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Ferrite in Austenitic Stainless Steel Weld Metal

1974 Adams Lecture

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(*Continued from the previous issue*)

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.

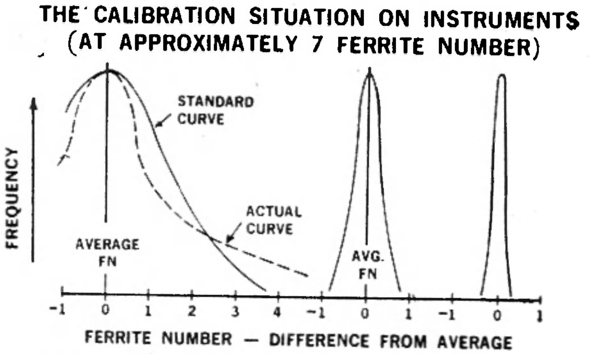
AWS Subcommittee IV on High Alloy Steel Filler Metal has adopted the FN system and described the background, and the next revision of AWS A-5.4-XX, which should issue in the near future, will include minimum FN requirements on the ferrite bearing grades of covered austenitic stainless steel electrodes.

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 co-operative 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 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.



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.

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.

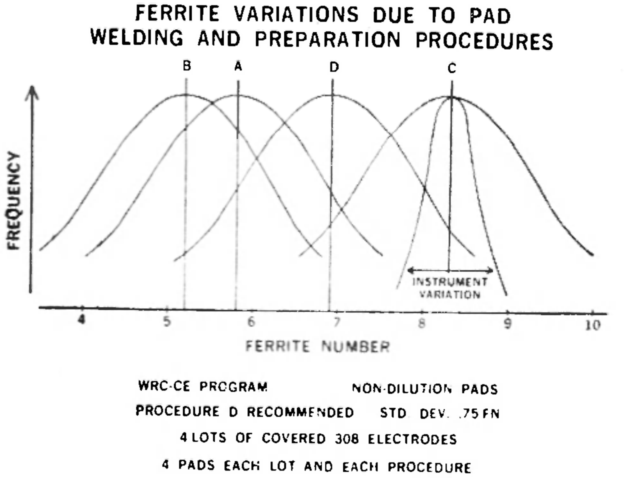


Fig. 9. A stylized representation of the precision and mean ferrite levels to be expected from four different pad welding and preparation procedures, A, B, C and D, described in the text. The supplemental curve at the right designating instrument variation shows the precision of multiple Magne-Gages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

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 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 FNX(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 arc 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 6FN 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.

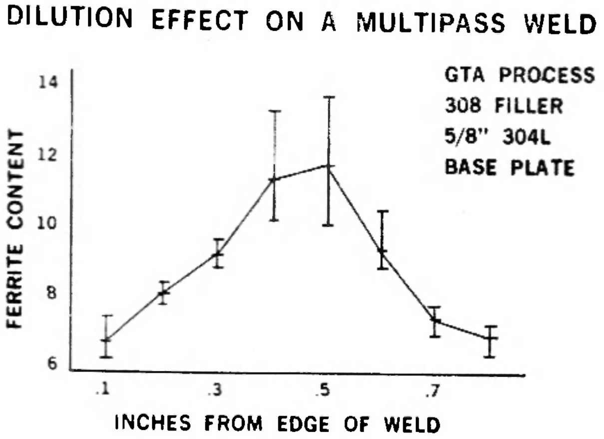


Fig. 10. Ferrite contents in a multipass weld. Dilution ranges from relatively high levels (bead just adjacent to the base plate) to essentially zero (beads in the center of the weld face).

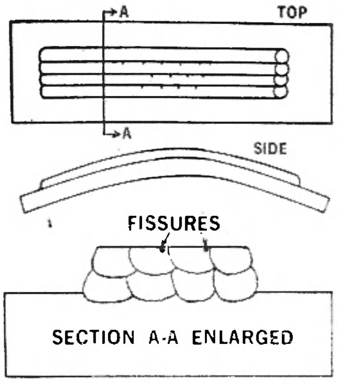
Fissuring Weld Metals

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



WRC
COOPERATIVE
PROGRAM

TESTING FROM
0 TO 6FN

308, 308L, 347
316, 316L, 318
309, AND PRODUCTION
16-8-2

TO DATE:
NO FISSURES AT 3FN OR HIGHER, BENT OR UNBENT.
FISSURES ONLY IN LOCAL 0 FN AREAS.
STUDY CONTINUING AT UNIVERSITY OF TENNESSEE
UNDER C. D. LUNDIN.

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

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 co-operating 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.

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 incouraged to continue what in his case is an imagnative 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.

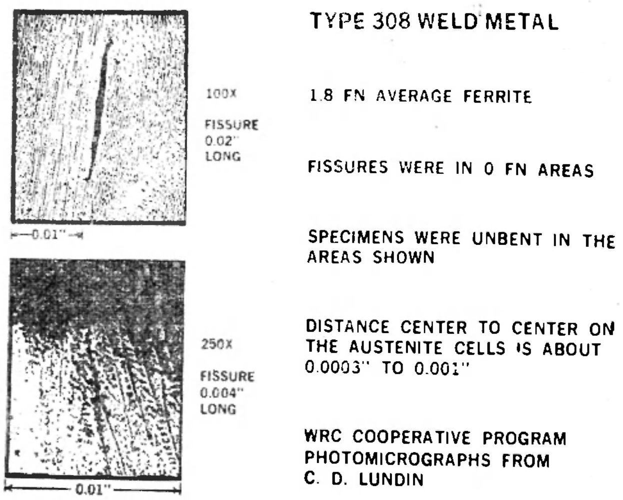


Fig. 12. Fissures in unbent sections of the fissure-bend specimens described in fig. 11.

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 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.

Acknowledgement

I would like to acknowledge the support of Teledyne McKay over the past twenty years in their field of investigation, particularly the support of Dr. David F. Helm, and the effort and assistance of many co-workers, among them Edwin R. Szumachowski, Charles J. Long, and G. A. Ostrom.

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