Effect of Manganese on the Microstructure and Properties of All-Weld-Metal Deposits

Going from 0.6 to 1.8% Mn increasingly refines weld microstructures and promotes acicular ferrite formation, and optimal impact is attained with approximately 1.5% Mn although strain aging affects notch toughness and displaces optimum Mn to a higher concentration.

BY G. M. EVANS

SYNOPSIS. The effect of manganese, in the range 0.6 to 1.8%, on the microstructure and mechanical properties of manual metal arc deposits (ISO 2560) has been investigated. It was found that manganese increasingly refined the microstructure and promoted the formation of acicular ferrite. Both tensile strength and yield strength increased by approximately 30 N/mm² per 0.1% Mn addition to the deposit.

Charpy V, Schnadt and COD tests graded “as-deposited” weld metals in the same relative order, the optimal impact properties being attained at a manganese level of approximately 1.5%. Stress relieving was found to have only a marginal effect on impact properties. Strain aging, on the other hand, markedly affected notch toughness and displaced the optimum manganese level to a higher concentration.

Introduction

The working program of Subcommission II-A of the International Institute of Welding calls for a joint effort to study the microstructure of weld metal. As a first step, four all-weld metal deposits have been distributed to various laboratories with recommendations for the characterization of the microstructural components.

The present paper details the findings of the Swiss delegation in collaboration with the Welding Institute (United Kingdom). In addition to the metallographic studies, a test program was conducted to evaluate the influence of manganese on the tensile and impact properties of the weldments.

Experimental Procedure

Electrodes

Four experimental iron powder type basic electrodes, coded A, B, C and D, were prepared using 4 mm (0.16 in.) diameter core wire. The ferro-manganese contents of the coatings were 3, 5, 7 and 9%, respectively, and the ferro-silicon content was balanced. The coating factor was 1.70 and the electrodes were baked for 1 h at 400°C (752°F) to yield a diffusible hydrogen content of 2.3 ml/100 g deposit, according to the ISO procedure.

Weld Preparation

The weld preparation employed was that specified in the International Standard for the code of symbols for manual metal arc electrodes, namely ISO 2560-1973.

Welding was done in the flat position using the stringer bead technique. Direct current (electrode positive) was employed, the amperage being 170 A, the voltage 21 V and the heat-input nominally 1 kJ/mm. The interlayer temperature was 150°C (302°F).

Heat Treatment

The weldments were tested in both the as-welded and the stress-relieved states.
Table 1—Weld Metal Composition (As-Welded), Wt-%

<table>
<thead>
<tr>
<th>Electrode</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>N</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.035</td>
<td>0.66</td>
<td>0.30</td>
<td>0.006</td>
<td>0.013</td>
<td>0.007</td>
<td>0.049</td>
</tr>
<tr>
<td>B</td>
<td>0.038</td>
<td>1.00</td>
<td>0.30</td>
<td>0.005</td>
<td>0.014</td>
<td>0.010</td>
<td>0.046</td>
</tr>
<tr>
<td>C</td>
<td>0.049</td>
<td>1.42</td>
<td>0.34</td>
<td>0.005</td>
<td>0.013</td>
<td>0.009</td>
<td>0.041</td>
</tr>
<tr>
<td>D</td>
<td>0.051</td>
<td>1.82</td>
<td>0.34</td>
<td>0.006</td>
<td>0.017</td>
<td>0.009</td>
<td>0.039</td>
</tr>
</tbody>
</table>

(2 h/580°C or 2 h at 1076°F) condition. Impact tests (Charpy V notch) were also conducted on strain aged specimens, compressed 10% and aged for ½ h at 250°C (482°F).

Mechanical Testing

Two sub-size all-weld-metal tensile specimens (Minitrac) were machined and tested for each type of electrode and condition. Also approximately 35 Charpy V notch specimens were struck, so as to obtain the complete transition curve.

Schnadt impact specimens were prepared from as-welded deposits and were tested under bradycrheracy (Bc) and tachycrheracy (Kc) conditions. In addition, as-welded plates were COD tested in full thickness (20 mm or 0.79 in.) at the Welding Institute. The weld metal was saw notched (0.15 mm or 0.006 in.) transversely to provide subsidiary-type specimens, as proposed in DD 19 but without a fatigue crack.

Results

Chemical Composition

Typical chemical analyses of the deposits are given in Table 1. The systematic increase in the amount of ferro-manganese in the coating resulted in four distinct weld metals containing, nominally, 0.65, 1.0, 1.4 and 1.8% Mn.

The weld silicon content was relatively constant, but the carbon and phosphorus contents increased progressively over the range. Weld metal oxygen level, on the other hand, decreased, thus substantiating the deoxidation potential of manganese. Essentially the same results as given in Table 1 were obtained on repeated analysis for the stress-relieved samples.

Metallographic Examination

General. A transverse section of one of the multi-run deposits is shown in Fig. 1, a total of nine layers being required to fill the gap. Three beads were deposited per layer, and the macroscopic effect was of repeated sequences of as-deposited and supercritically heat-affected weld metal zones.

The widths of the columnar, coarse

grained and fine grained regions were measured in the vertical mid-plane position and the duplicate results, obtained by examining as-welded and stress-relieved specimens, are depicted in Fig. 2. The percentages of the

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Table 2—Zone Percentages in the Equivalent ISO-V Notch Position (AW = As-Welded, SR = Stress-Relieved)

<table>
<thead>
<tr>
<th>Zone</th>
<th>AW</th>
<th>SR</th>
<th>AW</th>
<th>SR</th>
<th>AW</th>
<th>SR</th>
<th>AW</th>
<th>SR</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columnar</td>
<td>18</td>
<td>32</td>
<td>23</td>
<td>19</td>
<td>22</td>
<td>12</td>
<td>11</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Coarse grained</td>
<td>35</td>
<td>24</td>
<td>34</td>
<td>35</td>
<td>34</td>
<td>37</td>
<td>34</td>
<td>37</td>
<td>34</td>
</tr>
<tr>
<td>Fine grained</td>
<td>47</td>
<td>42</td>
<td>43</td>
<td>46</td>
<td>44</td>
<td>51</td>
<td>55</td>
<td>45</td>
<td>46</td>
</tr>
</tbody>
</table>

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Fig. 1—Cross section of multi-run deposit

Fig. 2—Zone distribution along the vertical centerline position
zones in the central 10 mm (0.39 in.) region of the deposits, i.e., the Charpy V-notch location, are given in Table 2.

The width of the columnar regions varied from layer to layer, and penetration was such that, in some instances, two critically heated regions were adjacent to one another. A difference due to manganese could not be ascertained, the values for duplicate specimens scattering to an equivalent extent. The average value for the sum of the coarse and fine grained regions at the notch location was found to be 80%. A slight vertical displacement would affect the relative proportions of the zones, since the lower runs tended to contain wider columnar bands.

The columnar grains broadened as the weld progressed during deposition, due to the epitaxial growth effect. As an approximation, however, it can be presumed that the sequence is repetitive throughout and that the central top bead and the adjacent heat-affected weld metal serve to characterize the bulk of the deposit.

Typical microstructures of the four manganese-containing weld metals are shown in Figs. 3, 4, and 5, for the columnar, coarse grained and fine grained regions, respectively.

**Columnar Region.** The top central bead of each specimen was examined at X200 and quantitative metallographic measurements were made as described in Doc. II-A-389-76, using a
Swift point counter. The area traversed measured 2.5 × 2.0 mm² (Fig. 6), and 500 points were recorded by each of two investigators.

Three major microstructural components (Fig. 3B) were identified, namely:

1. Pro-eutectoid ferrite (light etching).
2. Intermediate lamellar products, mainly ferrite side plates resembling upper bainite (light etching).
3. Acicular ferrite, consisting of a fine structure of interlocking ferrite plates (dark etching).

The results obtained on point counting are plotted in Fig. 7. It can be seen that the amount of acicular ferrite increased markedly, at the expense of pro-eutectoid ferrite, as the manganese content increased. Also, a clear trend existed for the intermediate lamellar component to decrease with increasing manganese.

Carbon replicas of the top beads were examined at the Welding Institute, in a transmission electron microscope (TEM), and a linear intercept method was applied at a magnification of X2500. The results are given in Table 3, the values for the high manganese welds being indicative of the acicular ferrite lath size.

Examination of the replicas showed that there was a gradual transition between acicular ferrite and pro-eutectoid ferrite. Also, the distinction normally made between the two microstructures in the optical microscope was purely arbitrary at high magnification.

Small and widely dispersed areas of retained austenite were observed on the replicas. The amount of austenite increased with increasing manganese but only in the case of weld D was sufficient austenite present (1%) to be detected by X-ray diffraction. All the replicas from stress-relieved welds could be readily distinguished by the presence of grain boundary carbides which were formed by the tempering out of the retained austenite.

Any martensite which might have formed within the retained austenite was difficult to detect because of the fine scale of the structure. Such indications of martensite, as were found, were of considerably smaller areas than those reported by Garland and Kirkwood as occurring in submerged arc welds. Furthermore, it was not possible to identify the areas as either lath or twinned martensite or to assess them quantitatively.

Coarse Grained Region. Photomicrographs of the reheated weld metal taken directly below the central top bead are shown in Fig. 4. With increasing manganese the structure became increasingly more dark etching, and the pro-eutectoid ferrite delineating the prior austenite grain boundaries which became finer and hence tended to accentuate the coarse grained nature of the zone. The fusion boundary in the case of the lowest manganese weld (A) was difficult to locate microstructurally but the segregation bands (ripples) could readily be seen by varying the focus.

<table>
<thead>
<tr>
<th>Electrode</th>
<th>As-deposited</th>
<th>Stress-relieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.30</td>
<td>3.96</td>
</tr>
<tr>
<td>B</td>
<td>2.87</td>
<td>2.60</td>
</tr>
<tr>
<td>C</td>
<td>1.72</td>
<td>1.70</td>
</tr>
<tr>
<td>D</td>
<td>1.05</td>
<td>1.59</td>
</tr>
</tbody>
</table>

Table 3—Average Linear Intercept in Top Beads of As-Welded and Stress-Relieved Specimens

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Intercept/mm</th>
<th>Ratio</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>A H</td>
<td>155</td>
<td>1.06</td>
<td>150</td>
</tr>
<tr>
<td>B H</td>
<td>173</td>
<td>1.01</td>
<td>172</td>
</tr>
<tr>
<td>C H</td>
<td>199</td>
<td>0.96</td>
<td>203</td>
</tr>
<tr>
<td>D H</td>
<td>237</td>
<td>0.94</td>
<td>245</td>
</tr>
</tbody>
</table>

Table 4—Linear Intercept Results From Fine Grained Region (H = horizontal, V = vertical)
The microstructure within the proeutectoid ferrite envelopes appeared to be optically identical to the acicular ferrite occurring in the as-deposited weld metal. The areas surrounded by the proeutectoid ferrite differed in size and the boundary of the coarse-grained zone was difficult to locate, since the microstructure tended to be dependent on the underlying solidification and transformation pattern. This latter phenomenon was particularly noticeable at the periphery of the top bead where the heat-affected zone weld metal had transformed back into columnar-type grains. Also, interaction occurred between superimposed heat-affected zones, a typical occurrence being the continuation of a fine-grained region into a coarse-grained region at the point of interception with a new fusion boundary. The deposition sequence, however, was such that overlapping of heat-affected zones did not occur at the Ch V-notch location.

The scanning electron microscope (SEM) was used at the Welding Institute to study the as-deposited and reheated regions of the weldments. A linear intercept method was applied and the results obtained for as-welded specimens are given in Fig. 8, the change in intercept being monotonic with increasing manganese. The fusion boundaries were clearly visible, and there was also a sudden change in linear intercept when the boundaries were crossed. The boundaries between the intercritically and fully reheated regions, however, could not be located by direct observation, nor were they detected by the intercept measurements (Fig. 8), since little or no discontinuity of slope occurred within the reheated regions.

Fine-Grained Region. The fine-grained regions (Fig. 6) were photographed at X630, and linear intercepts of grain boundaries were made as described in Doc. II-A-389-76. The results obtained for the vertical (through-thickness) and horizontal directions are given in Table 4 and show a fair degree of equiaxiality.

The reciprocal of the square root of the mean grain interval is plotted, against weld metal manganese content, in Fig. 9. A straight-line relationship was obtained, manganese again being found to have a monotonic influence. Of particular interest is that the present grain size measurements can virtually be superimposed on those reported by Tuliani for reheated runs of submerged arc weld metal.

Mechanical Properties

Tensile Results. The tensile test data obtained are given in Table 5 for both the as-welded and stress-relieved con-

![Graph](image)

**Fig. 9—Effect of manganese on the mean linear grain intercept (fine-grained region)**

![Graph](image)

**Fig. 10—Effect of manganese on the tensile properties of multi-run deposits**

ditions. Yield strength and ultimate tensile strength are plotted in Fig. 10 and are seen to increase linearly with increasing manganese.

For the as-welded condition, the results (in N/mm²) are described as follows where YS is yield strength and UTS is ultimate tensile strength:

\[
\begin{align*}
YS &= 314 + 108 \text{ Mn} \quad (1) \\
UTS &= 394 + 108 \text{ Mn} \quad (2).
\end{align*}
\]

For the stress-relieved condition, the equivalent equations were calculated to be:

\[
\begin{align*}
YS &= 311 + 89 \text{ Mn} \quad (3) \\
UTS &= 390 + 98 \text{ Mn} \quad (4).
\end{align*}
\]

For the specific welding conditions employed, it was found that an increase of 0.1% manganese in the deposit increased the tensile parameters by approximately 10 N/mm². Stress relieving of the system (C-Mn) induced the tensile parameters to decrease, the drop being dependent on the manganese level.

Toughness Results. The Charpy V transition curves for as-welded deposits are given in Fig. 11. The COD test results obtained for saw notched specimens are plotted in Fig. 12 and the Schnadt test results are given in Figs. 13 and 14 for the K₁ and Bₙ conditions, respectively.

The data are replotted consecutively in Figs. 15 to 18, as a function of weld metal manganese and it is seen that the four different test procedures exhibited the same general trends. Increasing manganese lowered the upper shelf and displaced the transition curves to lower temperatures until an optimum condition had been attained at a manganese content of approximately 1.5%. Thereafter, increasing manganese became deleteri-
ous, except at very low temperatures where the lower shelf was raised.

The Charpy V-notch impact curves for stress-relieved deposits are plotted in Fig. 19 and the data are reconsidered in Fig. 20, as a function of manganese. Comparison with the as-welded condition (Fig. 11) indicates only a slight displacement, the heat treatment having had a beneficial effect at low manganese and a detrimental effect at high manganese contents. The extent of the temperature displacement, at the 100 J level, is given in Table 6.

The Charpy V curves obtained on testing strain aged impact specimens are shown in Fig. 21 and the equivalent results are plotted against manganese content in Fig. 22. Aging displaced the curves to higher temperatures, the shift at the 100 J level being reported in Table 7.

The lateral shift to higher temperatures differed according to manganese content, attaining a maximum (C) and then decreasing at the highest concentration investigated. The overall effect was for electrode D to become the best of the series and for the optimum to be displaced relative to that exhibited for as-welded and stress-relieved deposits.

Discussion

The metallographic studies of the four different manganese-containing deposits revealed marked differences in microstructure. In as-deposited weld metal, as exemplified by the top central bead, increasing amounts of manganese progressively increased the amount of acicular ferrite, at the expense of pro-eutectoid ferrite and of intermediate lamellar component. Furthermore, the acicular ferrite, per se, became progressively more refined (Table 3). The reheated regions were
similarly affected, the coarse grained and the fine grained zones also becoming increasingly finer. The overall influence of manganese on microstructure thus appeared to be beneficial throughout, the measured parameters changing monotonically.

The specific welding conditions employed were such as to induce the larger portion of the central part of the ISO 2560 deposits to recrystallize. For example, at the Charpy V-notch location, it was found, on the average, that only 20% of the structure remained in the columnar form. The amount of recrystallization is considered to be an important factor influencing mechanical properties and must therefore be borne in mind when attempting to evaluate the influence of alloying elements.

Tensile tests results confirm that manganese increases the yield strength and tensile strength of iron-manganese alloys. For the range of manganese contents investigated, solid solution hardening and grain refinement led to a linear influence, an increase of 0.1% Mn increasing the tensile parameters by 10 N/mm². The latter value compares favorably, but perhaps inadvertently, to that quoted by Brain and Smith for mild steel CO₂ weld metal and by Tuliani for submerged arc weld metal.

The tensile properties decreased after stress relieving, the drop being greater in the case of yield strength and high manganese levels. Carbide precipitation occurred at grain boundaries during the heat treatment, but evidently no secondary hardening occurred in the plain C-Mn weld metal system over the time involved.

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**Table 6—Effect of Stress Relief (at 100 J)**

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Temp. °C at 100 J</th>
<th>Displacement, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-27</td>
<td>-32</td>
</tr>
<tr>
<td>B</td>
<td>-44</td>
<td>-44</td>
</tr>
<tr>
<td>C</td>
<td>-53</td>
<td>-50</td>
</tr>
<tr>
<td>D</td>
<td>-43</td>
<td>-36</td>
</tr>
</tbody>
</table>

*AW—as-welded; SR—stress-relieved.  
**T = (9/5)°C + 32°*F.

The toughness data obtained using the Charpy V-notch, Schnadt (K, and B₅) and COD test revealed the same general trend in all cases. Thus, it can be concluded that the universal Charpy V test can be confidently applied for routine classification of electrodes according to ISO 2560. In practical applications, however, when considering properties in the full thickness of the joint, the COD test is a requisite for evaluating fitness for purpose and determining critical defect sizes.

In the transition region of the impact curves for as-welded deposits, manganese had an optimum influence at 1.5% Mn, despite the progressive improvement in microstructure throughout. The pattern of behavior is thus dependent on the competing actions of the element:

1. Increase the yield strength.
2. Increase the acicular ferrite volume fraction and to refine the grain size in the reheated region.

Stress relieving of the deposits had virtually no influence on the Charpy V-notch test results, and peak properties were also exhibited at the 1.5% Mn level. Furthermore, it appears that the decrease in toughness expected as a result of carbide precipitation was compensated for by an opposing mechanism, e.g., a softening of the ferrite.

Strain aging of the four experimental weld metals induced a considerable degree of embrittlement. In C-Mn deposits it is generally accepted that the major solute causing the decrease in resistance to cleavage fracture is nitrogen. Within the range of scatter, no trend in nitrogen content existed over the range of manganese contents studied, the values being between 69 and 96 ppm. Manganese is reported to diminish the aging tendency of steel, and opinion varies as to whether the element should be judged on its own merits or whether the combined effect of manganese and carbon is of greater significance. The relative displacement on strain aging (Table 7) was inconsistent and the reason remains enigmatic, other than that grain refinement alone becomes the controlling factor. The observed trend...
was such that deposit D exhibited the
best impact properties, the optimum
being displaced away from the pre-
vvious level of 1.5% Mn.

The present work is considered as an
initial step for the ultimate under-
standing of the role of microstructure
in multi-run manual metal arc de-
posits. Eventually, it is intended to add
alloying elements, e.g., Mo, Ni and Cr,
to the four different manganese levels
and evaluate the changes in structure
and properties. Firstly, however, it is
felt that further work should be con-
ducted on the C-Mn system so as to
appreciate the part played by carbide
distribution and morphology. To facil­
itate this, it is intended to study the
four weldments in the normalized and
normalized-and-tempered conditions.

Conclusions

For ISO 2560 weldments deposited
at 1 kJ/mm with basic electrodes of a
specific slag-base type, the following
conclusions applied:

1. Increasing manganese, in the
range 0.6 to 1.8%, increased the
amount of acicular ferrite in as-deposi-
ted weld metal and decreased the
amount of pro-eutectoid ferrite and
intermediate component.

2. Increasing manganese refined the
acicular ferrite in the as-deposited
weld metal.

3. Increasing manganese refined the
coarse grained region of the heat-
affected weld metal.

4. Increasing manganese reduced the
grain size of the equiaxed line
grained zone of the heat-affected
weld metal.

5. The yield and tensile strengths of the
deposits increased by approxi-
mately 10 N/mm² per 0.1% increase of
manganese.

6. Charpy V-notch, Schnadt (Kt, and
Bt) and COD tests graded the test
welds in the same relative order.

7. The optimum impact properties of
as-welded and stress-relieved de-
posits were attained at 1.5% Mn, due
to the competitive influence of yield
strength and microstructure.

8. Strain aging embrittled the de-
posits and changed the relative order
such that optimum impact properties
were achieved at a higher manganese
content.

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