Assessment Criterion for Variability of Delta Ferrite in Austenitic Weld and Clad Metals

Macrostructural variability of ferrite content is found to be within 0.5 to 1.5 FN vs. microstructural variability which ranges from 8 to 12%

BY K. PRASAD RAO AND S. PRASANNAKUMAR

ABSTRACT. Fusion welded or clad austenitic stainless steel normally contains some amount of delta ferrite. The amount of ferrite that is present will depend upon the chemical composition of the filler and the base metals, type of welding or cladding process and the probable variation of the process conditions during the welding or cladding operation.

The ferrite content that can be allowed in a weld or a clad is usually determined after considering its effect on one or more of the following: cracking, fissuring, intergranular corrosion, stress corrosion and sigma phase embrittlement. The decision on the optimum content of delta ferrite rests on the correlation obtained between the ferrite content and the properties referred to. When the decision is based on the minimum or maximum contents, any departure from these values has to be properly defined.

In this paper, the variation of the ferrite content along as well as across the welds or clads of Types 304, 347 and 309Cb stainless steels is plotted by traversing the probe of the Ferritescope on the test pads. Welds and clads from various fusion welding processes like SMAW, GTAW, GMAW, PAW and SAW are thus analyzed for ferrite variation and distribution. The macrostructural variability of ferrite content is then defined for these processes.

It is shown that the statistical average arrived at after a linear survey along the weld or clad is a better representation than a random sampling method. The range between the maximum and minimum values as well as the standard deviation give an idea of the homogeneity of the weld/clad metal with a given process or procedure. It is suggested that such a procedure may be adopted for procedure or process qualification, whenever ferrite control is specified. The survey can also be used to identify "high" or "low" regions of rewelded components.

Introduction

Welding or cladding operations are extensively applied whenever austenitic stainless steel materials are used for fabrication in chemical, petrochemical, nuclear or other allied industries. One significant difference between the fusion welded or clad metals and the wrought types is the presence of delta ferrite in the welds and clad. The amount of delta ferrite that can be present is decided by optimizing its role on cracking, fissuring, corrosion or embrittling actions.

The problem of hot cracking and microfissuring has been the subject of study from an early period (Refs. 1, 2, 3), when the beneficial effects of delta ferrite were indicated. Also, the work of Lundin (Ref. 4) specified a no-fissure boundary for each type of stainless steel, giving a minimum Ferrite Number for fissure resistance. Recent studies (Refs. 5, 6) suggest the mechanism of solidification must also be considered rather than ferrite content alone.

The effects of delta ferrite on the susceptibility of the weld metal to general corrosion (Ref. 7), intergranular corrosion (Refs. 8, 9) and stress corrosion (Refs. 10, 11) aspects have been investigated. Baumel (Ref. 8) discussed the amount and type of delta ferrite and its influence on corrosion behavior, when the dissociation of ferrite occurs during heat treatment. Devine (Ref. 9) studied the influence of volume percentage of delta ferrite and reported that a critical amount and distribution may be needed for resistance to intergranular corrosion. Recent work on our part (Ref. 12) also indicates a correlation between the ferrite content and the resistance to intergranular corrosion of strip cladaded materials. Manning (Ref. 13) reported that pit initiation occurs preferentially on the ferrite-austenite boundary for duplex stainless steels.

As noted above, various investigations indicated that the amount of ferrite-austenite boundary may be important, but this again depends on the ferrite content. If a proper correlation between the ferrite content and the various properties can be obtained, ferrite content may be reported with more confidence. Extensive work by the Welding Research Council (Ref. 14) has resulted in the standardization of Ferrite Number, and procedures are available for specifying (Ref. 15) the variability expected of the Type A, B and C instruments for measuring ferrite. In this paper, the variability of ferrite content for the weld and clad metals of various fusion welding processes is measured.

Experimental Procedure

Test Pads

For the experiments, 200 mm (77/8 in.) long test pads were prepared by employing bead-on-plate welds. Type 304 stainless steel was used for the fusion welding.
Table 1—Typical Chemical Compositions, %

<table>
<thead>
<tr>
<th>Material(a)</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Nb</th>
<th>P</th>
<th>S</th>
<th>Mo</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low carbon steel base metal</td>
<td>0.16</td>
<td>0.15</td>
<td>0.80</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.03</td>
<td>0.034</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>304 SS (wrought)</td>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>19.70</td>
<td>11.13</td>
<td>—</td>
<td>0.089</td>
<td>0.023</td>
<td>0.17</td>
</tr>
<tr>
<td>309 Cb SS strip</td>
<td>0.054</td>
<td>0.63</td>
<td>2.4</td>
<td>25.81</td>
<td>11.82</td>
<td>0.896</td>
<td>0.014</td>
<td>0.017</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>SMAW 309 SS clad</td>
<td>0.048</td>
<td>0.29</td>
<td>1.35</td>
<td>20.53</td>
<td>12.05</td>
<td>0.024</td>
<td>0.019</td>
<td>0.014</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>GMAW 347 SS clad (single pass)</td>
<td>0.065</td>
<td>0.35</td>
<td>1.14</td>
<td>18.83</td>
<td>8.51</td>
<td>0.846</td>
<td>0.031</td>
<td>0.015</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>GMAW 347 SS clad (two pass)</td>
<td>0.049</td>
<td>0.35</td>
<td>1.01</td>
<td>20.16</td>
<td>9.33</td>
<td>0.928</td>
<td>0.014</td>
<td>0.017</td>
<td>0.10</td>
<td>0.03</td>
</tr>
<tr>
<td>SAW 309 SS Cb clad (single pass)</td>
<td>0.061</td>
<td>0.83</td>
<td>1.97</td>
<td>18.68</td>
<td>10.36</td>
<td>0.471</td>
<td>0.018</td>
<td>0.02</td>
<td>0.02</td>
<td>0.09</td>
</tr>
</tbody>
</table>

(a) Numbers indicate specific Type stainless steel (SS); SMAW—shielded metal arc welding; GMAW—gas metal arc welding; SAW—submerged arc welding.

Table 2—Welding Operational Data

<table>
<thead>
<tr>
<th>Process(a)</th>
<th>Consumables</th>
<th>Conditions</th>
<th>25—30 V; 60—80 A; 15 cm/min = 2.5 mm/s (5.9 ipm)</th>
<th>24—26 V; 160—175 A; 15 cm/min = 2.5 mm/s (5.9 ipm)</th>
<th>5 A; 25 cm/min = 4.2 mm/s (9.8 ipm)</th>
<th>24—26 V; 160—180 A; 10—20 cm/min = 1.67—3.67 mm/s (3.9—8.66 ipm)</th>
<th>28—30 V; 650—700 A; 10 cm/min = 1.67 mm/s (neutral type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAW</td>
<td>3.25 mm (0.13 in.) diameter AWS E308L-16 filler metal Autogenous welding on Type 304 stainless steel strip</td>
<td>5 A; 25 cm/min = 4.2 mm/s (9.8 ipm)</td>
<td>28 V; I_b = 90 A; I_peak = 140 A; pulses = 10 cm/min (3.9 ipm)</td>
<td>Autoogenous welding on Type 304 stainless steel strip; argon shielding gas</td>
<td>24—26 V; 160—175 A; 15 cm/min = 2.5 mm/s (5.9 ipm)</td>
<td>28—30 V; 650—700 A; 10 cm/min = 1.67 mm/s (neutral type)</td>
<td></td>
</tr>
<tr>
<td>GTAW</td>
<td>1.2 mm (0.047 in.) Type 347 stainless steel filler metal; argon shielding gas</td>
<td>Autoogenous welding on Type 304 stainless steel strip; argon shielding gas</td>
<td>28 V; I_b = 90 A; I_peak = 140 A; pulses = 10 cm/min (3.9 ipm)</td>
<td>Pulsed GTAW Autogenous welding on Type 304 stainless steel; argon shielding gas</td>
<td>28 V; I_b = 90 A; I_peak = 140 A; pulses = 10 cm/min (3.9 ipm)</td>
<td>24—26 V; 160—180 A; 10—20 cm/min = 1.67—3.67 mm/s (3.9—8.66 ipm)</td>
<td></td>
</tr>
<tr>
<td>PAW</td>
<td>Autogenous on Type 309 Cb stainless steel strip</td>
<td></td>
<td></td>
<td>Pulsed GTAW</td>
<td></td>
<td>24—26 V; 160—180 A; 10—20 cm/min = 1.67—3.67 mm/s (3.9—8.66 ipm)</td>
<td></td>
</tr>
<tr>
<td>GMAW</td>
<td>1.2 mm (0.047 in.) Type 347 stainless steel filler metal; argon shielding gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAW</td>
<td>60 X 0.5 mm (2.36 X 0.02 in.) Type 309 Cb stainless steel strip</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) SMAW—shielded metal arc welding with Linde (West Germany) equipment; GTAW—gas tungsten arc welding with Messer-Griesheim (M.-G), West Germany, LGW301 Type Av. 218 machine. Pulsed GTAW—accomplished with GL251/150PT machine from Advani Oerlikon, India. PAW—plasma arc welding with M.-G Pew 100 machine; GMAW—gas metal welding with M.-G LCG 355 machine; SAW—submerged arc welding with M.-G LG 800 machine.

Welding Processes

Similar metal combination, bead-on-plate welds of Type 304 were made by depositing Types 347 filler metals on Type 304 base metal. Shielded metal arc, gas tungsten arc, gas metal arc and plasma arc welding processes were used—Table 2.

Experiments were also carried out using a GTAW torch for re-melting the GMAW deposited metal.

Cladding Processes

For preparing dissimilar combinations of stainless steel surfacing on mild steel, four different cladding processes—SMAW, GTAW, GMAW and SAW—were used. Multiple pass cladding was also carried out.

Microstructural Examination

Representative samples were taken for observation under a light microscope. Typical as well as atypical micrographs are shown in Figs. 5-8.

Results and Discussion

Figure 2A shows the trace obtained by traversing the probe of the Ferritescopescope on Type 309 Cb stainless steel strip containing 12FN ferrite in the wrought condition. The smoothness of the traverse establishes the feasibility of such a technique.

Figures 2 to 4 give variations of delta ferrite in various weld and clad metals. It can be seen that variation oscillates...
around a mean value; this has been analyzed statistically. The important points to be noted from Table 3 are:
1. The range of ferrite values (minimum and maximum) is within 0.5 and 1.5 FN.
2. The standard deviation lies in the range of 0.25 to 0.85 FN.

The points noted above are significant because they indicate that the macrostructural variability of ferrite content is reasonably constant and lies within a narrow range. This is in contrast to the microstructural variability quoted and discussed by DeLong (Ref. 16) where the range varies from 8 to 12%. However, our results indicate that, by resorting to a macrostructural variability concept, the variability is within 1.5 FN; this can be advantageously used by the various codes and specifications.

Further, the standard deviation is observed to be in the range of 0.25 and 0.85 FN only for the various welds as well as clad metals. Even though the processes investigated ranged in their heat input from 1 to 12 kJ/mm (25.4 to 304.8 kJ/in.), the homogeneity of the deposited metals is within reasonable limits. The accuracy of the type C instrument made use of is ±0.2 FN, and as indicated by AWS A4.2.74 the type C gages can have allowable deviation in the range of ±0.2 to ±0.6 FN.

The values given above are for the variability of the measuring instrument. Our results indicate that the variability of the ferrite in the weld and clad metals is in the range of ±0.25 to 0.85 FN; the lower limit is bound by the instrument capability.

A comparison of the various traces and the values in Table 3 indicates that, among the processes, there is some difference in the ferrite variability. The variability is generally less with higher heat input processes like SAW and more for lower heat input manual processes. With multiple pass cladding, variability decreases significantly as observed in GMAW as well as SAW processes.

Autogenous GTAW melting provided more uniform ferrite content than GTAW welding with filler metal. Pulsed GTAW produced a significantly smoother variation compared to normal GTAW welding. The GTAW arc remelting of GMAW clad metal did not improve ferrite homogeneity. For the SAW cladding, the variability is more (=3 FN) across the transverse direction, but smoother transition between the clad metals is provided in multipass cladding.

It must be noted that the investigation was concerned only with good or optimum welds. For example, when the process is not controlled properly (because of human or equipment factors), the variation in process conditions is very
Table 3—Statistical Analysis of Ferrite Variation

<table>
<thead>
<tr>
<th>Type stainless steel, process and weld/clad deposit</th>
<th>Average X, %</th>
<th>Ferrite content, %</th>
<th>Standard deviation (S.D.), %</th>
<th>Cr\text{eq}</th>
<th>N\text{eq}</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAW 304 weld</td>
<td>5.2</td>
<td>4.0-5.7</td>
<td>1.7</td>
<td>0.40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SMAW 304 clad</td>
<td>1.7</td>
<td>1.2-2.2</td>
<td>1.0</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SMAW 309 clad</td>
<td>6.8</td>
<td>6.1-7.6</td>
<td>1.5</td>
<td>0.52</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SMAW 309 clad</td>
<td>10.2</td>
<td>9.0-11.0</td>
<td>2.0</td>
<td>0.70</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GTAW 304 autogenous weld</td>
<td>4.3</td>
<td>3.2-4.9</td>
<td>1.7</td>
<td>0.32</td>
<td>21.18</td>
<td>13.25</td>
</tr>
<tr>
<td>GTAW 347 weld</td>
<td>4.6</td>
<td>3.3-5.8</td>
<td>1.5</td>
<td>0.51</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GTAW 347 clad</td>
<td>7.7</td>
<td>6.5-9.0</td>
<td>2.5</td>
<td>0.85</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GTAW 347 clad</td>
<td>9.4</td>
<td>8.0-10.2</td>
<td>2.2</td>
<td>0.80</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pulsed GTAW 304 autogenous weld</td>
<td>4.6</td>
<td>4.1-5.1</td>
<td>1.0</td>
<td>0.41</td>
<td>21.18</td>
<td>13.25</td>
</tr>
<tr>
<td>PAW 309 Cb autogenous weld</td>
<td>17.3</td>
<td>17.0-18.5</td>
<td>1.5</td>
<td>0.49</td>
<td>27.04</td>
<td>14.07</td>
</tr>
<tr>
<td>GMAW 347 weld</td>
<td>4.8</td>
<td>3.8-5.3</td>
<td>1.5</td>
<td>0.38</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GMAW 347 clad</td>
<td>5.4</td>
<td>4.9-6.0</td>
<td>1.1</td>
<td>0.27</td>
<td>19.87</td>
<td>10.03</td>
</tr>
<tr>
<td>GMAW 347 clad</td>
<td>7.4</td>
<td>7.0-8.0</td>
<td>1.0</td>
<td>0.30</td>
<td>21.25</td>
<td>11.33</td>
</tr>
<tr>
<td>GTAW torch over GMAW 347 clad</td>
<td>3.6</td>
<td>4.3-5.1</td>
<td>0.8</td>
<td>0.46</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GTAW torch over GMAW 347 clad</td>
<td>5.9</td>
<td>7.3-8.4</td>
<td>1.1</td>
<td>0.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SAW 309 Cb clad</td>
<td>4.5</td>
<td>4.0-5.1</td>
<td>1.1</td>
<td>0.25</td>
<td>20.14</td>
<td>13.16</td>
</tr>
<tr>
<td>SAW 309 Cb clad</td>
<td>10.53</td>
<td>10.0-11.2</td>
<td>1.2</td>
<td>0.36</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SAW 309 Cb clad</td>
<td>13.84</td>
<td>13.0-14.2</td>
<td>1.2</td>
<td>0.33</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SAW 309 Cb clad</td>
<td>7.0</td>
<td>5.5-8.5</td>
<td>3.0</td>
<td>0.69</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Any variation in delta ferrite content occurs as a result of the difference in chemical composition due, in turn, to differences in metal transfer, element losses in arc, dilution and gas pick-up. Such differences for an expected ferrite content appear because of the variation in process conditions. In the literature, there have been conflicting reports about the effect of heat input (Refs. 16-18) on ferrite content. However, no literature is available on the variation of ferrite for the normal variations expected in pre-selected weld heat input during the welding or cladding operation.

Some earlier reports are available for the effect on ferrite content with the variation in process parameters, but again the results suffer because of the use of the non-standard instrumentation. A change of even 0.67 Cr\text{eq} and 0.8 Ni\text{eq} can cause (Ref. 16) a change of 2 FN even from an analysis of a DeLong constitution diagram.

It has been reported that arc voltage (Refs. 19, 20) decreases ferrite content because of a loss of chromium and pick-up of nitrogen. Kotecki (Ref. 19)
observed a change of about 2 FN for either a change of 1 V in arc voltage or a change of 25 A in arc current. Boeckholt (Ref. 21) reported a decrease from 5 to 0.5% ferrite for an increase from 22 to 34 V.

In the case of manual or semi-automatic processes, the expected variation in process conditions is appreciable. In the case of bare metallic GMAW welding or cladding, process control becomes equally difficult. In the case of the submerged-arc process, process control is better but suffers when alloyed fluxes are used. In the case of high heat intensity processes like plasma welding, the process is much more stable. The results of this investigation indicate that, with reasonably good process control in all those processes when used either for welding or for cladding, the deposited metal exhibits a reasonably smaller magnitude of ferrite variability.

Fitness for Purpose

The variability of ferrite content can be expressed schematically as indicated in Fig. 9. There are three types of behavior that can be analyzed from this curve. The type I or macrostructural variation takes the variation of ferrite over the order of a few millimeters. Type II behavior averages over the dimensions of grain size, whereas the type III behavior is significant over the dimensions of ferrite platelets.

The Magne-Gage and Ferritescope measurements can be equated to type I. QTM and other microscopic measurements can be taken as type II measurements, and the use of SEM with high magnifications can be said to be of type III. Hence, the variability also depends on the types of measurement, the variability ranging from 50 to 100% for type III (SEM), of the order of 10% for type II (QTM), and of the order of 1% for type I (Ferritescope and Magne-Gages). This is shown schematically in Fig. 10.

The use of type I behavior is justified when we consider the term, “fitness for purpose.” The ferrite content is correlated with properties like resistance to corrosion and microfissuring. In test methods for an evaluation like the fissure bend test and the copper-copper sulfate-16% acid test, the test specimens are subjected to bending over significant dimensions of the order comparable to type I dimensions here referred to.

This paper proposes an assessment criterion for the measurement and
The linear traverse of the Ferrite-scope probe on austenitic weld deposits gives a better representation of the variability of the delta ferrite content along the weld direction, than a random sampling alone.

2. Statistical analysis of the delta ferrite values so obtained reveals that the range between the maximum and minimum values and the standard deviation gives a quantitative description of the macrostructural variability of the ferrite content.

3. For fusion welds and clads deposited by different processes like SMAW, GTAW, GMAW, pulsed GTAW, PAW, and SAW, the range of variation is within 1.5 FN and the standard deviation lies between 0.4 and 1.0, the lower limit being bound by the instrument variability.

4. The macrostructural variability of delta ferrite is generally low with higher heat input and automatic processes, but higher with the lower heat input manual processes.

5. With multipass cladding, variability decreases significantly.

6. Erratic distribution of ferrite content occurs for welds/clads made with improper process control, whereas a proper process control restricts ferrite content variation to a low level.

7. Type I behavior for describing the macrostructural variability of ferrite content is better suited for correlation with the tests designed for corrosion resistance and microfissuring.

8. Ferrite structure changes from discontinuous to continuous vermicular type and to acicular type with increases in ferrite content.

Conclusions

1. The linear traverse of the Ferrite-scope probe on austenitic weld deposits gives a better representation of the variability of the delta ferrite content along the weld direction, than a random sampling alone.

2. Statistical analysis of the delta ferrite values so obtained reveals that the range between the maximum and minimum values and the standard deviation gives a quantitative description of the macrostructural variability of the ferrite content.

3. For fusion welds and clads deposited by different processes like SMAW, GTAW, GMAW, pulsed GTAW, PAW, and SAW, the range of variation is within 1.5 FN and the standard deviation lies between 0.4 and 1.0, the lower limit being bound by the instrument variability.

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References

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- Engineer-Other
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- Welder, welding or cutting operator
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- Consultant
- Metallurgist
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- Technician
- Educator
- Student
- Other...

**TECHNICAL INTERESTS**

(check one or more)

- Ferrous metals
- Nonferrous–aluminum
- Nonferrous except aluminum
- NDT
- Safety and health
- Arc welding
- Brazing and soldering
- Cutting
- Gas welding
- Resistance welding
- Thermal spraying
- Aerospace
- Automotive
- Machinery
- Marine
- Pipe and tubing
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- Structures
- Other...

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**FOR OFFICE USE ONLY**

- Company Code
- State Code
- Grade
- Date Joined
- City Code
- Paid thru Date
- Sponsors ID#
- Officer Code
- Source Code
- Committee Code
- Check#
- Date
- Amount
- Acc't. #

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**MEMBER**

Any individual who has a degree or has at least five years of experience having a direct bearing on the science and technology of welding and its allied processes shall be eligible to be a Member.

Each Member receives the Welding Journal each month, the current Welding Handbook the year of enrollment, an AWS Membership Certificate and a discount on AWS Publications.

**Annual Dues** $41.00

**Initiation Fee** $ 5.00

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**ASSOCIATE MEMBER**

Any individual interested in the science and technology of welding and its allied processes shall be eligible to be an Associate Member.

Each Associate Member receives the Welding Journal each month, an AWS Membership Certificate and a discount on AWS Publications.

**Annual Dues** $35.00

**Initiation Fee** $ 5.00
Have you recruited a NEW member? You are encouraged to “CLONE YOURSELF” as an AWS member in the new Membership Campaign, EVERY MEMBER GET A MEMBER (EMGAM II). Tell your friends and associates what an AWS membership entails and the professional benefits it provides.

You, as an AWS member, can receive valuable merchandise, educational or publication discounts and will be eligible to win the Grand Prize for getting new members to join the AWS team. You can increase your chances of winning the Grand Prize through each new individual member you get to join AWS.

Information on the Grand Prize and EMGAM II Campaign Rules can be obtained from the AWS office at (305) 443-9353 or your Section Officers.

Start now! Recruit those NEW members today. You will be doing yourself and that NEW member a favor.

Come on! Be an “EMGAMer II”!