



## Toward Developing a SMA Welding Electrode for HSLA-100 Grade Steel

*Keeping heat input constant, flux components were varied to find the best combination of performance and mechanical properties*

BY D. A. FLEMING, A. Q. BRACARENSE, S. LIU, AND D. L. OLSON

**ABSTRACT.** A sequential flux coating formulation methodology was used to study the effects of welding flux type on high-strength steel weld metal microstructure and properties. Systematic variations in flux composition were made starting with an initial flux that can be classified as rutile-based and ending up with a more basic flux. The objective of these variations was to identify/develop a formulation of a SMA welding electrode flux that would exhibit the excellent welding behavior found typically in a rutile electrode, balanced with the superior weld metal properties deposited by a basic electrode.

Nine separate series of electrodes were investigated, each with one substitution for a specific component in the flux. The electrode that produced the best results for a given series was used as the basis for the formulation of the next series. The best experimental electrode formulated produced welds exhibiting an estimated yield strength of approximately 800 MPa (120 ksi) and acceptable toughness at  $-60^{\circ}\text{C}$  ( $-76^{\circ}\text{F}$ ) in single-pass welds. The weld metal impact fracture appearance at this temperature was predominantly ductile. The microstructure of this weld deposit was characterized by 60 vol-% acicular ferrite and 30 vol-%

lath martensite. The dual-phase microstructure and the 2:1 acicular ferrite-to-martensite volume ratio were results of controlled additions of titanium in the weld metal, at approximately 150 ppm. The weld metal oxygen was approximately 400 ppm.

The synergistic effects of weld metal oxygen and weld metal alloy content were characterized to develop an understanding of the deoxidation reactions that occurred in the weld pool. The oxygen-alloying content relationship observed in this program can be used as a basis to modify weld metal composition and design consumables to produce weld metals meeting specific weld metal property requirements.

### Introduction

The welding of high-strength low-alloy (HSLA) steel has gained significant importance during the past twenty years as structural requirements demand steels with higher strength to reduce section size and weight. A combination of eutectoidal decomposition and property enhancement due to microalloying addition has provided HSLA-100 steel with excellent strength and toughness properties. The welding of HSLA-100 steel is the primary concern in this research. In particular, this study addresses the formulation of a base composition of a shielded metal arc (SMA) welding electrode for joining HSLA-100 steel plates. The challenge of welding HSLA steels lies in controlling the weld metal microstructure, as well as developing a consumable that performs adequately in all positions. Also important is the reduction and/or elimination of pre- and postweld heat treatment to reduce production costs. The metallurgical development of the weld metal microstructure and properties is the major focus of this consumables research.

### Weld Metal Microstructure

HSLA steels are typically characterized with very low carbon content to improve their weldability. The mechanical properties of HSLA-100 steel are basically achieved by solid solution strength-

### KEY WORDS

SMA Welding  
HSLA Steel Welding  
Weld Pool Deoxidation  
Electrode Formulation  
 $P_{cm}$  Equation  
Dual Phase Microstruc.  
Acicular Ferrite  
Martensite  
Weld Metal Impact Tough.  
Weld Fracture

D. A. FLEMING, A. Q. BRACARENSE, S. LIU, and D. L. OLSON are with the Center for Welding and Joining Research, Colorado School of Mines, Golden, Colo.

ening, precipitation strengthening and microstructural transformation to bainite and martensite. Because of the intricate relationship between microstructure and thermal experience, one of the major problems in welding HSLA-100 steel is its microstructural instability during the thermal cycle of welding.

To achieve successful shielded metal arc welds of HSLA-100 steel with properties comparable to those of the original plate, a consumable with excellent properties is required. The electrode must produce weld metal with proper microstructure to give both sufficient strength and toughness.

Acicular ferrite is the weld metal constituent that has been reported to best promote toughness in HSLA steels with around 500 MPa (72 ksi) yield strength because of the random orientation of the ferrite laths and their ability to deflect cracks during propagation (Refs. 1–6). As such, a large amount of acicular ferrite optimizes the weld metal mechanical properties. Factors considered in the nucleation and growth of acicular ferrite are as follows (Ref. 7):

- 1) Chemical composition of the weld deposit.
- 2) Chemical composition of inclusions (mainly oxides).
- 3) Size distribution of inclusions.
- 4) Crystallographic and thermal discrepancy between inclusions and the matrix.

Intragranular transformation of austenite to acicular ferrite is favored when large prior austenite grains exist, which occurs when the inclusion density is low or when the inclusion sizes are greater than the Zener diameter, and grain boundary pinning sites are limited; and nonmetallic, intragranular inclusions are available for acicular ferrite nucleation. In addition to inclusion size, size distribution and chemical composition of second phase particles are important. However, an excessively low oxygen content, and thus a small inclusion population, will likely result in insufficient nuclei for acicular ferrite formation, and possibly leading to a bainitic microstructure.

To understand weld metal phase transformations, it is essential to know the weld metal oxygen content. Oxygen has a very low solubility in iron, suggesting that the oxygen found in the weld metal occurs as inclusions, which will have a variety of sizes and compositions (Ref. 8). A majority of these inclusions form as a result of different deoxidation steps in the liquid weld pool, with the final inclusions forming interdendritically during solidification (Refs. 9–11). It is these inclusions that affect the formation of weld metal ferrite.

In the case of an HSLA-100 steel, gas

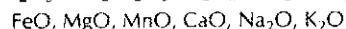
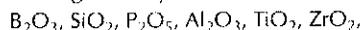
tungsten arc welding at 1.3 kJ/mm produced weld metals of high hardness (35 HRC) and of microstructure consisting of martensite and bainite (Ref. 12). The mechanical properties of this type of weld metal microstructure can be improved by introducing acicular ferrite laths to create small packets of martensite and bainite. The behavior of these martensite/bainite packets resembles that of refined grains, which enhance strength and improve toughness. Similar behavior was observed in HY-130 steel weldments by Ramsay, *et al.* (Ref. 13). Based on these observations, the development of acicular ferrite in HSLA-100 steel weldments is of great importance and must be promoted.

### Factors That Control Weld Metal Oxygen

The molten flux that is transferred to the weld pool will act as a slag cover for the weld bead. However, some of the oxides formed as a result of weld pool deoxidation may be trapped in the weld metal during solidification in the form of inclusions (e.g., silicates, aluminates, titanates) and affect subsequent solid-state transformations (Ref. 9). Since these deoxidation reactions will occur rapidly due to the high temperatures and large interfacial areas available for reaction (Refs. 14, 15), an understanding of the mechanisms that control weld metal oxygen is essential to the formulation of electrodes.

One important concept related to the various chemical reactions that occur during welding with electrodes covered by flux is the basicity of the slag or "basicity index" (Refs. 16–18). The basicity index is an empirical index developed to describe the metallurgical behavior of a slag, even though imperfectly. It has also been correlated with the amount of oxygen present in a weld metal. Higher basicity fluxes generally result in welds of lower oxygen content. And it is based on these experimental evidences that basicity index has also been related to the ability of oxides in a welding flux to dissociate into a metallic cation and an oxygen anion. Oxides which dissociate easily are termed basic, while those which dissociate only to a small degree are termed acid. The more common oxides in slags can be arranged according to their relative acidity or basicity as follows:

Increasing basicity  $\Rightarrow$



However, the definition of basicity of an oxide is not absolute. In fact, any oxide in the series shown above will

react as a base with any oxide that is more acidic in nature (to its left) and vice-versa.

As a result of still incomplete understanding of the thermodynamic properties of the slags, the empirical concept of basicity has been developed to predict flux and weld properties. Basicity index (BI) is determined by the ratio between basic and acidic ingredients, and may be estimated using the following equation (Refs. 18–22):

$$E = \frac{1}{2} CV^2 \quad (1)$$

In the above equation, each basic or acidic ingredient is represented by its mass percent in the flux. According to the International Institute of Welding interpretation, a flux is acidic when the basicity index is less than 1; neutral when it is between 1.0 and 1.5; semibasic when it is from 1.5 to 2.5; and basic when the index is greater than 2.5 (Ref. 20). It was found that in general the higher the basicity, the cleaner the weld metal with respect to nonmetallic inclusions, that is, lower weld metal oxygen content. Although a nonoxide,  $\text{CaF}_2$  has been included in the basicity index equation as a basic ingredient because of its ability of dissociation in  $\text{Ca}^{+2}$  and  $\text{F}^{-1}$  ions. (For additional discussion on basicity index, see Refs. 15, 18, 19, 46.)

Alloying elements in the weld metal will have a significant effect on the final microstructural phases present by affecting the hardenability and by reacting with oxygen to form inclusions, which serve as nucleation sites within the weld metal. These elements can also strengthen the weld metal through solid solution or precipitation strengthening (Ref. 1). The weld metal composition is directly affected by alloy additions from the flux or specially alloyed core rods used. Dilution of the base plate will also add alloying elements to the weldment. Each of the alloying elements will have an effect on the final weld metal properties. The individual effect is sometimes difficult to determine due to the synergistic effects of other additions.

Manganese, the primary weld metal alloy addition, stabilizes austenite to lower temperatures, which may lead to the formation of bainite and martensite. It is also suggested that manganese forms inclusions, for example,  $\text{MnO-Al}_2\text{O}_3$ , which acts as nucleation sites for acicular ferrite (Refs. 23, 24). The presence of acicular ferrite balances with the formation of harder phases to result in a microstructure that is characterized by both high strength and high tough-



**Table 1 — Expected Recovery of Elements From Electrode Coatings (Ref. 52)**

Alloy Element	Form of Material in Electrode Covering	Approximate Recovery of Element, wt-%
Aluminum	Ferro-aluminum	20
Boron	Ferro-boron	2
Carbon	Graphite	75
Chromium	Ferro-chromium	95
Columbium	Ferro-columbium	70
Copper	Copper metal	100
Manganese	Ferro-manganese	75
Molybdenum	Ferro-molybdenum	97
Nickel	Electrolytic nickel	100
Silicon	Ferro-silicon	45
Titanium	Ferro-titanium	5
Vanadium	Ferro-vanadium	80

that will occur in the solidifying weld pool, it is possible to predict the direction toward which these reactions will go as changes are made in the welding flux. The results of these calculations can assist in the development of a specified final weld metal composition.

Competing chemical reactions within the weld pool will also affect the final weld metal chemical composition. As local concentrations of alloy elements vary with solidification (Refs. 50, 51), the local activity of alloying elements will change, altering the amount of alloying additions that will be oxidized. As a result, these competitive reactions will alter the predicted weld metal chemical composition.

One parameter to quantify the role of a flux in determining the final weld metal chemical composition is the "delta quantity." The delta quantity for a specific alloying element is the amount of that element either gained or lost during the welding process and can be represented as:

$$[\text{Delta Quantity}] = [\text{Analytic Content}] - [\text{Estimated Content}] \quad (7)$$

**Table 2 — Chemical Composition of the HSLA-100 Steel Plate and Core Rod Used in the Experiments**

Chemical Composition of Plate and Core Rod (wt-%)		
Chemical Element	HSLA-100 Plate	ER100S-1 Rod
Carbon	0.06	0.061
Manganese	0.83	1.303
Phosphorus	0.011	0.006
Sulfur	0.002	0.006
Silicon	0.35	0.48
Copper	1.64	0.032
Nickel	3.43	2.043
Chromium	0.57	0.088
Molybdenum	0.62	0.502
Vanadium	—	0.011
Titanium	—	0.017
Aluminum	—	0.007
Zirconium	—	0.013

The estimated value for the chemical composition is determined by adding the contribution of elements from the welding wire to those of the contribution from the base plate by dilution calculation. The analytical content is that determined by the chemical analysis. A negative value of the delta quantity implies that the alloying element in consideration is lost to the slag and a positive value implies that the flux is contributing the alloying element in question to the weld pool. Zero delta quantity (null point) signifies no transfer of alloying elements from any of the sources. The most desirable flux systems are those that have delta quantities (at least for the major alloying elements) that remain relatively constant with variations in flux composition and welding condition. These fluxes allow for easy weld metal composition adjustment by adding or removing alloying elements from them. Additionally, the most stable flux systems are those fluxes that maintain the weld metal oxygen at low concentrations and thus minimize the deoxidation process.

Alloy additions can be made to the weld metal via the flux, and usually in the form of ferroalloys (e.g., Fe-Mn, Fe-Si, Fe-Ti, Fe-B, etc.). The use of ferroalloys in the welding flux for alloying is not ideal in the sense that the alloying element transfer to the weld metal may not be effective due to losses in slag-metal reactions or to the welding fume. Table 1 lists the commonly used ferro-additions with their expected element recovery in the weld deposit.

**Table 3 — Welding Parameters Used for All Welds**

Welding Parameters	
Current	130 Amperes
Voltage	29 Volts
Travel Speed	2.3 mm/s
Heat Input	1.6 kJ/mm

In this research, a methodology for the development of a SMA welding consumable for HSLA-100 steel was evaluated. Systematic changes were made to a rutile-based coating leading to a more basic electrode for this steel. Alloying elements, such as titanium and manganese, were introduced into the weld metal via ferro-additions. The synergistic effect of weld metal oxygen and weld metal alloy content on weld metal microstructure and properties was characterized to establish near-equilibrium trends for the deoxidation reactions that occur in the weld metal.

## Experimental Procedure

### Materials Used

The HSLA-100 steel welding coupons were 19.0 mm (3/4 in.) thick, and 101.6 by 152.4 mm (4 by 6 in.). The surface for welding was ground to remove any mill scale. Table 2 lists the chemical composition of the steel plate.

The steel core rod used in the consumables was an ER100S-1 (AWS A5.28-79) bare solid wire. The rod was 355.6 mm (14 in.) long and had a diameter of 3.2 mm (1/8 in.). The chemical composition for this rod is also shown in Table 2. The rod was chosen because of its commercial availability.

### Welding Procedure

A constant current power source was used to produce welds using DCEP (direct current electrode positive). A constant arc voltage was maintained to the desired preset value by the use of a potential sensing device and a stepping motor that would either move the rod closer to the plate to decrease the voltage or increase the arc length to increase voltage. The welding parameters used for all the welds are shown in Table 3. The welding parameters were kept constant for all the welds to allow for more consistent evaluation of the effects of specific flux ingredients on the welding process. The heat input used was relatively high for the SMA welding process, but the instability found in some of the experimental electrodes could only be controlled at higher voltages. For this investigation, it is important to make variations in the flux components only, and that the parameters controlling heat input remain constant in order to understand the specific role of flux additions.

For microstructural analysis, single bead-on-plate welds were deposited in the flat position, without preheat. For Charpy impact testing, single bead-in-

the flat position, without preheat. For Charpy impact testing, single bead-in-groove welds were produced. The grooves were 4 mm (0.16 in.) deep and had an included angle of 60 deg. These welds were also deposited in the flat position, without preheat.

### Flux Formulation Concept and Test Matrix

Figure 2 is a ternary representation of the general changes in electrode coating as the formulation progressed. The initial electrodes had a high rutile and silica content and their flux composition can be located in the lower portion of the diagram. As the changes were made in the flux formulation, the silica and rutile were replaced with more basic components, which moved the coating composition toward the top portion of the ternary diagram. Although  $\text{CaCO}_3$  ( $\text{CaO}$ ) and  $\text{CaF}_2$  are not expected to behave the same, they are both considered to be the primary constituents of a basic flux, and are therefore grouped together in this figure. Following the arrow indicated in Fig. 2, an initial rutile-based electrode coating was modified to improve its metallurgical characteristics in weld pool oxygen and alloying elements control. The changes were made gradually such that the good electrode performance of a rutile-based electrode would not be radically altered.

### Electrode Formulation

An experimental matrix was devised to systematically vary two components at a time in the flux. The experimental electrode designation has the format Axxx, with x representing numbers from 0 to 9. The first digit is the series number, the second digit is the sequence number within each series, and the third digit is used to designate later modifications in each series.

There are two methods of making changes in electrode composition. The first consists of changing the target component, which decreases the overall mass percent of the remaining components, while maintaining the ratio among them. The second approach requires changing two components simultaneously (one decreasing a specific amount while the other is increased by the same amount).

In this research, the second approach was used and changes in the coating were made by direct replacement of one component with another. A one-for-one substitution maintains the weight percent of the remaining flux components at a constant, allowing for better determination of the influence of the specific

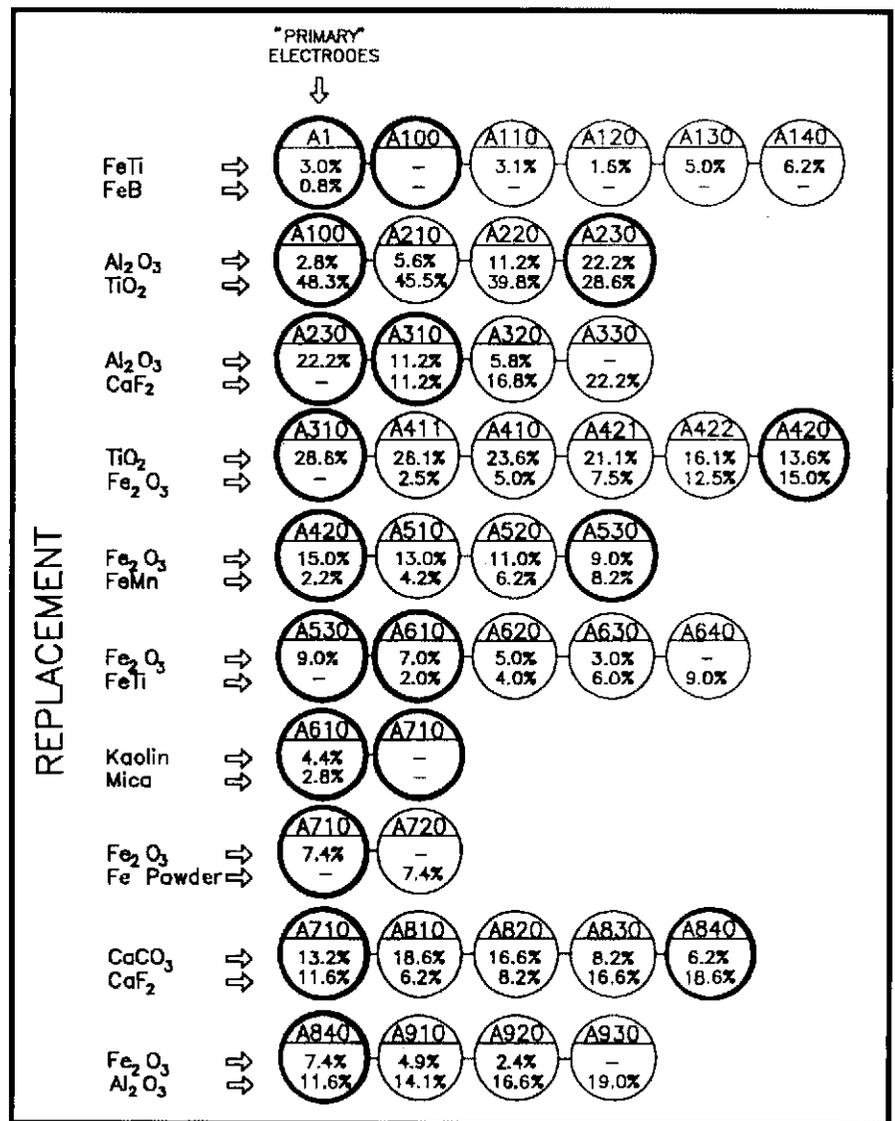


Fig. 3 — Representation of the electrode formulation sequence. Primary changes made in each series are designated above the corresponding line. Electrodes used as the starting composition for each new series are placed at the beginning of each new line (Ref. 56).

Table 4 — Components and Primary Functions of the Flux Ingredients Used in the Experiments

Component	Formulae	Primary Function
Alumina	$\text{Al}_2\text{O}_3$	Arc Stabilizer
Calcium Carbonate	$\text{CaCO}_3$	Shielding Gas
Calcium Fluoride	$\text{CaF}_2$	Slag Former
Feldspar	$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$	Shielding Gas
Ferroboron	Fe-B	Alloying
Ferromanganese	Fe-Mn	Deoxidizer
Ferrotitanium	Fe-Ti	Alloying
Iron Oxide	$\text{Fe}_2\text{O}_3$	Slag Former
Kaolin	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot \text{H}_2\text{O}$	Slipping Agent
Mica	$\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$	Slipping Agent
Potassium Silicate	$\text{K}_2\text{SiO}_2$	Binder
Potassium Titanate	$2\text{K}_2\text{O} \cdot 2\text{TiO}_2$	Arc Stabilizer
Silica	$\text{SiO}_2$	Slag Former
Sodium Silicate	$\text{Na}_2\text{SiO}_2$	Binder
Titanium Dioxide	$\text{TiO}_2$	Slag Former

**Table 5 — Ferromanganese Additions, Weld Metal Manganese Content, and Manganese Delta Quantity for the A5xx Welding Electrodes**

A5xx Welding Electrode			
Electrode Designation	Ferromanganese Addition (wt-%)	Weld Metal Manganese Content (wt-%)	Manganese Delta Quantity (wt-%)
A420	2.2	0.26	-0.79
A510	4.2	0.39	-0.68
A520	6.2	0.64	-0.45
A530	8.2	0.83	-0.24

changes made. All electrodes within each series were evaluated and the one that produced the best results for the flux system analyzed was used as the starting formulation for the next series. Considering Table 4, each substitution was made with the primary function of each component in mind. Nevertheless, careful considerations that each change would have an influence on the metallurgical properties of the resultant weldment, in the form of weld metal chemical composition and microstructure, were also made.

Figure 3 shows the electrode "genealogy" for the entire test matrix. The major constituents changed are placed at the start of each line, and the electrode selected as the starting point for the next series appears highlighted (circled by a bold circle) along the series line. These electrodes are the primary electrodes. For example, in the A2xx series, CaF<sub>2</sub> was added to gradually replace Al<sub>2</sub>O<sub>3</sub>. Electrode A230 performed most satisfactorily in the series and was chosen to be further modified in the A3xx series. The overall consideration in the modification of the welding flux was to characterize the significant changes in the behavior of the welding electrode as the coating was adjusted from rutile to more basic in nature.

#### Methodology of Formulation

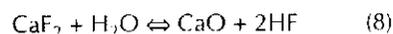
The first electrode (A1) was formulated from an experimental rutile-based electrode, developed prior to this inves-

tigation (Ref. 53). Its composition was chosen because of its good welding performance such as slag formability, slag detachability, arc stability, and weld bead morphology.

The initial electrode series was designated A1xx. These electrodes had high rutile content and were comparable to a commercial E6013 steel welding electrode. Systematic additions of FeTi were made in this coating to study the influence of titanium on the microstructure in an electrode with high oxygen potential. Ferro-boron was removed from the electrode at this point, with the intention of adding it back into the system in a later series. However, the idea of reintroducing ferro-boron was eventually abandoned.

The A2xx series was characterized by the replacement of TiO<sub>2</sub> with Al<sub>2</sub>O<sub>3</sub>, with alumina increasing from 2.8 to 22.2 wt-%. Alumina is amphoteric and should reduce the oxygen in the weld metal while decreasing the viscosity of the slag. This step was the first in a series of alterations to the oxygen potential of the electrode to characterize the effect of oxygen on weld metal microstructure.

For the A3xx series, the alumina was removed and substituted with CaF<sub>2</sub>. This procedure was done to further reduce the oxygen in the weld metal, as well as decrease the viscosity of the slag. It is also suggested (Ref. 54) that calcium fluoride reduces the free hydrogen in the weld metal by the reaction:



Despite the desirable properties of CaF<sub>2</sub>, high content of this ingredient in the flux formulation causes arc instability during welding, requiring extremely high mean voltage to sustain the arc.

The A4xx series involved the substitution of rutile with ferric oxide (Fe<sub>2</sub>O<sub>3</sub>). This substitution resulted in a further increase of the basicity index and improved arc stability, although there was a subsequent increase in the weld metal oxygen. The hematite was to be removed in subsequent steps with the substitution of ferroalloys.

The A5xx series consisted of additions of Fe-Mn at the expense of Fe<sub>2</sub>O<sub>3</sub>. The manganese content in the weld metal was increased at this point in an effort to increase the hardenability of the weld metal, depressing the ferrite start temperature to promote lower transformation temperature products. The lowering of the austenite decomposition temperature occurred also as a result of the decrease in oxygen and oxide inclusions. This test series led to an understanding of the recovery of manganese in this system.

Addition of Fe-Ti to the coating was made in the A6xx series. Ferric oxide was further reduced at this point. Titanium was added to promote the formation of acicular ferrite in the weld metal with the formation of titanium oxides in the weld metal. Also, comparison of the recovery of titanium in this series (more basic in nature), could be made with the initial ferro-titanium additions in the A1xx series (rutile in nature).

For the A7xx series, mica and kaolin, both containing water of crystallization, were removed. This removal was done in an attempt to verify the importance of chemically bonded water on oxygen generation in the weld metal. Also, ferric oxide was replaced with iron powder in an effort to further decrease oxygen.

The CaF<sub>2</sub> to CaCO<sub>3</sub> ratio was altered in the A8xx series. Control of the weld metal oxygen, as well as slag viscosity, was the goal of this alteration. Calcium fluoride is known from steelmaking to reduce the melting temperature of the slag and thus lower the viscosity. CaCO<sub>3</sub> decomposes in the arc resulting in the formation of CO<sub>2</sub> gas and CaO. Carbon dioxide will serve to shield the weld pool while CaO, incorporated in the slag, will affect the melting temperature and viscosity of the slag, and the amount of oxygen in the weld metal.

In the final series, A9xx, ferric oxide was replaced with alumina in an effort to improve slag viscosity for out-of-position

**Table 6 — Ferrotitanium Additions, Weld Metal Titanium Content, and Titanium Delta Quantity for the A6xx Welding Electrodes**

A6xx Welding Electrodes			
Electrode Designation	Ferrotitanium Addition (wt-%)	Weld Metal Titanium Content (wt-%)	Titanium Delta Quantity (wt-%)
A530	0.0	0.007	-0.002
A610	2.0	0.017	0.007
A620	4.0	0.021	0.011
A630	6.0	0.029	0.020
A640	9.0	0.036	0.027













