Extension of the WRC Ferrite Number System

Extended Ferrite Numbers (EFN) are identical to Welding Research Council Ferrite Numbers 0 to 28 and, in addition, cover the full range of duplex austenite-ferritic to fully ferritic material

BY D. J. KOTECKI

ABSTRACT. A four step procedure is described that permits a Magne-Gage with its no. 3 magnet to be used for ferrite measurements above the 28 FN limit imposed by the Magne-Gage spring strength. This procedure defines Extended Ferrite Numbers (EFN) which are identical to the WRC Ferrite Numbers from 0 to 28 but can cover the full range of duplex austenite-ferrite alloys up to fully ferritic material. When the no. 3 magnet strength range is suitably restricted, the procedure gives instrument-to-instrument reproducibility no worse than ±7.5% of the average EFN of a particular sample.

It is found that fully ferritic steels in general give EFN values which are a function of their iron content. The EFN of a sample can be normalized using the EFN of a fully ferritic sample of the same iron content. This normalization procedure brings reproducibility of results even to a Magne-Gage whose no. 3 magnet is outside the normal strength range. The Normalized Ferrite Numbers (NFN) of cast alloys are shown to agree with the volume percent ferrite determined by metallographic means.

The effects of ferrite content on mechanical properties of duplex austenite-ferrite Type 312 stainless steel weld metal are examined.

Introduction

In order to meet the need for a system to measure weld metal ferrite that would give reproducible results from laboratory to laboratory, the Welding Research Council's Advisory Subcommittee on Welding Stainless Steels undertook a long and arduous study of weld metal ferrite measurement. This work culminated in the 1974 publication of AWS A4.2-74 *Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic Stainless Steel Weld Metal* (Ref. 1). The method defined in AWS A4.2-74 covers the range from zero to about 28 FN, which includes the more common austenitic stainless weld metals such as Types 308(L), 309(L), 316(L) and 347. This method abandons the notion of percent ferrite because no suitable method for determining volume percent ferrite in weld metal exists. Instead, it defines an arbitrary FN scale based upon magnetic attraction between a standard magnet and a mild steel substrate electroplated with a non-magnetic coating (NBS coating thickness standards). The limit of approximately 28 FN is imposed by the strength of the spring in the Magne-Gage instrument.

There are certain stainless weld metal types which cannot be characterized as to ferrite content using the procedure of A4.2-74. These include Type 312 and the duplex austenite/ferrite alloys currently being proposed for seawater, oil field and chemical processing applications. The duplex austenite/ferrite alloys combine yield strengths of approximately twice the levels of common austenitic stainless steels with resistance to stress corrosion cracking in chloride-containing environments (Ref. 2). Weld metals in these materials are normally above 28 FN and are in the vicinity of "50% Ferrite" on the Schaeffler Diagram. It is known that excessive ferrite in duplex weld metals damages ductility and toughness (Ref. 3). But since these ferrite levels cannot be measured, no one can specify what constitutes "excessive ferrite". Because of increasing interest in these duplex alloys, a need exists to devise a system of ferrite measurement for weld metals in these alloys. Such a method is developed herein.

The International Institute of Welding (IIW) has proposed a method of measuring weld metal ferrite that agrees with A4.2-74 but does not require use of the Magne-Gage (Ref. 4). Instead, it permits measurement of the attractive force between a standard magnet (identical to a Magne-Gage no. 3 magnet) by any suitable means (such as a beam balance or a Magne-Gage) and calibration with the same NBS coating thickness standards of A4.2-74. In principle this method would be free of the approximately 28 FN maximum imposed by the spring strength of the Magne-Gage.

The author has previously shown that Magne-Gage no. 3 magnets can be used with the IIW method and a beam balance to measure ferrite on weld metals in the 0-28 FN range; the results obtained agree excellently with those obtained directly from a Magne-Gage (Ref. 5). The work has further shown with a total of 21 Magne-Gage no. 3 magnets that a straight line calibration can be developed for each magnet. The calibration line, pinned to zero, for each of the 21 magnets had a slope of about 5 FN per gram (the range was 4.49 to 5.81 with a mean of 4.95 and a standard deviation of 0.35).

Principle of the EFN System

The principle of the Extended Ferrite Number (EFN) system proposed herein is to measure the attractive force between a Magne-Gage no. 3 magnet and the sample, and assign an EFN by extrapolating the calibration line beyond the range of 0–28 FN. In other words, the EFN is obtained by multiplying the attractive force measured on the sample by the slope of the calibration line. Over the range 0–28 EFN, the EFN so determined is identical with the FN determined by AWS

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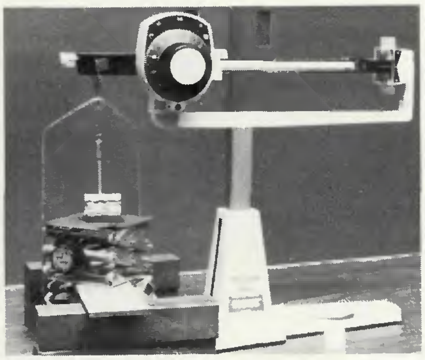

Fig. 1—Torsion spring beam balance with Magne-Gage no. 3 magnet used to measure TF on a secondary weld metal standard

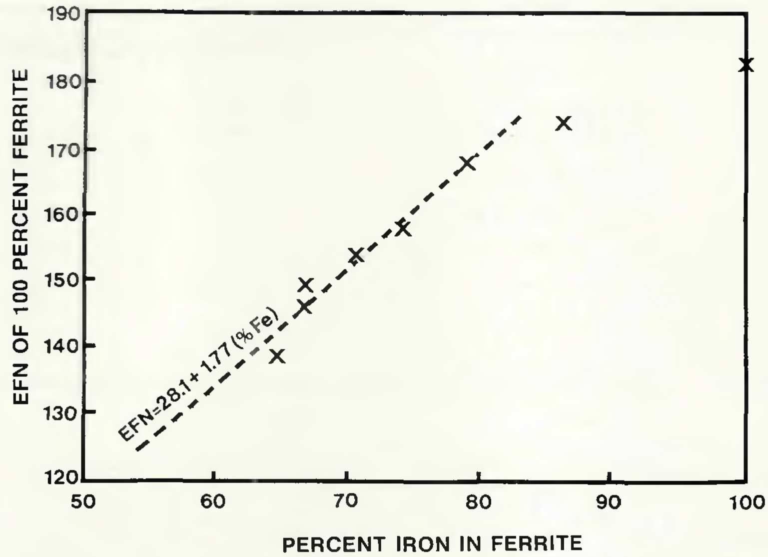

Fig. 2—EFN vs. percent iron in fully ferritic steel samples using beam balance procedure with Magne-Gage P5831 no. 3 magnet. Note straight line fit to all but the two datum points on the far right; this straight line was used in preparing Fig. 4

A4.2-74 or by the IIW method. The principle can be applied either by using a balance beam following the IIW method or by using a Magne-Gage following the WRC-AWS method with suitable modifications.

Method 1—Balance Beam

A single pan beam balance was used for the earlier work in this study. The balance is capable of measuring 0-310 grams in increments of 0.01 gram. The range of 0-11 grams is covered by a torsion spring and Vernier scale. Provision is made for adding counterweights in increments of 10 grams and 100 grams to cover the full range of the balance.

The no. 3 magnet from Magne-Gage #P5861 was attached to the pan hanger of the beam balance and a null reading was determined. A platform with a height adjusting screw was suspended independent of the balance over the pan. The sample to be measured for attractive force (TF) to the no. 3 magnet was placed on the platform and weighted if necessary to prevent the magnet from lifting it.

The platform was raised to bring the specimen into contact with the magnet, then lowered to bring the balance indicator to the balance position. The force on the balance torsion spring (and counterweights if necessary) would then be increased until the force necessary to pull the magnet loose from the specimen (corrected by the null reading) was determined as the TF. Figure 1 shows the arrangement used in measuring TF on a secondary weld metal standard.

In practice, this system was found to have a drawback in that the balance beam system is sensitive to vibration. Very slight vibrations would cause the magnet to detach prematurely from the specimen giving an artificially low TF. It was found necessary to repeat the readings at each point on the specimen several times and accept only the highest value of TF at that point as a true reading. Then the specimen would be moved to sample another point on it. The highest TF values at a minimum of 3 separate locations on the specimen surface for NBS coating thickness standards, and 5 separate locations for all other specimens, would then be averaged to arrive at a TF value for that specimen.

Using the set of 8 NBS coating thickness standards from the Magne-Gage, whose serial number is P5861, and its no. 3 magnet, the data of Table 1 was obtained to provide the calibration line for this method. Then the FN values assigned to the coating thickness standards according to AWS A4.2 and the measured TF for each FN were used to compute the slope of the calibration line pinned to zero that best fits these data. This slope m is calculated by:

$$m = \frac{\Sigma(FN_i)\,(TF_i)}{\Sigma(TF_i)^2} \qquad (1)$$

For the data of Table 1, m = 5.11. Then for a given TF, an FN can be calculated from:

$$FN = 5.11\ TF \qquad (2)$$

The measured TF values of Table 1 were used in equation (2) to calculate FN for each TF in Table 1 to show how well the data is fit by a straight line pinned to zero as above. The calculated FN's are included in Table 1 and show an excellent agreement with the assigned FN values. They are well within the calibration requirements of AWS A4.2.

The method was then used on 3 secondary weld metal standards with previously assigned FN values. The FN values obtained from the TF measurements on these samples were also well within the calibration limits of AWS A4.2.

EFN Measurements With the Balance Beam. Seven samples of fully ferritic wrought stainless steels of different compositions were obtained from suppliers. These ranged from 18 Cr-2 Mo (Type 444) to 29 Cr-4 Mo-2 Ni. In addition, weld samples of Type 409 stainless steel (13 Cr-0.5 Ti) and ingot iron were obtained. All of these materials are 100% ferrite except for minute traces of various carbo-nitrides and other inclusions.

These samples were evaluated with the beam balance system to observe how the TF and EFN would vary with composition of the ferrite as the only

Table 1—Calibration Data for the P5861 Magne-Gage No. 3 Magnet Using a Beam Balance

NBS coating thickness standard number	A4.2 assigned FN	Average TF, grams	Calculated FN from FN = 5.11 TF
1312	26.2	5.15	26.3
1313	22.0	4.31	22.0
1314	15.2	2.99	15.3
1315	11.7	2.27	11.6
1316	9.9	1.93	9.9
1317	7.25	1.37	7.0
1318	5.3	1.02	5.2
1319	3.25	0.60	3.1

Table 2—Ferrite Measurements on 100% Ferrite Materials, Beam Balance Procedure

Sample number	Nominal composition	Calculated iron, %	TF with P5861 Magne-Gage no. 3 magnet, gms	EFN = 5.11(TF)
95928	29Cr-4Mo-2Ni	64.1	26.92	138
8-4638	29Cr-4Mo	66.4	28.63	146
1783C	25Cr-5Ni-3.5Mo	66.4	29.25	149
2125A	25Cr-3.5Mo	70.6	30.21	154
1274E	21Cr-3Mo	74.2	30.87	158
31606	18Cr-2Mo	77.7	32.39	166
U2	18Cr-2Mo	78.3	32.51	166
9317-448	13Cr-.5Ti	86.2	34.09	174
Ingot iron	Fe	100.0	35.89	183

variable. Compositions of each sample were obtained from the supplier except for the 409 weld metal, which was run in the author's lab.

A very clear trend in TF (and EFN) was noted on these samples when the amount of iron in each sample was calculated by subtracting the known alloy composition from 100%. The TF and EFN decrease consistently with decreasing percent iron, although each sample is essentially 100% ferrite. The data are shown in Table 2 and Fig. 2. The relationship appears to be parabolic, although it can be approximated by a straight line over a limited range.

Samples of stainless steel casting alloys CF8 (308) and CF8M (316) were obtained from the Steel Founders' Society. These samples have varying compositions to cover a range of ferrite contents from 0 to 48 volume percent as determined metallographically by point counting. The samples and analytical methods are completely described in the SFS report (Ref. 6). It should be noted that point counting is considered a valid method of measuring true volume percent of ferrite in castings, because the ferrite is relatively coarse and tends to be at least partly spheroidized. Point counting has not proved suitable for weld metal, however, because the ferrite tends to be extremely fine and irregularly shaped.

The casting alloy samples had been polished on 2 or more faces for the prior point counting work, and it was not clear which face corresponded to which ferrite data point in the SFS report. So the procedure adopted was to make EFN measurements on each polished face of each sample, average the results for all the polished faces on a given sample, and compare the results with the averaged reported volume percent ferrite data for the given sample.

Direct FN Magne-Gage measurements using a no. 3 magnet were also made on the polished faces and averaged as well. In the process of making measurements of FN by the AWS procedure or EFN by the beam balance procedure, a slight tendency for the magnet to "hunt" (presumably seeking ferrite islands on the casting surface) was noted. The data obtained as described above are given in Table 3.

It can be seen from Table 3 that the EFN values obtained by the beam balance procedure agree quite well with the FN values obtained with a Magne-Gage. It can also be seen that the FN and EFN values are numerically greater than the volume percent ferrite measured by point counting.

A graphical display of EFN vs. volume percent ferrite by point counting for the casting alloy samples shows a straight line relationship—Fig. 3. A regression fit of a straight line to the data of Fig. 3 shows a near-zero intercept, a slope of about 1.4 and a correlation of 0.99. This is an excellent fit and seems to indicate that the EFN (or FN) overestimates the volume percent ferrite in these alloys by about 40%.

Figure 2 indicates that the magnetic response of ferrite in iron-base material is strongly a function of the composition of that ferrite. In particular, the attractive force to a Magne-Gage no. 3 magnet is a function of the weight-percent of iron in the ferrite. One might know the composition of the ferrite, and there might be no effect of ferrite shape and distribution on its magnetic response. Then from the ratio of the magnetic response of an

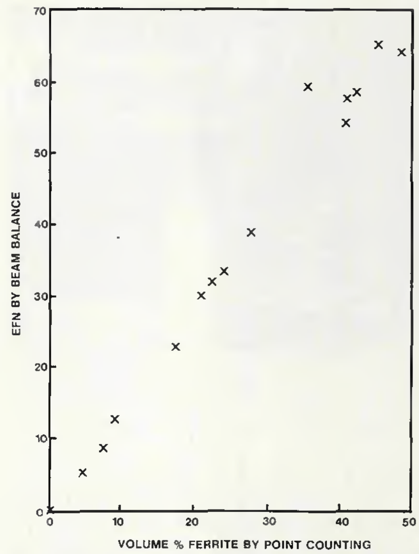

Fig. 3—EFN vs. volume-% ferrite for stainless casting alloys

unknown sample (its EFN, for example) to the magnetic response of a sample of 100% ferrite of the same composition as the ferrite in the unknown sample, one could directly calculate the volume percent ferrite in the unknown sample.

Solidification theory tells us that under ordinary conditions of cooling, duplex austenitic-ferritic materials experience a partitioning of alloying elements between ferrite and austenite. This occurs such that the composition of the ferrite in a duplex alloy is not the same as the overall alloy composition. For example, Lyman (Ref. 7) has shown by scanning transmission electron microscopy (STEM) that chromium and nickel in a Type 304L stainless weld metal of about 18.75 Cr, 9.75 Ni will redistribute themselves so that the ferrite is about 26 Cr, 4 Ni. However, it can be inferred from the data of Lyman that the iron content of the ferrite is nearly the same as that of the overall alloy despite the very pro-

Table 3—Ferrite Measurements on Stainless Casting Alloy Samples

Sample number	Average volume percent ferrite by point counting (Ref. 6)	Average FN by AWS procedure with Magne-Gage	Average beam balance TF, gms	Average EFN by beam balance procedure
45T	0.23	0.4	0.03	0.2
6882	4.40	5.8	0.99	5.1
6851	7.04	8.7	1.66	8.5
3492	8.98	12.2	2.44	12.5
3496	17.16	22.5	4.46	22.8
3491	20.85	Off scale	5.87	30.0
3485	22.46	Off scale	6.24	31.9
3494	23.94	Off scale	6.51	33.3
3499	27.98	Off scale	7.60	38.8
3631	35.56	Off scale	11.58	59.2
3488	40.78	Off scale	10.57	54.0
3611	41.30	Off scale	11.27	57.6
3501	42.43	Off scale	11.46	58.6
3489	45.45	Off scale	12.75	65.2
3495	48.64	Off scale	12.59	64.3

Table 4—Ferrite Ratios or NFN's For Cast Alloys

Sample no.	Alloy	Fe, %	Equation (3) EFN at 100% ferrite	EFN from Table 3	NFN = 100 × EFN / EFN @ 100% ferrite	Avg. volume % ferrite by point counting
45T	CF8M	64.41	142.0	0.2	.14	.23
6882	CF8	68.34	149.0	5.1	3.42	4.40
6851	CF8M	66.27	145.3	8.5	5.85	7.04
3492	CF8M	67.12	146.8	12.5	8.51	8.98
3496	CF8	68.84	149.9	22.9	15.28	17.16
3491	CF8M	65.69	144.3	30.1	20.86	20.85
3485	CF8M	65.67	144.2	32.0	22.19	22.46
3494	CF8	69.38	150.8	33.4	22.15	23.94
3499	CF8	68.91	150.0	39.0	26.00	27.98
3631	CF8	70.04	152.0	59.4	39.08	35.56
3488	CF8M	65.70	144.3	54.2	37.56	40.78
3611	CF8M	64.16	141.6	57.8	40.82	41.30
3501	CF8	69.12	150.4	58.8	39.10	42.43
3489	CF8M	63.83	141.0	65.4	46.38	45.45
3495	CF8M	64.99	143.0	64.2	44.90	48.64

nounced redistribution of elements such as Cr and Ni.

If this is the case, then the information in Table 2 and Fig. 2 can be used to estimate the magnetic response or EFN of 100% ferrite having an iron content similar to the iron contents of the CF 8 and CF 8M castings. Then if the effect of ferrite shape and distribution on magnetic response were negligible, one could estimate the true volume fraction of ferrite in an unknown sample by the ratio of its EFN to the EFN of 100% ferrite of the same iron content.

Figure 2 gives the appearance of a slightly parabolic relationship between the EFN of 100% ferrite and the percent iron in the ferrite. The casting alloys of Table 3 cover a nominal iron content range from their compositions (given in Reference 6) of 63.83 to 70.04% iron. Over the range of about 64 to 78% iron, the data of Fig. 2 can be fit by a straight line with very good correlation. This regression line (omitting the ingot iron and 13 Cr-0.5 Ti points from the data of Table 2) is given by:

$$EFN = 28.1 + 1.77\ (\%\ Fe) \qquad (3)$$

with a correlation of 0.9785. This line is shown on Fig. 2.

Using the composition data of Aubrey et al. (Ref. 6), equation (3) can be used to estimate the EFN of 100% ferrite of the same iron content as the casting alloys of Table 3. When this is done and the ratio of the measured EFN of each casting alloy to the EFN of 100% ferrite of the same iron content is calculated and converted to percent by multiplying by 100, the result is an almost perfect 1:1 correlation between that ratio converted to percent and the volume percent ferrite measured by point counting for each casting alloy. These results are given in Table 4 and shown graphically in Fig. 4.

The last result is rather exciting. This is because it seems to indicate that this ratio converted to percent (which will hereafter be referred to as the Normalized FN or NFN) numerically agrees well with the volume percent ferrite of casting samples. However, the reader is cautioned that there is no assurance that such agreement would be obtained with weld metal since, as has been noted previously, point counting is unsuitable for measuring ferrite in weld metal due to the fineness and irregular shape of weld metal ferrite. Nevertheless, the results with the casting alloys encouraged the author to explore further the idea of Extended Ferrite Numbers and their possible application to the measurement of stainless steel weld metal ferrite.

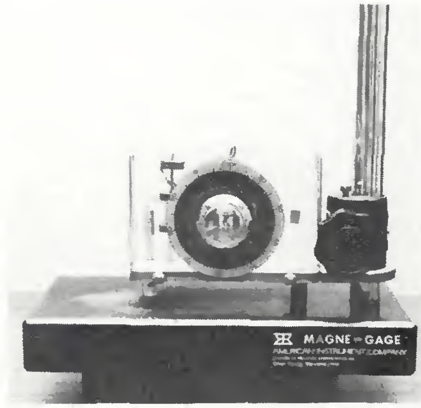

Fig. 5—A standard Magne-Gage. The white dial used for FN measurements is visible

Method 2—EFN Measurements With a Magne-Gage

As noted previously, while a beam balance can be used to make FN measurements according to the IIW method or EFN measurements as described above, its use is inconvenient and subject to some interpretation of readings due to the tendency for very slight vibrations to cause premature detachment of the magnet from the specimen as the load is increased. Experience with the Magne-Gage over perhaps 10 years by numerous users has shown very little tendency

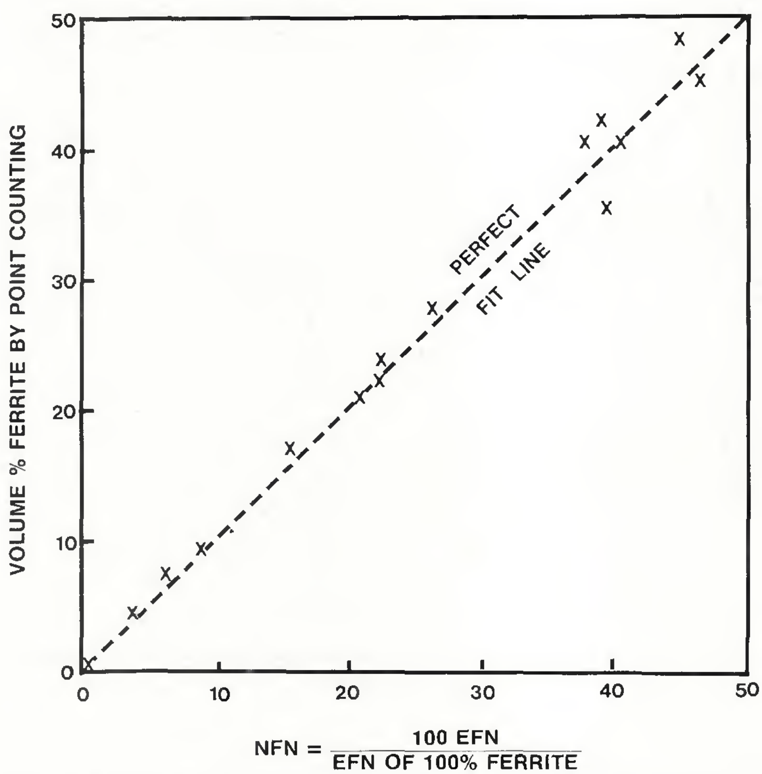

Fig. 4—Volume-% ferrite by point counting vs. normalized ferrite number (NFN) for CF8 and CF8M casting alloys

for premature detachment. This seems due to the design of the Magne-Gage which effectively damps out vibrations. Clearly, then, it would be desirable to use a Magne-Gage, if possible, for EFN measurements, in preference to use of a beam balance.

Discussions with the designers of the Magne-Gage indicated that the limitation of spring strength could be overcome by adding counterweights to the balance beam of the instrument. The spring and corresponding white dial readings will cover a range of about 5 to 6 grams of force. By adding appropriate counterweights, one can then cover any expected TF, provided one first determines a scaling factor for the counterweights and another for the white dial readings of the instrument. Figure 5 shows a Magne-Gage with its white dial scale.

A four-step procedure was devised to calibrate a Magne-Gage with its no. 3 magnet to obtain EFN values consistent with the beam balance method described previously. These steps are:

1. Develop a straight line relation between the Magne-Gage white dial reading (WD) and the force in grams (TF) required to pull the magnet from a specimen or raise the magnet with a known weight attached past the balance point of the Magne-Gage.
2. Develop a straight line relation pinned to zero between the TF and the Ferrite Number (FN) assigned to a set of eight NBS Coating Thickness Standards by AWS A4.2.
3. Determine the scale factor (M) between counterweights (W) hung from a small hole about 1½ in. (38 mm) from the Magne-Gage balance beam fulcrum opposite the magnet hanger and weights hung from the magnet.
4. Combine the relations of steps 1, 2 and 3 to produce a relation of the EFN to the white dial reading (WD) and the added counterweight (W).

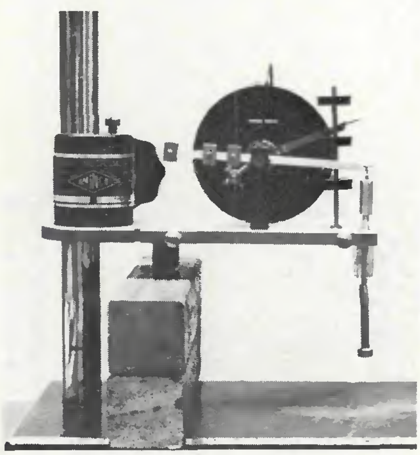

Fig. 6 — Rear view of Magne-Gage with cover removed and a small weight hanging from the no. 3 magnet

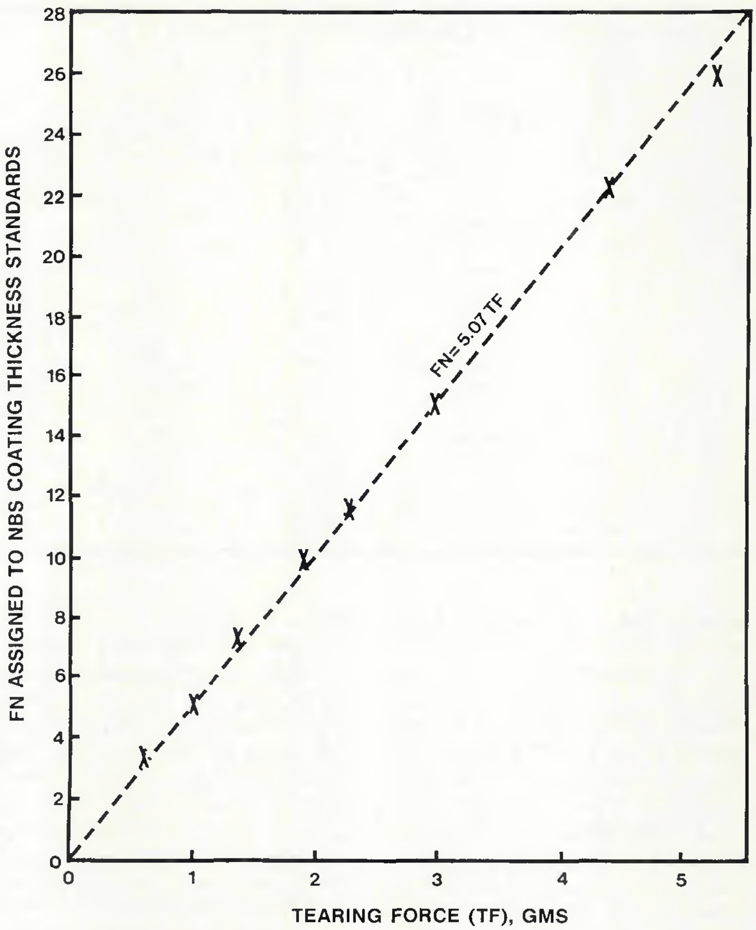

Fig. 7 — FN vs. tearing force for Magne-Gage P5861

Once a calibration has been made, it is only necessary to check that the instrument calibration is unchanged according to AWS A4.2 before beginning to use it for EFN measurements, although a check on a fully ferritic sample of previously assigned EFN is recommended.

Details of the four-step calibration procedure follow.

Step 1. Prepare a set of iron-base magnetic weights covering the range of about ½ gram or less to about 6 grams in increments of 1 gram or less. Determine the weight of each to the nearest 0.01 gram. It is necessary that each weight be small enough at one end to fit into the hole in the plastic collar around the Magne-Gage magnet through which the magnet would contact a test specimen.

Hang each weight, in turn, from the Magne-Gage no. 3 magnet and adjust the white dial of the Magne-Gage so that the magnet is pulled out of the hole in the plastic collar a short distance. Then increase the spring tension by slowly turning the white dial clockwise until the spring tension exactly balances the weight. Read and record the white dial reading (WD) at this point along with the weight. This weight is equal to the force (TF) applied when the magnet is pulled from a weld specimen at this white dial reading.

Repeat this procedure for each of the weights. A table of white dial readings vs. weights will be obtained. Table 5 was so obtained with Magne-Gage no. P5861. Figure 6 shows the Magne-Gage with a small weight hung from the no. 3 magnet.

Then a straight line is fitted to this tabular data by the method of least squares. Many pocket calculators can do this simply. This relation will have the form:

$$TF = C_o - C_1 (WD) \quad (4)$$

For the P5861 Magne-Gage, the regression line obtained with the above data is:

$$TF = 5.527 - 0.050 (WD) \quad (5)$$

Table 5—Weight or TF vs. WD for Magne-Gage P5861

Weight number	1	2	3	4	5	6	7	8
Weight, grams	0.00	0.50	1.02	1.98	2.78	3.90	4.56	5.46
WD	110	100	90	71	55	33	19	1

Table 6—TF vs. Assigned FN of NBS Coating Thickness Standards with Magne-Gage P5861

Coating thickness standard no.	1319	1318	1317	1316	1315	1314	1313	1312
Assigned FN	3.25	5.3	7.25	9.9	11.7	15.2	22.0	26.2
WD	98	90	83	72.5	65	51	23	6
TF from equation (5), gms	.61	1.01	1.365	1.89	2.27	2.97	4.37	5.23

with a correlation of better than 0.9999.

Step 2. Obtain a set of NBS coating thickness standards. Determine the FN assigned to each standard from the table in AWS A4.2. Determine the WD corresponding to each FN for the set of standards. Convert the WD to a corresponding TF using equation (4) above. This generates a new table which has a TF corresponding to each FN. Table 6 was so obtained with Magne-Gage P5861.

Determine a straight line relation pinned to zero between FN and TF. This relation has the form:

$$FN = m\ (TF) \qquad (6)$$

The slope m of this line is calculated by equation (1) noted previously. For the data of the table above, m = 5.07 and the relation is:

$$FN = 5.07\ (TF) \qquad (7)$$

Figure 7 shows the data of Table 6 along with equation (7).

Step 3. The no. 3 magnet of a Magne-Gage hangs from a balance beam. The hanging point of the magnet is about 2 in. (51 mm) from the fulcrum. There is a small hole in the balance beam on the side of the fulcrum opposite the magnet and about 1½ in. (38 mm) from the fulcrum. The manufacturer of the Magne-Gage has indicated to the author that this hole is specifically intended for hanging counterweights to extend the working range of the Magne-Gage.

If the magnet was exactly 2 in. (50.8 mm) from the fulcrum and the hole was exactly 1½ in. (38 mm) from the fulcrum, then by the lever principle, a counterweight W_2 at the hole would exactly balance a weight W_1 hung from the magnet of:

$$W_1 = 0.75\ W_2$$

In fact, the dimensions may not be exactly 2 and 1½ in. (51 and 38 mm) respectively, so that it is necessary to determine a scaling factor M such that:

$$W_1 = M\ W_2$$

This can be done by hanging a known weight W_1 from the magnet and a known counterweight W_2 from the hole and then adjusting the white dial to find the balance point. Figure 8 shows this arrangement. When balance is attained, the scaling factor M can be calculated from the force TF (calculated from equation (4) above) and the two weights:

$$W_1 - TF = M\ W_2 \qquad (8)$$

For the P5861 Magne-Gage, two different weight-counterweight pairs were used to calculate M from equation (8). The data and calculated values for M are given in Table 7. If the calculated values of M do not agree, they can be averaged.

Step 4. The FN defined by the A4.2 Standard is limited to about 28 FN. The FN calculated by equation (6) is not necessarily limited to 28 FN. By use of appropriate counterweights in the hole of the Magne-Gage balance beam, TF greater than the limit of the spring can be measured. This TF is the sum of the force applied by the counterweight and the force applied by the spring—that is:

$$TF = C_o - C_1\ (WD) + M\ (W_2) \qquad (9)$$

If an Extended Ferrite Number (EFN) is defined by extrapolating equation (6) beyond 28 FN and the TF is calculated from the white dial reading (WD) of the Magne-Gage and the added counterweight (W_2) as above, then the EFN is defined by:

$$EFN = m\ [C_o - C_1\ (WD) + M\ (W_2)\ ] \qquad (10)$$

For the P5861 Magne-Gage, equation (10) becomes:

$$EFN = 5.07\ [5.527 - 0.050\ (WD) + 0.7518\ (W_2)] \qquad (11)$$

Then once a particular Magne-Gage is calibrated as described above, it can be used to measure EFN's on materials from relatively low ferrite 300-series stainless steel weld metal through duplex austenite-ferrite alloys to fully ferritic materials. Within the range of 0-28 EFN, the EFN so obtained will be identical (within limits of experimental error) with the FN obtained according to AWS A4.2 or according to the recently drafted IIW Procedure soon to be published.

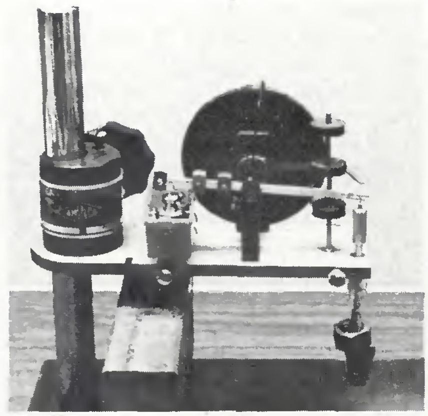

Fig. 8—Rear of Magne-Gage showing rather large weight hanging from the no. 3 magnet and a large counterweight hanging from the hole in the balance beam

Once the calibration procedure above was completed, the P5861 Magne-Gage was then used to measure EFN on the same fully ferritic steel samples described previously. These results are given in Table 8 along with the results from the beam balance procedure for comparison.

The results by the two procedures are nearly identical. It should be noted that the same no. 3 magnet was used for both procedures. Figure 9 is a graphical display of EFN on these samples by the Magne-Gage procedure vs. iron content of the samples. As with Fig. 2, a parabolic relationship is evident. Also as in Fig. 2, over the range of about 64 to 78% iron, the data of Fig. 9 can be fit by a straight line with very good correlation. This regression line (omitting the ingot iron and 13 Cr – 0.5 Ti data points from Table 8) is given by:

$$EFN = 20.5 + 1.91\ (\%\ Fe) \qquad (12)$$

This relationship is used later, as equa-

Table 7—Weight, Counterweight, White Dial Reading at Balance and Calculated Scaling Factor M, Magne-Gage P5861

Test	W_1, gms	W_2, gms	WD	M
1	5.46	4.50	69	0.7518
2	30.44	40.52	111	0.7518

tion (3) was used, for computing Normalized EFN values.

Reproducibility of the Magne-Gage Procedure

The utility of the WRC Ferrite Number system given in AWS A4.2 lies in the fact, established in countless tests, that Magne-Gage "A" at Company "X" will produce the same FN within a relatively small scatter band as Magne-Gage "B" at Company "Y". Table 9, which is reproduced from AWS A4.2-74, indicates that the instrument-to-instrument variation in Ferrite Number readings on a given weld metal sample will be on the order of ±5% of the average value for 95% of all instruments tested. It is this excellent reproducibility from instrument-to-instrument that makes the WRC Ferrite Number system the best available yardstick for measuring and/or specifying weld metal ferrite content.

It is, therefore, appropriate to consider the reproducibility of the EFN procedure developed herein. While the EFN procedure is based upon the WRC Ferrite Number system, it should be kept in mind that the EFN procedure is really an extrapolation of the FN system. Extrapolation tends to amplify errors. The author (Ref. 5) has shown that there is a very small systematic error from Magne-Gage to Magne-Gage that is linked to the strength of the magnet of the particular instrument.

A Magne-Gage with a stronger magnet tends to give a lower FN on weld metal than a Magne-Gage with a weaker magnet even though both Magne-Gages are calibrated to A4.2 using the same set of NBS coating thickness standards. As a result, the IIW has found it appropriate to define a strength range for the magnet used in its procedure (Ref. 4). This strength range amounts to a calibration line slope as developed in equation (1) of 5 FN per gram (±0.5). The AWS A4.2, on the other hand, sets no limit on magnet strength directly, relying upon the Magne-Gage manufacturer to supply magnets of appropriate strength. The magnets can lose strength with mishandling and possibly with age. This shifts the calibration line of the instrument sufficiently so that service by the manufacturer becomes necessary to meet the requirements of A4.2 and the magnet may be replaced at that time.

With these considerations in mind, the author obtained from various sources five Magne-Gages in addition to the P5861 Magne-Gage used initially. The complete four-step calibration procedure described above was performed with each Magne-Gage. An EFN was obtained for each of the nine 100% ferrite steels of Table 8 with each Magne-Gage.

In addition to the nine 100% ferrite samples, a duplex weld metal sample was prepared from a specially-produced flux-cored filler metal. This alloy is one of the compositions given in the literature (Ref. 2) as suitable for stress-corrosion cracking resistance in chloride environments. The weld metal composition obtained with this flux-cored filler metal is given in Table 10. The alloy is, therefore, nominally 68.9% iron.

This duplex alloy weld metal served as a check on reproducibility of results from one instrument to another. The EFN values with each Magne-Gage on the nine 100% ferrite samples and on the duplex alloy weld metal are given in Table 11. In addition, an EFN for 100% ferrite of the same iron content as that of the duplex alloy weld metal was calculated for each Magne-Gage as done earlier with the cast alloys in the beam balance procedure. Then an NFN for the duplex alloy weld metal could be calculated as well. All of these results are also included in Table 11 along with the slope of the calibration line for each Magne-Gage.

It will be noted in Table 11 that the magnet strength of one Magne-Gage (P6443) is well outside the allowable strength range of the IIW procedure for FN measurements (though acceptable according to AWS A4.2). It should be noted that a large numerical value for the slope of the calibration line indicates a weak magnet, while a numerically small slope indicates a strong magnet. As predicted by the author's previous work (Ref. 5), the very weak magnet of P6443 produces numerically much larger values

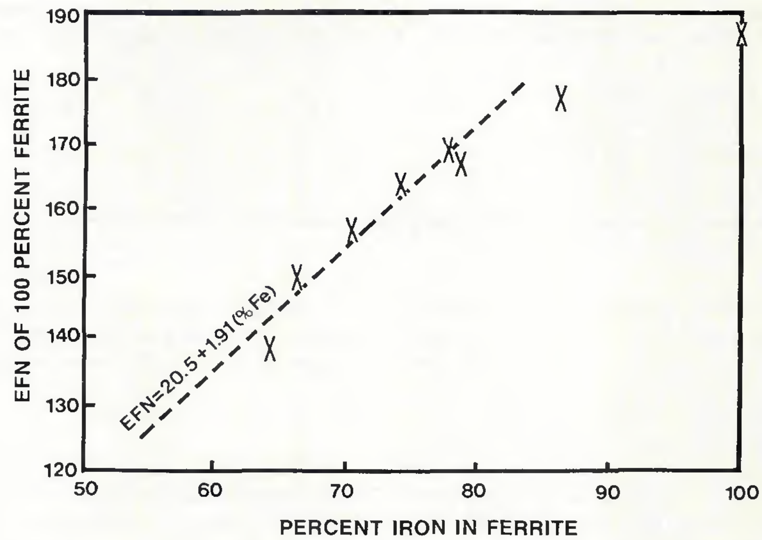

Fig. 9—EFN vs. percent iron in fully ferritic steel samples using Magne-Gage procedure, Magne-Gage P5861. Compare with Fig. 2

Table 8—Ferrite Measurements on 100% Ferrite Samples with the Magne-Gage Procedure and, for Comparison, with the Beam Balance Procedure, in Both Cases using the P5861 No. 3 Magnet

Sample number	Nominal composition	Iron, %	EFN by Magne-Gage	EFN by beam balance (from Table 2)
95928	29Cr-4Mo-2Ni	64.1	139	138
8-4638	29Cr-4Mo	66.4	149	146
1783C	25Cr-5Ni-3.5Mo	66.4	149	149
2125A	25Cr-3.5Mo	70.6	156	154
1274E	21Cr-3Mo	74.2	163	158
31606	18Cr-2Mo	77.7	169	166
U2	18Cr-2Mo	78.3	168	166
9317-448	13Cr-.5Ti	86.2	177	174
Ingot iron	100 Fe	100.0	187	183

Table 9—Expected Range of Variation in Measurements with Calibrated Magne-Gages (reproduced from AWS A4.2-74)

Ferrite Number range	67% of the instruments	95% of the instruments
0-10	±0.30 FN	±0.60 FN
over 10 to 18	±0.35 FN	±0.70 FN
over 18	±0.45 FN	±0.90 FN

Table 11—Tests of Reproducibility of the Extended Ferrite Number System from Magne-Gage to Magne-Gage[a]

Sample number	Nominal composition	Iron, %	EFN by Magne-Gage P5861	EFN by Magne-Gage P4930	EFN by Magne-Gage P6443	EFN by Magne-Gage 19304-51	EFN by Magne-Gage P6261	EFN by Magne-Gage 18032-106	Average EFN all Magne-Gages	Average EFN, Magne-Gage P6443 omitted
95928	29Cr-4Mo-2Ni	64.1	139	127	169	132	145	133	141	135
8-4638	29Cr-4Mo	66.4	149	136	179	140	152	143	150	144
1783C	25Cr-5Ni-3.5Mo	66.4	149	137	180	141	153	144	151	145
2125A	25Cr-3.5Mo	70.6	156	142	186	145	160	150	157	151
1274E	21Cr-3Mo	74.2	163	149	196	152	168	157	164	158
31606	18Cr-2Mo	77.7	169	154	204	158	172	162	170	163
U2	18Cr-2Mo	78.3	168	152	203	157	172	160	169	162
9317-448	13Cr-.5Ti	86.2	177	160	211	165	181	168	177	170
Ingot Iron	100Fe	100.0	187	171	223	175	192	179	188	181
Duplex Alloy Weld Metal 9276-817		68.9	75	71	86	74	76	75	76	74
EFN of 100% Ferrite of 68.9% Iron		DNA	152	139	183	143	156	146	153	147
NFN of 9276-817		DNA	49	51	47	52	49	51	50	50
Slope m of EFN = m (TF)		DNA	5.07	4.51	7.97	4.92	4.77	4.70	DNA	DNA

[a]DNA = Does not apply.

Table 10—Duplex Alloy Weld Metal Composition, %

C	0.039	Ni	5.37
Mn	1.29	Mo	3.00
Si	0.26	N	0.154
Cr	21.02	P	0.009
	S	0.012	

Table 12—Type 312 Weld Metal Test Results

	9276-821	9276-822	9276-823	E312 in AWS A5.4
C	0.097	0.103	0.102	0.15 max.
Mn	1.43	1.49	1.50	0.5-2.5
Si	0.47	0.56	0.56	0.90 max.
Cr	27.8	30.2	32.0	28.0-32.0
Ni	8.44	8.42	8.52	8.0-10.5
N	0.075	0.064	0.086	—
EFN	65.1	88.5	98.1	—
Pad hardness, Rc	16.0	20.8	24.2	—
Tensile strength, ksi	111.7	114.9	99.6[a]	95
Yield strength, ksi	88.6	97.0	—[a]	—
Elongation, %	24.5	19.5	3.0[a]	22
Reduction in area, %	39.5	24.0	7.8[a]	—

[a]Premature brittle fracture occurred outside the extensometer but in the reduced section before a yield value could be obtained.

of EFN for all of the samples of Table 11 than any of the other Magne-Gages produce.

The average EFN for each sample and the average EFN omitting the reading with P6443 are also given in Table 11. If the P6443 Magne-Gage is treated as an outlier because of its very weak magnet and is omitted from consideration for the time being, then the instrument-to-instrument variation in EFN assigned to each fully ferritic specimen and to the duplex alloy weld metal sample in each case is less than ±7.5% of the average. This is not greatly different from the ±5% variation in readings for 95% of all Magne-Gages given in A4.2-74 and reproduced in Table 9.

Furthermore, when the EFN values obtained on the duplex alloy weld metal are normalized, then the NFN values fall within ±6% of the average value even when the outlier Magne-Gage P6443 data are included.

Tests of Type 312 Stainless Steel Weld Metal

As noted in the introduction, duplex alloy weld metals can suffer from lack of ductility when ferrite is excessive. But since Type 312 stainless steel weld metal is generally greater than 28 FN as determined by the WRC procedure, it has not been clear how to determine excessive ferrite. The EFN scale developed herein provides a means of doing so. To demonstrate this, three Type 312 compositions were produced in ⅛ in. (3.2 mm) diameter electrodes with an AC-DC coating (E312-16). The chromium was deliberately varied to cover the extremes and the mid-range of the 312 composition limits given in AWS A5.4 (28-32% Cr), and thereby produce three ferrite levels.

A chemistry/ferrite pad was produced with each composition as specified in AWS A5.4. Ferrite was measured on the pads using the P5861 Magne-Gage and counterweights. Rockwell C hardness readings were also taken on the pads. An all-weld-metal 0.250 in. (6.4 mm) diameter tensile specimen was produced and tested. All the test results are given in Table 12.

The data of Table 12 demonstrate the correlation between mechanical properties and Extended Ferrite Number. As the EFN increases, the tensile strength and hardness increase; at the same time the ductility decreases until, at very high ferrite levels, premature brittle fracture occurs. NFN values were not calculated for these weld metals because their iron contents (57-61%) lie outside the range of the fully ferritic steel samples available. Since the data of Fig. 9 appear to have a parabolic relationship, linear extrapolation outside the range of the data was considered inadvisable.

It appears from the data of Table 12 that a maximum EFN of perhaps 75 is appropriate to meet the ductility requirements of Type 312 stainless steel weld metal. In fact, the 22% elongation requirement cannot be met over a considerable portion of the composition range permitted for this alloy. In general, filler metal producers seem to produce Type 312 weld metals near the low end of the allowable chromium range, because this effect has been understood at least in a qualitative way.

Discussion of Results

The range of variation from instrument to instrument in EFN values obtained on fully ferritic samples and on duplex alloy weld metal by the procedures described herein is comparable to the range of variation stated in AWS A4.2-74 for FN values from instrument to instrument. An outlier instrument can be readily detected by its magnet strength being outside the range of 5.0 FN per gram ±0.5 FN per gram.

By the normalization procedure, even an outlier Magne-Gage gives good reproducibility in NFN values compared to other Magne-Gages. It is, therefore, possible to use either the EFN scale or the NFN scale as a yardstick for measuring and/or specifying duplex alloy weld metal ferrite content. The EFN scale offers the advantage of being continuous with both the WRC FN scale and the IIW FN scale. However, the EFN scale must be concerned with outlier Magne-Gages calibrated to AWS A4.2.

The IIW procedure, which is exactly compatible with A4.2 except that it restricts magnet strength, should not be bothered by outliers. The EFN scale also offers the somewhat unsettling possibility of obtaining values greater than 100 for weld metals that are not fully ferritic. The NFN scale eliminates this possibility but is not continuous with the now familiar FN scale; also, it requires measurement or estimation of the EFN of 100% ferrite of approximately the same composition as the ferrite in the unknown sample.

In view of the excellent agreement of NFN values with volume percent ferrite measurements obtained by point counting on the Steel Founders' Society casting samples, it is tempting to suppose that the NFN on weld metal is an estimate of the true volume percent ferrite in that weld metal. This supposition would, however, seriously disagree with a statement in the Appendix of AWS A4.2-74. In Section "A2.2. Ferrite Number" it is stated, "Thus Ferrite Number is an arbitrary, standardized value related to the ferrite content of an equivalently magnetic weld metal. It is not necessarily the true absolute ferrite percentage of the weld; however, FN's below 10 do represent an excellent average of the percent ferrite as determined by present U.S. and world methods of measuring delta ferrite, based upon the previously discussed round robins conducted by the WRC Advisory Subcommittee and the IIW Subcommission II-C."

The results given in Table 11 indicate that the EFN is a function not only of volume percent ferrite, but also of the composition of that ferrite. Thus the ferrite of a Type 309 stainless steel weld metal of perhaps 24 Cr-13 Ni (perhaps 61% iron) would have a weaker magnetic response than the same amount of ferrite in a Type 308 stainless steel weld metal of perhaps 20 Cr-10 Ni (perhaps 68% iron). Then using the average EFN values (with the outlier omitted) in Table 11, the EFN of 100% ferrite of the same composition as the ferrite in a 308 weld metal would be about 146.

By the same reasoning, the EFN of 100% ferrite of the same composition in a 309 weld metal would be about 125. Then the NFN of a 20 Cr-10 Ni Type 308 weld metal would be obtained by dividing the FN or EFN by 1.46, while the NFN of a 24 Cr-13 Ni Type 309 weld metal would be obtained by dividing the FN or EFN by 1.25. In other words, if the NFN is a good estimate of the true volume percent ferrite in a weld metal sample, then the FN measured by the WRC or IIW procedure or the EFN measured by the procedures developed herein overestimates the true volume percent ferrite by about 46% in Type 308 weld metal and by about 25% in Type 309 weld metal. This would be at variance with the previously cited statement in the Appendix of AWS A4.2.

In contrast to the situation with castings, wherein the volume percent ferrite can be measured with good laboratory-to-laboratory reproducibility by metallographic means such as point counting, there is no universally accepted method of measuring volume percent ferrite in weld metals.

Stalmasek (Ref. 8), in a literature survey of ferrite determination methods, concludes that measurement of the intensity of magnetic saturation gives at present the best obtainable measure of "true volume percent ferrite". The USSR has adopted magnetic saturation as its standard method of specifying weld metal ferrite for certification of stainless steel electrodes. Recent work in the USSR by Merinov et al. (Ref. 9, 10) concludes that the magnetic saturation response of Type 309 weld metal is only 80% of the magnetic saturation response of Type 308 weld metal having the same "true volume percent ferrite". This result quantitatively agrees with the estimates made above based upon NFN values.

Further, Merinov et al. have considered the relationship between "true volume percent ferrite" using their magnetic saturation device on various weld metals and the FN values assigned to the same weld metals using a Magne-Gage calibrated according to the WRC procedure. They arrive at a linear relationship for 19 Cr-9 Ni weld metal (Type 304):

$$FN = 1.70\ (\%\ \text{delta ferrite}).$$

Using the data of Table 11 and assuming that a 19 Cr-9 Ni weld metal would contain 70% iron (allowing for some manganese and silicon), the EFN for 100% ferrite of the same composition as the ferrite in 19 Cr-9 Ni weld metal would be about 150, so that the relationship between NFN and EFN or FN as developed above would be for this material:

$$FN = 1.50\ (NFN).$$

Thus, the NFN determined as outlined herein may not agree exactly with the "true volume percent ferrite" determined by the Russian magnetic saturation method. More comparative work needs to be done.

However, the Russian work does support two implications of the EFN procedure work described herein. These are that the magnetic response of ferrite depends upon its composition and that the WRC Ferrite Number overestimates the "true volume percent ferrite" even at FN's below 10. The Russian magnetic saturation method is a destructive test so that it may not be best suited for production applications, although it is used in the USSR for certifying welding electrodes. However, at the present time, it is probably impossible to prove whether the "true volume percent ferrite" is given by the Russian magnetic saturation measurement, the NFN number described herein, or the WRC Ferrite Number.

Conclusions

1. A procedure has been developed for extending the WRC Ferrite Number scale given in AWS A4.2 beyond the limit of about 28 FN imposed by the limits of the Magne-Gage to cover duplex alloy weld metals by adding counterweights to the Magne-Gage.
2. The EFN measured by the procedure developed agrees numerically (within limits of experimental error) with the FN measured by AWS A4.2 for EFN values below 28.
3. The EFN measured on a given sample is reproducible within ±7.5% of the EFN value, or better, from Magne-Gage to Magne-Gage so long as the magnet strength of the Magne-Gage is within the limits of the IIW procedure for measuring Ferrite Numbers. It, therefore, presents a usable scale for measuring and/or specifying ferrite in duplex alloy weld metals.
4. The EFN can be normalized using the EFN measured on 100% ferrite of approximately the same iron content as the weld sample being tested. The Normalized Ferrite Number so measured provides a scale for measuring and/or specifying weld metal ferrite content which gives reproducible results even with Magne-Gages whose magnet strengths are outside the limits of the IIW procedure.

Acknowledgments

This work would have been impossible without the permission of Teledyne McKay for the author to pursue it. Helpful discussions with Mr. William DeLong, Dr. Joel Feldstein, Mr. Ernest Schoefer and Dr. Hallock Campbell provided insights. The Steel Founders' Society of America provided casting alloy samples which had been characterized as to ferrite content by metallographic methods. Climax Molybdenum and Allegheny Ludlum provided fully ferritic steel samples. Mr. Sam Greenberg of Super Pressure, Inc. (formerly American Instrument Company)

advised as to the suitability of using counterweights with the Magne-Gage. Access to Magne-Gages was provided by Babcock and Wilcox, Westinghouse and Alloy Rods Division of Allegheny Ludlum. To all of the above, the author is indebted.

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Discussion by H. C. Campbell*

Dr. Kotecki has postulated that each ferrite island in an austenitic stainless steel weld deposit or casting attracts a standardized Magne-Gage in proportion of its iron content. This is an attractive hypothesis.

His studies of fully ferritic weld metals show a quasi-linear relationship for half-a-dozen iron contents in the range that will be met in stainless weld metals. When he corrects his magnetic readings on ACI castings for their iron content, they agree nicely with the ferrite contents estimated by the Steel Founders' Society.

I like Dr. Kotecki's hypothesis. It needs refinement to pull in the outliers, but I predict it will survive critical examination.

The naturally occurring ferromagnetic elements are iron, cobalt, and nickel. I think the nickel content of a ferrite island may also contribute to its magnetic attraction. Dr. Kotecki's 100% ferrite specimens included only two nickel-bearing alloys; including a factor for nickel in the EFN formula for Extended Ferrite Number would much improve the fit of sample 1783C with 5 nickel; it would not improve the sample with 2 nickel. Ferritic samples with various iron and nickel contents should reveal a workable formula.

Ten years ago I encouraged Bill DeLong and my reluctant fellow members of the WRC Advisory Subcommittee for Stainless Steel to arbitrarily establish an innovative Ferrite Number System we had been slowly developing, making it the official measure of the Delta Ferrite Content of Austenitic Stainless Steel Weld Metal. I am delighted to see this encouraging agreement between our highly reproducible FN readings and point counts made by the Steel Founders' Society.

H. C. CAMPBELL is a Consultant, Vero Beach, Florida, and a charter member of the AEC Advisory Committee on Type 347 Weld Metal, now the Welding Research Council Subcommittee on Welding Stainless Steel.

Author's Reply

Dr. Campbell's point regarding the effect of nickel on the magnetic attraction of ferrite is worth considering since many, but not all, nickel base alloys are ferromagnetic. The limited data of the present study is insufficient to reach a conclusion regarding this. However the work of Bungardt, Dietrich and Arntz cited in Reference 8 of the paper considers the effects of composition of ferrite on the field intensity for magnetic saturation of 100% ferrite stainless steels. They arrive at the following relation between field intensity and composition:

$$4\pi\ I_F = 21{,}200 - 305\ (\%\ Cr) - 322\ (\%\ Ni) \pm 410\ \text{gauss}$$

This relation shows that both nickel and chromium have negative effects on the field intensity for magnetic saturation, and the magnitude of the effects of the two elements are similar. The difference in field intensity in the above relation for a 5% nickel change vs. a 5% chromium change would be far less than the error scatter band indicated. This supports my assumption that both nickel and chromium in place of iron in the ferrite reduce the magnetic attraction of the ferrite.

Subsequent to completion of the manuscript, I considered the EFN of 9% nickel steel. In the as-received condition, this material is martensite which is also ferromagnetic. It had a measured EFN of 178. Since I wanted to work with ferrite, I austenitized the 9 nickel steel at 1600°F (871°C), furnace cooled in 1 hour to 1300°F (704°C) (which is above the upper critical temperature) then furnace cooled at 10°F (5.6°C) per hour to 620°F (327°C) (the Ms is about 680°F (360°C) for this alloy) and air-cooled to room temperature. Then I cooled to −320°F (−196°C) in liquid nitrogen and reheated to room temperature to be certain that any retained austenite transformed to martensite.

The resulting microstructure is ferrite with perhaps 10–20% tempered martensite. The measured EFN on this material is 184 using the P5861 Magne-Gage. From Table 8 and Fig. 9 of the paper, since 9% nickel steel is approximately 90% iron, we could expect an EFN of 180 if iron content were the only factor affecting EFN. The agreement of experiment with prediction is not perfect but it is quite close.

Obviously, a more thorough investigation of the effects of various alloy elements on the magnetic response of ferrite could be undertaken. One might anticipate that silicon, since it is only half the atomic weight of iron, would have a larger effect while molybdenum, which is a much heavier atom, would have a smaller effect. However, such effects would not detract from the main utility of the Extended Ferrite Number system proposed, which is to provide a convenient yardstick for characterizing duplex austenite-ferrite stainless steels.

—CALL FOR PAPERS—

IIW CONFERENCE ON UNDERWATER WELDING

A Conference on Underwater Welding (including thermal cutting) will be held June 27-28, 1983, as part of the 36th Annual Assembly of the International Institute of Welding. The IIW Assembly will be conducted June 25 through July 2, 1983, in Trondheim, Norway.

The provisional program for the two-day Conference on Underwater Welding includes general survey sessions on June 27 covering: 1) Technology of Underwater Welding and 2) Metallurgy of Underwater Welding. Conference colloquia scheduled for June 28 include: 1) Wet and Dry Welding; 2) Repair and Other Applications; 3) Physical, Metallurgical and Mechanical Problems; and 4) Inspection and Performance. Conference proceedings will be published in book form and distributed to conference participants.

The following schedule has been set for authors interested in presenting a paper at the conference:

November 15, 1982: Author must submit proposal, including author's name, title of contribution, and a summary of approximately 150 words.

December 15, 1982: The Organizing Committee will report back to prospective speakers.

March 1, 1983: Manuscripts of accepted contributions must be received by the Norwegian Organizing Committee. Manuscripts should be typed and illustrations prepared according to instructions that will be mailed to authors by December 15, 1982. The paper should not exceed 10 pages in length.

Responses to this call for papers should be addressed to:

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