to diffuse to austenite areas.[34],[35] Increasing the nitrogen content increases the temperature at which austenite begins to form, which reduces or eliminates nitride formation[6].

Secondary austenite precipitates in duplex stainless steel weld metal when ferrite of a previously deposited weld run is reheated by deposition of a subsequent weld run.[34],[35] This austenite tends to be lower in nitrogen, chromium and molybdenum compared to the composition of the primary austenite that forms at higher temperatures.

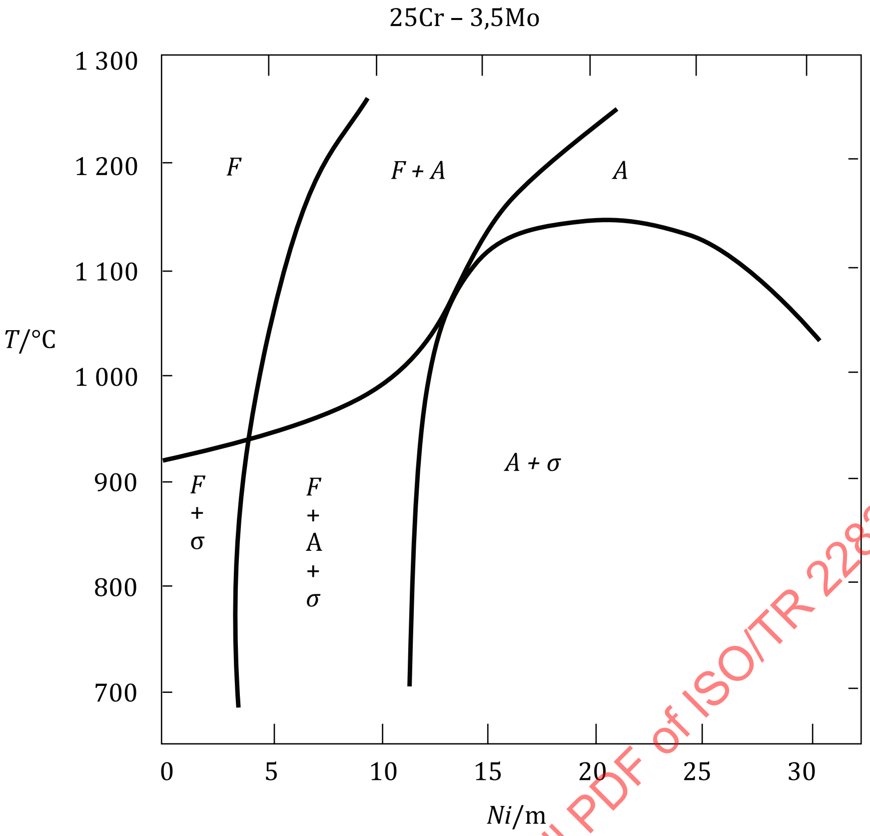
4.8 Postweld heat treatment

As the intermetallic phases form from ferrite at elevated temperatures, the ferrite content is decreased. In 19 9 (308) type weld metals containing normal ferrite content initially, it was found that as little as one hour at 650 °C, 750 °C or 850 °C caused 20 to 40 % of the initial ferrite content to be gone (due mainly to $M_{23}C_6$ precipitation at the original ferrite-austenite interface).[36] Most stainless steel filler metals intended for service where creep is a consideration are not low carbon grades. In these, carbides precipitate at the ferrite/austenite interface with the tendency for the austenite to supply the carbon and the ferrite to supply chromium and other carbide forming elements to the interface. Chromium and other carbide forming elements are generally at higher concentrations in the ferrite than in the austenite, and they diffuse more rapidly in the ferrite. When these carbides precipitate at the ferrite/austenite interface, the result is depletion of these elements in the ferrite adjacent to the original interface and partial transformation of ferrite to austenite in the depleted areas. The overall ferrite content of the weld metal is accordingly decreased. Sigma phase was apparent after 20 h or more. Almost all of the remaining ferrite present had transformed to sigma phase after about 1 000 h. However, the properties of the weld metal were not greatly damaged.

The very lean nominally austenitic filler metal 16 8 2 (16-8-2) can experience sufficient chromium carbide precipitation to raise its martensite start temperature to above ambient temperature.[37] The result can be a false high ferrite measurement because instruments sensing magnetic properties cannot distinguish between ferrite and martensite.

Alpha prime and intermetallic phases form readily in ferrite during high temperature exposure of duplex stainless steels and their weld metals.[34],[35] Both cause serious detrimental effects to mechanical properties and corrosion resistance. This damage is reversible by proper annealing heat treatment with rapid quench from the annealing temperature. Intermetallic phases such as sigma form during heating to the annealing temperature and these need to be dissolved at the annealing temperature. Base metal specifications typically call for annealing of duplex stainless steels at or above 1 020 °C.[38] However, Grobner[39] indicated (see Figure 8) that the maximum temperature at which sigma can be found increases with increasing nickel content in duplex stainless steels. Since welding filler metals for duplex stainless typically contain about 9 % nickel as compared to 4 % to 7 % nickel in the corresponding base metal, this can increase the required minimum temperature for proper annealing of weldments made with filler metal. It has been demonstrated that 2205 type duplex stainless steel weld metal containing 8,3 % Ni contained a large amount of sigma phase after 1 066 °C anneal and required annealing at 1 093 °C to eliminate sigma[40].

As with alpha prime precipitation, intermetallic formation is accompanied by a marked hardness increase in duplex stainless steels[34],[35].



Key

A	austenite	*σ*	sigma
F	ferrite	m	percent by mass

Figure 8 — Increasing maximum temperature at which sigma can be found with increasing nickel content[39]

5 Effects of ferrite variations on service performance of stainless steel weld metal

5.1 General

Nominally austenitic stainless steel weld metals have useful engineering properties over a very broad range of service temperatures, from as low as −269 °C to as high as 900 °C or more. Duplex ferritic-austenitic stainless steel weld metals have useful engineering properties over a much narrower temperature range, from as low as −50 °C to as high as 280 °C or somewhat higher. Ferrite is considered for its effects on weld metal properties within these temperature ranges.

In nominally austenitic stainless steel weld metals, over the range of compositions that solidify in the AF and FA modes, a change in ferrite content can be caused by a change in composition within the specification range for the classification (e.g., by introduction of another heat or lot of filler metal or by gain or loss of nitrogen due to welding conditions), by a change in composition due to dilution from the substrate, by a large change in cooling rate from solidification temperature, or by a reheat cycle (e.g., in the weld metal that becomes the high temperature HAZ of a subsequent weld deposit or due to a postweld heat treatment). In duplex ferritic-austenitic stainless steel weld metals, which solidify in F mode, the same factors can cause similar changes in ferrite content, except that there is more sensitivity to smaller cooling rate changes from solidification temperature, particularly if the nitrogen content of the metal is towards the low end of the specification range.

5.2 Tensile properties at ambient temperatures

In nominally austenitic stainless steel weld metals, an increase in ferrite content caused by composition changes or by cooling rate changes is generally accompanied by a modest increase in tensile and yield strength, and by a modest decrease in tensile elongation and reduction in area. A minor exception to this general behaviour is if the reduction in ferrite is caused by an increase in the interstitial elements carbon and/or nitrogen. Carbon and nitrogen tend to increase tensile and yield strength which can more than offset the effect of the reduction in ferrite. Overall, these effects of changes in ferrite content are generally minor and can generally be ignored because the weld metal properties will exceed specification requirements.

In duplex ferritic-austenitic stainless steel weld metals, tensile properties are little affected by ferrite changes caused by composition changes so long as the ferrite content does not exceed commonly specified maximum limits.[41] These limits will be considered in more detail later. Ferrite content due to high cooling rates from solidification temperature can exceed specified maximum limits and can cause serious reduction in tensile elongation and reduction of area. For example, the high cooling rates of resistance spot welds tend to result in very high ferrite contents, with chromium nitride precipitation within the ferrite.[27] The same is true of laser welds[42].

In nominally austenitic stainless steel weld metals, annealing heat treatments generally reduce ferrite content and reduce tensile and yield strength as compared to the as-welded condition, but increase tensile elongation and reduction in area. In general, this effect is not important because the weld metal strength still exceeds the corresponding base metal requirements.

In duplex ferritic-austenitic stainless steel weld metals, proper annealing might reduce ferrite content, but it invariably reduces tensile strength and yield strength.[40] This strength reduction appears to be due to partial spheroidization of the microstructure. It can be significant when welds are made in castings that are subsequently annealed.

5.3 Toughness

In general, as ferrite increases in nominally austenitic stainless steel weld metals, toughness as measured by Charpy V-notch testing at a given temperature tends to decrease, other factors being equal. Both oxygen and nitrogen are detrimental to toughness, particularly at cryogenic temperatures,[43],[44] therefore any investigation of toughness must take these factors into account. In particular, increasing nitrogen in nominally austenitic stainless steel weld metal in an effort to reduce ferrite is likely to prove counterproductive as regards toughness.

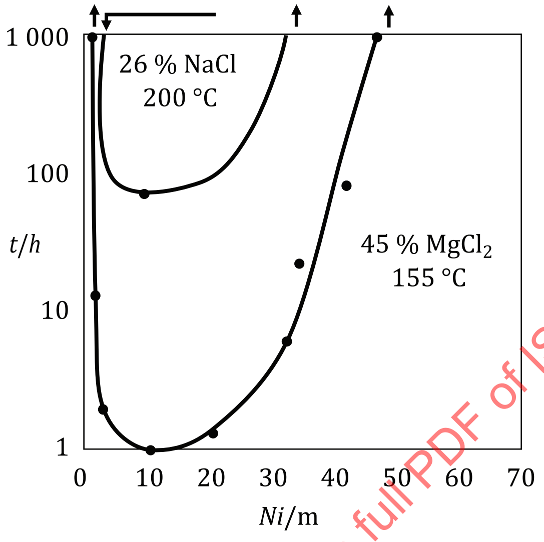
In duplex ferritic-austenitic stainless steel weld metals, increasing ferrite is also generally detrimental to toughness at temperatures such as -40 °C[41]. Ferrite content near the lower end of the normally specified range becomes especially necessary for meeting toughness requirements when the filler metal is flux shielded (manual metal arc, flux cored arc and submerged arc welding) because the relatively high oxygen content of the weld metal, as compared to that of inert gas shielded weld metal, has a negative effect on toughness that generally needs to be offset by lower ferrite content. Although service temperatures for duplex stainless steels are seldom as low as -40 °C, toughness testing at -40 °C or even -46 °C is sometimes used to assess whether embrittlement due to precipitation of intermetallic compounds has occurred[34],[35].

5.4 Resistance to chloride stress corrosion cracking (CSCC)

The nominally austenitic stainless steels and their matching weld metals that can contain ferrite are not considered suitable for service in environments that require resistance to CSCC.[45] These steels and weld metals fall in the range of austenitic stainless steel nickel contents that is most susceptible to CSCC, as indicated by the well-known Copson curves shown in Figure 9[46].

On the other hand, the ferritic stainless steels and the duplex ferritic-austenitic stainless steels have useful resistance to CSCC.[45] Over the range of ferrite requirements normally specified, there appears to be no information concerning the effect of the ferrite content on CSCC resistance. In duplex stainless steels, a ferrite content above the normally specified range is detrimental both to mechanical properties and corrosion resistance.[49] Of more interest is the effect of ferrite content below the range normally specified. The American Petroleum Institute allows ferrite content as low as 25 % if corrosion and other tests are satisfactory to the purchaser[48].

There are two somewhat contradictory reports of studies of low ferrite content. Both used covered electrodes of varying nickel content, based upon a 22 9 3 N L (2209) composition, to vary the ferrite content of the weld metal. A 1993 study examined CSCC in boiling 44 % $MgCl_2$, in 40 % $CaCl_2$ at 100 °C, in the "Wick Test", and in simulated evaporated seawater.[49] In the highest nickel weld (14,8 %, ferrite content not given), CSCC was observed in boiling 44 % $MgCl_2$, and pitting was observed in the lower nickel welds. No mechanical properties of the weld metals were reported. A 2019 report of a study of 22 % Cr duplex stainless steel weld metal in which nickel content was used to vary the ferrite content showed that specified base metal mechanical properties and acceptable CSCC resistance in boiling 26 % NaCl were met at as low as 14 % ferrite or 20 FN.[50] No similar information is available on other duplex stainless steel alloy weld metals. The matter of an appropriate minimum ferrite requirement for CSCC resistance is unsettled.



Key

t	time to cracking
m	percent by mass

Figure 9 — Copson curves of CSCC susceptibility of austenitic stainless steels[46]

5.5 Susceptibility to corrosion in certain media

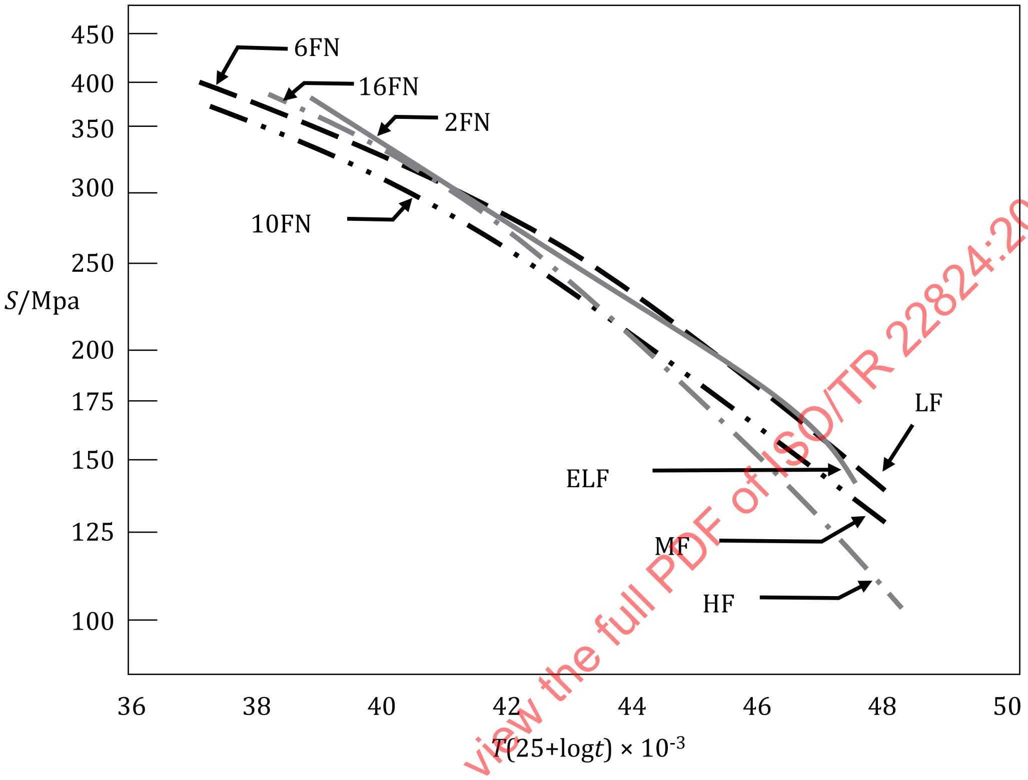
In general, the presence of ferrite in a stainless steel weld metal is not detrimental to corrosion resistance. However, in certain special media where nominally austenitic stainless steel weld metals are used, ferrite can be aggressively attacked. Probably the best known example arises in the manufacture of urea.[24] It is then necessary to specify very low ferrite limits (A or AF solidification mode) and design the weld metal to provide acceptable solidification cracking resistance as well as acceptable corrosion resistance. A filler metal composition such as 20 16 3 Mn N L (316LMn) might be selected for this type of application. A duplex stainless steel base metal and filler metal would clearly be inappropriate for such service.

5.6 Creep resistance

At high temperatures (approximately 480 °C and up), slow plastic deformation (creep) takes place in stainless steel base metal and stainless steel weld metal over extended time periods (often many thousands of hours) when subjected to stresses below the short time yield strength of the metal. In service at these temperatures, a number of transformations take place within the ferrite or at the ferrite/austenite interface, as discussed in 4.6. Service under creep loading tends to accelerate these transformations. The design life of nominally austenitic stainless steel weld metal under creep conditions can range from a few minutes, as in a rocket motor case, to thirty years or more, as in a power generation plant.

The effect of ferrite content in 19 9 (308) MMA (SMA) weld metal on creep and stress rupture properties has been investigated.[51] Weld metals of 2 FN, 6 FN and 10 FN were found to behave similarly, while 16 FN weld metal performance was somewhat inferior, as can be seen in Figure 10. Sigma phase was found in the tested samples of all but the 2 FN weld metal. Oddly, rupture elongation was lower for the 2 FN and 16 FN weld metals than for the 6 FN and 10 FN weld metals. Since the 2 FN weld metal likely solidified as AF mode, perhaps the lower elongation was due to the presence of microfissures, but that is not stated in the report. Small amounts of sigma phase appear to not affect the creep properties of the lower FN weld metals, but the 16 FN weld metal was adversely affected.

Duplex ferritic-austenitic stainless steels and their corresponding weld metals are not appropriate for service under creep conditions.



Key

S	stress	LF	low ferrite
T	temperature	ELF	extra low ferrite phase
t	time	MF	medium ferrite
FN	Ferrite Number	HF	high ferrite

Figure 10 — Larson-Miller comparison of stress-rupture properties of 19 9 (308) weld metal[51]

6 Measurement of ferrite in stainless steel weld metal

6.1 General

The presence of ferrite in nominally austenitic and duplex ferritic-austenitic stainless steel weld metals can be detected and, to a certain extent, measured by several methods. These include metallographic means (point counting, linear intercept analysis, quantitative television microscope, comparison with atlas), x-ray diffraction, Mössbauer effect, saturation magnetization, magnetic permeability, and magnetic attractive force[52],[53]. More recently, electron backscattered diffraction (EBSD) has arisen as a laboratory tool for ferrite measurement.[54] Of these methods, metallographic methods, magnetic permeability, saturation magnetization and magnetic attractive force are used in industry. Saturation magnetization, as practiced in Russia and some other parts of eastern Europe, uses a cylinder machined from the weld metal. The methods most used in industry outside Russia and eastern Europe seem to be metallographic means and instruments based on magnetic permeability or magnetic attractive force. Constitution Diagrams (Schaeffler Diagram, DeLong Diagram, WRC-1988 and WRC-1992 Diagrams) are sometimes considered measurements, but they are actually predictions, somewhat akin to weather forecasts, rather than measurements.

6.2 Considerations in ferrite measurement

The following considerations need to be kept in mind when making ferrite measurements, and especially in comparing ferrite measurements from different sources and/or from different measuring methods or instruments.

a) Ferrite in a stainless steel weld metal is non-uniformly distributed even in a single weld run.

b) In a multi-run weld deposit of nominally austenitic or duplex stainless steel weld metal, each succeeding run reheats and therefore partially anneals the substrate weld metal, generally causing a reduction of ferrite in the reheated weld metal, at least in the reheated weld metal close to the fusion boundary.

c) Different measurement methods sense different volumes of weld metal. An instrument measuring by magnetic permeability does not normally sense the same volume of weld metal as does an instrument measuring by magnetic attractive force. And magnets of different size and/or strength sense different volumes of weld metal.

d) For magnetic permeability measurements and magnetic attractive force measurements, the quality of the surface preparation influences the measurement. A rough surface can produce false low results, while a cold-worked surface can produce false high results if martensite forms during cold-work.

e) Instruments measuring by magnetic attractive force or magnetic permeability cannot distinguish between ferrite and martensite since both phases are ferromagnetic.

f) The heat-affected zone of a weld is generally too small for ferrite content to be measured reliably by an instrument measuring by magnetic permeability or by magnetic attractive force. The same applies to the weld metal of narrow laser and electron beam welds.

g) Metallographic ferrite measurements are critically dependent upon the precision and consistency of the etching procedure and on interpretation of the contrast distinction between ferrite and austenite. The quality increases with freshly polished surfaces, recently mixed etchants, taping off areas of no interest with an adhesive tape and examining welds directly or after storing in air-free environment.

h) It is generally assumed that area measurements on a two-dimensional image are equal to the three-dimensional (volumetric) ferrite percent. In reality, the validity of this assumption, depends, to a certain extent, upon the homogeneity of the ferrite distribution.

i) Metallographic measurements and saturation magnetization measurements are destructive tests.

6.3 Metallographic percent ferrite by optical methods

Originally, measurements were done by polishing and etching, then counting the fraction of the image that corresponds to ferrite. This is a destructive test and is still used extensively by industry. Standard methods today include point counting according to ASTM E562[55] and automatic image analysis according to ASTM E1245.[56] For these methods to produce accurate and reproducible measurements of percent ferrite, it is essential that the etching produce complete optical contrast between ferrite and austenite. Over-etching broadens the interface between the two phases and thereby results in one or the other phase being over-counted. Under-etching leaves one (or both) phases without optical contrast and thereby results in under-counting of the phase. Failure to obtain consistent and complete optical contrast between the two phases seems to be responsible for generally poor reproducibility of measurement in round robin tests. For example, a round robin among five laboratories in the USA reported measurements on a single sample ranging from 5,9 % to 11,6 % ferrite, average 9,0 %[52].

In a much more recent round robin, Hosseini et al.[54] evaluated various etchants and procedures for obtaining complete optical contrast between ferrite and austenite in 25 % Cr super duplex stainless steel weld metal. They settled on a particular etch and procedure, and generated a round robin of weld metal ferrite measurements among four laboratories that seemed reproducible. However, heat affected zone measurements were substantially less reproducible.

It seems clear that metallographic measurements by optical methods are capable of providing reproducible results provided that careful attention is paid to the etching procedure to obtain uniform optical contrast between ferrite and austenite without broadening the interface between phases. Image analysis dominates duplex stainless steel welding procedure qualifications in Europe.

6.4 Metallographic measurement of ferrite by EBSD

Metallographic measurement by EBSD avoids the etching problem of metallographic measurement by optical methods. The sample is polished but not etched. For the highest quality, the polishing procedure would result in completely deformation-free surfaces. This can require an extra vibrational polishing step using colloidal silica. A scanning electron microscope (SEM) with EBSD capability produces a map contrasting ferrite with austenite that is free of the problems with etching uniformity, under-etching and over-etching.[54] Automatic image analysis software then calculates the ferrite percent. This method seems capable of measuring percent ferrite accurately. However, at this time it is not widely used in industry, mainly due to the high investment costs of the instrument. It is also a destructive test.

6.5 Ferrite measurement by x-ray diffraction

Measurement by x-ray diffraction has been evaluated and found to be unsuitable due to the highly textured crystal structure of the weld metal[52],[53],[57].

6.6 Ferrite measurement by electrochemical dissolution of austenite

Gill et al.[58] used selective electrochemical dissolution of austenite, with gravimetric measurements, to estimate ferrite in 18 12 3 (316) weld metal. The method is very time-consuming and it is not possible to ascertain that all and only austenite was dissolved. The method is a destructive test and has not been used by industry.

6.7 Ferrite measurement by saturation magnetization

Ferrite measurement as a volumetric percent determined by saturation magnetization is the standard method used in Russia and many other countries of the former Soviet Union[59]. It is a destructive test. Apparently both 4,0 mm diameter[60] and 5,0 mm diameter[61] by 60 mm specimen length have been used for weld metal testing. Depending upon the weld run size and the position of the centre of the cylindrical sample in the weldment, this cylindrical sample might or might not include reheated weld metal of reduced ferrite content. The intensity of saturation magnetization of ferrite ($4\pi I_\delta$), in units of Tesla, is a function of the composition of the ferrite, as given by Formula (1)[62]:

$$4\pi I_\delta = 2{,}1 - 0{,}027\,5\ \%\mathrm{Cr} - 0{,}033\,0\ \%\mathrm{Ni} - 0{,}026\,0\ \%\mathrm{Mo} - 0{,}067\,0\ \%\ \mathrm{Ti} - 0{,}061\,0\ \%\mathrm{Si} - 0{,}063\,0\ \%\mathrm{Al} - 0{,}060\,0\ \%\mathrm{V} - 0{,}028\,0\ \%\mathrm{Mn} \qquad (1)$$

Formula (1) indicates that all alloy elements considered diminish the saturation magnetization of the ferrite. It is necessary to know the ferrite composition as well as to measure the saturation magnetization of the ferrite-containing weld metal ($4\pi I$) to arrive at the ferrite content of the weld metal using Formula (2) below:

$$\%\ F = 100\ (4\pi I / 4\pi I_\delta) \qquad (2)$$

Where $\%F$ is percent ferrite

Another saturation magnetization approach, a vibrating sample magnetometer (VSM), has been used experimentally to measure percent ferrite content of very small (0,5 mm by 3 mm by 3 mm) melt spun ribbons[63]. There is no known standard applicable to this method.

6.8 Ferrite measurement by magnetic attraction

A proprietary instrument for measuring ferrite in nominally austenitic stainless steel weld metal by magnetic attraction dates from 1956 according to Severn Engineering Company. A USA national standard based on magnetic attraction measurements was first published in 1974[64]. This method later became the basis of ISO 8249[1], the international standard for ferrite determination.

ISO 8249[1] provides the procedure for calibrating instruments based upon measuring the attractive force of a magnet to arrive at the ferrite content of a weld sample. Primary calibration employs a magnet of specified geometry. The attractive force (sometimes called the "tearing-off force") is converted to an arbitrary Ferrite Number according to a table or equation in the standard. The Ferrite Number is defined by the thicknesses of non-magnetic coatings over a low carbon steel. Sets of such coating thickness standards are available from the US National Institute of Standards and Technology (NIST). The calibration is a straight line. The standard magnet can be used with a laboratory beam balance to measure attractive force directly, or it can be part of an instrument such as a Magne-Gage (of USA origin).

A critical element of the calibration is the strength of the standard magnet which is required to be 5,0 FN/g (±0,5 FN/g). After the calibration line has been established with the coating thickness standards, the magnet strength requirement is easily checked by hanging a ferro-magnetic weight of about 5 g from the magnet and determining the FN from the calibration line that corresponds when the instrument barely lifts the weight. If the magnet is found to be weaker than allowed (i.e., producing a relationship that is more than 5,5 FN/g), experience has shown that false high FNs will be found[65]. Conversely, false low FNs will be found when measuring weld metal with a magnet stronger than allowed (i.e., producing a relationship that is less than 4,5 FN/g).

Calibration for FN measurements of instruments using magnets other than the defined magnet of ISO 8249[1], or of instruments using a principle other than magnetic attraction (such as magnetic permeability), is provided for in ISO 8249[1] by the use of secondary standards which have a weld-metal-like microstructure. Ferrite Numbers are initially assigned to secondary standards by instruments that are calibrated with the primary standards (coating thickness standards). Such secondary standards have been sold in the past by Teledyne McKay in the USA and later by TWI in the United Kingdom. They are currently available for sale by NIST in the USA. It is a requirement of ISO 8249[1] that the calibration of an instrument be checked regularly before using it for measurements. It is known that the standard magnet strength can be affected by close proximity to another magnet or by mechanical shock. So primary standards (coating thickness standards) or secondary standards must be readily available to ensure correct measurements of FN according to ISO 8249[1].

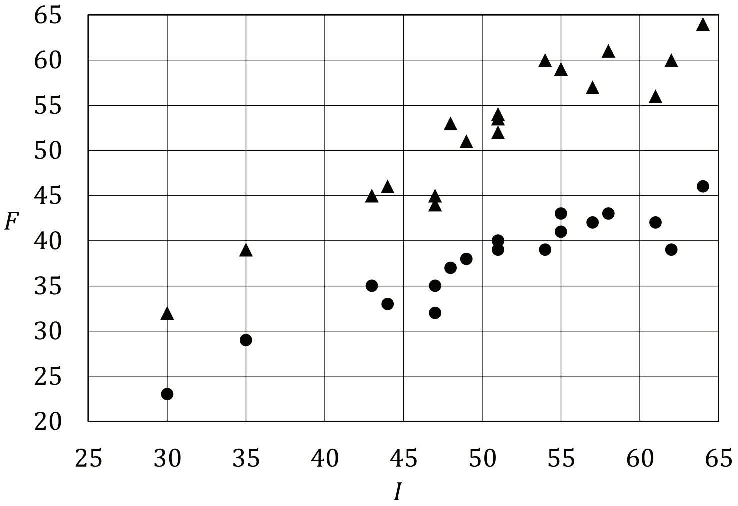
Measurement of Ferrite Numbers according to ISO 8249[1] is required to be done along the smoothed flat top centreline of a weld run in order to characterize that weld run. If the surface is not smoothed flat, false low FN readings will result. Smoothness becomes more critical when measuring high FNs such as on duplex ferritic-austenitic stainless steel weld metals. In smoothing the surface (filing, grinding or polishing), cold work must be avoided because it can induce martensite formation, especially in lower alloyed austenitic stainless steel weld metals. Since martensite is ferro-magnetic as is ferrite, the presence of martensite causes false high Ferrite Numbers to be obtained.

This method is non-destructive and is extensively used by industry in North America, but little or not at all in Europe.

6.9 Measurement by magnetic permeability (magnetic induction)

Commercial instruments using this method of measuring ferrite apply a pulse of electric current through a coil with a ferromagnetic core in contact with the material under test, or a pulse of electric current through the material under test, and evaluate the magnetic response of the material under test. Instruments can be obtained to provide results in Ferrite Number or in ferrite percent, depending upon calibration. The primary standards (coating thickness standards) provided by NIST are generally not applicable for calibration of these instruments. Secondary standards must be readily available for regular checking of calibration of any given instrument according to ISO 8249[1]. Figure 11[57] illustrates results when secondary standards are and are not used to check calibration. This method can be non-destructive if used on the top surface of a weld rather than on a cross-section, and is extensively used by industry.

Note that the calibration standards provided by the magnetic permeability instrument manufacturer are not always stainless steel.[66] In the case cited, the instrument manufacturer's calibration proved to be incorrect. This observation agrees with the finding shown in Figure 11.[57] Calibration checks using secondary standards of well-established ferrite content are essential to verify the calibration of such an instrument.



Key

F	fisher calibration samples	I	IIW secondary standard

Method

1 horizontal axis using TWI standards

2 vertical axis: Fisher set prior to the secondary TWI standards: (circles)

3 vertical axis: Fisher set posterior to the secondary TWI standards (triangles)

Figure 11 — Comparison of FN measurements using a MP30 Feritscope calibrated using three methods[57]

6.10 Location and volume of measurement

ISO 8249[1] is very specific about making FN measurements along the smoothed flat top centreline of a weld run. This is practical because it is non-destructive – the material on which the measurement is made can be put into service. Since it is known that ferrite distribution in a weld is not homogeneous, more so in a multi-run weld, location of measurement is a significant concern. Metallographic measurements of percent ferrite as reported in the literature are generally made on a cross-section of a weld, so these latter measurements don't necessarily correspond to measurements of FN according to ISO 8249.[1] Measurements made by instruments using magnetic permeability (magnetic inductance) principles, especially if reporting results as ferrite percent, are sometimes made on a cross-section of the weld.

ISO 8249[1] is also specific in requiring a minimum of six locations along a weld run centreline to be measured and then averaged to provide the FN for the weld run.

The volume of weld metal sensed by an instrument measuring magnetic attraction force depends upon the size and strength of the magnet. The volume of weld metal sensed by the standard magnet of ISO 8249[1] is on the order of a few cubic mm. The volume of weld metal sensed by an instrument based on magnetic permeability (magnetic inductance) principles seems to be similarly on the order of a few cubic mm. Metallographic measurements each consider one square mm or less, so many areas are usually measured to reach an average value. Measurements made by saturation magnetization according to GOST 26364[61] sense a volume of several hundred cubic mm, much larger than that of any of the other methods described above. Measurements made by saturation magnetization using a VSM[63] sense a volume of about 5 cubic mm. These points must be kept in mind when selecting a measurement method and especially in drawing conclusions about results from one method as compared to results of another method.

The effect of weld size or volume, and proximity to a ferro-magnetic substrate, on ferrite measurement using two instruments with permanent magnets was examined by Gittos[67]. Cylinders of various diameters were machined from SAW weld metal and embedded in non-magnetic plastic mount or placed in snug fitting holes in ferro-magnetic carbon steel. A collar was used with the Magne-Gage to place the magnet precisely on the centre of the cylinder surface. Cylinders smaller than 12 mm diameter were found to produce reduced Ferrite Numbers on plastic mounted cylinders and inflated Ferrite Numbers on carbon steel mounted cylinders. This is a more severe condition than making measurements of weld metals of varying width in which the weld metal is essentially infinitely long in two directions and is limited only in width. Both a Magne-Gage and an Elcometer Inspector Gauge were used to make Ferrite Number measurements on stacks of 23 12 Nb (309Nb), 19 9 Nb (347) and Ni 6082 (NiCr-3) strips 0,5 mm in thickness over carbon steel. Similar results were obtained with both instruments. About 5 mm of strip thickness was required to make the result insensitive to the carbon steel presence under the strips.

6.11 Measurement in the HAZ

Ferrite measurement in the HAZ of welds in duplex stainless steels has been of concern because the rapid cooling rates of common welding processes tend to result in considerably more ferrite in a thin layer of the HAZ immediately adjacent to the fusion boundary than is present in the base metal. This thin layer of the HAZ is on the order of 10 microns in width. Due to its small width, measurement by any method described above, except for metallographic measurement, is unsuitable. The ferrite content in this region is of importance because excessive ferrite, if present at the surface exposed to the corrodent, can result in poor corrosion resistance and poor toughness. Ferrite measurements in portions of the HAZ of duplex stainless steel welds heated to peak temperatures close to but below the austenite solvus temperature can detect small decreases in ferrite content.

Ferrite measurements in the HAZ of nominally austenitic stainless steels, as in the case of duplex stainless steels, are only possible by metallographic methods. Metallography can detect a small amount of ferrite in the portion of the HAZ closest to the fusion boundary. This ferrite is generally of no consequence.

6.12 Reproducibility of measurement

If a specification is to be written requiring a selected range of ferrite content in a weld, the reproducibility of measurement by any applicable method has to be taken into account. For this discussion, reproducibility means the confidence interval that is obtained when several agents make measurements independently. These agents can include any or all of the following: a filler metal producer, a certification body, a fabricator, a master contractor, an insurance company and a regulatory body. There could be others involved.

The reproducibility of Ferrite Number measurements made according to ISO 8249[1] has been extensively studied by IIW Commission II. Several round robins of measurement were conducted, using both magnetic attraction and magnetic permeability methods. The most recent of these is that led by Farrar,[68] consisting of 17 participating laboratories in 8 countries. The results of these round robins indicate that the reproducibility (scatter) of measurement for all-weld metal pads (as might be produced for certifying a batch of filler metal) is plus or minus 10 % around the mean value. On groove welds as might be made in production, the scatter was greater, about plus or minus 20 % around the mean value.

In contrast to the many round robins conducted on the method of ISO 8249,[1] there are few round robins of other methods, and they involve significantly smaller numbers of participants. An early round robin, with five participants, of metallographic ferrite measurements in nominally austenitic stainless steel weld metals found scatter of about plus or minus 30 % of the mean value.[52] Much more recently, a round robin, with four participants, of metallographic measurements in duplex ferritic-austenitic stainless steel weld metal found scatter of only about plus or minus 4 % of the mean value[54].

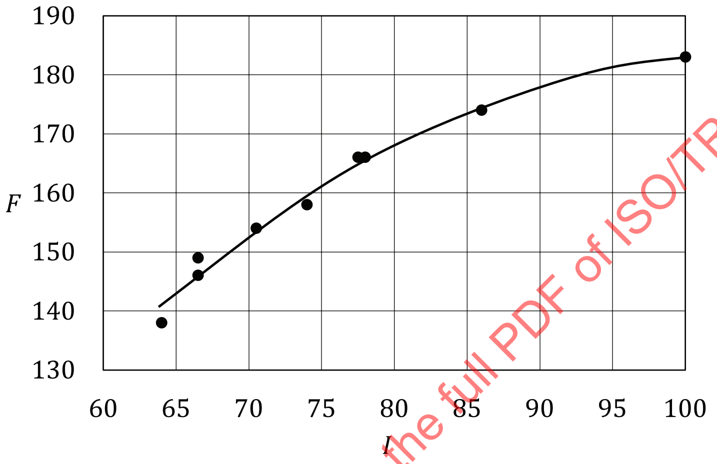
Round robins of ferrite measurements by saturation magnetization are unknown.

6.13 Correlations between Ferrite Number and ferrite percent

The magnetic properties of ferrite depend upon the chemical composition of the ferrite. Both saturation magnetization,[62] as shown by Formula (1), and Ferrite Number measurements on 100 % ferrite steels (see Figure 12[69]) demonstrate this. Consequently, a simple relationship between Ferrite Number and ferrite percent cannot be expected, and ferrite percent measurements from instruments purportedly calibrated in ferrite percent, without a correction for ferrite chemical composition, must be viewed with scepticism.

On the other hand, Ferrite Numbers are independent of ferrite chemical composition. This means that the engineering significance of a given Ferrite Number needs to be considered in view of the chemical composition of the alloy under consideration.

Various conversion factors from Ferrite Number to ferrite percent have been proposed. Figure 12 can provide estimates of conversions when ferrite composition is taken into account. To use Figure 12, one must know the iron content of the ferrite in the weld metal of interest. In weld metals that solidify in the FA mode, austenite and ferrite can coexist at temperatures high enough for diffusion of alloy elements to take place. Lyman[5] investigated the composition of the austenite and the ferrite in autogenous 19 10 L (304L) type GTA weld metal and found that the ferrite contained about 26 % Cr versus about 18 % in austenite, and about 4 % Ni in the ferrite versus about 12 % Ni in the austenite. This leads to the conclusion that the iron content of the ferrite in such weld metal can be taken, to a first approximation, as the overall iron content of the alloy. In alloys which solidify in the F mode (duplex ferritic-austenitic stainless steel weld metals), very little diffusion of elements other than nitrogen can take place in the as-welded condition[6], which again leads to the conclusion that, to a first approximation, the iron content of the ferrite can be taken as the overall iron content of the alloy. Conversions using Figure 12 can be compared to conversions found in the literature[54],[62],[70],[71] which might or might not take ferrite composition into account. Some conversions are shown for comparison in Table 1. No consistent pattern of conversion is evident.



Key

F fisher calibration samples

I IIW secondary standard

Figure 12 — Ferrite Number of 100 % ferrite steels as a function of iron content[69]

Table 1 — Relationships proposed between Ferrite Number (FN) and ferrite percent (FP)

Weld Metal Type	Ferrite percent method	Relationship	Bibliography Reference
19 9 (308)	Saturation Magnetization	FN = 1,70 FP	[62]
19 9 (308)	Figure 12	FN = 1,55 FP	[69]
22 9 3 N L (2209)	Metallography	FN = 1,67 FP – 10	[71]
22 9 3 N L (2209)	Figure 12	FN = 1,42 FP	[69]
22 9 3 N L (2209)	Metallography	FN = 1,69 FP – 7,6	[71]
22 9 3 N L (2209)	Metallography	FN = 1,18 FP	[74]
25 9 4 N L (2594)	Metallography	FN = 1,1 FP	[54]
25 9 4 N L (2594)	Figure 12	FN = 1,3 FP	[69]

7 Specification of ferrite in stainless steel weld metal

7.1 General

When ferrite content limits are to be imposed on filler metals in a purchase order, or on weldments via contract documents, it is essential that the method of measurement be specified and that the limits be both necessary for the intended application and realistic in view of the reproducibility of measurement. Failure to adhere to these principles in specifications can result in needless expenses and delays in completion of a weldment. It is therefore appropriate to consider what limits are necessary and realistic for various weldments.

Because it is non-destructive and because of its well-established reproducibility of measurement, the method of ISO 8249[1] is used when applicable. The WRC-1992 Diagram (see Figure 6) is useful for predicting the ferrite content of weld metal, but it cannot replace measurement by ISO 8249[1] for providing a high degree of assurance that weld metal properties will be as desired.

Guidance based on experience for appropriate weld metal (and HAZ where of concern) ferrite content follow.

7.2 Non-magnetic requirements

In weldments requiring non-magnetic weld metal, such as in magnetic resonance imaging (MRI) equipment, weld metal with as near as possible to 0 FN are desired. A filler metal providing Type A solidification mode (see Figure 6) would normally be used. The weld metal can be susceptible to solidification cracking, so that tighter than normal restriction of P and S impurities, greater than normal Mn content, and/or low heat input welding procedures promoting convex weld profile can be helpful towards preventing solidification cracking. It is not possible to reproducibly measure 0 FN with instruments calibrated according to ISO 8249.[1] The raw data from the round robin of ferrite measurements is not shown in the Farrar report cited earlier,[68] but can be found as an IIW Commission II document.[72] The study included a weldment produced with a “nil ferrite” type 18 15 3 L filler metal. Of the 15 laboratories measuring ferrite on that weldment, 13 reported 0 FN, but two reported non-zero FN ≤ 0,2. While Ferrite Number measurements can have some applicability for a non-magnetic requirement, more appropriate can be an acceptance criterion of magnetic permeability (μ) less than or equal to 1,01[24].

7.3 Service environments in which ferrite is aggressively attacked

Certain corrosive environments aggressively attack ferrite, for example, environments found in the manufacture of urea. For successful service in such environments, any ferrite, if present must be discontinuous. A filler metal providing Type A solidification mode (see Figure 6) would normally be required. The same restrictions on composition and/or welding procedure mentioned in 7.1 would again be used. Limitation of ferrite content to FN ≤ 0,5 is the guideline.

7.4 Cryogenic applications requiring weld metal toughness

A typical requirement is 0,38 mm lateral expansion, minimum, in a Charpy V-notch test at -196 °C. Ferrite is detrimental to toughness at cryogenic temperatures so that some limitation of maximum ferrite content is necessary. However, weld metal oxygen and nitrogen content also have detrimental effects on toughness so that a single blanket ferrite range is not the guideline. It is usually desirable to obtain Type FA solidification mode for freedom from solidification cracking concerns.

Desire for low ferrite and for Type FA solidification mode are somewhat conflicting concerns. The inert gas shielded welding processes GMAW and GTAW offer the most freedom in specifying weld metal ferrite content. Ferrite contents of 10 FN or even higher have been shown to provide cryogenic toughness of 0,38 mm lateral expansion with 19 9 L (308L), 19 9 L Si (308LSi), 19 12 3 L (316L) and 19 12 3 L Si (316LSi) filler metals. At the same time, the 19 9 L and 19 9 L Si filler metals provide FA solidification generally at or above 3 FN, while the 19 12 3 L and 19 12 3 L Si filler metals provide FA solidification above 4 FN. Therefore, specification of 3 to 10 FN or 4 to 10 FN, respectively, is workable and realistic for GTAW and GMAW deposits in view of the reproducibility of ferrite measurement.

On the other hand, the flux shielded welding processes MMA (SMAW), SAW and FCAW produce weld metals with considerably more oxygen content (typically 500 to 900 ppm) than do the inert gas shielded processes (typically 100 to 150 ppm). As a result, the tolerance for ferrite is more limited if a cryogenic toughness requirement of 0,38 mm lateral expansion is to be met consistently. Commercial products offering up to 5 FN, or even 6 FN, maximum ferrite content, and offering to meet 0,38 mm lateral expansion minimum can be found for these flux shielded processes. However, it is by no means certain that both FA solidification and 0,38 mm lateral expansion minimum will be consistently achieved. If the cryogenic toughness requirement is to be consistently met, it can prove necessary to accept ferrite levels indicating AF solidification mode (less than 3 FN) for these processes and to take extra precautions (such as producing small convex weld runs and filling craters) to avoid or lessen tendencies towards solidification cracking. Crack-free weld metal would then need to be verified by extensive non-destructive examination (NDE). Engineering judgement needs to be applied when deciding fitness for purpose.

7.5 High temperature service

As noted in 4.5 and 5.5, precipitation of intermetallic compounds (generally lumped together as sigma phase for discussion), and of alpha prime, occurs in the ferrite of nominally austenitic stainless steel weld metals at about 300 °C and higher. Small amounts of these precipitations are generally not detrimental to the intended service, but larger amounts are detrimental. As a result, an upper limit on as-welded ferrite content is often specified along with a lower limit that would imply FA solidification mode. For non-stabilized filler metal types such as 19 9 H (308H) and 19 12 3 H (316H), a lower limit of 3 or 4 FN and an upper limit of 12 or 15 FN is the guideline.

Very low alloyed nominally austenitic stainless steel weld metals such as 16 8 2 (16-8-2) achieve FA solidification mode above about 1 FN, so that a minimum of 1 FN has been the guideline for that filler metal[48] along with a maximum of 5 FN. This latter requirement seems somewhat unnecessary in view of the higher allowable ferrite contents noted above for other non-stabilized filler metals.

Weld metals stabilized with Nb or Ti, such as 321 or 19 9 Nb (347), seem to require more ferrite than implied solely by the need for FA solidification in order to avoid solidification cracking. A lower limit of 5 or 6 FN, along with an upper limit of 12 FN is the guideline.

7.6 Dissimilar welds

Probably the most common dissimilar welds involve joints of stainless steel to carbon steel or low alloy steel support structures or attachments. Filler metals such as 29 9 (312), 23 12 L (309L), 23 12 2 L (309LMo) or 23 12 L Si (309LSi) are often selected for this purpose. The selection is normally based on mechanical properties, not corrosion resistance. As a result, the main concern is obtaining FA solidification under the dilution conditions expected. The root run is most at risk for solidification cracking if FA solidification is not achieved. Filler metal providing at least 10 FN in the undiluted condition can be specified to provide FA solidification in such dissimilar welds with 30 to 35 % dilution, with the dilution equally provided by the two base metals. Higher dilution, as possible in SAW and GTAW, can require filler metal of higher FN to achieve FA solidification mode. Alternately, at least 3 FN in the root run of the dissimilar weld can be specified. If there is no high temperature service anticipated, no upper limit on ferrite content of the filler metal or weld metal is generally necessary.

An exception to this guideline applies to 18 8 Mn and 307 filler metals. Due to the high Mn content (about 6 % in 18 8 Mn and about 4 % in 307), FA solidification is not necessary to avoid solidification cracking – under conditions of AF or even A solidification, such weld metal is generally resistant to solidification cracking.

7.7 Buffer layers and cladding

Application of buffer layers and cladding using stainless steel filler metals is done by a variety of welding processes. Some welding processes, particularly submerged arc welding and gas tungsten arc welding, are capable of producing a broad range of dilution. In most cases, FA solidification mode provides resistance to solidification cracking so that specification of 3 FN minimum (5 or 6 FN minimum for weld metal stabilized with Nb or Ti) is appropriate. An upper ferrite limit is unnecessary unless the weld metal will undergo postweld heat treatment and/or experience high temperature service. In these latter cases, an upper ferrite content limit of 12 FN is the guideline, as in 7.4.

An exception to this guideline applies to the situation where ferrite in the cladding would be aggressively attacked, as in 7.2. Again, cladding with filler metal such as 20 16 3 Mn N L (316LMn) must be specified to contain no more than 0,5 FN.