ABSTRACT. Electron beam welds, laser beam welds and rapidly solidified stainless steel alloys have small physical dimensions and very fine microstructures. These characteristics prevent accurate measurements of the residual ferrite by conventional techniques. To overcome these difficulties, a new technique for measuring ferrite is applicable to specimens that weigh as little as 5 mg and are less than 0.5 mm (0.02 in.) thick. This technique uses a vibrating sample magnetometer to measure the magnetic properties of a small specimen removed from the weld. This measurement can then be used to calculate the residual ferrite content of the specimen if the saturation magnetization of the ferrite is known. The saturation magnetization of the ferrite depends on its Fe content, and a method was developed (using thermodynamically created diagrams) to predict the Fe content of the residual ferrite from the nominal alloy composition. The saturation magnetization of the residual ferrite was further determined as a function of its Fe content by measuring the magnetic properties of fully ferritic stainless steel specimens containing between 30 and 80 wt-% Fe. This allowed the vibrating sample magnetometer to be “calibrated” for a wide range of stainless steel alloy compositions. The results of this study were used to show that the Magne-Gage and ferrite meters have been developed to measure the amount of residual ferrite in duplex stainless steel alloys (Refs. 8, 9). These instruments can be used to measure the residual ferrite content of cast and arc welded stainless steel alloys containing between 65 and 70 wt-% iron. However, for alloys that are outside this Fe content range, the composition-dependent magnetic properties of the ferrite must be taken into account (Refs. 10, 11), and these corrections are not well established.

The conventional magnetic instruments have an additional limitation resulting from the uncertainty of the magnetic field generated by the measuring probe. These fields are nonuniform within the volume of the material tested and do not uniformly saturate the ferrite. Consequently, the instruments respond to the specimen’s magnetic permeability, which is not a material property. As a result, conventional magnetic instruments are sensitive to the orientation and shape of the residual ferrite particles as well as to the geometry and volume of the specimen being tested.

In order to reliably measure ferrite with these instruments, the specimen must be large enough to obtain the maximum magnetic attraction between the probe and the specimen. For these conditions, empirical relationships have been developed to convert the magnetic readings into an equivalent ferrite content. However, these measurements are only valid if the specimen exceeds some minimum physical dimension, which is about 10 mm (0.4 in.) for a Magne-Gage and other conventional magnetic instruments (Ref. 9). These instruments respond to smaller specimens in a way that gives a false value by averaging in the magnetic properties of the base metal.

This limitation on the specimen size presents a problem for measuring the ferrite content of high-cooling-rate welds and rapidly solidified alloys. For example, electron beam welds may be less than 1 mm (0.04 in.) wide, pulsed laser welds may be only 0.25 mm (0.01 in.) deep, and rapidly solidified alloys have even smaller physical dimensions. It is impossible to measure ferrite content of these specimens using conventional magnetic instruments, so that only quantitative metallography (QTM) can be used to inspect these rapidly solidified microstructures. However, QTM is not capable of accurate ferrite determination in welded and rapidly solidified alloys because of the small size of ferrite particles in the microstructure.

The recommended practice for measuring ferrite in stainless steel alloys is summarized in AWS document A4.2-86.
The Vibrating Sample Magnetometer

The VSM measures the magnetic moment of a specimen by oscillating the specimen in a magnetic field. The method is based on the change in flux when the specimen is vibrated within a detection coil, as illustrated in Fig. 1A. The specimen is attached to the end of a quartz rod, which is fixed to a mechanical vibrator that oscillates at about 80 Hz. The motion is perpendicular to the applied magnetic field, and a small permanent magnet is also attached to the rod to act as a reference specimen. Both the reference specimen and the unknown specimen induce an emf in their respective coils; the difference between the two signals is proportional to the magnetic moment of the unknown specimen.

Figure 1B illustrates the output from a typical VSM run, and plots the magnetization (M) of the specimen in response to the applied magnetic field (H). The M-H curve can be used to determine the saturation magnetization of the unknown specimen. At high H fields, the ferrite saturates and the slope of the M-H curve decreases to a low value. Extrapolating this "high-field susceptibility" to an applied field of zero gives the spontaneous magnetization, which will be taken to be equal to the saturation magnetization. This parameter corresponds to the magnetization required to saturate the ferrite and is a material property. The units used to describe the magnetization of the specimen are emu/g; this and the other units used to describe the magnetic measurements are summarized in Table 1.

By calibrating the VSM with a specimen of known saturation magnetization, the VSM can be used to detect changes in the magnetization of less than \(10^{-3}\) emu. The high sensitivity of the VSM is apparent since a single gram of ferrite in stainless steel alloys has a saturation magnetization of about 100 emu; hence, the VSM is sensitive to approximately 10 µg of ferrite.

The saturation magnetization tests were performed by first calibrating the VSM with a pure nickel standard, then measuring the magnetic properties of the unknown specimen using the VSM. The stainless steel specimens consisted of thin wafers (~0.5 x 3 x 3 mm/0.02 x 0.12 x 0.12 in) weighing between 10 and 50 mg. These specimens were prepared using a low-speed diamond cut-off saw to minimize mechanical deformation of the thin wafers. The VSM tests were conducted by attaching the samples to a quartz holder using teflon tape and measuring the magnetization of the sample as a function of applied magnetic field varying from -10 kOe to +10 kOe in 200 Oe increments. The M-H curve was plotted from these data, and \(\sigma_r\) was determined from this curve using a graphical technique.

The amount of residual ferrite in the stainless steel alloy specimens was calculated from its saturation magnetization using the following equation:

\[
\sigma_r = \sigma_s / \sigma_f
\]

where \(\sigma_r\) is the specific saturation magnetization of the ferrite, \(\sigma_s\) is the saturation magnetization of the unknown specimen, and \(\sigma_f\) is the weight fraction of the residual ferrite.

Therefore, if \(\sigma_r\) is known, the residual ferrite content of the specimen can be calculated from a single M-H curve. The saturation magnetization of ferrite is a strong function of composition and must be estimated as discussed in the following sections.

Alloy Preparation

Two series of high-purity Fe-Ni-Cr ternary alloys were investigated. The first series of alloys was developed with a constant Cr/Ni ratio and a range of Fe contents. These alloys were rapidly solidified by a melt-spinning process, which produced fully ferritic specimens that were used to determine the influence of iron content on the saturation magnetization of ferrite. The second series of alloys was developed with a constant Fe content and a range of Cr/Ni ratios. These alloys were arc-cast to produce duplex microstructures with different residual ferrite contents so that the VSM method could be verified for a wide range of stainless steel alloy microstructures.

Melt-Spun Ribbons. The compositions of the alloys used in the melt-spinning process are listed in Table 2, which shows that the Fe content varies from 50 to 80 wt-% and the Cr/Ni ratio is constant at 4:1. Arc-grown ingots of each alloy composition were induction melted from high-purity elements (99.93 wt-% pure electrolytic Fe, 99.94 wt-% pure electrolytic Ni, and 99.56 wt-% pure electrolytic Cr), and then
Table 2—Compositions of the Fully Ferritic, Melt-Spun Alloys (wt-%)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Fe</th>
<th>Ni</th>
<th>Cr</th>
<th>Cr/Ni</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>56.2</td>
<td>19.3</td>
<td>22.4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>58.3</td>
<td>17.3</td>
<td>24.3</td>
<td></td>
</tr>
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</tr>
<tr>
<td>4</td>
<td>58.6</td>
<td>15.8</td>
<td>25.5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>59.2</td>
<td>14.3</td>
<td>26.4</td>
<td></td>
</tr>
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<tr>
<td>7</td>
<td>59.2</td>
<td>12.7</td>
<td>28.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 3—Chemical Composition of the Arc-Cast Buttons (wt-%)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Fe</th>
<th>Ni</th>
<th>Cr</th>
<th>Ni/Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>58.2</td>
<td>19.3</td>
<td>22.4</td>
<td></td>
</tr>
<tr>
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<td>7</td>
<td>59.2</td>
<td>12.7</td>
<td>28.0</td>
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</tr>
</tbody>
</table>

Results and Discussion

The Saturation Magnetization Of Ferrite

The saturation magnetization of ferrite, \( \sigma_F \), is a function of its composition, which presents two problems. First, in two-phase stainless steel alloys, the ferrite phase has a different composition than the nominal alloy composition. Therefore, the composition of the ferrite phase is not known a priori. Measuring the composition by microchemical analysis techniques can be done, but is only practical for laboratory experiments. Estimating the composition of ferrite is not a standard calculation and requires thermodynamic calculations. Second, magnetic theory can only predict \( \sigma_F \) from compositional data in certain binary-alloy solid solutions; therefore, in more complex alloy systems, \( \sigma_F \) must be experimentally determined. This section discusses methods for calculating \( \sigma_F \) from the ferrite composition. Methods for predicting the ferrite composition from the nominal alloy composition will be developed in the following section.

Previous Investigations. Rigid-band theory can be used to calculate the magnetic moment of an alloy as a function of composition. However, this theory is only accurate for certain binary-alloy combinations (Ref. 14). This approach assumes that the saturation magnetization of the alloy is related to the number, \( n \), of (3d+4s) electron per atom. For \( n \) values greater than about 8.3, there is good agreement between experiments and theory as long as the binary alloys consist of certain adjacent elements on the periodic table. For nonadjacent elements or for \( n \) values less than about 8.3, simple rigid-band theory and experiment do not agree.

Figure 2 includes several Slater-Pauling curves, which show the magnetic moment of the alloy versus \( n \) for binary-alloy systems. Chromium and Ni are the two most important alloying additions to stainless steel alloys, and the curves indicate that: 1) additions of Cr to Fe-Cr alloys (solid circles) lower the magnetic moment in proportion to the amount of Cr added; 2) additions of Ni to Fe-Ni alloys (open circles) have little effect on the magnetic moment at low concentrations, but the magnetic moment at high concentrations (> 15%) is decreased in proportion to the amount of Ni in the alloy. Nontransition elements such as Si and Al are also used in the processing of stainless steel alloys. They tend to reduce the magnetic moment if the Fe atoms were being replaced by atoms of zero magnetic moment (Ref. 14). For ternary and higher alloy systems, rigid-band theory is not capable of accurately describing the magnetic moment as a function of composition.

One attempt to predict the effects of composition on the saturation magnetization of Fe-Ni-Cr ternary alloys was developed by Curtis and Sherwin (Ref. 15), and is based on the magnetic moment of the individual elements and a "rule of mixtures" approach expressed by:

\[
4\pi\mu_A = 4\pi \frac{N}{100} \left( 0.22 \frac{\rho(Cr)}{\rho(Cr)} + 0.6 \frac{\rho(Ni)}{\rho(Ni)} + \frac{2.2}{\rho(Fe)} \right) \times (0.927 \times 10^{-2}) \text{[gauss]}
\]

Here \( \mu_A \) refers to the atomic weight of element i, \( N \) is Avogadro's number, and \( \rho_i \) is the density of element i. This equation predicts a saturation magnetization for...
pure Fe to be 21,910 gauss and predicts a higher decrease in $\sigma_F$ for Cr than for Ni additions.

Empirical relationships have also been derived to predict the saturation magnetization of residual ferrite from the alloy composition. These relationships were developed by measuring both $\sigma_F$ and ferrite content of a large number of alloys, and calculating $\sigma_F$ from these results. One such relationship derived by Merinov, et al. (Ref. 10, 11), is the following:

$$4\pi M_s = 21,600 - 275(\%Cr) - 330(\%Ni)$$

This relationship shows that $\sigma_F$ decreases with the addition of all typical alloying elements in stainless steel alloys. The higher multiplicity factors associated with the lower-density elements suggest that Equation 3 is written in terms of wt-%; however, the units are not specifically stated in Merinov's paper.

Merinov's equation reduces to $4\pi M_s = 21,600 - 275(\%Cr) - 330(\%Ni)$ for Fe-Ni-Cr ternary alloys. The multiplying factors for chromium and nickel are similar, suggesting that the iron content of the ferrite is the principal factor in determining $\sigma_F$ in the ternary system. That is, for a given Fe content, $\sigma_F$ changes only a few percent for large differences in the Cr/Ni ratio. A comparison of Equation 2 with Equation 3 for a chromium and nickel content representative of ferrite in high-alloy stainless steels (35.5 wt-% Ni, 55.4 wt-% Fe) gives values of 13,600 and 8300 gauss, respectively, for $\sigma_F$. This large difference could not be reconciled from the data provided by the investigators; therefore, a separate study was initiated to measure $\sigma_F$ as a function of chemical composition.

The results of this study confirmed Merinov's empirical relationship (using element concentration in wt-%).

**Experimental Determination of the Saturation Magnetization of Ferrite.**

The VSM was used to measure the specific saturation magnetization of the fully ferritic specimens listed in Table 2. These specimens were produced by melt-spinning seven alloys that had different Fe contents but identical Cr/Ni ratios. The Cr/Ni ratio was held constant at 4.0, which is similar to that of residual ferrite in two-phase stainless steel alloys, and the different Fe contents allowed $\sigma_F$ to be measured as a function of Fe content in the ferrite.

The results of these measurements, listed in Table 4, indicate that $\sigma_F$ increases from 80 to 170 emu/g as the iron content of the alloy increases from 50 to 80 wt-%. These data are plotted in Fig. 3, and a linear-regression analysis of these data was used to determine the following relationship (also plotted in Fig. 3) between $\sigma_F$ and the Fe content of the ferrite:

$$\sigma_F = 313(\text{Fe}) - 80$$

The specific saturation magnetization of ferrite, $\sigma_F$, was converted from emu/g to gauss using 7.77 g/cm$^3$ for the density of the residual ferrite (Ref. 13). The $\sigma_F$ in these units is also reported in Table 4. A regression analysis of these data gives the following relationship between $4\pi M_s$ and the weight fraction Fe:

$$4\pi M_s = 30,560(\text{Fe})-7,810$$

These results show a decrease in $\sigma_F$ of 306 gauss for each percent Fe that is replaced by Cr+Ni in these alloys that have a Cr/Ni ratio of 4:1.

Merinov's equation predicts a decrease in $\sigma_F$ of 275 gauss for each percent Cr and 330 gauss for each percent Ni for each percent Fe that is replaced. Combining these data for stainless steel alloys with a Cr/Ni ratio of 4:1, Merinov's equation predicts a decrease in $\sigma_F$ of 286 gauss for each percent Fe that is replaced by Cr+Ni. This value is similar to the value measured in this investigation of 306 gauss, considering the differences in alloys studied and the differences in the experimental techniques.

**Predicting the Composition of Residual Ferrite**

The previous section developed a relationship between the Fe content of the
ferrite and its saturation magnetization. This information is useful if the Fe content of the residual ferrite is known. Typically, however, the nominal alloy composition is specified but the specific ferrite composition is not known. In this section, a procedure for predicting the Fe content of the residual ferrite from the nominal alloy composition will be developed so that the VSM and other ferrite-measuring devices can be calibrated for any stainless steel alloy composition.

The Cr/Ni Ratio of Ferrite. The composition of the ferrite phase can be calculated at a given temperature from the nominal alloy composition using thermodynamic modeling. Figure 4 illustrates the results of one such model by reproducing the 1200°C (2192°F) isothermal section of the Fe-Ni-Cr system from Chuang and Chang (Ref. 19). This figure shows the location of the equilibrium ferrite solvus, austenite solvus, and selected tie-lines in the ferrite+austenite two-phase field.

By compiling the results of eight isothermal sections between 900° and 1400°C (1652° and 2552°F) (Ref. 19), the equilibrium composition of ferrite can be determined as a function of temperature. These results are shown in Figs. 5 and 6, which plot the Cr content and the Ni content of the ferrite as a function of temperature for ferrite containing 50, 60, 70 and 80 wt-% iron. As the temperature decreases, the chromium content of the ferrite increases and the nickel content of the ferrite decreases. Therefore, the Cr/Ni ratio of ferrite increases with the decreasing temperature.

The Cr/Ni ratio of ferrite as a function of temperature for these same alloys is plotted in Fig. 7. The Cr/Ni ratio of the 50, 60, and 70 wt-% iron alloys are all similar for the temperature range examined. These values increase from about 2.5 at 1400°C to about 7.5 at 900°C. For ferrite containing more than 70 wt-% Fe, the Cr/Ni ratio is significantly higher than the other alloys and reaches a value of 19 at 900°C. However, since most stainless steel alloys contain less than 70 wt-% Fe, the Cr/Ni ratio of the residual ferrite can be assumed to be insensitive to the alloy composition and depends primarily on the temperature. These results, combined with the previous observations regarding the insensitivity of τ to the Cr/Ni ratio, indicate that the Fe content of the ferrite is the most important factor in determining the saturation magnetization of ferrite. Therefore, a method was developed to estimate the iron content of the residual ferrite from the nominal alloy composition.

Estimating the Fe Content of Residual Ferrite. The isothermal sections were used to determine the Fe content of the ferrite and austenite as a function of temperature. The ratio between these two quantities, R, is defined as:

\[ R = \frac{\text{Fe}_{A}}{\text{Fe}_{F}} \]

where \( \text{Fe}_{A} \) is the Fe content of the austenite phase and \( \text{Fe}_{F} \) is the Fe content of the ferrite phase. This ratio can be used to estimate the Fe content of the ferrite from the nominal alloy composition.

The ratio R was calculated from the Fe-Ni-Cr isothermal sections of Ref. 19 and is plotted in Fig. 7 for ferrite compositions of 50, 60, 70 and 80 wt-% Fe. This figure gives R for temperatures between 900° and 1400°C and can be used to calculate the range of possible iron contents that form in the residual ferrite for a given stainless steel alloy.

The range of possible ferrite compositions that forms from a given Fe-Ni-Cr alloy is illustrated in Fig. 8. Alloys that have compositions that lie along line segment...
AC are on an iron isopleth and are in the ferrite+austenite two-phase field. The ferrite that forms from these alloys has a range of compositions, thus a range of iron contents, that lie along the ferrite solvus, AB. This range of ferrite compositions is bounded by the Fe content of the stainless steel alloy at point A and by the tie-line end point at B. The maximum Fe content of the ferrite, \( F_{Fe}^{(max)} \), that forms from this alloy is the Fe content of composition A, which is the same as that of the nominal alloy, \( F_{Fe}^{N} \).

\[
F_{Fe}^{(max)} = F_{Fe}^{N}
\]  

(7)

The minimum Fe content of the ferrite, \( F_{Fe}^{(min)} \), is the Fe content of composition B, which can be calculated from \( R \) and the Fe content of the stainless steel alloy:

\[
F_{Fe}^{(min)} = R(F_{Fe}^{N})
\]  

(8)

Therefore, by knowing \( R \), the range of possible Fe contents of the residual ferrite can be calculated from the nominal alloy composition. For typical stainless steel compositions, this range is relatively small (<3%) because the tie lines are close to the Fe isopleth.

**The Effective Quench Temperature.**

The iron content of the ferrite depends on the temperature at which the ferrite forms. This temperature can be predicted by the effective quench temperature (EQT), the temperature at which equilibrium can no longer be maintained during cooling (Ref. 18). The EQT is a function of cooling rate and is related to the solidification processing conditions. Examples will be shown later indicating that the EQT is approximately 1150°C (2102°F) for small castings that cool at intermediate rates. At higher cooling rates, such as those in welds and rapidly solidified stainless steel alloys, the EQT is closer to the melting temperature, which is about 1430°C (2606°F) for these alloys.

To estimate the EQT, the residual ferrite content of the arc-cast alloys was compared to thermodynamic calculations. The composition of the ferrite phase in these castings was measured using electron microprobe analysis (Ref. 13), and these results are listed in Table 5. The average composition of the residual ferrite in these alloys is 55.1 wt-% Fe, 8.7 wt-% Ni and 36.2 wt-% Cr.

For determining the EQT values, the ferrite solvus in the Fe-Ni-Cr ternary alloy system is plotted in Fig. 10 for several temperatures between 1000°C and 1350°C (1832°F and 2462°F). These data are reproduced from the isothermal sections by Chuang and Chang (Ref. 19), and show that the ferrite solvus moves to Cr-rich compositions as the temperature decreases. The actual composition of the residual ferrite that forms in the 59 wt-% Fe alloys is located in this figure, and it can be seen that it falls between the 1100°C and 1200°C (2012°F and 2192°F) solvus temperatures. Therefore, the EQT for the arc-cast buttons was taken to be 1150°C. Welds and rapidly solidified alloys, which cool at higher rates, will have even higher EQT's, but these temperatures were not determined in this investigation.

**Verification of the VSM Method.**

In the previous section, methods were developed to 1) estimate the EQT from the solidification process, 2) estimate the Fe content of the residual ferrite from the EQT and the nominal alloy composition, using thermodynamically created diagrams, and 3) calculate the saturation magnetization of the residual ferrite from its Fe content. This allowed the VSM to be calibrated for a wide range of stainless steel alloys and solidification conditions. In this section, the VSM technique will be verified by measuring the ferrite content of a series of high-purity cast alloys in Table 5—Average Compositions (wt-%) of the Ferrite in the Arc-Cast Buttons

<table>
<thead>
<tr>
<th>Casting</th>
<th>Cr</th>
<th>Ni</th>
<th>Fe</th>
<th>Cr/Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35.4</td>
<td>10.1</td>
<td>54.5</td>
<td>3.00</td>
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<td>2</td>
<td>35.8</td>
<td>9.2</td>
<td>54.9</td>
<td>3.89</td>
</tr>
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<td>35.2</td>
<td>8.7</td>
<td>55.1</td>
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</tr>
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<td>35.1</td>
<td>8.3</td>
<td>56.6</td>
<td>4.23</td>
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<tr>
<td>7</td>
<td>39.9</td>
<td>6.3</td>
<td>53.8</td>
<td>6.33</td>
</tr>
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</table>

Fig. 6—Thermodynamic calculations of the nickel content in ferrite as a function of temperature and iron content of the ferrite.

Fig. 7—Thermodynamic calculations of the Cr/Ni ratio of ferrite as a function of temperature and iron content of the ferrite.
which the ferrite content ranges from 0 to over 30 vol-%.

Quantitative Metallography. Quantitative metallography (QTM) measurements were easily performed on the arc-cast alloys (see Table 3) because of the relatively coarse microstructure of the castings. These alloys increase in ferrite content from Alloy 1 (0%) to Alloy 7 (37.2 vol-%), and were metallographically prepared for QTM analysis according to Ref. 8, using a KOH electrolytic etch. Micrographs from these specimens were analyzed using a computer-assisted QTM system that has the ability to discriminate 512 levels of grey.

Metallographic sections were analyzed from each alloy to determine the vol-% ferrite. These measurements are presented in Table 6, which gives the number of micrographs analyzed, \( n \), and the standard deviation, \( s \), of the readings. The results of these measurements show that the ferrite content of the cast alloys varies from 0 to 37.2 vol-%.

Vibrating Sample Magnetometer. The VSM measurements were made on three samples from each cast alloy. Each specimen weighed approximately 50 mg and the room-temperature magnetic properties of these specimens were measured to determine the saturation magnetization of the cast alloys. The M-H curves for the seven alloys are summarized in Fig. 11 and indicate that all of the alloys saturate at an applied magnetic field of about 4 kOe.

Table 7 summarizes the saturation magnetization measurements for all of the specimens, indicating that \( \sigma_5 \) varies from 0 in Alloy 1 to 31.4 emu/g in Alloy 7. In order to convert these data into percent ferrite, the saturation magnetization of the residual ferrite in these alloys must be known. This was done by first calculating \( \sigma_f \) from the Fe content of the ferrite (determined from the thermodynamic calculations), and then checking this value by calculating \( \sigma_f \) from the measured Fe content of the residual ferrite. This comparison was useful to verify the accuracy of thermodynamic calculations.

The saturation magnetization of ferrite was first estimated from the EQT and the nominal alloy composition. Using an EQT of 1150°C for the castings and a nominal

---

**Table 6—QTM Measurements of the Residual Ferrite in the Arc-Cast Alloys**

<table>
<thead>
<tr>
<th>Cast Alloy</th>
<th>( n )</th>
<th>( s )</th>
<th>Ferrite (vol-%)</th>
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</thead>
<tbody>
<tr>
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<td>0.74</td>
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<td>37.2</td>
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</table>

**Table 7—VSM Measurements of \( \sigma_5 \) in the Cast Alloys and the Residual Ferrite Contents Calculated from the Average \( \sigma_5 \) Values**

<table>
<thead>
<tr>
<th>Cast Alloy</th>
<th>( \sigma_5 ) (emu/g)</th>
<th>Residual (wt-%)</th>
<th>Ferrite (vol-%)</th>
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<tr>
<td>1</td>
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<td>0</td>
</tr>
<tr>
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<td>6</td>
<td>26.6</td>
<td>27.4</td>
<td>28.9</td>
</tr>
<tr>
<td>7</td>
<td>30.2</td>
<td>31.2</td>
<td>34.0</td>
</tr>
</tbody>
</table>

**Fig. 8—Thermodynamic calculations of the ratio between the Fe content of ferrite to the Fe content of austenite, \( R \), as a function of temperature and iron content of the ferrite.**

**Fig. 9—Schematic illustration of the phase equilibrium in the Fe-Ni-Cr system. The range of possible ferrite compositions lies along the ferrite solvus between points A and B for alloys with compositions between points A and C.**
Fe content equal to the average of the 7 alloys, 58.6 wt-%, R was interpolated to be 0.945 from Fig. 8. Therefore, the possible iron contents of the ferrite in the arc-cast alloys range from 53.4 (R × wt-% Fe) to 58.6 wt-%. Using these values, Equation 4 shows \( a_f \) to be between 93.3 and 103.4 emu/g. The actual value of \( a_f \) would be expected to be close to the lower limit, 93.3 emu/g, since two-phase stainless steel alloys have compositions closer to the austenite solvus than to the ferrite solvus. The relatively wide range of possible values of \( a_f \) is related to the low EQT of the castings and the high-alloy content of these stainless steel alloys. Typical stainless steel alloy welds with higher EQT's would have a much smaller range.

The average Fe content of the ferrite in the cast alloys was measured to be 55.1 wt-%, which is slightly lower than the nominal Fe content. The \( a_f \), as calculated from Equation 4, for this measured value of the Fe content of the residual ferrite is 92.5 emu/g, which compares favorably to thermodynamically predicted value.

To convert the VSM measurements to wt-% ferrite, the saturation magnetization of the ferrite in these castings was taken to be the value from the measured Fe content (92.5 emu/g). Using Equation 1, the residual ferrite contents were shown to vary from 0 to 34.0 wt-%. These data are presented in Table 7, and must further be converted into vol-% in order to compare these results with QTMs and the Magne-Gage. To do this, the density of ferrite and austenite were measured by a liquid-immersion technique to be 7.77 and 7.97 g/cm\(^3\), respectively (Ref. 13). These values were used to calculate the vol-% ferrite from the wt-% ferrite measurements using the following relationship:

\[
\bar{V}_f = \frac{\bar{W}_f}{\bar{W}_f + (1 - \bar{W}_f) \left( \frac{p_f}{p_a} \right)}
\]

where \( \bar{V}_f \) and \( \bar{W}_f \) represent the vol-% ferrite and wt-% ferrite, respectively, and \( p_f \) and \( p_a \) represent the density of ferrite and austenite, respectively.

The vol-% ferrite was found to range from 0 to 34.7 vol-%, which compares favorably to the QTMs measurements. Although some differences exist between these two measurement techniques, the discrepancies are not large and are believed to be caused by the small population size of the QTMs measurements. The small number of samples inspected led to the relatively high standard deviations for several of the alloys. Because of this level of uncertainty in the QTMs measurements, it is most likely that the VSM measurements are more accurate since they average the ferrite content over a much larger effective area.

Magne-Gage

The two principal limitations of the Magne-Gage already discussed are: 1) the
The extended ferrite number, EFN, for a series of 15 cast alloys of CF8 and CF8M was determined from a point-counting technique, and a linear-regression analysis on these data was averaged to estimate the saturation magnetization effects that deviate from this composition, the reference ferrite composition. For alloys that deviate from this composition, the saturation magnetization effects can be used to convert the FN to vol-% ferrite.

Kotecki (Ref. 20) measured the FN on the arc-cast alloys was converted to vol-% ferrite using Equation 10. These results are summarized in Table 8 and indicate that the ferrite content varies from 0% to 38.3 vol-%. These results also compare favorably to the VSM measurements.

The iron content of each alloy was reduced to a residual ferrite, and the FN/EFN must be multiplied by the ratio of \( \sigma_f \) in the CF8 alloys to \( \sigma_f \) in the alloy being measured:

\[
\text{vol-}%F = 0.7(FN)
\]

where \( \sigma_f \) is the unknown alloy is in emu/g, and can be determined from Equation 4.

Specimens must exceed a minimum dimension of about 10 mm (0.4 in.), and 2) the saturation magnetization of ferrite in nonstandard stainless steel alloys must be taken into account to accurately measure the ferrite content. The specimens from the arc-cast alloys were large enough to meet the thickness criteria; however, the composition of these alloys (Table 3) is nonstandard. Therefore, the readings require corrections before they are compared to QTM or VSM measurements.

The Magne-Gage was used to determine the ferrite number (FN) of the cast alloys, which is defined by the force of attraction between the magnetic probe and the specimen. However, since the saturation magnetization of these alloys is lower than that of the secondaries standards that the Magne-Gage is calibrated against, the FN can not be directly converted into vol-% ferrite unless the saturation magnetization of the ferrite in these alloys is taken into account.

Although the effect of ferrite composition on the FN is often neglected, the saturation magnetization ferrite can easily be incorporated in the Magne-Gage measurements to improve its accuracy for nonstandard stainless steel alloys. To do this, a relationship was derived to calculate the vol-% ferrite from the FN at a given (reference) ferrite composition. For alloys that deviate from this composition, the saturation magnetization effects can be used to convert the FN to vol-% ferrite.

Kotecki (Ref. 20) measured the FN and the extended ferrite number, EFN, for a series of 15 cast alloys of CF8 and CF8M composition. The ferrite content of these alloys varied from 0.2 to 48.6 vol-% as determined from a point-counting technique, and a linear-regression analysis on these data gives the following relationship:

\[
\text{vol-}%F = 0.7(FN) + 0.54
\]

where \( F \) refers to the residual ferrite, and the FN and EFN are assumed to be equivalent measures of the ferrite content.

The iron content of each alloy was reported by Kotecki and has an average value of 66.8 wt-% with a standard deviation of 2.1 wt-%. This nominal Fe content can be used to calculate the average Fe content of the residual ferrite that forms in these alloys, as previously discussed. From Fig. 8, R was determined to be 0.966 for these alloys at an EQT of 1150°C. Therefore, the range of possible Fe contents of the residual ferrite for these alloys is between 0.966 and 1.000 of the nominal Fe content of 66.8 wt-%. This gives a range of \( \sigma_f \) values between 124.7 and 129.1 emu/g, as determined from Equation 5. These data were averaged to estimate the saturation magnetization of residual ferrite in the CF8 alloys to be 126.9 emu/g.

In order to convert the Magne-Gage measurements from FN to percent ferrite, the FN/EFN must be multiplied by the ratio of \( \sigma_f \) in the CF8 alloys to \( \sigma_f \) in the alloy being measured:

\[
\text{vol-}%F = 0.7(FN)
\]

\[
\left(\frac{126.9}{\sigma_f}\right) + 0.54
\]

where \( \sigma_f \) is the unknown alloy is in emu/g, and can be determined from Equation 4.

The saturation magnetization of the residual ferrite in the arc-cast alloys was measured to be 92.5 emu/g (9030 gauss). From this value, the FN measured on the arc-cast alloys was converted to vol-% ferrite using Equation 10. These results are summarized in Table 8 and indicate that the ferrite content varies from 0% to 38.3 vol-%. These results also compare favorably to the VSM measurements.

### Table 8—Magne-Gage Measurements and Calculated Ferrite Contents

<table>
<thead>
<tr>
<th>Cast Alloy</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Avg.</th>
<th>FN</th>
<th>Ferrite (vol-%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>109</td>
<td>110</td>
<td>110</td>
<td>110</td>
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<td>0</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>90</td>
<td>89</td>
<td>90</td>
<td>4.9</td>
<td>5.2</td>
</tr>
<tr>
<td>3</td>
<td>72</td>
<td>72</td>
<td>69</td>
<td>71</td>
<td>9.3</td>
<td>9.3</td>
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<tr>
<td>4</td>
<td>52</td>
<td>49</td>
<td>51</td>
<td>51</td>
<td>14</td>
<td>13.7</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>13</td>
<td>24</td>
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<tr>
<td>6</td>
<td>63</td>
<td>67</td>
<td>69</td>
<td>66</td>
<td>30</td>
<td>28.9</td>
</tr>
<tr>
<td>10</td>
<td>26</td>
<td>28</td>
<td>24</td>
<td>26</td>
<td>40</td>
<td>38.3</td>
</tr>
</tbody>
</table>

### Table 9—Comparison of the vol-% Ferrite as Measured by the Three Techniques

<table>
<thead>
<tr>
<th>Cast Alloy</th>
<th>VSM</th>
<th>% Ferrite</th>
<th>QTM</th>
<th>% Ferrite</th>
<th>Δ(%)</th>
<th>% Ferrite</th>
<th>MG</th>
<th>Δ(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0</td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>4.8</td>
<td>5.4</td>
<td>12.5</td>
<td>12.5</td>
<td>0</td>
<td>5.2</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>3</td>
<td>10.2</td>
<td>11.0</td>
<td>7.8</td>
<td>7.8</td>
<td>—</td>
<td>9.3</td>
<td>—8.8</td>
<td>—8.8</td>
</tr>
<tr>
<td>4</td>
<td>16.4</td>
<td>14.2</td>
<td>—15.9</td>
<td>—15.9</td>
<td>13.7</td>
<td>16.5</td>
<td>—16.5</td>
<td>—16.5</td>
</tr>
<tr>
<td>5</td>
<td>24.0</td>
<td>22.8</td>
<td>—5.0</td>
<td>—5.0</td>
<td>23.2</td>
<td>3.3</td>
<td>—3.3</td>
<td>—3.3</td>
</tr>
<tr>
<td>6</td>
<td>29.5</td>
<td>32.4</td>
<td>9.8</td>
<td>9.8</td>
<td>28.9</td>
<td>2.0</td>
<td>—2.0</td>
<td>—2.0</td>
</tr>
<tr>
<td>7</td>
<td>34.7</td>
<td>37.2</td>
<td>7.2</td>
<td>7.2</td>
<td>38.3</td>
<td>10.3</td>
<td>—10.3</td>
<td>—10.3</td>
</tr>
</tbody>
</table>
These data are summarized in Table 9 using the quantity Δ to refer to the percent difference between the QTM (and Magne-Gage) measurements and the VSM measurements. The quantity Δ varies between −16.5% and +12.5% with an average value of 0.37%, based on the twelve values used to compute these statistics. This amount of scatter is not unusual for ferrite measurements in welded stainless steel alloys, and there do not appear to be any consistent differences between Δ and the alloy composition for either of the ferrite measurement techniques. Therefore, it was concluded that each of the three methods gave similar results and the VSM technique can be used in place of conventional ferrite measurement techniques when sample size is too small or cooling rate is too high to give accurate conventional ferrite measurements.

Conclusions

1) The amount of residual ferrite in stainless steel alloys can be measured using a vibrating sample magnetometer. This technique is not limited by sample size and can be used to measure the ferrite content of mg-sized samples taken from cast, welded or rapidly solidified stainless steel alloys. This measurement technique requires the determination of the saturation magnetization of ferrite, σf, and a method was presented to show how σf can be calculated from the nominal alloy composition. This method requires an estimation of the magnetic content of ferrite from thermodynamically created diagrams, and an estimation of the effective quench temperature.

2) The saturation magnetization of ferrite was experimentally determined as a function of its Fe content. These measurements were made on a series of rapidly-solidified Fe-Ni-Cr alloys, which had compositions similar to that of residual ferrite and stainless steel alloys. The Fe content of these alloys ranged from 50 to 80 wt-%, which allowed σf to be determined for a wide variety of stainless steel alloys. The saturation magnetization of ferrite was measured in emu/g to give the following relationship between σf and its Fe content:

\[ \sigma_f = 313(\text{wt}-%\text{Fe}) - 80 \] (emu/g)

These data were then converted to gauss, to give the same relationship in these different units:

\[ 4\pi M_s = 30,560 (\text{wt}-%\text{Fe}) - 7810 \] (gauss)

3) The results of this study were used as a basis to calibrate the Magne-Gage (or any other magnetic instrument) for measuring ferrite in nonstandard stainless steel alloys, where secondary standards have not been established. By considering the saturation magnetization of residual ferrite, the ferrite number (measured by the Magne-Gage) can be converted directly into vol-% ferrite for a wide range of nominal alloy compositions using the following relationship:

\[ \text{vol}-\%F = 0.7(FN)(\frac{126.9}{\sigma_f}) + 0.54 \]

where \( \sigma_f \) is the units of emu/g.

Acknowledgments

This work was supported under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48. Some of the work was supported by the Office of Naval Research under contract N00014-80-C-0384. The authors would like to acknowledge the careful review of this work by D.J. Kotecki, Dr. R. O’Handly and W. H. Giedt. We would also like to express our thanks to Professor S. M. Allen for his interest in this work, Dr. Y. Hara for sharing his knowledge of the VSM, and A. McFayden for conducting many of the laboratory experiments.

References