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Ferrite in Austenitic Stainless Steel Weld Metal

Report interprets the nature, role, measurement and control of ferrite based on a summary of present information

BY W. T. DELONG

William T. DeLong graduated in 1943 with honors from Lehigh University with a BS degree in Metallurgical Engineering. During the first six years of his professional life he worked for General Motors, served in the U.S. Army and worked for a time with Induction Heating Corporation.

In 1949 he began a lifetime career with The McKay Company, now known as Teledyne McKay. After a brief period in Technical Service, DeLong was put in charge of the Welding Research Laboratory at York, Pa. Here he wrestled for over 20 years with various problems of welding electrode formulations including that of the role and control of ferrite in stainless steel welds. He was later made Director of Research, Welding Products Division, and in November 1973 was made Vice President, Corporate Development.

During his research career, Mr. DeLong served with distinction on many AWS Filler Metal Subcommittees and became Chairman of the main AWS Filler Metal Committee. Among his other AWS activities, he was Vice Chairman of the Technical Activities Committee and served as Chairman of the York Central Pennsylvania Section, later becoming an AWS Director at Large.

DeLong also contributed significantly to the work of the Welding Research Council's High Alloys Committee. Here he served as Chairman of the Discontinuities Subcommittee and is presently Chairman of the Advisory Subcommittee on the Welding of Stainless Steels.

On the international scene, Mr. DeLong is the U.S. delegate to Commission II (Arc Welding) and a member of Commission XII (Flux and Gas Shielded Welding Processes).

He is the author or coauthor of a number of technical articles published in the Welding Journal and in ASM's Metal Progress. His two most recent papers deal with the detection and measurement of ferrite in austenitic stainless steels and will be found in the July 1973 and January 1974 issues of the Welding Journal.

Lecture was presented at the 55th AWS Annual Meeting held in Houston, Texas, during May 6-10, 1974.

Introduction

The subject of ferrite in austenitic stainless steel weld metal is extremely complex, and many investigators over the world have spent a tremendous amount of time on it.

This paper is presented as a brief description of the state of the art and

a status report. Areas that have been well covered in the literature and which seem understood and accepted will be given relatively little attention. Areas that are newer, less understood, and more controversial will be covered in more detail. Much of the new information presented will be drawn from unpublished data and reports coming from several committees — the Advisory Subcommittee and the Discontinuities Subcommittee of the Welding Research Council, Commission II and Subcommission II-C of the International Institute of Welding and the ASME Joint Task Group on Stainless Steel Welding Material.

The concern of this paper is with stainless steel weld metal. Although the principles are also applicable in a general way to cast materials, and to a lesser degree to wrought materials, a too direct and too literal application to these other forms of stainless steel can lead to incorrect conclusions.

The paper is also limited in scope and concentrates on the fundamentals, because a far more detailed and comprehensive review of many of the topics is now underway under the auspices of the WRC High Alloys Committee, by both the Advisory Subcommittee and the Discontinuities Subcomittee. Their reports will be published collectively in a WRC Bulletin early next year and the areas which are expected to be covered in that Bulletin will be mentioned as they are discussed here. Thus many portions of this paper should be regarded as a preliminary or progress report pending publication of the new WRC Bulletin on ferrite.

In a very general sense the overall data also point to general problems encountered in many research, quality control, and production areas, problems involving the variables affecting material characteristics, the calibration and use of instruments, and almost all of the factors which influence the amount of ferrite present and its effect. It does not seem an overstatement to say that significant variability is a characteristic that must be recognized and understood and factored into almost every situation involving quantitative measurement of ferrite. Much of this paper will be devoted to pointing out the sources and scope of this variability.

Characteristics of Ferrite

Ferrite is the magnetic form of iron and has a body centered cubic crystal. In iron and in mild or low alloy steels it is both the high temperature form, which develops as the alloy freezes, and the room temperature form. Most people who have had any metallurgy or materials courses dealing with steel are familiar with the iron-carbon equilibrium diagram (Ref. 1) shown in Fig. 1a.

The equilibrium diagram becomes more complex with the addition of alloy elements such as chromium. In Fig. 1b (Ref. 2) it can be seen that chromium levels over about 13 weight percent can eliminate the austenite phase, which is the nonmagnetic face centered cubic crystal form of iron. Other elements which have similar effects, but to different degrees, are silicon, titanium, columbium, molybdenum, and tungsten. Because all of these elements tend to make the alloy favor the ferrite phase they are frequently referred to as "ferritizers."

Other alloying elements such as nickel, carbon, nitrogen, and manganese tend to cause the alloy to favor the austenite phase and are thus often referred to as "austenitizers."

With rather high levels of both chromium and nickel, for example in a Type 308 weld metal typically containing 10% nickel and 20% chromium, a still more complex situation exists, as in the center of the 70% iron-nickel-chromium diagram (Ref. 3) of Fig. 1c. This less familiar diagram is used in the same manner as the other two; as the 10% Ni, 20% Cr, 70% Fe alloy cools from the molten state (moves down the vertical line shown in the center of the diagram), it would be expected to transform successively from liquid to liquid plus ferrite, then to pure ferrite, ferrite plus austenite, and finally to pure austenite. In practice this transformation does occur.

Ferrite in Weld Metal is not an Equilibrium Structure

The constitution diagrams shown in Fig. 1 are useful in understanding the relationship between ferrite and austenite at various temperatures, but they only represent conditions at or close to equilibrium, i.e., with cooling rates slow enough to allow diffusion of the alloying elements so as to reach the stable condition for the alloy at each temperature. In contrast, cooling rates for welding processes are extremely rapid, and equilibrium is not attained.

Warren Savage of RPI has stated that he has produced over 50 volume percent ferrite in a commercial wrought Type 347 specimen which would normally have little or no ferrite. This abnormally high level was obtained by soaking the very small specimen at a high temperature

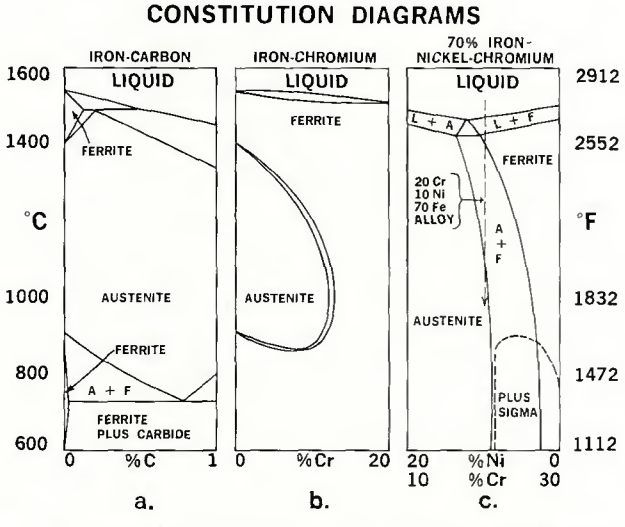


Fig. 1 — The iron-carbon (a), iron-chromium (b), and 70% iron-nickel-chromium (c) diagrams. The center line in diagram (c) represents a pure type 308 metal, i.e., one with 20% Cr, 10% Ni, and 70% Fe

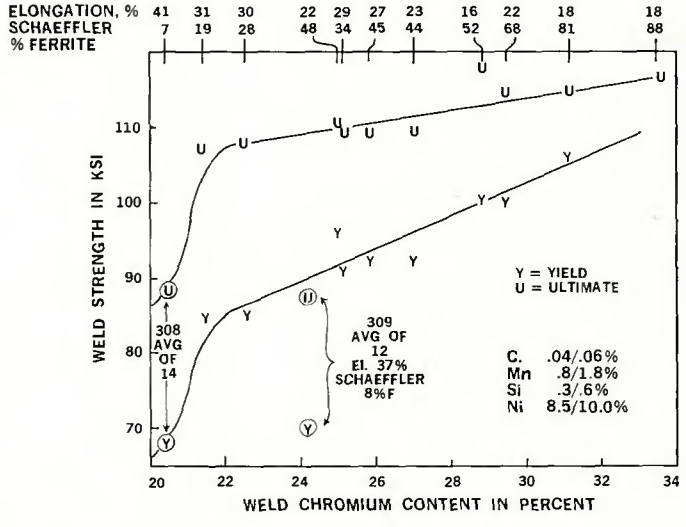
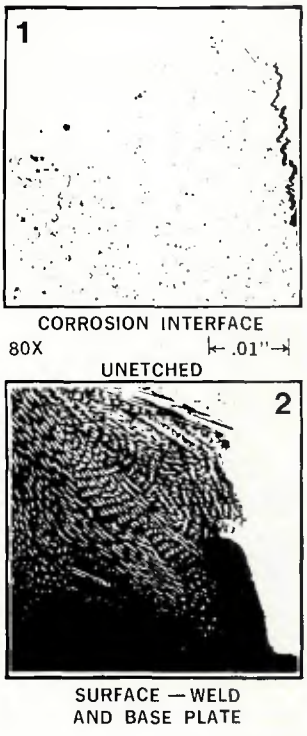


Fig. 2 — Influence of chromium on the ferrite content, strength and ductility of weld metal. Welds were made with ac-dc covered electrodes (AWS — 16 coating)

where the equilibrium condition resulted in a high level of ferrite, and then quenching it extremely rapidly to prevent the reorientation of the atoms necessary to transform the ferrite into austenite. In a reverse situation, Gene Goodwin of ORNL has stated that small electron beam welds in heavy plates were found to be fully austenitic even in such highly alloyed stainless as Type 312, which normally produces well over 20 volume percent ferrite in welds. Presumably the cooling rate was so rapid that freezing occurred below the ferrite region, and austenite was the stable form at the time and temperature of freezing. In the same area, however, Carl Lundin of the University of Tennessee reports electron beam welds on thin plate in which more than the expected amount of ferrite was obtained, indicating a still different combination of cooling rates and freezing temperatures. These are interesting observations, but they involve cooling rates which are far afield from those generally encountered in commercial covered electrode, submerged arc, and GMA or GTA welding. In these more common commercial processes, the weld metal cooling rate has some effect but not an extremely large one. Various members of the ASME Joint Task Group on Stainless Steel Welding Material recently reviewed data on the influence of heat input on ferrite in deposits from standard commercial welding processes. Five sources were reviewed, only one of which was published. The conclusion was that heat input over quite broad ranges did not have any significant effect on the ferrite content of welds. However, heat input did affect the morphology of the ferrite, i.e., its size, shape, and distribution. The only significant caution to be applied with this finding is that if the welding conditions, e.g. welding position, current, arc voltage, etc., influence the amount of nitrogen pick-up the ferrite level can be substantially influenced by the change in the nitrogen level.

Commercial stainless steel alloys, of course, have more complex chemical analyses than those covered by the diagrams of Fig. 1, with impurities such as carbon and nitrogen and deliberate additions such as silicon and manganese having an appreciable influence on the ferrite-austenite balance. In addition, alloying levels such as those found in Type 308 weld metal tend to make the alloy very sluggish, i.e., they tend to make the attainment of equilibrium virtually impossible. For example, the segregation of alloying elements which tends to occur in the crystals upon freezing (called "coring") is very difficult to eliminate in commercial stainless steels.



5/16" WALL 317L PIPE SINGLE PASS GTA WELD

CORROSION THROUGH CONTINUOUS SIGMA DENDRITES TO A DEPTH OF .125". RATE 600X GREATER THAN THROUGH THE AUSTENITE.

CENTER TO CENTER DISTANCE ON THE AUSTENITE CELLS IS APPROXIMATELY 0.0004". SIGMA FILMS (ORIGINALLY FERRITE) ABOUT 0.00004" THICK.

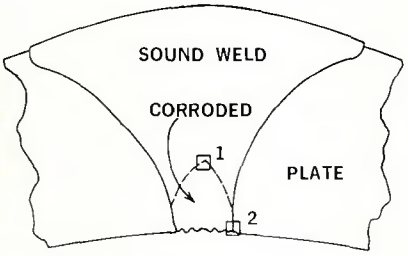


Fig. 3 — An example of selective corrosion of 317L weld metal in which the ferrite had been converted to sigma phase by heat treatment

Commercial Practices

In spite of the above mentioned difficulties, however, almost all of the commercial Type 308, 308L, 309, 312, 347 welding alloys and their variations are balanced so that some ferrite, typically 4 volume percent minimum, is present in the weld metal at room temperature. Similarly, Type 316, 316L, and 317 welding alloys may also be balanced to produce ferrite if this is judged desirable, although their usual form is entirely austenitic for reasons of corrosion resistance.

Weld Metal Ferrite is Very Fine

Because of the fast freezing of weld metal, its ferrite-austenite structure tends to be very fine, with the ferrite generally occurring in a lacy, interlocked dendritic form. My personal opinion is that as the ferrite content increases it becomes continuous at levels beginning somewhere in the range of 4 to 7 volume percent. It is not easy to judge the continuity of the ferrite from a photomicrograph, because only one plane can be observed; thus the interlocking can be present in the three dimensional structure but not observable in the particular plane being examined. Ferrite dendrites grow perpendicular to the plane in which freezing occurs; consequently they grow from the bottom in a rather flat stringer bead and from the side walls in a weld bead in a narrow groove. The primary continuity of the ferrite stringers is in the direction of growth, but there seems also to be extensive interlocking in side branches.

The dimensions and morphology of the austenite-ferrite substructure within the much larger crystals of weld metal vary depending on the welding process, bead size and shape, and cooling rate. In two specific cases discussed below, Figs. 3 and 12, representing GTA and covered electrode welds respectively, the center-to-center distances on the austenite subcells were on the order of 0.0003 to 0.001 in. At ferrite levels of under 10% of the overall volume, the ferrite films between these austenite subcells would be on the order of 0.00003 to 0.0001 in. thick, so it is not surprising that accurate measurement of the volume of such films is a difficult task!

Effect of Annealing

As discussed above, the ferrite dendrites are very fine, quite strongly segregated in chemistry due to their high freezing rate, and in a non-equilibrium state. It follows that thermal treatments at any temperature which allows some reasonable diffusion of the alloying elements can appreciably modify the size, shape, and quantity of the ferrite. For example, a conventional stainless steel solution annealing treatment at about 1900 F (1038 C) will reduce the as-welded ferrite content by five volume percent or more. It also tends to spheroidize the remaining ferrite

Table 1 — Low Temperature Impact Data on Some Common Stainless Steel Weld Metals at Various Ferrite Levels and in the As-Welded, Annealed, and Sensitized Condition

Type	Weld deposit chemical analyses, % C	Mn	Si	Cr	Ni	Mo	Cb	As-welded % ferrite by McKay Calc.	Meas.	Avg. ft-lb impact strength, 3 specimens, –320 F as-welded V-Notch	Keyhole	annealed [a] V-Notch	Keyhole	sensitized [b] V-Notch	Keyhole
308L[c]	.023	1.47*	.41*	18.02	12.34	.16*		0.0	0.0	43.3	29.0				
	.025	1.47	.41	18.49	10.23	.16*		3.0	5.0	33.5	25.3	44.2	27.3	22.7	14.3
	.025	1.47*	.41*	20.42	10.08	.16*		9.5	10.5	23.7	19.5				
	.026	1.47*	.41*	22.00	9.84	.16*		14.5	15.5	30.8	20.0				
308[c]	.075	1.51*	.46*	19.43*	10.13*	.16*		2.5	5.0	27.3	20.0	47.3	25.7	14.0	9.5
347L[c]	.023	1.56*	.50	18.00	12.20	.16*	.25	0.0	0.0	48.2	21.8				
	.025	1.56	.46	18.50	10.13	.16*	.29	3.5	5.5	27.5	23.0	51.5	30.7	28.0	19.0
	.024	1.56*	.50	20.31	9.88	.16*	.28	10.8	11.5	34.7	22.7				
347[c]	.077	1.61	.54	19.10*	9.88*	.16*	.80	3.5	6.0	17.8	16.7	36.7	23.5	16.0	10.7
316L[d]	.028	1.47*	.51*	17.80*	14.23*	2.07*		0.0	0.0	46.0	27.3				
	.031	1.47	.51*	19.70	12.93	2.07*		7.0	8.0	21.5	18.3	45.7	22.8	11.2	9.0
316[d]	.075	1.52*	.60*	17.95*	13.15*	2.07*		0.0	0.0	43.3	21.7				

*Analysis estimated either from the heat analysis and losses or gains or from the data on neighboring tests.
(a) Anneal was 1950 F for one hour, water quench.
(b) Sensitization was 1250 F for one hour.
(c) Core Wire Type 308L, Heat 897316; .016 C, 1.73 Mn, .021 P, .015 S, 20.40 Cr, 10.20 Ni, .16 Mo, .11 Cu, .042 N.
(d) Core Wire Type 316L, Heat 450123; .023 C, 1.66 Mn, .023 P, .017 s, 19.75 Cr, 13.15 Ni, 2.07 Mo, .20 Cu, .024 N.

and make it noncontinuous, unless the ferrite level is quite high.

The Microstructural Variability of Ferrite

It has been pointed out by many investigators that ferrite varies appreciably on a microstructural scale. One of the most comprehensive investigations was that reported in WRC Bulletin 132 by Gunia and Ratz (Ref. 4). Using a quantitative television microscope (QTM) at 1350X and higher magnification so that all visible ferrite in the field was integrated into the results, variations of the following magnitude were observed in the volume percent ferrite.

Average	*Range*
2.8%	0.3/8.1%
3.7	1.4/11.5
8.0	3.8/14.5
8.5	5.3/12.5
9.0	4.5/16.8
10.0	5.3/17.2

These variations occur within a cross section of a bead, along its length, and from bead to bead. They result from variations in cooling or freezing rates, from changes in chemistry within the bead due to segregation of elements upon freezing, and perhaps from changes in the amount of nitrogen picked up from the air as the welding progresses.

In terms of measuring or defining either the ferrite content of a weld or the potential deposit ferrite level attainable from a lot of electrodes, obviously all that can be specified is the average ferrite content of the weld. This, of course, means that minima and maxima must also be based on average values.

Effects of Ferrite

Cracking and Fissuring

Probably the earliest recognized effect of ferrite was that if it were present in sufficient quantity it effectively prevented centerline cracking of the root passes in highly restrained welds between armor plates. This effect was first recognized and used in World War II, and studies which followed its recognition led to the Schaeffler diagram which will be discussed in more detail below. Ferrite also helps to prevent microcracking or fissuring, another topic discussed in more detail below.

Strengthening Effect

It is well accepted and understood that ferrite in weld metal acts as a strengthening agent. The interrelationship of chromium, ferrite content calculated from the Schaeffler (Ref. 5) diagram and the strength and ductility of the weld measured on conventional tensile bars is shown in Fig. 2 (Ref. 6). The base analysis for that study was a conventional Type 308 electrode deposit averaging about 0.05% carbon, 1.3% manganese, 0.45% silicon, and 9.4% nickel. Both the ferrite level and the strength increased quite rapidly as the chromium increased from an average 20.4% to 22.0%, the strength by approximately 25% and the ferrite calculated by the Schaeffler diagram from about 7% to about 23%. However, the ductility decreased from an average 41% to about 30%. Above 22.0% chromium the strength increase was linear with increasing chromium content, and the ductility continued to decrease as the ferrite and strength levels increased. At about 31% chromium, the yield strength was on the order of 105 ksi, ultimate about 115 ksi, elongation about 18% and ferrite over 80%.

It was neither the chromium content as such nor the total alloy content which caused the above described changes, but the increase in the ferrite content. This is shown by the data in Fig. 2 on Type 309 weld metal, which contains an average of 24.2% chromium. The strength, ductility, and ferrite level of the Type 309 are essentially equal to those of the Type 308, and are substantially different from the strength and ductility shown by the curve for the high ferrite welds with chromium at the Type 309 level.

Corrosion

Generally ferrite is neutral or modestly beneficial as far as corrosion is concerned. In stress corrosion applications, high levels of ferrite can be distinctly beneficial. In a few cases, however, specifically with the molybdenum-bearing types 316 and 317, and only in certain media, selective corrosion of the ferrite can occur. Carrouthers, Linnert and Espy have done considerable work in this area (Ref. 7). One such corrosion-sensitive application is in the manufacture of urea, where the Type 316 material used is required to either have a very low ferrite level or be fully austenitic.

Figure 3 illustrates the effect of a very selective corrosion attack on sigma phase formed from ferrite. The corroding medium was not identified by the customer that encountered this problem, but the rate of attack on the sigma phase was on the order of six hundred times more rapid than on the austenite matrix! The application involved 5/16 in. wall Type 317L base metal welded in a single pass with 317L bare wire using the GTA process. The expected ferrite content of the weld and pipe was about 7 volume percent based on the chem-

istry of each, and the weld structure did appear metallographically to contain approximately this level of a second phase. The wrought material appeared to contain a few large plates of a second phase, but was essentially fully austenitic in most areas. The welded pipe had been stress relieved at 1350 F before use, a situation that would be expected to convert the ferrite to sigma phase. The weld in the specimen examined metallographically was completely nonmagnetic, indicating that the conversion of ferrite to sigma had been essentially complete. Linnert and Espy (Ref. 7) had concluded that a 7.2/1.0 minimum chromium-to-molybdenum ratio is important in some media for corrosion resistance of a ferrite phase, and it seemed logical that the ratio requirement might also apply to sigma phase formed from ferrite. The Cr/Mo ratio of the Type 317L weld metal involved here was a very unfavorable 5.4/1.0. Corrosion had occurred very rapidly through the sigma phase, with the austenite matrix left virtually untouched, as shown by the Fig. 3 photomicrographs of unetched surfaces. The result was that the welds "punctured" and leaked after a relatively short time in service. The same base metal and filler metal had been used in elbows and other fittings, but had been solution anneal heat treated before being put into service. They contained little or no sigma phase, certainly not in a continuous form, and they were completely unaffected by the corrosion media, as was the base metal of the pipe.

Corrosion is a complex subject, and if the application is not a time tested one experts should be consulted, irrespective of whether ferrite bearing materials are involved.

Cryogenic Use

As a general rule, ferritic materials are much less tough at low temperatures than austenitic materials. Thus high ferrite materials such as Type 312 are not suitable for cryogenic use. Table 1 presents some data (Ref. 8) on the interrelationship of ferrite, carbon content, and the toughness of weld metals at –320 F. To eliminate other variables, one heat of 308L was used for the 308L, 308, and 347 data, and one heat of 316L for the 316L and 316 tests. Ferrite in general is shown to be detrimental to impact values. Annealing welds with 5 to 8 volume percent ferrite as-welded very consistently restored the impact values to the levels found in the as-welded tests which had zero ferrite. This is quite logical, since the annealing would remove most or all of the ferrite and produce zero ferrite or a structure with only small levels of spheroidized ferrite. Sensitizing the materials had a generally, but not consistently, detrimental effect, due possibly to minor amounts of carbide precipitation or sigma formation. Molybdenum and columbium seemed to have little effect other than their effect on the ferrite content.

High Temperature Exposure

As partially indicated in the 70% Fe-Ni-Cr diagram of Fig. 1c, sigma phase can form from ferrite at temperatures between approximately 900 C (1650 F) and 460 C (860 F). Depending upon the alloy content, sigma can also form from austenite. It is a hard, brittle phase and is generally undesirable except in those cases where it is deliberately utilized to harden and strengthen the steel for a special purpose, such as valves for heavy duty internal combustion engines. If sigma forms, it can be redissolved above 900 C, preferably at 1000 C.

At high temperatures, ferrite and austenite differ from each other in strength and ductility. This presents problems to steel mills, where ingots with certain compositions and ferrite levels above 10 volume percent based on the commonly used diagrams can be very sensitive to cracking and are thus difficult to hot work in the early reduction steps. At higher ferrite levels, e.g. 20 volume percent or more, the difficulties in hot working may be reduced because more of the softer (at the working temperature) ferrite is present in the structure.

The relationships between creep and stress rupture and the ferrite content are rather complex in the ferrite bearing weld metals, for obvious reasons involving both the relative strengths and ductilities of the weld metals at the service temperatures and possible transformation effects. These relationships are beyond the scope of this paper.

Techniques Used in Analyzing Data on Ferrite Content

A valid and easily understood format is essential for presenting any data on ferrite calculation and measurement. This is particularly true because the variability of the test data is rather substantial in almost all the studies made. There are variables inherent in all of the data, for example in chemical analysis, readings taken on one magnetic instrument, readings from one instrument to another, variations from pad to pad with a given procedure and welding machine, variations between welders, variations due to different pad welding and preparation procedures, etc.

Principles drawn from the ASTM Standard Recommended Practices E177-71, E178-68, and E180-67, ASTM Annual Book of ASTM Standards, Part 30, (Ref. 9) have been very helpful and are utilized in the analysis of the data in this paper. Figures 4 and 5 illustrate the essential terms and concepts used in this discussion of ferrite.

Referring first to Fig. 4, the normal curve is that expected due to normal experimental variations. Large quantities of data are expected to fall within the following limits if no abnormalities are present.

1. Within +1 standard deviation — 68.26% of the data
2. Bands from 1 to 2 standard deviations — 27.08% of the data
3. Bands from 2 to 3 standard deviations — 4.40% of the data
4. Over 3 standard deviations — 0.25% of the data
5. Over 4 standard deviations — 0.01% of the data

As is conventional in statistics, the standard deviation of a group of data is calculated from the total variance of the group divided by the number of items less one.

Precision is expressed in a manner which defines the range of values expected with the specified test procedure. For present purposes it can best be defined using a value for a standard deviation, which then defines the distribution curve provided that distribution curve is essentially normal as shown in Fig. 4.

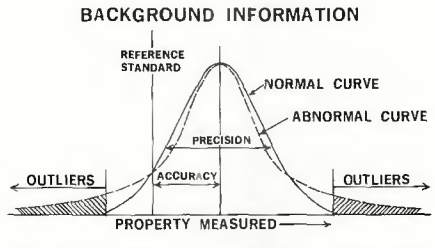


Fig. 4 — Pictorial representation of the terms precision, accuracy, normal and abnormal distribution curves for the data, and outliers

INFLUENCE OF MULTIPLE VARIABLES

INDIVIDUAL STANDARD DEVIATIONS				OVERALL
S_1	S_2	S_3	S_4	S_0
1.000				1.000
1.000	1.000			1.414
1.000	1.000	1.000	1.000	2.000
1.000	0.300			1.044

$$\sqrt{(S_1)^2 + (S_2)^2 + \ldots (S_x)^2} = S_0$$

Fig. 5 — Table showing formula for determining the combined effect of several different variables, and examples to illustrate their overall effects on the total standard deviation. This formula may be used to combine data only when a single mean is involved and each test group includes the same number of tests

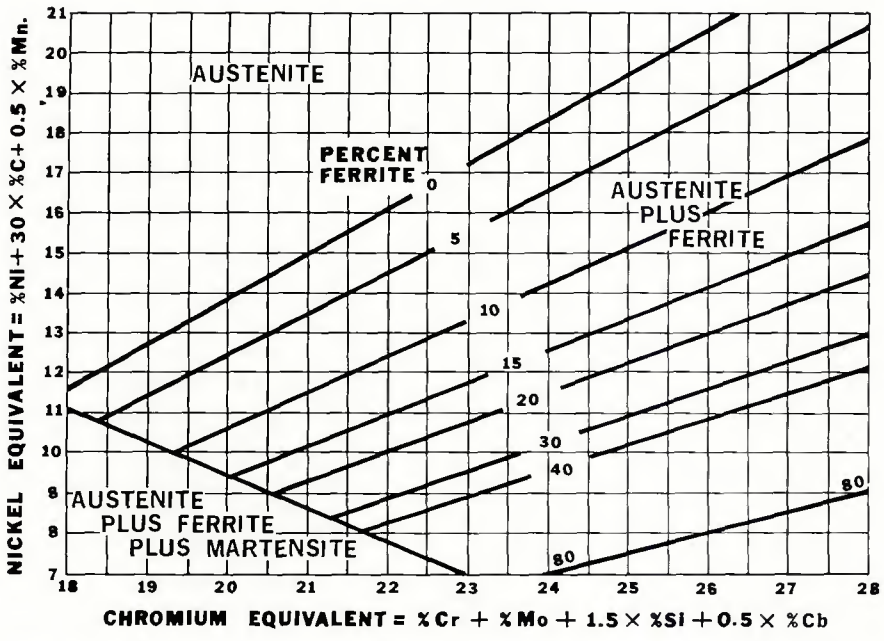


Fig. 6 — An expanded form of the center section of the Schaeffler diagram

Accuracy is the difference between the mean obtained from the test data and a reference standard. The reference standard can be defined either as the "true" ferrite, if agreement can be reached on how to establish the true ferrite, or as the ferrite value obtained on one pad with a group of calibrated instruments.

One of the essential concepts in a study such as this is that of "outliers". The ASTM procedures describe outliers as data points which differ markedly from the rest of the data in a group, i.e., those which fall well outside the expected normal distribution curve if the great bulk of the data indicate such a normal curve. They are generally the result of such factors as gross deviations from prescribed experimental procedure, errors in calculation or recording, etc. They may be rejected or accepted, but should be recognized. Outliers can be identified by procedures defined in the ASTM recommended practices, or recognized in a population distribution curve such as the dashed curve of Fig. 4. In Fig. 4, for example, data beyond the vertical lines on either side of the normal curve are not within the normal expected distribution and must be regarded as outliers if precision is defined in the convenient terms of a standard deviation with normal distribution. Ferrite data from various test series described later show such outliers, which can and should be recognized and studied. An effort must be made to eliminate them from future data by learning both their causes and their cures.

Figure 5 presents a formula and example to illustrate how the influences of different independent variables may be combined with or separated from one another. The formula has certain limitations, e.g., the sample groups must be of equal size and must have a single mean, although in some cases the end use of the data and the assumptions made in deriving the data allow the requirement of a single mean to be validly waived.

Calculation of Ferrite from Deposit Chemistry

Basically the ferrite content of weld metals is determined by the chemical composition of the molten metal, as described earlier and in Fig. 1. Other variables do have an influence but the chemistry is the essential variable. Anton Schaeffler recognized this in the 1940s and prepared and published his very well known and accepted "Schaeffler diagram", (Ref. 5) of which Fig. 6 shows an expanded version of the central section. His diagram was based upon metallographic examination, and was stated to be accurate to within ±4 volume percent ferrite. This statement of precision gives some immediate indication of Schaeffler's opinion that there is significant variability in the several independent factors which combine to determine the final ferrite content of the weld.

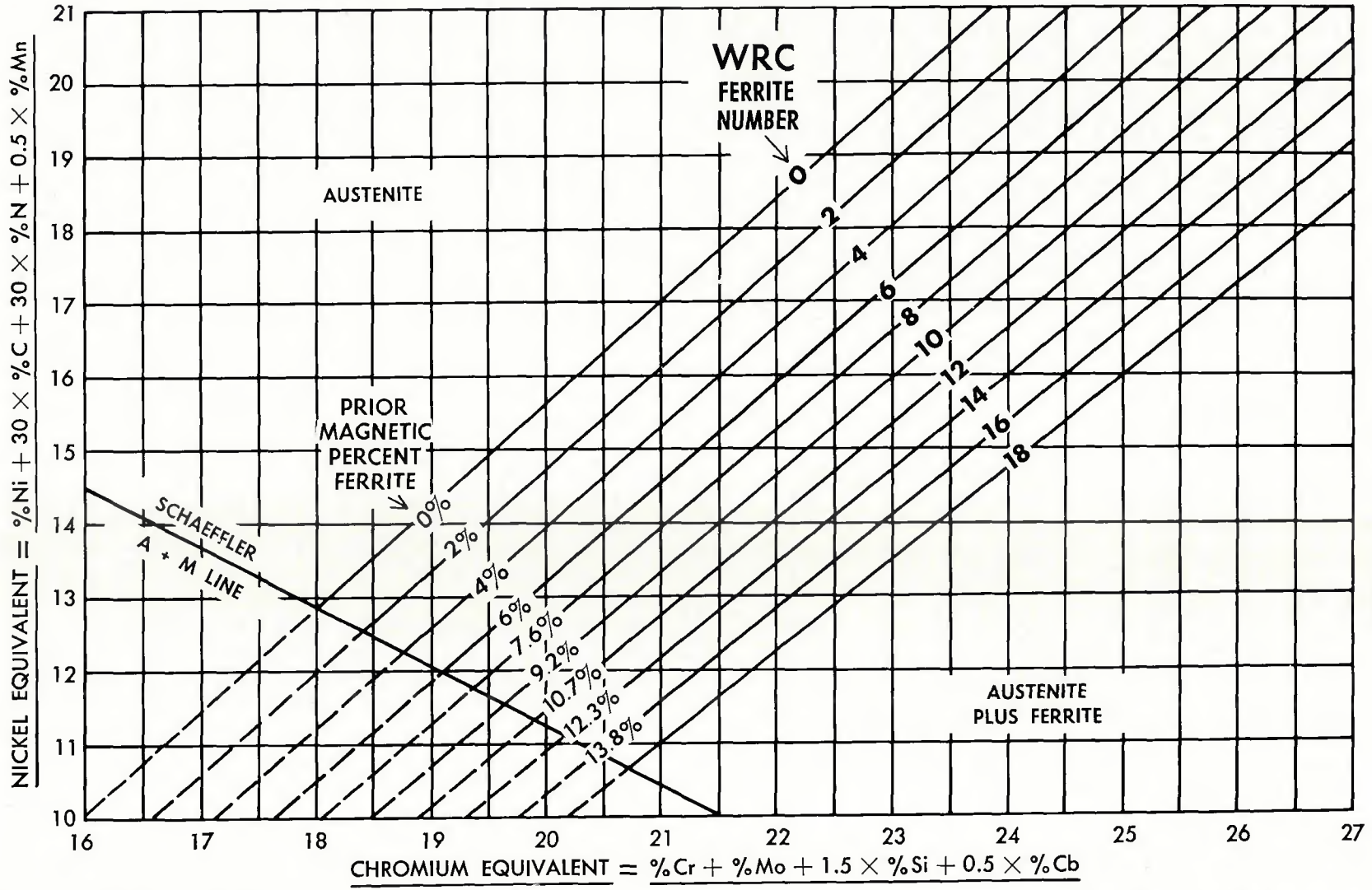
The Schaeffler diagram became very useful to both users and manufacturers. Through techniques described by Schaeffler for use with the diagram users were able to determine not only approximate ferrite levels of undiluted weld metal but also the probable ferrite levels of welds diluted with various amounts of base metals of known chemistry.

In 1956 a modified diagram based on magnetically determined ferrite values was published by research personnel at the McKay Company (now Teledyne McKay); the accuracy claimed for the diagram was ±3 volume percent ferrite. The latest version of the diagram, generally known as the DeLong diagram, is given in Fig. 7 (Ref. 11). It resembled the Schaeffler diagram, but was different in three significant respects. First, it added a factor for nitrogen, which had presented a problem to at least one manufacturer when some heats of wire found to have abnormally high levels of nitrogen produced radically low deposit ferrite when used in covered electrodes, even though calculation with the Schaeffler diagram indicated adequate ferrite levels. Second, the diagram incorporated a significant change in the slope of the lines. While it was in essential agreement with the Schaeffler diagram for the lower alloy types such as the 308 family, it predicted higher ferrite levels for the more highly alloyed 316, 317, and 309 families as shown in Table 2. This higher predicted ferrite was shown to be valid for covered electrodes in the original paper (Ref. 10), and also in a more recent paper on GMA and GTA welds (Ref. 11). The third change was that the spacings between the lines representing 0, 2, 4, 6, up to 14 volume percent ferrite were nearly equal as opposed to the changing spacings on the Schaeffler diagram.

In the original DeLong et al paper, the major influence of chemical analysis variations on the calculated value was discussed. The authors were aware of the fact that not all chemical laboratories are under good control on all elements at all times. Steel producers' laboratories must be good, and many other highly controlled high volume labs are also good, but many laboratories running analyses at low volume can and do sometimes report analysis values that are inaccurate.

As part of an extensive WRC Advisory Subcommittee cooperative program (Ref. 12), supervised by Pickering and Vandergriff of Combustion Engineering, some interesting chemical analysis data were obtained. Table 3 gives some specific data from this study illustrating the variability which can be expected in chemical analyses and the resulting variability of calculated ferrite. Considering that a 2 FN change in calculated ferrite can be produced by a change of only 0.67% in the chromium equivalent or 0.80% in the nickel equivalent, the variation in chemical analysis is appreciable.

In terms of standard deviations, the analysis values obtained from electrode users' (as opposed to producers)



Calculate the nickel and chromium equivalents from the weld metal analysis. If nitrogen analysis of the weld metal is not available, assume 0.06% for GTA and covered electrode, or 0.08% for GMA weld metals. If the chemistry is accurate the diagram predicts the WRC Ferrite Number within plus or minus 3 in approximately 90% of the tests for the 308, 309, 316 and 317 families.

Comparison with the Schaeffler Diagram.

1. A *nickel equivalent* of 30 × %N has been added.
2. Ferrite Numbers for 308, 308L and 347 covered electrodes are similar. The higher alloy 309, 316 and 317 families have about 2 to 4 higher FN on this diagram.
3. Generally this diagram correlates better with GTA and GMA weld metals because it allows for nitrogen pick up.
4. The Schaeffler austenite-martensite boundary has been included here for reference.

Fig. 7 — The DeLong Constitution Diagram, revised January, 1973 to convert it to the WRC Ferrite Number system for weld metals

Table 2 — Ferrite Content in Weld Metal by Calculation from Constitution Diagrams[a] Illustrating the Progressive Increases in Spread Between Values as the Alloy Content of the Welds Increases

Diagram	Value	Type 308L	Type 316L	Type 309
Schaeffler	%	7.8	3.9	7.0
McKay (DeLong) Revised January, 1973	FN	8.3	4.9	10.7

(a) Assumes typical covered electrode C, Mn, Si, N, with AWS midpoints of Cr, Ni, and Mo.

Table 3 — Spread in Results Obtained from Four Laboratories Each on Deposits from Five Lots of Covered Electrodes

Lot Designation →	A	B	C	D	E
No. of Laboratories Testing					
Producers	1	1	1	1	4
Users	3	3	3	3	0
Chemical Analysis, %	Spread between the four test facilities				
Carbon	.028	.014	.014	.004	.005[a]
Manganese	.61	.26	.20	.23	.25
Silicon	.10	.09	.03	.06	.11
Molybdenum (residual)	.03	.05	.10	.08	.03
Chromium	1.04	1.00	1.33	.18	.60
Nickel	.29	.20	.28	.49	.30
Nitrogen	.041	.020	.058	.031	.012
Ferrite Calculations					
Standard deviations by:					
Schaeffler (%)	1.13	1.16	1.32	.34	1.14
DeLong (FN)	2.99	2.62	3.38	1.41	1.99

(a) This was a 308L, which would in itself tend to reduce the total test spread encountered.

laboratories and converted into calculated Schaeffler ferrite percentages show a somewhat higher standard deviation than that obtained with direct ferrite measurements of weld pads by multiple laboratories (which is described below). The standard deviation based on the DeLong diagram is even larger because of the very wide spread in reported nitrogen values, this being the only essential difference between the results obtained from the two diagrams in this case.

It can be concluded that it is better to use direct measurement of ferrite weld pads in user laboratories than to use chemical analysis from either user labs or commercial labs and calculate the ferrite. The precision, and presumably also the accuracy, of the ferrite value obtained is better with direct measurement of a welded pad, and direct measurement involves less time and cost. It is also easier and cheaper to run multiple or repeat tests with the direct measurement approach than with chemical analysis.

From the data given, as well as from fundamental considerations, it can also be tentatively concluded that chemical data from an electrode producer's lab is on the average more accurate than that likely to be obtained from a user's lab or an outside commercial lab. The producer has the added advantage of having the steel mill analysis plus his knowledge of past performance on gains or losses of the elements to guide him on whether his analytical data on the lot is reasonable.

Beyond the questions of the precision and accuracy of chemical analysis, the diagrams obviously include some further variability coming from the assignment of multiplying factors to the elements, placement of the lines, reading of the diagrams, etc.

In addition, when the ferrite values obtained from either diagram are compared with values obtained by measuring the ferrite, questions are introduced as to the precision and accuracy of the measuring techniques used in establishing the data from which the diagram was constructed. In the Schaeffler diagram this involves metallographic technique variables; in the DeLong diagram, variables of magnetic measurements. Finally, in both cases there exist the inherent variables influencing the ferrite content of the pad being observed, such as the cooling rate and other variables affecting the size and morphology of the ferrite being measured.

Methods of Measuring Ferrite

Various possible methods of measuring ferrite have been discussed in detail by Gunia and Ratz (Ref. 4) in WRC Bulletin 132 and will be only briefly touched on here. The status of some of the methods will be reviewed in more detail in the new WRC Bulletin on ferrite which is being prepared for publication early in 1975.

Metallographic measurements are helpful but they are difficult to run accurately, due primarily to the very small size of the ferrite particles, as discussed earlier and shown in Figs. 3 and 12. This fineness, plus the inherently different corrosion responses of ferrites of varying analyses to different etching media, make an optimum etch difficult to establish and an accurate quantitative result difficult to obtain. Under or over etching can obviously influence the amount of "ferrite" observed. Point counting or linear intercept counting is difficult because of the fineness of the ferrite; even with a QTM, machine settings can influence the readout value on a given field of view (Ref. 13). Moreover, ferrite is quite variable locally within the bead and from bead to bead.

Magnetic measurements are easy to make with several commercially available instruments with low field strength probes of various types. They will be discussed in more detail later in this paper.

X-ray diffraction is a well established method of measuring the quantity of one phase in a matrix of one or more other phases. It has not proved satisfactory for the measurement of delta ferrite in austenitic stainless steel weld metals, however, presumably because of their very fine structure, the very strongly cored composition of the ferrite, and internal stresses in the ferrite. The diffraction patterns are quite diffuse, and satisfactory quantitative determinations have been judged to be unattainable.

A more sophisticated magnetic method involving the permeability of weld specimens at saturation has been recommended by a number of researchers as a potentially accurate method of measuring the true absolute ferrite of the weld, but it is complex and involves a number of assumptions and calculations regarding the chemical composition of the ferrite, which in itself is difficult to establish accurately. An excellent paper on this subject has been presented by Bungardt et al (Ref. 14) and furnishes one possible reference point for establishing the "true" ferrite of weld deposits.

A second possible reference point for the "true" ferrite involves Mössbauer effect measurements such as reported by Schwartzendruber et al (Ref. 15).

Both the magnetic saturation work and the Mössbauer work will be considered in more detail versus the WRC work in the coming WRC Bulletin.

Commercial Magnetic Instruments for Measuring Ferrite

Background

Very extensive round robins have been run in the past ten years in both the United States and Europe by the International Institute of Welding, Subcommission IIC, and the Advisory Subcommittee of the High Alloys Committee of the WRC. From the viewpoint of making further progress, three important conclusions from these studies were as follows:

1. The prime cause of the wide variations found in readings was that there were no accepted common procedures or standards for calibration. The extent of the variations found in the instruments surveyed in the round robin was substantial, as shown by the left hand set of curves in Fig. 8 and the data in the column of the table headed "Instruments Prior to Calibration." As the figure shows, the distribution curve of the data did not fit a standard curve and had an excessive number of outliers. A standard deviation of 1.2% ferrite for uncalibrated instruments only partially represents the data, because the number of outliers which exceeded three times the standard deviation was substantial. This is not surprising, because there was no reason to feel that there was really any common base around which the values should have grouped themselves, since there was no common calibration program. The curve is shown to illustrate in a general way the improvements which came later through the WRC work.

2. The instruments did check rather well against each other on a relative basis, i.e., if a large series of specimens of different ferrite contents were run a curve could be set up which rather accurately portrayed the relationship of the readings from one instrument to the readings from the other.

3. The spread in data on the type of curves described in 2 above was wider for large specimens and randomly selected (i.e. unmarked) measuring points, due to the variation in ferrite within the specimen. There was much less spread with small specimens having defined locations for measurements.

Based on the information derived from the above described studies, the WRC Advisory Subcommittee made two basic decisions over a period of time. The first was to adopt the term "Ferrite Number" (FN) to replace "percent ferrite," since "percent ferrite" had become meaningless because of the lack of reference standards or agreement on calibration procedure. The term Ferrite Number (FN) is meant to directly replace "percent ferrite" on a 1 to 1 basis for all uses.

The second WRC decision was to approve calibration of Magne-Gages using NBS Coating Thickness Standards; this resulted in the WRC publication "Calibration Procedure for Instruments to Measure the Delta Ferrite Content of Austenitic Stainless Steel Weld Metal," July 1, 1972 (available from the WRC), which was reproduced in the February, 1973, *Welding Journal,* pages 69-s to 71-s. Calibration of other instruments is to be effectively derived from this calibration so that FN readings on weld metals will be relatively constant (within much closer limits than in the past) from lab to lab on any given weld metal pad.

The IIW accepted the FN system and agreed to establish instrument calibration procedures that would insure numerical values equal to the WRC values on whatever calibration system the IIW ultimately establishes. This is expected to insure worldwide uniformity.

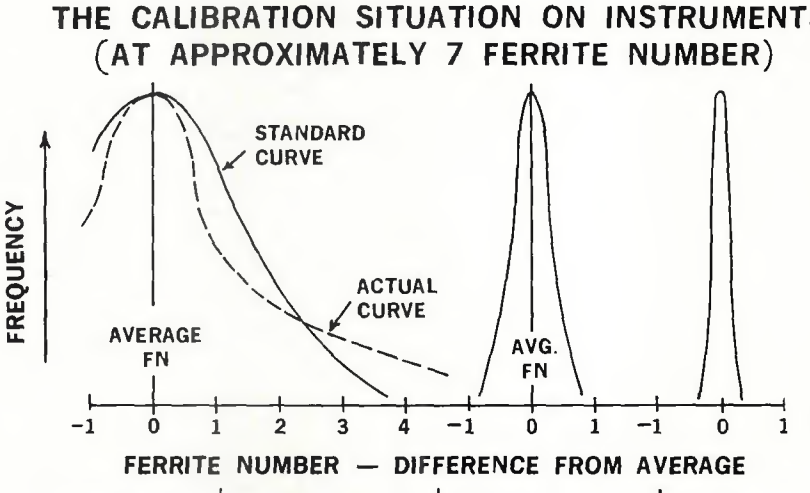
The AWS Filler Metal Committee established a Task Group to expand and strengthen the WRC procedure. The resulting AWS procedure, AWS A4.2-74 "Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic Stainless Steel Weld Metal," should be in print before this paper is in print.

AWS Subcommittee IV on High Alloy Steel Filler Metal has adopted the FN system and described the background, and the next revision of AWS A5.4-XX, which should issue in the near future, will include minimum FN requirements on the ferrite bearing grades of covered austenitic stainless steel electrodes.

The ASME and NAVSEC are both moving toward adoption of the FN system and the accompanying and essential instrument calibration. The system is also currently specified by the AEC Regulatory Guide 1.31, Revision 2, 1974, "Control of Stainless Steel Welding."

WRC Program on Pad Welding and Measurement Procedures

An extensive multilaboratory cooperative program has been underway for over two years, designed and supervised by Earl Pickering and Douglas Vandergriff of Combustion Engineering. The first phase has been completed and a report is being prepared for publication in the coming WRC Bulletin. This paper will review only certain conclusions and not the entire project. The findings in several areas are extremely pertinent



NORMAL DISTRIBUTION OF DATA	INSTRUMENTS PRIOR TO CALIBRATION	CALIBRATED INSTRUMENTS —WRC—	SINGLE INSTRUMENTS —MG—
1σ 68.3%	1.2% F	.27 FN	.10 FN
2σ 95.4%	2.4% F	.53 FN	.20 FN
3σ 99.7%	3.6% F	.80 FN	.30 FN
COMMENTS ON OUTLIERS	10% AND UP TO 4 OR 5σ	A FEW INSTRUMENTS	VERY FEW

Fig. 8 — Precision of ferrite measurements with low field strength magnetic instruments such as a Magne-Gage. The curve and data on the left are for instruments prior to the acceptance of the WRC calibration procedure, those in the center for Magne-Gages after calibration, and the curve and data on the right for a single Magne-Gage and operator. The precision values shown may be applied to weld metal ferrite contents of 8 FN and below, but should be increased for higher FN contents in proportion to the increase in FN

to an understanding of what the WRC work to date has accomplished, what tolerances on measurements can be expected, and what remains to be done.

The study involved five lots of Type 308 electrodes from different producers, four welding and pad preparation procedures, 22 laboratories, and four test pads with each lot and procedure prepared by four separate laboratories.

The two curves on the right of Fig. 8 were derived from data from the program. They should be compared with the curve for uncalibrated instruments on the left of the figure. The right hand curve was derived in a way that enabled the determination of what are believed to be the outside limits for the tolerance of a single instrument (a Magne-Gage, in this case) and operator. There may be a slight tendency for outliers beyond the curve shown and beyond the figure for three standard deviations shown in the corresponding table, but such tendency is not significant. The center curve and the portion of the table headed "Calibrated Instruments — WRC" is more pertinent because it gives precision data on multiple instruments calibrated to the WRC procedure. The WRC calibration procedure obviously has greatly improved the situation as compared to the uncalibrated data of the curve and table on the left. However, it has been found that some instruments tend to be outliers, i.e., tend to give values somewhat higher or lower than the three sigma limits (three standard deviation limits) shown. This situation must be investigated in more detail, and it is hoped that procedures and practices can be developed by the instrument manufacturers to reduce or eliminate these outliers.

The limits shown in Fig. 8 should be expected to apply from approximately 8 FN down to 0 FN. As the ferrite number increases above 8 FN the agreement to be expected within a single instrument or from one instrument to another should be scaled up in proportion to the increase in ferrite number; for example, at 12 FN limits 50% higher than these would be recommended and a range 50% higher than these would be expected.

Each of the five lots of 5/32 in. diam Type 308 covered electrodes was used to prepare pads with four different procedures by four of the 16 participating welding labs. The ferrite data from the pads are being combined and averaged in various ways. A summary of some of the findings is shown in Fig. 9. Because of their derivation, the data include variations due to welders, repeat pads, different laboratories, and different instruments, but represent only one lot of typical 308 covered electrodes. All pads were of nondilution types, i.e., the measuring surface comprised pure weld metal.

The highest ferrite was obtained with procedure C, which produces a four-bead-wide chemical laboratory type pad with its top surface ground. The other three procedures produced pads which were only one bead wide. Procedure A is the present standard MIL-E-22200/2B procedure, with air cooling on the final two beads and a ground top surface. Procedure B produced the lowest ferrite, about 3 FN lower on the average than pads of procedure C. The pad from procedure B is similar to that from procedure A except that all beads are quenched in water immediately after welding, and ferrite measurements are taken on the final top surface after cleaning but without any grinding or machining of the surface. Procedure D produced ferrite values close to the overall average ferrite content of the four different procedures. It is similar to procedure A but welding is between copper blocks to shield and control the weld puddle and the top surface is draw filed to smooth it for ferrite measurements. The most regular weld beads are obtained with procedure D, and, because the spacing between the copper bars is specified, it produces the most uniform pads. The overall standard deviation of the D pads was the lowest of the group, on the order of 0.75 FN, the other procedures showing standard deviations ranging up to 1.06 FN.

The differences between the mean ferrite contents of procedures A, B, C, and D are neither imaginary nor random. They are both genuine and surprisingly consistent from lab to lab, although there are some expected variations due to the overlap of the precision envelopes shown in Fig. 9. The differences in the mean ferrite contents presumably come in part from differences in cooling rate, possibly in larger measure from changes in the tendency for nitrogen pickup in the specific procedures, and also from such details as surface preparation of the pad.

Figure 9 has been stylized to some degree. It has been drawn assuming a 0.85 FN standard deviation for each procedure, since it was felt that the differences in standard deviations were not particularly significant. An analysis of the 80 different weld metal pads made in the program (20 with each procedure) indicated that outliers were not a problem in these tests; in fact, there were somewhat fewer values beyond 2.5 standard deviations than would be predicted by the standard curve. These results would indicate that the distribution of values around the mean FN of a given welding and pad preparation

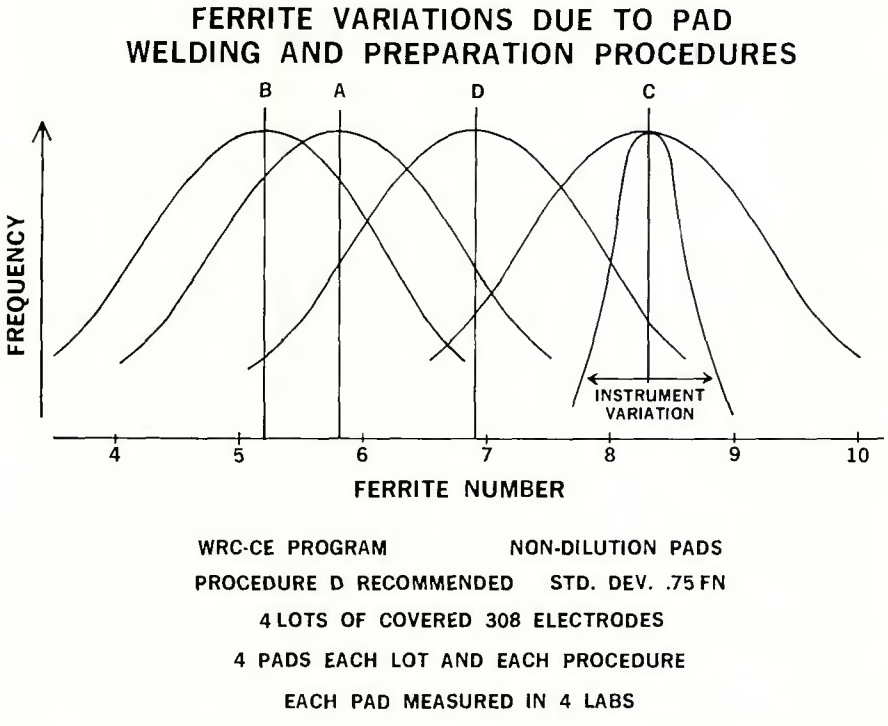


Fig. 9 — A stylized representation of the precision and mean ferrite levels to be expected from four different pad welding and preparation procedures, A, B, C, and D, described in the text. The supplemental curve at the right designated "instrument variation" shows the precision of multiple Magne-Gages calibrated to the WRC procedure

procedure, such as described here, can be assumed to be normal, even in different laboratories and with different welders and different instruments and operators. It can also be assumed that the overall standard deviation with any given lot of electrodes averaging about 8 FN or less is on the order of 0.8 FN. The standard deviation will increase above this, as previously discussed; in addition abnormally low outliers are likely whenever the welder holds a longer than normal arc and allows excessive nitrogen pickup.

It is also logical to consider the overall envelope of all four curves in Fig. 9 as the potential spread for any given lot of electrodes used in a range of undiluted production welds. The various procedures involve different levels of heat input, mass and cooling rate, and include the variables of multiple welders, multiple laboratories or construction sites, and multiple instruments and operators. The overall spread shown in Fig. 9 is from approximately 3.5 FN to approximately 10 FN, rather substantial for a single lot of electrodes!

Other Data on the Variability of FN Results from a Given Lot

Two other sources of major amounts of data can be analyzed in a manner similar to that used in the preceding discussion.

One source is a group of data from covered electrodes presented in Table 3 and Fig. 6 of the original DeLong et al paper in 1954 (Ref. 10). This consisted of tests of the ferrite content of deposits from two to seven different lots of production electrodes produced from the same heat and diameter of wire, and the same type of coating, but sometimes over a wide span of time and with different welders. The data were recently reanalyzed with the statistical procedures used in the WRC program, and about 3% were found to be outliers. Some of the sets were removed because the ferrite content was very low and zero ferrite was encountered on one or more pads. In addition, an upward correction in the calculated standard deviation was made to correct from the percent ferrite used at that time to the WRC Ferrite Number. In total, approximately 300 pads (118 sets) remained to be studied. The overall standard deviation of that group was calculated to be in the range of 0.9 to 1.0 FN. This is in reasonable agreement with the findings in the cooperative WRC program.

The other source of data was Table 22 of the 1973 paper by Long et al (Ref. 11) on GTA and GMA weld metal; that paper also contained the DeLong diagram revised to show the WRC FN values. In total, 94 tests were available in groups of two or more, representing 36 different wire heats; these were commercial tests run over a period of time by several different welders. An overall standard deviation of 1.19 FN was reported at an average FN of 9.4. It was also shown that the standard deviation increased as the total FN increased, which can logically be expected and has been discussed previously. It has been concluded that this increase should be proportional to the increase in FN. The 308 and 308L involved 56 tests with 21 heats in all, having a mean standard deviation of 1.19 FN and a mean ferrite content of 10.6 FN. It has been stated above that a reasonable standard deviation drawn from the cooperative WRC program on 308 is about 0.85 FN for the range 0 to 8 FN, with proportional increases above 8 FN. At an average 10.6 FN a standard deviation of 0.85 FN × (10.6 FN ÷ 8.0 FN) or approximately 1.13 FN would be expected, which is very close to the 1.19 FN standard deviation reported. A re-analysis of the data on the GTA welds shows that the distribution for the 308 and 308L welds was normal, with no outliers. (There were two outliers in the fourteen 309 pads, which explains the higher standard deviation reported in the paper for the 309 heats.)

Dilution

Dilution is a significant influence on the ferrite content of welds. It can increase the ferrite content if the chemistry of the base metal has a higher calculated ferrite potential (based on the DeLong or Schaeffler diagram) than the undiluted weld, and decrease the ferrite if the base metal potential is lower than that of the undiluted weld. It is generally expressed as the percentage of base metal in the final weld, i.e., the ratio of the cross sectional area of melted base metal to the area of the entire weld nugget, and can be calculated by sectioning the weld and examining it.

Dilution is quite variable; the expected dilution levels can range up to 65% base metal in the submerged arc and GMA processes, up to 50% in the covered electrode process, and to some lower figure in the GTA process. It depends heavily on the procedure variables, with joint configuration being a major factor. In many processes, dilution can be controlled to a substantial degree.

Schaeffler (Ref. 16) described a procedure for calculating the weld ferrite from the chemistries of the base and weld metals and the dilution. In this procedure the locations of the base metal and the weld metal are individually plotted from their chemistries on the constitution diagram used, and a line is drawn connecting the two points. The ferrite content of the diluted weld lies along this line, at a point whose distance from the undiluted weld point is related to the length of the line in direct proportion to the percent dilution. For example, with 30% dilution the predicted ferrite content of the weld deposit is located at the point along the line which is 30% of the way from the undiluted weld metal point to the pure base metal point.

Figure 10 (Ref. 17) is an example showing the effect of dilution on the ferrite of a multipass GTA weld. Similar effects would be expected using other welding processes. Commercial 304L and 316L wrought plates have calculated ferrite potentials of about 6 FN and 2.5 FN respectively, based on their center point chemistries. In practice, however, they both usually average below their respective center point potentials because a more strongly austenitic structure involves less risk of scrap for the mill. Wrought base metals with such low ferrite potentials will obviously reduce the ferrite content of the welds by dilution. On the other hand, cast stainless steels are generally aimed at a high and controlled ferrite. CF-3 (304L) has a center point potential of about 9.5 FN, and CF-3M (316L) of about 15.9 FN. Thus these materials are more likely to increase the ferrite content of typical welds through dilution than to lower them.

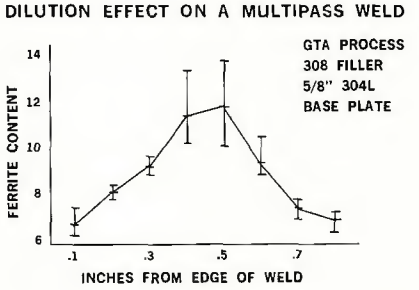


Fig. 10 — Ferrite contents in a multipass weld. Dilution ranges from relatively high levels (beads just adjacent to the base plate) to essentially zero (beads in the center of the weld face)

Fissuring of Weld Metals

Cracking sensitivity and fissuring sensitivity seem to be closely related in stainless weld metals, i.e., the analyses that are most crack sensitive are also the most fissure sensitive. However, there is one difference between cracking and fissuring fundamentals: the cracking of concern here is generally longitudinal centerline cracking or crater cracking, both of which occur during the final stages of the freezing cycle (this

paper will not cover the age hardening or stress relief cracking of heavily restrained 347 welds or some of the other causes of cracking); regarding fissuring, however, the consensus is that it occurs in welds during the reheating process when an additional bead is deposited next to or over an existing bead. Fissures are small cracks with a preferred orientation perpendicular to the axis of the weld and perpendicular to the direction of high residual stress. They are usually in the heat-affected zone (HAZ) in the prior weld, the area which has attained temperatures just below the melting point of the steel, and they may extend into the bead which caused them.

Except in very severe cases the great bulk of fissures seem to be small, below 1/16 in. in maximum dimension. In a very notch tough material such as austenitic stainless steel it would require very unusual service conditions for such small defects to adversely affect the service life of the structure. Small stress raisers of any type, such as notches or roughness on the surface, slag inclusions, corners or edges, i.e., any surface or internal irregularities, would be expected to have detrimental effects on fatigue life perhaps equivalent to the effect of fissures of 1/16 in. maximum dimension or smaller. This complex topic will not be discussed further in this paper.

From a practical viewpoint, millions of pounds of multipass fully austenitic weld metal of types 310, 316, 316L, and more special types such as 320 and 330 have been used in production weldments over the past forty years with virtually no failures attributable to fissures, yet virtually all of these weldments do contain fissures. Until recently I was not aware of any failures due to fissures, but I have since heard of one case involving a fully austenitic columbium-bearing weldment in which a fissure is reported to have led to a stress corrosion failure. If any reader is aware of reasonably well documented instances where fissures have resulted in a failure, I would appreciate receiving as complete a description of them as possible.

Two subcommittees of the WRC High Alloys Committee, the Discontinuities Subcommittee and the Advisory Subcommittee, have recently begun a joint industry cooperative program to establish quantitatively the relationship between fissures and the ferrite content of weld deposits. Covered electrodes of Types 308, 308L, 309, 316, 316L, 318, and 347 were made in several laboratories with production formula coatings and aimed at undiluted deposit ferrite levels of 0, 2, 4, and 6 FN; in addition, commercial 16-8-2 covered electrodes with rather low deposit ferrite contents were included. These electrodes were used to prepare pads on Type 304L base plate supplied by ORNL to a number of industrial laboratories. The pad shape is shown schematically in Fig. 11. In practice the deposits were two layers high and six beads wide. The location and orientation of the fissures was typically as shown in Fig. 11 and described earlier in this paper. Fissures are also presumably present at lower levels between beads and in the top portions of the first layer, but these are not shown on the diagram because they have not been documented in this particular study.

The pads, which were welded, prepared, and examined by the cooperating industrial laboratories, are now at the University of Tennessee where Professor Carl Lundin and a graduate student are making a more detailed study of them. This program, under WRC sponsorship, will continue through 1974. Figure 12 displays two photomicrographs supplied by Professor Lundin of fissures in unbent ends of Type 308 weld metal pads. To date, no fissures have been observed in weld deposits on any of the grades containing an average of 3.0 FN or more. Professor Lundin reports that when fissures are observed they are in local ferrite-free areas, even though the specimen may contain up to 3 FN on the average. The fissures shown, and the general fissures reported, have been less than 1/16 in. long and usually are under 1/32 in. long. The photomicrographs again illustrate the extreme fineness of the austenite subcell structure.

A report will be made on the overall program and the University of Tennessee findings. This may issue as a part of the coming WRC Bulletin or as a separate publication.

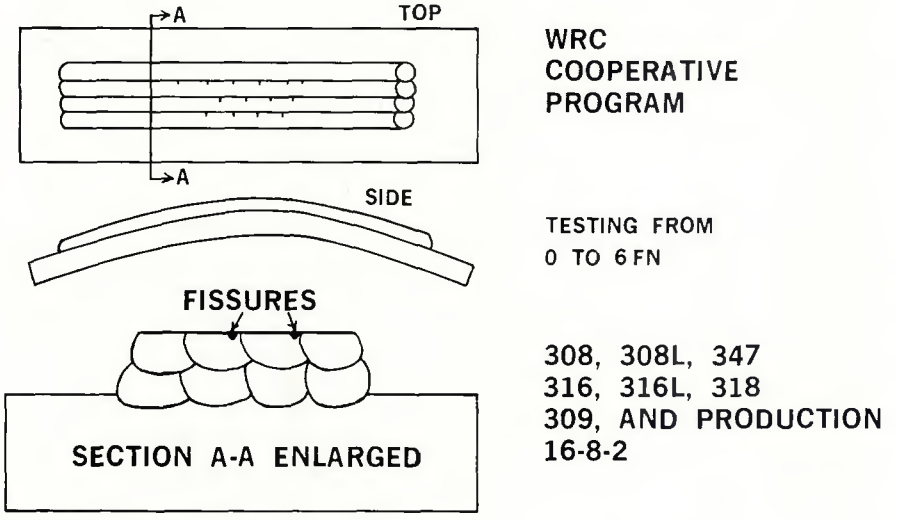


Fig. 11 — Schematic representation of the fissure-bend test used by the WRC High Alloys Committee to investigate the effect of ferrite content of various weld metals on fissuring tendency

Research Needs Related to the Ferrite Content of Weld Metals

It is obvious that more needs to be known about this subject. It seems worthwhile to briefly outline some of the more important needs.

Fundamentals

A better understanding is needed of the fundamentals of ferrite, how and when it forms, and why it has the effect that it does on cracking and fissuring.

A second basic need is to determine whether fully austenitic deposits that are free of fissures, or at least less subject to fissures than present analyses, can be obtained while retaining the necessary creep rupture performance and freedom from undesirable phase changes at the service temperatures and times required, for example, in the new atomic power plants, which clearly must be completely safe.

Here should be mentioned the excellent work being done by F. C. Hull (Ref. 18), of which the referenced article is only a recent sample. Other investigators, for example I. Masumoto (Ref. 3), should be encouraged to con-

tinue what in his case is an imaginative line of investigation.

Other approaches to establishing more accurately the true ferrite content of welds are also of interest. While two good approaches have been discussed in this paper, other solutions, if available, should be investigated. For research purposes it is desirable to be able to more accurately establish the "true volume percent ferrite" of welds.

Effect of Fissures

Further information is needed on the possible effects of fissures. Have they caused failures in service, and, if so, under what conditions? Documented case histories are of interest and can be of major help in avoiding similar problems in the future.

The possible effect of fissures on fatigue has been considered by a number of organizations in studies that are proprietary or restricted in nature. While they have been helpful, it is desirable to continue such studies so that fissures of additional sizes, orientations and densities can be generated on a laboratory basis to allow a more comprehensive study of their influence on fatigue and on high temperature performance. It is hoped that the present work of the Discontinuities Subcommittee of the High Alloys Committee will lead to an expanded program along these lines.

Effect of Ferrite as Such

There is a need to know more about the effect of ferrite on high and low temperature properties of stainless weld metals. Work such as that by Goodwin, Cole, and Slaughter (Ref. 19) on the influence of ferrite on creep performance should be continued and expanded.

It is also necessary to follow any new lead pointing to ferrite as a problem from a corrosion viewpoint. There are no significant leads that I am aware of at this point, but any problems of which readers are aware should be brought to the attention of such groups as the WRC High Alloy Committee for study.

Summary — Ferrite in Weld Metals and Its Measurement

1. Ferrite may be beneficial or detrimental. Past experience on the specific application should be relied upon to judge whether ferrite-bearing or ferrite-free deposits are most suitable. In new or less well documented uses, the merits of ferrite-bearing versus ferrite-free deposits should be considered and tested.

2. Millions of pounds of fully austenitic materials such as Types 310, 316, and 316L have given excellent field service for over 30 years. Ferrite is not essential in all uses.

3. Ferrite is helpful in preventing cracking and fissuring during fabrication, and in strengthening the weld.

4. Ferrite is detrimental in a few special corrosion situations involving molybdenum-bearing grades, in cryogenic service, and perhaps in some high temperature applications. These areas should be judged by specialists in the subject.

5. The term Ferrite Number, first sponsored by the WRC, is being adopted widely as the best accurately defined means of specifying the ferrite content of austenitic stainless steel welding materials.

6. A substantial range in test values must be expected in measuring the ferrite content from lots of welding products and in production welds. Information presented in this paper gives the user sound quantitative data on this variability under various conditions.

7. The two constitution diagrams which are widely used for the calculation of ferrite content from deposit chemistry are both very useful and, in fact, essential tools for electrode manufacturers and for special situations such as considering the effects of dilution.

8. Constitution diagrams are less satisfactory than direct magnetic measurements on pads for lot control purposes, because their precision is not as good as results obtained with direct measurement. The major problem is obtaining the chemistry with sufficient precision to allow a good calculation. A standard deviation of over 1 FN should be expected due to the chemical analysis variable alone.

9. Comparisons between calculated ferrite and measured ferrite obviously incorporate the variations (defined as standard deviations if possible) of both the calculation method and the measuring method.

10. Magnetic instruments calibrated to the WRC Ferrite Number scale are available and are the best practical means of measuring the ferrite content of welds. The calibration of the instrument is the crucial factor, and care must be exercised in calibrating and maintaining calibration.

11. With controlled pad welding, preparation and measuring procedures, standard deviations of approximately 0.75 FN to 1 FN are attainable from 0 to 8 FN weld metal. Above 8 FN the expected standard deviation increases in direct proportion to the increase in mean FN. Large numbers of tests indicate that a normal distribution curve may be expected.

12. Changing the pad welding and preparation procedures with manual electrodes changed the mean ferrite by 3 FN over the range of four procedures studied.

13. Field use of electrodes in a wide variety of joint sizes and shapes that produce undiluted weld metal will logically result in a spread in mean ferrite contents as large as 3 FN, since field uses should at least match the range found in the laboratory tests on undiluted weld metal.

14. Allowing for the precision of the welding and measuring process, the full expected range on a specific lot of 308-16 electrodes in a variety

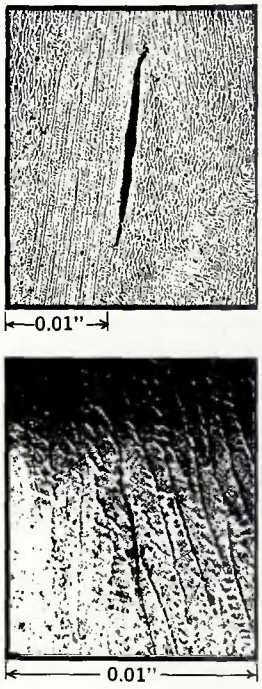


Fig. 12 — Fissures in unbent sections of the fissure-bend specimens described in Fig. 11

of welds is about 6.5 FN based on the data presented here.

15. Appreciable changes in heat input in the commercial SMA, GMA, and GTA welding processes do not have a significant effect on the mean Ferrite Number of the welds.

16. Dilution with base metal can have a significant effect in either increasing or decreasing the ferrite content of diluted welds, depending on the proportion and ferrite potential of the base metal.

17. Nitrogen pickup during welding can and in many instances does reduce the ferrite content. The relationship of process variables to nitrogen pickup must be understood and controlled.

18. Conclusions regarding the control of ferrite through specifications, acceptance tests, and field tests.

A. Ferrite content should be specified in terms of Ferrite Number, using instruments calibrated to read in Ferrite Number.

B. Ferrite controls should not be overdone. They are expensive and time consuming and should not be applied unless they are essential to the end use.

C. At all stages, recognize the range of values which must be expected in the ferrite content obtained in the tests, using the data supplied in this paper. Specification requirements and test requirements at all stages of testing should allow for these ranges.

D. Direct (magnetic) measurements are preferred to calculated values because of better precision.

E. The pad welding, preparation, and measurement procedures must be defined when the welding materials are purchased to specific ferrite requirements.

F. Do not combine both direct and calculated requirements. This only increases the potential for conflicting results and delays.

G. Because of the ranges in results which must be expected, provide for multiple retests in cases where results are outside of the specification requirements.

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