The Effects of Titanium on Submerged Arc Weld Metal

Graphs are plotted for predicting the effect of C, Mn, Si and Ti in varying amounts and combinations on weld-metal strength and toughness.

BY J. P. SNYDER, II AND A. W. PENSE

ABSTRACT. The effect of titanium on the mechanical properties and microstructure of the weld metal in HSLA Si-Al killed low-sulfur steels containing varying amounts of titanium was determined. The titanium was introduced into the weld via dilution from the base metal. The nominal C, Mn, Si and Ti ranges in the weld deposits were 0.05-0.15, 1.0-1.4, 0.35-0.60 and 0.0-0.15%, respectively. Welding was done primarily with C-Mn electrodes. The effect of flux basicity was also determined. Finally, welds were also made with C-Mn-Mo and C-Mn-Mo-Ni electrodes to determine the contribution of electrode composition to toughness. Weld-metal yield and tensile strengths were obtained using subsize all-weld-metal tensile specimens. Toughness data were developed from standard Charpy impact specimens. Various microstructural features found in the weld metals were identified and quantified by means of optical and electron metallography.

The data were statistically analyzed using a two-level, three-factorial design based on C, Si and Ti and a partial factorial design based on C, Mn and Ti. Equations were developed for mechanical properties for compositions within the design limits. From these equations, a series of graphs were plotted for predicting the effect of C, Mn, Si and Ti in various amounts and combinations on weld-metal strength and toughness. Generally, yield and tensile strengths correlated well with composition. As titanium increased, both yield and tensile strengths increased. Low- and high-temperature toughnesses, −46°C (−51°F) and +52°C (126°F), respectively, were dependent on all four elements, with titanium and manganese supplying the strongest effects. Decreasing the titanium and increasing the manganese increased the toughness. The toughness was also increased by decreasing the amount of proeutectoid ferrite and refining the microstructure.

A practical range of weld-metal toughnesses was found to be obtainable in titanium-bearing steels using appropriate combinations of electrode composition and flux basicity.

Introduction

Studies have suggested that small titanium additions up to an optimum level of about 0.04 wt-% can have a beneficial effect on the toughness of submerged arc weld metal (Ref. 1, 2, 3). Toughness though, appears to be continuously reduced by titanium additions greater than 0.04%, indicating that high dilution welding processes such as submerged arc may develop low toughness weld deposits when used on base metals containing high titanium. However, as opposed to columbium and vanadium, titanium offers the combined advantage of greater metallurgical versatility and lower cost.

Specifically, titanium acts as a strengthener and sulfide-shape modifier, whereas columbium and vanadium have the strengthening function but do not control sulfide shape. As to the economics, columbium and vanadium cost about two and a half times more than titanium.

Experimental Program

To determine the effects not only of titanium variation but also the interaction of other elements with titanium, the design of the experimental program was factorial.

Twenty-one 227 kg (500 lb) laboratory ingots were poured and rolled to 13 mm (½ in) thick plate to make up the two series of heats which were tested in this program. The chemistries of these heats are given in Table 1.

The first series, coded CTS, was chosen to fit a two-level three-factorial experimental design. These heats were based on variations in carbon, silicon, and titanium levels at a constant manganese level. The second series, coded CTM, was chosen to fit a partial factorial design based on variations in carbon, titanium, and manganese levels at a constant silicon level. Several of the heats provided base metal for both series as shown on Table 1.

Table 2 presents the compositions of the commercially produced welding electrodes and fluxes. A majority of the welds
were made with electrode 123 and flux 85. Electrodes 128 and 130 were used to determine the effect of adding molybde­num or molybdenum plus nickel on the weld metal properties. Flux 851 and 0091 were used to determine the effect of flux basicity on weld metal properties.

Welding Procedure

All welding was done with a Scott-connected tandem AC submerged-arc system. Full-penetration welds of one pass per side were deposited into a square-butt joint. All plates were welded at a travel speed of 163 cm/min (i.e., 27.2 mm/s or 64 ipm) with an energy input of 2.1 kJ/cm (53.3 kJ/in.) using the following current (amperes, A) and voltage (volts, V) parameters: lead arc — 900 A and 35 V; trail arc-600 A and 40 V.

This procedure resulted in the carbon, silicon, manganese and titanium values shown in Table 3. From the chemistries of both parent plate and weld metal, the titanium dilution was determined to be about 50%. The titanium dilution is shown graphically in Fig. 1.

Cooling rates were obtained from several of the welds by harpooning W-5% Re vs. W-26% Re thermocouples into the molten weld pool just in back of the trail electrode. Cooling rates for 10 such measurements had a mean value of 11.0°C/s (19.8°F/s) between 800 and 500°C (1472 and 932°F) with a standard deviation of 0.5°C/s (0.9°F/s).

Testing and Metallographic Procedures

Specimens were removed for tensile and Charpy testing and chemical analysis as indicated in Fig. 2. Full-size Charpy specimens were machined transverse to the welding direction and notched in the plate thickness direction so as to contain about 60% of the second weld bead and about 40% of the first weld bead. Small, 0.5 inch (12.7 mm) gage length all-weld-metal tensile specimens were taken entirely from the second weld bead in the longitudinal direction. Specimens for metallography and hardness testing were final-polished with 0.03 micron aluminum oxide powder and etched in 2% nital. Quantitative metallography was done with a Leitz texture analysis system.

Specimens for transmission electron microscopy (TEM) were taken from the second weld bead and mechanically polished to 0.40 mm (0.016 in), chemically thinned to 0.05 mm (0.002 in) in 5% hydrofluoric acid and 30% hydrogen peroxide in water followed by electropolishing in 10% perchloric acid in acetic acid at 12°C (54°F).

The scanning electron microscope and the electron microprobe were used, respectively, to examine the fracture surfaces of broken impact specimens and to qualitatively analyze inclusions on polished surfaces.

Results and Discussion

The first part of this study was a statistical analysis of chemistry effects on the mechanical properties of the weld metal. A stepwise regression program was employed to determine the relationships of several dependent variables to carbon, titanium, and silicon in the CTS welds and to carbon, titanium, and man-

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**Table 1—Base Metal Chemistries, %**

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<tr>
<th>Plate</th>
<th>Series</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Ti</th>
<th>Al</th>
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<td>0.005</td>
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<td>0.066</td>
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<td>1.48</td>
<td>0.004</td>
<td>0.005</td>
<td>0.53</td>
<td>0.100</td>
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<td>0.075</td>
<td>0.043</td>
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<td>0.005</td>
<td>0.48</td>
<td>0.310</td>
<td>0.045</td>
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**Table 2—Welding Consumables, %**

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<th>Electrode</th>
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<th>Si</th>
<th>Mo</th>
<th>Ni</th>
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<th>Flux</th>
<th>SiO₂</th>
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<th>MgO</th>
<th>MnO</th>
<th>FeO</th>
<th>Na₂O</th>
<th>CaF₂</th>
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<td>85</td>
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<td>5.5</td>
<td>18.6</td>
<td>20.7</td>
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<td>0.9</td>
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<td>851</td>
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<td>11.5</td>
<td>37.5</td>
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<td>0.4</td>
<td>0.4</td>
<td>0.05</td>
<td>4.5</td>
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<td>0091</td>
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<td>4.2</td>
<td>43.9</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>4.80</td>
<td>9.3</td>
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</table>

(a) Basicity index = \[ \frac{(CaO + CaF₂ + MgO + K₂O + 0.3[MnO + FeO])}{(SiO₂ + 0.3[Al₂O₃ + TiO₂ + ZrO₂])} \]
Table 3—Weld-Metal Chemistries, %<sup>(a)</sup>

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<tr>
<th>Weld</th>
<th>C</th>
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<th>Si</th>
<th>Ti</th>
<th>Al</th>
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<td>2-5066</td>
<td>0.100</td>
<td>1.37</td>
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<td>0.012</td>
<td>0.60</td>
<td>0.077</td>
<td>0.039</td>
<td>0.085</td>
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<td>0.081</td>
<td>1.12</td>
<td>0.088</td>
<td>0.015</td>
<td>0.48</td>
<td>0.036</td>
<td>0.019</td>
<td>0.007</td>
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<td>0.011</td>
<td>0.37</td>
<td>0.036</td>
<td>0.020</td>
<td>0.063</td>
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<td>0.012</td>
<td>0.012</td>
<td>0.39</td>
<td>0.150</td>
<td>0.017</td>
<td>0.081</td>
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<td>0.012</td>
<td>0.55</td>
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<td>0.160</td>
<td>0.016</td>
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<td>0.47</td>
<td>0.160</td>
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<td>0.072</td>
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<td>0.46</td>
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<td>0.38</td>
<td>0.090</td>
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<td>0.140</td>
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<td>0.013</td>
<td>0.58</td>
<td>0.062</td>
<td>0.021</td>
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<td>1.04</td>
<td>0.005</td>
<td>0.013</td>
<td>0.52</td>
<td>0.078</td>
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<td>0.040</td>
<td>0.033</td>
<td>0.079</td>
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</table>

(a) NA— not analyzed.

Variables were yield and tensile strengths, maximum hardness, Charpy V-notch energy, and Charpy energy transition temperatures for 20 and 55 J. The equation expressing the relationships was given the following form:

\[
\text{Variable} = B_0 + B_1C + B_2Ti + B_3Si + B_{11}C^2 + B_{23}Ti^2 + B_{33}Si^2 + \]

where \( C, \) \( Ti, \) and \( Si \) equal the respective weight percentages in the weld metal for the CTS series. A similar equation was developed for the CTM series where manganese was substituted for silicon.

The regression program generated the coefficients, the multiple correlation coefficient (R), the standard error of the estimate (S<sub>Err</sub>), and the P-tail (P). The P-tail is the percent of the variability explained by chance, i.e., if P of an equation is equal to 0.02, then the relationship expressed by the equation has two chances out of one hundred of having occurred by chance.

Results of the analysis are given in Table 4. In the last column of Table 4, a correlation is defined as: "Excellent" if P of the equation is \( \leq 0.01; \) "Good" if P of the equation is \( 0.01 < P \leq 0.05; \) "Fair" if P of the equation is \( 0.05 < P \leq 0.15; \) "Poor" if P of the equation is \( > 0.15. \)

With the exception of the CTM yield strengths, correlation was shown to be
The results of the regression analysis show that manganese and silicon have a significant effect on the mechanical properties of the welds. The strength of a factorial design is that it gives both main effects and interactions. The analyses showed that the effects of titanium and manganese were strong in comparison with those of carbon and silicon. Titanium and manganese strongly increased the yield strengths, the silicon effect was weak. The effect of silicon was weak on the absorbed energy at 20°C.

The toughness, hardness, strength, and microstructures of the welds were summarized in Figs. 3 to 6. The toughness was measured using the Charpy test at -18°C and -20°C. The hardness was measured using the Vickers hardness test. The strength was determined using the tensile test. The microstructures were observed using a scanning electron microscope (SEM).

The welds were made using a gas metal arc welding (GMAW) process. The welding parameters were controlled to ensure that the welds were of good quality. The welds were assessed for their mechanical properties and microstructures. The results showed that the welds had good mechanical properties and microstructures. The welds were of good quality and could be used for practical applications.

The results of the regression analysis showed that the manganese and silicon contents had a significant effect on the mechanical properties of the welds. The effects of titanium and manganese were strong in comparison with those of carbon and silicon. The effects of titanium and manganese were stronger than the effects of carbon and silicon. The effects of silicon were weak on the absorbed energy at 20°C. The results showed that the welds had good mechanical properties and microstructures. The welds were of good quality and could be used for practical applications.

Table 4—Results of Regression Analysis

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1) YSW = yield strength; TSW = tensile strength; 4W = 4th weld; 12W = 12th weld; 18W = 18th weld; 24W = 24th weld; 52W = 52nd weld; 801TT = 8011TT; 851TT = 8511TT; MHW = maximum weld hardness; HVS = hardness of Vickers; %V = tensile strength.
2) CTS = constant temperature.
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65) CTS = constant temperature.
Table 5—All-Weld-Metal Data

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<th>Yield strength, MPa</th>
<th>Tensile strength, MPa</th>
<th>Charpy V-notch energy, joules</th>
<th>20 J transition temp., °C</th>
<th>55 J transition temp., °C</th>
<th>Maximum hardness, HV5</th>
<th>Ferrite veining, %</th>
<th>Inclusions, vol.%</th>
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(a) NT—no test.  
(b) NM—not measured.

The strongest effects on toughness were caused by titanium and manganese, with carbon and silicon having only minor effects.

Charpy V-Notch Energy. Titanium was found to correlate well with the absorbed energy at all test temperatures and for both high (1.3%) and low (1.05%) manganese levels. As titanium increased, the toughness at -46°C (-51°F) decreased—Fig. 7. Also note that the lower manganese data points show lower toughness values than the higher manganese points. Data points on the graph are actual values taken from Tables 3 and 5.

The same trends of titanium decreasing and manganese increasing the toughness are evident at +52°C (126°F) —Fig. 8. As shown in Fig. 9, the 55 J transition temperature increased with increasing titanium and decreasing manganese contents.

Weld-Metal Hardness. The trend found in the preceding three figures is partially explained in Fig. 10. The maximum weld hardness (Vickers with a 5 kg load) increased with titanium content, a result that is consistent with the findings of Boniszewski (Ref. 1) and Baum (Ref. 4). They concluded that the titanium adversely affected the toughness of the weld deposit by increasing hardness through solid solution hardening with an attendant decrease in ductility. As Fig. 10 demonstrates, hardness increased with increasing manganese.

Figure 11 shows the relation between maximum hardness and the 55 J transition temperature. Toughness deteriorated as hardness increased. The observed effect of titanium on hardness can be attributed to solid solution hardening or, as noted later, to some precipitation effect.

Our results for the effects of titanium
on toughness and hardness find support (Fig. 12) in Thaulow's study, in which the COD vs. Charpy toughness of submerged-arc welds was investigated at various titanium levels (Ref. 5).

Chemistry Effects on Microstructure

The microstructural features examined to explain the toughness variations were ferrite veining, inclusions, and ferrite grain size. Not all of these microconstituents were measured or statistically analyzed for each weld. Table 5 lists the collected data.

Ferrite Veining. Of all the transformation products found in carbon-manganese weld deposits, ferrite veining, or proeutectoid ferrite, is the most unambiguously recognized. Figure 13A shows a micrograph of ferrite veining at X100. This veining surrounds areas of acicular ferrite, which forms at temperatures lower than that of the proeutectoid ferrite, as determined by Abson and Dolby (Ref. 6). Figure 13B shows acicular ferrite and a small area of ferrite veining (arrow). Microhardness measurements (10 gm load, kg/mm²) given below show the acicular ferrite to be harder than the proeutectoid ferrite.

Acicular Proeutectoid

\[
\begin{align*}
W058 & \quad 201 \quad 154 \\
S062 & \quad 265 \quad 227
\end{align*}
\]

It is in the proeutectoid ferrite veins that cracks often initiate and propagate during Charpy testing. The polished cross section of a broken Charpy specimen in Fig. 14 shows the crack-propagation path to be through the ferrite veins. The embrittling effect of the veins results not from any inherent brittleness but rather from a mortar-in-brickwork morphology. The harder acicular ferrite concentrates the strain in the softer veins.

Titanium had differing effects on the amount of ferrite veining, depending on the level of manganese. The titanium
effect was weak at the higher manganese contents—Fig. 15. In contrast, at lower manganese levels, the relationship is such that as titanium increases the amount of ferrite veining increases—Fig. 16. In one of his studies, Widgery noted that veining increased with increasing titanium (Ref. 2). Figure 17 shows that increased veining decreases the energy absorbed at +24 C. This deleterious effect of ferrite veining on toughness may also be accompanied by the adverse effect of increased hardness, as was shown in Fig. 10. Although the relation of toughness to veining is by no means a simple one, the practical point, as borne out by our own and other investigators’ observations, is that good weld-metal toughness is obtained by avoiding proeutectoid ferrite in favor of acicular ferrite. As evidenced by our results, when the manganese level is low, veining increases as the titanium increases—that is, there is a dichotomy in the effects of titanium on veining, depending on whether the manganese level is low or high. A possible explanation for this dichotomy is that the role of titanium as a ferrite promoter and stabilizer is overshadowed at the higher manganese levels where manganese effectively restricts the growth of grain-boundary ferrite and induces the formation of intragranularly nucleated ferrite.

Structure Size. Both titanium and manganese are known to refine the microstructure of base metals; they can also affect the weld deposit in a similar fashion. This effect is clearly shown for manganese in Fig. 18. The higher manganese content produced a finer microstructure than did the lower manganese content. Both compositions were similar except for the manganese.

According to Levin and Hill’s classification (Ref. 7), Fig. 18A would be a category I structure due to the presence of acicular ferrite, and Fig. 18B would be a category II structure due to the lath-like morphology of the proeutectoid ferrite and the reduced amount of acicular ferrite. The higher manganese welds were also found to have a finer grain size in the weld metal heat-affected zone. Titanium did not seem to have a well-defined effect on the structure size of the ferrite.

Inclusions. The volume percent (vol-%) of inclusions was measured for selected welds and compared to their oxygen content. The inclusion data are found in Table 5. Since all welds to this point were made using an acid flux, the oxygen levels were similar at nominally 0.08%. The inclusion contents were also similar at about 0.5%.

Fig. 9 — 55 joule transition temperature vs. titanium

Fig. 10 — Maximum hardness vs. titanium

Fig. 11 — 55 joule transition temperature vs. maximum hardness. Mn nominally 1.3%

Fig. 12 — 28 joule transition temperature vs. hardness and titanium
Fig. 13—Microconstituents in a HSLA steel weld deposit: A—ferrite veining, X100; B—acicular ferrite, X500 (A and B reduced 48% on reproduction)

Fig. 14—Crack-propagation path through ferrite veins

Fig. 15—% ferrite veining vs. titanium and manganese at 0.07% carbon (CTM series)

Fig. 16—% ferrite veining vs. titanium for low-Mn welds. Mn nominally 1.05%

Fig. 17—Charpy V-notch energy at +24°C (75°F) vs. % ferrite veining (CTM series)

Fig. 18—Effect of manganese on microstructure, −16°C (0°F): A—1.27% Mn, 27 J; B—1.07% Mn, 10 J. Nital etch; X500 (reduced 48% on reproduction)
Qualitative microanalysis showed that inclusions were mainly oxides, some sulfides also being present. Since the type and quantity of inclusions were all similar, their effect on properties and microstructures was not measurable. However, as discussed in a later section, quantity of inclusion can have a strong effect on Charpy energy.

Hardening Mechanism. Some investigators attribute the relationship between increased hardness and decreased toughness in a weld to precipitation hardening caused by carbides and nitrides (Ref. 8-10). However, their studies present no electron microscopic evidence of the presence of such precipitates. Consequently, precipitates other than these should be considered.

For example, the relationship between titanium and hardness in the present study might be explained by the formation of fine titanium carbides or nitrides, typical of experience in base metals. However, transmission electron microscopy work on both thin foils and extraction replicas, revealed no particles except for iron carbides which were associated with fine pearlite throughout the weld deposit. Scanning transmission electron microscope (STEM) work on thin foils revealed small titanium-aluminum oxide particles dispersed throughout the matrix but no titanium nitrates or carbides.

An attempt was made to extract particles by dissolving the matrix, and collecting and x-ray analyzing the residue according to Kreige's procedure (Ref. 11). The only particles thus obtained were oxides. As such evidence indicates, the higher oxygen contents of the weld metal would cause the titanium to be fixed as oxides rather than carbides or nitrides which develop in the base metal with its characteristically lower oxygen contents.

Thermodynamic data show that titanium carbides and nitrides are less stable than titanium oxides (Ref. 12, 13). Also, a hardness increase is typically found in the first weld bead where carbides and nitrides are active due to the aging in the first weld deposit that is caused by the heat of the second weld pass. Hardness traverses made from the second weld bead into the first weld bead showed no evidence of increased hardness—Fig. 19. The hardness decrease is due to the formation of stress-free polygonal ferrite.

As evidenced by these findings—in particular, by the absence of titanium nitrates or carbides as well as by the absence of a hardness increase—a carbide or nitride precipitation mechanism was ruled out in our study. On the other hand, the oxides found in the STEM work and the evidence of the type presented in Fig. 10, 15, and 19 point to the deleterious effect of titanium being due to dispersion hardening by oxide particles and, as discussed previously, to increased veining at low-manganese levels.

Effect of Flux Variation

For linepipe welding, acid fluxes have been popular because they produce sound, smoothly contoured deposits and have good operating characteristics at the high current levels and travel speeds typical of the application (Ref. 14, 15, 16). Unfortunately, acid fluxes produce high oxygen contents in the weld metal, an effect that is deleterious to toughness.

To determine acceptable oxygen levels, three fluxes of varying basicity were tried with a carbon-manganese electrode to produce welds on a medium-titanium plate. Generally, the higher the basicity, the lower the oxygen level and the higher the toughness—Fig. 20. As the basicity of the flux increased, the absorbed energy increased, especially near the upper shelf.

The data in Fig. 21 confirm the basicity (Ref. 17, 18). Figure 22 shows that as the oxygen decreased, the volume percent of inclusions decreased. From previous work done on fracture surfaces, it is known that fewer inclusions produce larger dimples on a ductile fracture surface due to the smaller number of inclusions available to initiate microvoid coalescence (Ref. 17, 18).

Effect of Electrode Variation

Some investigators have indicated that additions of molybdenum or molybdenum plus nickel improve weld-metal toughness by reducing the amount of ferrite veining. To determine the effect of molybdenum and nickel on weld metal that contains titanium, several welds were made with electrodes of carbon-manganese, carbon-manganese plus molybdenum, and carbon-manganese plus
molybdenum and nickel. The 85 flux was used because of its superior operating characteristics, particularly for linepipe. As the two elements were added, the toughness was improved — Table 6.

The improvement in toughness is due to the increased hardenability supplied by molybdenum and nickel; this, as seen in Fig. 25, suppressed the formation of the ferrite veining and replaced it with acicular ferrite. This effect is consistent with the findings of Yoshino and Stout (Ref. 21) and of Takahashi (Ref. 22). Note that the decrease in veining with the concomitant increase in acicular ferrite is sufficient to maintain toughness even though there is an increase in hardness and strength.

The explanation is that the shift in favor of acicular ferrite means a reduction in the amount of structure having a mortar-in-brickwork morphology, and therefore a reduction in the availability of crack-propagation paths.

The effect of molybdenum is active at both high and low titanium levels, as evidenced by welds W059 and S062 — Table 6. However, the deleterious effect of titanium is also active in the presence of molybdenum, as is seen in a comparison of welds S062 and W059.

Conclusions

The findings of this study demonstrate that the detrimental effect of titanium on the toughness of submerged-arc welds in HSLA steels can be offset by the proper selection of electrode composition and flux basicity. Specifically, the study showed that:

1. Toughness is strongly dependent on the titanium and manganese levels. The toughness increases with decreasing titanium and increasing manganese. Titanium increases the amount of ferrite veining at low manganese levels and also increases the maximum weld-metal hardness through dispersion hardening. Manganese decreases the amount of ferrite veining and refines the microstructure.

Carbon and silicon have comparatively
weak effects, with carbon decreasing and sillicon increasing the toughness.

2. Toughness is improved by using higher-basicity fluxes. These fluxes reduce the oxygen level with a concomitant reduction in inclusion volume. Also, ferrite veining is reduced slightly with the higher-basicity fluxes.

3. Molybdenum or molybdenum plus nickel additions improve toughness by reducing the amount of ferrite veining.


5. Yield and tensile strengths increase with carbon, manganese, silicon, and titanium content. Manganese and silicon have comparatively weak effects on, respectively, yield and tensile strength.

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References


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1. Design of Beam Columns with Lateral-Torsional End Restraints
by T. L. Hsu and G. C. Lee

The AISC interaction equation approach is a very convenient design tool and has been widely accepted as the basic design approach for beam-columns. This study has addressed itself to one special aspect of the interaction equation approach: lateral-torsional buckling failure mode.

2. Tapered Columns with Unequal Flanges
by G. C. Lee and T. L. Hsu

This paper describes an analytical study with regard to the formulation of design considerations of columns with unequal flange areas in gable-type rigid frames.

Publication of these papers was sponsored by the WRC-SSRC Joint Subcommittee on Tapered Columns of the Structural Steel Committee of the Welding Research Council.

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