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The Effect of Welding Consumables on Arc Welding Process Control and Weld Metal Structure and Properties

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Submitted by : David L. Olson and Robert H. Frost
Principal Investigators
Center for Welding, Joining, and Coating Research
Colorado School of Mines
Golden, CO 80401-1887

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Colorado School of Mines
Golden, Colorado 80401

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David L. Olson and Robert H. Frost

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Center for Welding, Joining, and Coating Research
Colorado School of Mines
1500 Illinois St, Golden
Colorado 80401-1887

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13. ABSTRACT

The effect of welding consumables on arc welding process control and weld metal structure and properties was investigated. The first study demonstrated the potential use of exothermically (thermite) assisting steel arc welding consumables for field repair welding. Both shielded metal arc (SMA) and flux cored arc (FCA) consumables were prepared to allow generation of chemical energy to supplement electrical energy during welding, allowing for welding with smaller or even no external power sources. Work is in progress to make these consumables both exothermic and self-shielding.

These research studies continued with issues related to weld metal microstructure control. Weld metal aluminum grain refining is being investigated to improve the weldability of aluminum alloys. Grain refiners, which are being introduced through the metal cored welding consumables, were selected based on an understanding of the inoculant dissolution kinetics, and weld metal solidification behavior. Also, the role of shielding gas oxygen on the welding pool chemistry was studied.

Finally, a project demonstrating the ability to use magnetic measurements to monitor weld metal phase changes was performed

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1 STATEMENT OF THE PROBLEM STUDIED

Field welding repair is essential to maintain the effective use of machinery, and mobile structures (light portable bridges and light watercraft) and technical assemblies (trucks, armor vehicles, etc.). Today, this requirement must address the advances in high strength low alloy steels, new aluminum alloys and the future increased use of titanium alloys. The primary hindrance in having field welding repair systems as advanced and as flexible as the today's Army are the following:

1. The weight and balkiness of the present welding power sources, and wire feeding and control systems is a liability to the needed mobility.
2. The Army is on the forefront in using advanced structural materials such as the use of advanced higher strength and thus lighter weight steels, the significant role of aluminum in Army portable structures and vehicles to achieve air mobility, and the increased interest in titanium alloys. The weldability, especially for field repair, requires special welding consumables.
3. Present welding practices require developed skills and along with the numerous functions that Army personnel must perform. It is very desirable to have welding processes that are more amenable to a wide range of personal skills. This "welder friendly" system is achievable through innovations in both power source controls and welding consumables.
4. Shielding gases for welding is a special burden to a mobile force. It requires repair personnel to use specific flux assisted welding processes and/or provide and handle bottled shielding gases. New self-shielding welding consumables and practices need to be developed to be consistent with the needs of mobility and to cope with various field environments.

1.1 EXOTHERMICALLY-ASSISTED WELDING CONSUMABLES

The primary focus of the ongoing ARO sponsored research at the Colorado School of Mines is to determine the heating potential of exothermic additions to the flux in arc welding consumables. The rapid oxidation of metallic elements such as magnesium, aluminum and titanium, to name a few, are known to release significant quantities of heat. It is possible that such reactions occurring in flux coatings during arc welding could greatly assist in the generation of heat for welding. Theoretical calculations indicate that with high concentrations of exothermic promoting additions it may be possible to formulate a welding flux that can supply all or most of the heat for welding through such chemical reactions.

1.1.1 CONCEPT

The weld bead is formed from both the melted electrode and the melted base metal. Therefore, an investigation of alternate heat sources must consider the total quantity of metal which is melted to form the weld deposit. Two parameters which relate directly to the formation of the weld deposit are the penetration depth and the cross-sectional area of the weld bead. Studies of the welding arc heat distribution have shown that higher currents and higher welding speeds more efficiently use energy for melting (1). It has been shown that the amount of fused base metal increases with

increasing welding current, and that voltage does not significantly affect the weld bead cross sectional area.

To demonstrate the effect of current and voltage on the fusion zone area, Jackson (1) made a series of constant voltage submerged arc welds at two different currents, and adjusted the welding speed to yield the same electrical heat input. Although both sets of welding parameters provided the same calculated heat input, the weld nugget produced by the high-current weld was larger. These results suggest that weld deposit formation depends on the intensity of the arc energy transferred to the base material and the influence of fluid flow in the weld pool.

The effects of welding variables on electrode melting characteristics have been the subject of extensive research (2-9). A number of variables has been shown to affect electrode melting rate, including current, polarity, and electrode diameter. It has been shown that the electrode melting rate increases with current. Humrntzch (9) investigated the effect of covering composition of coated electrodes on the electrode melting rate. The heats of formation, vaporization and ionization of the compounds in the covering were related to the electrode melting rate. The lowest melting rates were reported for cesium and barium compounds and the rate was increased with magnesium, titanium, and silicon compounds. The addition of different elements to the welding arc can change the temperature of the arc and consequently the ability of the arc to transfer heat to the weld deposit. Elemental additions which are capable of producing heat through exothermic interactions may or may not change the arc efficiency, but are potential heat generators.

Another measure of the efficiency of the welding process is referred to as the melting efficiency (2). This parameter has been defined for both the electrode and the base material. Melting efficiency measures the amount of arc energy that is used to melt the electrode and the amount of arc energy available to melt the base plate. Melting efficiency relates the physical dimensions of the weld deposit to the energy input from the arc, and it is used as a measure of the heat evolved and used to melt the weld nugget during exothermically-assisted welding. This parameter is evaluated using calorimetric data to determine the potential of chemically-assisted welding electrodes.

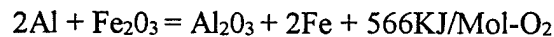
The mechanism by which plate melting occurs during arc welding is not well understood. However, three major influencing factors that have been identified (3,8) are: (i) heat generated from the cathode/anode potential drop zones, (ii) heat generated from the arc column, and (iii) the superheat of the molten metal from the electrode. The heat generated in the arc plasma is dependent on the welding current and voltage. Thus, the higher the current and/or voltage the higher the amount of heat generated. The higher the heat generated in the arc plasma, the greater the plate melting. Theoretically, one joule of heat will melt 0.0854 mm^3 of steel (assuming the temperature of molten steel during welding is 1750°C). For a given electrical heat input, the theoretical volume melted is given by 0.0854 VI/S (S.I units), where V, I, and S are the welding voltage, current and travel speed, respectively.

Weld pool convection or stirring has also been shown to influence the weld bead penetration and morphology. There are two primary factors which contribute to weld pool convection. Current flowing into the weld pool exerts a force (Lorentz) on the liquid metal. This force will stir the molten metal toroidally inward. The downward flow of metal at the center enhances the flow of heat and tends to produce a relatively deep weld pool (10,11). The second force originates from surface tension gradients (Marangoni effect) produced by temperature gradients at the weld pool surface.

Near the center of the weld pool, the arc heating is greater than at the weld pool edge where the pool is solidifying which produces a temperature gradient. Weld pool composition has been found to affect the surface tension temperature coefficient, (10). Low concentrations (less than 150 ppm) of surface active elements (S, O, and Se) have been found to substantially alter the shape of the weld deposits. In the presence of surface active elements, the surface tension-temperature coefficient is positive, producing the negative capillarity driven fluid flow which is responding to the weld pool thermal gradient. This response results in an inward toroidal stirring and a relatively deep and narrow bead geometry. The opposite occurs when the surface tension temperature coefficient is negative, producing outward toroidal stirring and in a wide pool with shallow penetration. The dominant stirring mode has been shown to be related to the magnitude of the welding current. Below approximately 150 amperes the surface tension force controls the dominant stirring mode. Above 150 amperes, the Lorentz force dominates the stirring characteristics. The exothermic addition will significantly alter the weld metal nonmetallic concentration and alter the weld pool fluid flow and resulting weld bead size and morphology.

1.1.2 EXOTHERMIC CONSUMABLES

Goldschmidt discovered that if fine metallic oxide powders are mixed with fine aluminum powders they will, if ignited, fuse and produce temperatures of 5400° F (2500° C) in less than thirty seconds without the use of outside heat or power (12). This thermite (exothermic) reaction is stated as follows:



Similar reactions occur when magnesium, titanium or calcium are oxidized. (1) Applying Hess's law from room temperature to the temperature of the steel weld pool (~1750° C), the quantity of heat produced by the reactions between aluminum or magnesium with hematite can be calculated. Table I shows the amount of heat released during these exothermic reactions.

Table I -Enthalpies of Reaction for the Aluminum and Magnesium Plus

Hematite Systems

Reaction	Enthalpy (kJ/mol-O ₂)
$2/3 \text{ Al} + 1/3 \text{ Fe}_2\text{O}_3 = 1/3 \text{ Al}_2\text{O}_3 + 2/3 \text{ Fe}$	566
$\text{Mg} + 1/3 \text{ Fe}_2\text{O}_3 = \text{MgO} + 2/3 \text{ Fe}$	1060
50/50 Mg-Al alloy reacted with hematite	Quantity of heat between 566 and 1060

The thermite welding process does not require external heat, welding electrodes, or welding machines, and has been used to join large sections of material. Several US companies currently market exothermic systems for joining high-conductivity electrical connections.

During the 1980's, several Russian researchers investigated the effect of exothermic additions to flux covered and flux cored electrodes, and focused on the effect of these additions on deposition rate and electrode melting efficiency. Glushchenko (13) investigated the effect of thermite (exothermic) mixtures in submerged arc fluxes on welding productivity parameters (i.e. deposition rate, melting efficiency, etc.). He has derived equations which may predict these parameters for a given exothermic flux mixture. Zarechenskii (14) used the exothermic reaction between a magnesium-aluminum alloy and hematite to increase the melting efficiency of the flux-cored welding process. His work showed that the additional heat produced by the reactive addition assists in melting the flux core. This behavior is thought to be the factor limiting the melting efficiency for this process. Karpenko (15) investigated the effects of thermite (aluminum + iron oxide) additions on the melting characteristics of flux coated SMA welding electrodes. The results of this study indicate that the reactive additions increase the weld deposition rate, and that particular values of welding parameters and the oxide-to-reactive element ratio optimize productivity. Ioffe et al. (16) studied the effects of a titanothermite mixture on melting parameters, and they have derived theoretical equations to predict the percent increase in heating due to exothermic reactions. They report increases from 3 to 26 percent in heat generation, and increases of 8 to 29 percent in melting efficiency depending on the amount of reactive reagent in the flux coating.

Exothermic cutting systems are currently used for cutting of ferrous and nonferrous materials. They can be used in the absence of an external power source once the reaction is initiated (17,18). Olson and Schwemmer (19) discovered that submerged arc fluxes high in iron oxide increase penetration and actually cut high-chromium steel. It is thought that an exothermic reaction between the chromium in the steel and the iron oxide in the flux is responsible for the cutting phenomena. This approach could be used by flux formulators to design a SMA electrode which could be used for cutting stainless steel equipment in the field.

It has been demonstrated by the present ARO project that exothermically coated or flux-cored welding electrodes are capable of chemically supplying most of the heat required for welding (20). Exothermic welding consumables could be employed in emergency repair situations where conventional power supplies are not available. Conceptually the repair welds would be initiated using a twelve volt battery to ignite the exothermic electrode, and the exothermic reaction would supply the remainder of the heat. In addition, exothermic additions could enable large manual electrodes to be used with small, portable, garage type power supplies. In this case the combustion would serve to increase the productivity and the deposition rate, and a sufficient current would maintain penetration. This combination would allow for smaller welding power sources. Exothermic welding consumable could also be used with lower welding currents to alleviate overheating and blow complications.

1.1.3 WELDING CONSUMABLES AND FLUXES

The selection of a suitable welding consumable is critical for the production of a weld deposit with high mechanical integrity. The manufacturers of welding consumables have consistently satisfied the needs of the welding industry in this respect. For a number of different reasons, the success of several arc welding processes relies heavily on the development of consumables which produce specific behavior of solid flux ingredients (21-25).

Each process requires a different flux formulation. Typical fluxes can contain as two or three ingredients and as many as ten or fifteen. Each constituent ingredient performs a necessary function during either the manufacture and storage of the consumable, or during the welding process itself. The interaction of these ingredients also plays an important role in determining the final welding performance of the flux. Table II lists the necessary functions of the flux and the constituents commonly employed to perform these functions during shielded-metal arc welding. Similar ingredients and functions are required for the FCA welding processes. This investigation is to evaluate new flux additions which will produce exothermic heat and be compatible with the other additions to achieve an optimum behavior of the total welding flux.

Table II - Typical Shielded Metal Arc Flux Coating
Constituents and Their Functions

Constituent	Functions of Constituent	
	Primary	Secondary
Cellulose	Shielding Gas	
Calcium Carbonate	Shielding Gas	Fluxing Agent
Fluorspar	Slag Former	Fluxing Agent
Dolomite	Shielding Gas	Fluxing Agent
Titanium Dioxide	Slag Former	Arc Stabilizer
Potassium Titanate	Arc Stabilizer	Slag Former
Feldspar	Slag Former	Arc Stabilizer
Mica	Extrusion	Arc Stabilizer
Clay	Extrusion	Slag Former
Silica	Slag Former	
Manganese	Slag Former	Alloying
Iron Oxide	Slag Former	
Iron Powder	Deposition Rate	Contact Welding
Ferromanganese	Deoxidizer	
Sodium Silicate	Alloying	Deoxidizer
Potassium Silicate	Arc Stabilizer	Binder

1.2 SELF SHIELDING CONSUMMABLES

Self shielding welding consumables can result from the use of additions to the welding consumable which will serve as both a very strong deoxidizer and denitrider. These additions must protect the weld deposit from the exposure of air. This protection has been achieved by using an aluminum addition up to one percent of the total deposit for deoxidation and denitridation. Lithium additions are used to assist of denitridation and arc control. Magnesium additions are added for weld metal desulfurization. It is obvious that self shielding additions are the same or very similar in selection as to the exothermic additions discuss above. There is an excellent opportunity to combine these two objectives and produce a self shielded exothermic assisted flux cored welding consumable which will allow for elimination or reduction in the size of the power source and no need for porting shielding gas during field repair welding. The results from the present ARO contract has shown that the first objective can be achieved but needs optimization in the amount of addition and determination of the proper welding parameter space.

Since no wrought commercial steels content more than 0.3 wt. pct. aluminum, there may be concern over the resulting microstructure and properties. When welding in air one would expect that the weld pool would experience nitrogen boiling which would result in weld porosity. When air enters the welding plasma the diatomic nitrogen is disassociated into atomic nitrogen which readily dissolved into the weld pool. Then on solidification the dissolved nitrogen recombine to form diatomic nitrogen but this time in the form of weld metal pores. It has been reported that lithium vapor in the plasma displaces significant amount of the nitrogen in the welding plasma and thus a reduced nitrogen absorption in the weld pool.

There is evidence that if the proper welding practice, cooling rate, is used in welding structural steels that acceptable properties can be achieved and that self shielded welding products are being used for welding mild steel structures. The primary issue is the formation of weld metal aluminum nitride which it has been seen in castings to form along grain boundaries and can cause brittle fracture. The welding process has a significantly faster cooling rate, than experienced in castings, which allows for a more desirable denitridding process and produces acceptable weld metal microstructure. The amount of aluminum used is based on a weld pool nitrogen concentration necessary to prevent nitrogen boil. Ferrosilicon addition is also optimized for a given carbon content to prevent carbon boil. No significant problem with weld porosity has been reported for self shielded FCA weld deposits. The complex chemistry between aluminum and lithium with air and in the weld metal needs to be investigated and modeled to allow for designing flux formulations for self shielded exothermic assisted welding consumables needed to advance field welding repair, which experiences a wide variety of welding environments.

Self shielded, exothermically assisted welding consumables are needed to advance field welding repair, and the flux additions to achieve self shielding will also be investigated for their functional efficiency and their compatibility with other needed flux components.

1.3 FIELD WELDING REPAIR OF ALUMINUM STRUCTURES

The weldability of an alloy depends mainly on the ability to create a weldment free from defects inherent to the welding process. The weldability of aluminum alloys is often defined by their susceptibility to the formation of the hot tears which are fractures created in the mushy zone. Hot tears form during welding if the alloy possesses an inherent susceptibility and if sufficient strain exists in the weld to cause their formation. The major factors that contribute to the susceptibility of a specific alloy to hot tear formation are: the coarseness of the solidification structure, the amount and species of the alloy additions, and the geometry of the welded joint. The primary solution to the weldability problem has been to avoid the use of certain alloys with high hot tear susceptibilities or to use filler metal alloy compositions that reduce the susceptibility by modifying weld bead composition. A secondary solution has been to address the dependence of hot tearing on the coarseness of the solidification structure.

Competitive growth between grains exists because of the relationship between the preferred crystallographic growth direction and the thermal gradient in the weld pool. The nucleation of new grains with more favorable orientations is seldom observed, however, in the absence of heterogeneous nuclei. The low frequency of nucleation of new weld metal grains allows the growth of large columnar grains and the development of a coarse solidification structure. This type of solidification is particularly deleterious, because it leads to a greater degree of alloy element segregation at the centerline, and to enhanced hot tear formation in this localized region.

Major improvements in aluminum alloy weldability have been achieved through weld metal grain refinement. Methods utilized for nucleation of new weld metal grains have included: a) the use of grain refining additions to promote heterogeneous nucleation (26-31); b) stirring of the weld pool to promote dendrite fragmentation and thus new growth sites (32-34); and c) The modification of heat input to promote banding and other disrupted solidification behavior (35-37). The grain refinement method frequently chosen has been to make elemental additions that provide a heterogeneous substrates for the nucleation of new weld metal grains. Titanium and zirconium have been the two most common elements used in aluminum alloys to promote heterogeneous nucleation. These two elements are able to produce refinement because of the existence of inter-metallic compounds (TiAl_3 or ZrAl_3) in the aluminum alloy systems. These particles provide a substrate upon which the nucleation of new grains may take place (26-31).

The variability of the reported effectiveness of the grain refining additions has led to concern about the sensitivity of intermetallic particles to welding and solidification process variables. The currently accepted models suggest that the grain refining additions must be present in the intermetallic form prior to welding for grain refining to occur. These intermetallic phase particles are susceptible to dissolution under the weld pool environment, and once dissolved, they can not reform at the high cooling rates experienced during weld pool solidification (37-41). Multipass welding experiments (26,42) have shown that the refined structure is present after the first welding pass, but that subsequent passes produce a less refined solidification structure with larger grains.

2 RESULTS OF ARO PROJECT AT THE COLORADO SCHOOL OF MINES

The proposed research is for both the continuation of pyrochemical and metallurgical research presently sponsored by ARO, and new, but related, proposed advances in the knowledge and use of welding consumables. The existing project presently involves one Ph.D. thesis project and one M.S. thesis projects.

2.1 EXOTHERMICALLY ASSISTED SHIELDED METAL ARC WELDING CONSUMABLES

Aluminum and magnesium additions to welding fluxes have been evaluated as to their ability to assist in the generation of heat through exothermic reactions during shielded metal arc welding. A calorimeter was designed to directly measure the heat produced by the electrodes (electrical heating plus chemical heating), and used in conjunction with measurements of the weld bead area. These combined measurements helped explain the heat potential differences among the electrodes, and the mechanism by which melting of the weld bead occurs (20).

Electrodes were formulated with three types of exothermic reagents: aluminum, magnesium, a fifty/fifty weight percent aluminum/magnesium alloy, and in special experiments with excess hematite. Calorimetric measurement of the as-welded plates indicated that exothermic heating does occur when welding with these electrodes. All three types (Mg, Al, Mg/Al) of exothermic additions show definite trends towards increasing the effective heat transfer with increasing concentration of reactive addition. Figure 1 summarizes how the measured heat input changes with amount and type of reactive addition. It is apparent that a maximum heat exists in the range of twenty-five thirty weight percent reactive addition in all three cases. Beyond this maximum, further addition of reagent does not increase the measured heat.

It has been shown (21) that exothermic reactions occur primarily at the tip of the electrode, and that they significantly affect the electrode melting rate. Given this observation, the peak in the measured heat input curve can be explained by the physical limitations of heat transfer from a molten droplet. The amount of excess heat which can be transferred to the work piece from the droplet is controlled by the heat capacity of the droplet. Any quantity of heat exceeding this capacity is transferred by conduction to the portion of electrode directly above the molten drop or is lost to the atmosphere producing the peak in the measured heat input curves. The results indicate that exothermic additions can assist in weld bead formation and penetration. The calorific effect seems to be directly responsible for the melting of additional metal.

The measured heat changes with increases in the aluminum reactive addition with excess hematite in the mixture were also determined. The results indicate that additional hematite (twice the amount), which is thought to be the primary source of oxygen for the exothermic reaction, does increase the measured heat input. This result confirms that the availability of oxygen influences the heat generated by the exothermic reaction.

The effects of current and voltage on the measured heat input were determined using welds made with the aluminum reactive metal additions to electrodes. Higher currents were found to be more efficient at transferring the arc heat and producing larger weld bead and greater penetration than

lower currents (44-45). Glushchenko (13) has also shown that the melting efficiency of his exothermic electrodes is optimized at currents the range of 300-325 amperes.

Once ignited, a purely exothermic reaction can propagate without further addition of energy. Some of the electrodes with twenty five and forty weight percent reactive addition would spontaneously ignite ahead of the arc during welding. After the arc was extinguished, the reaction would propagate up the length of the electrode, without melting the wire core. Premature reactions seriously limit the ability of exothermically-assisted SMA welding electrodes. Also, precautions were needed during extrusion of the shielded metal arc welding electrodes.

2.1.1 PENETRATION AND WELD BEAD SIZE

The effect of type and amount of reactive addition on weld bead area is illustrated in Figure 2. The general trend is toward increasing bead area with increasing concentration of reactive addition. For the aluminum and magnesium additions, the weld bead area increases with increasing concentration of reactive component. This trend is expected because increasing amounts of reactive addition were found to produce increasing measured heat inputs during the calorimetry tests. An interesting feature of Figure 1 is that the aluminum additions produce weld beads which are approximately twice as large as the magnesium and Mg/Al alloy additions. The difference in weld bead size is interesting because as Figure 1 shows, the measurement heat input changes only slightly between the type of reactive element at a given concentration of element. For the magnesium/aluminum alloy reactive addition, the weld bead area actually decreases and then increases slightly. Factors other than measured heat input must therefore also influence weld bead area.

Figure 2 shows how measured heat input changes with increasing weight percent of reactive addition. The heat inputs produced by the five weight percent rods are boxed to indicate that these rods produced approximately the same measured heat inputs (about 1.1 -1.15 KJ/mm). Figure 2 shows that this heat input produces weld beads of differing area depending on the type of reactive reagent used in the electrode. Equivalent measured heat inputs were found to produce a weld bead of about twenty-five mm² for the aluminum addition, and an area of about thirteen mm² for the Mg/Al alloy addition. Thus, the type of reactive addition must influence how the heat input melts the weld bead. Weld beads formed with the excess hematite rods are considerably smaller than those formed without excess hematite. It is apparent that heat input is not the primary variable which determines weld nugget area. These data indicate that oxygen may play a role in determining how the weld bead is formed. Oxygen seems to be responsible for increasing the measured heat input for the aluminum reactive electrodes.

The general trend is towards increasing penetration with increasing amount of reactive addition. Recall that other investigations have shown that penetration and weld bead area increase with increasing current (1, 93), and increasing current increases the heat input. The aluminum reactive component produces considerably deeper penetration than either the magnesium reagent or the magnesium/aluminum reagent. This situation was the case for the weld bead areas and suggests that the type of reactive component influences the penetration.

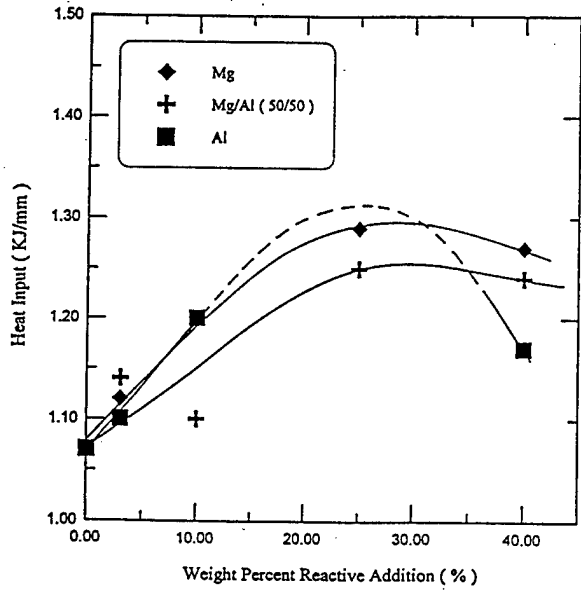


Figure 1. Measured Heat Input as a function of Reactive Addition. Boxed points indicate approximately equal measured heat input.

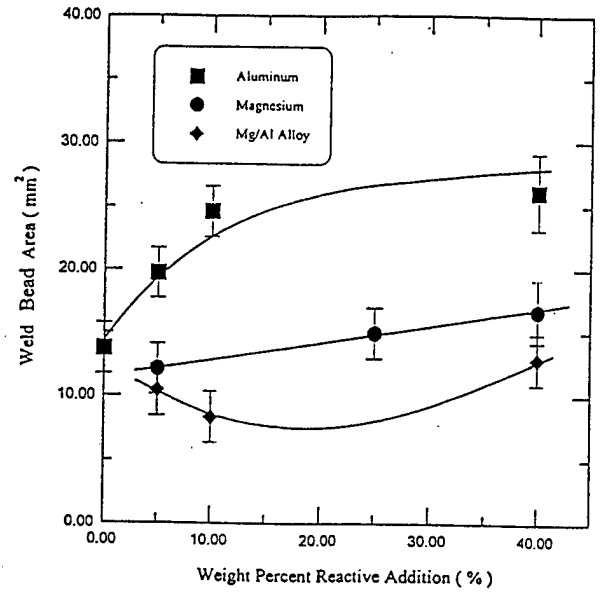


Figure 2. The Effect of Type and Amount of Reactive Component on Weld Bead Area. Boxed points indicate weld bead area produced with the same measured heat input.

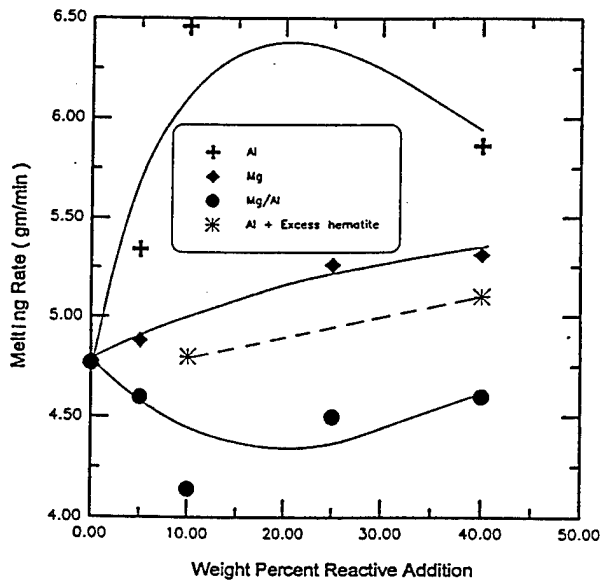


Figure 3. The Effect of Type and Amount of Reactive Addition on Electrode Melting Rate.

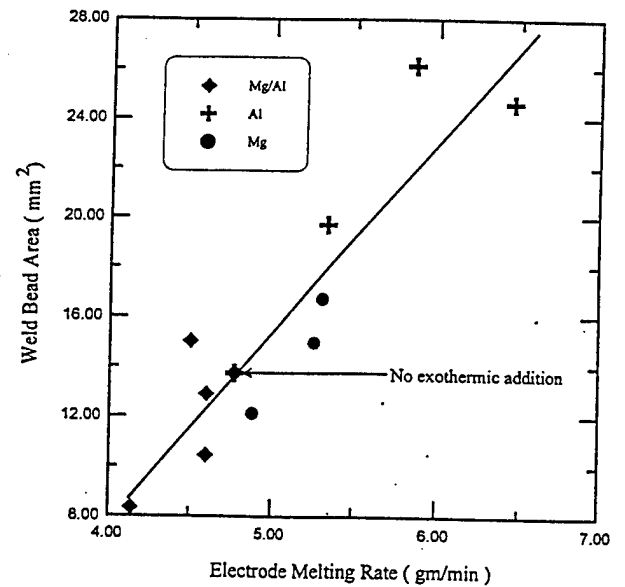


Figure 4. Melting Rate as a function of Weld Bead Area for Three Types of Exothermic Additions.

2.1.2 ELECTRODE MELTING

Because the weld bead is formed from the melted base plate and the melted consumable electrode, the electrode melting rate should be indicative of the weld bead area. The electrode melting rate plotted as a function of type and amount of reactive addition is shown in Figure 3. The general trend is towards a higher melting rate with increasing concentration of reactive component.

The melting rate was found to be directly related to weld bead area and the measured heat input. For each type of addition (Mg, Al, and Mg/Al), the relative magnitudes of melting rate, and the weld bead area correspond to the measured heat input. For example, the aluminum reactive addition produced the largest measured heat input, weld bead area, and had the greatest melting rate at each concentration. The direct relationship between weld bead area and electrode melting rate indicates (Figure 4) that excess heat from exothermic reactions effectively melts more of the electrode per unit time giving a larger weld bead. Thus, the mechanisms influencing the weld bead area, electrode melting rate and measured heat input must be heat transfer from the molten droplets moving from the electrode tip to the base material.

The electrode melting rate produced without exothermic addition is indicated in Figure 4. The electrodes with additions of the magnesium/aluminum alloy mixture had melting rates below that of the zero-exothermic addition rod. The Mg/Al alloy rich electrode also produced the smallest weld beads and had the lowest measured heat input. Thus, depending on the type of exothermic addition made, the electrode melting rate and weld bead size can either increase or decrease.

Extremely positive weld pool stirring could promote the sub-size (below zero-exothermic addition) weld beads produced with the Mg/Al alloy rods. This concept will be discussed further in the weld pool stirring section. Electrode melting rates below that produced at the zero-exothermic addition level are difficult to explain. The exothermic "burn back" phenomenon could be responsible for decomposing other exothermic components in the flux, giving the very low melting rates of the Mg/Al alloy rich rods. A detailed analysis of the possible reactions occurring in the coating needs to be performed to draw any further conclusions.

The relationship between the electrode melting rate and the heat inputs measured with the calorimeter for the three types of exothermic additions is shown in Figure 5. This plot indicates that the aluminum additions increase the electrode melting rate more efficiently than either of the magnesium rich additions. This behavior can be explained by considering the spontaneous reactions which were observed in the magnesium rich electrodes. These observations indicate that the magnesium exothermic additions may be reacting ahead of the welding arc, exhausting the exothermic source and its heating ability. Thus it is important to match the rate of the exothermic reactions with the rate at which the arc consumes the electrode. When these rates are equal, the ability of the exothermic reactions to assist in heating and melting is optimized.

2.1.3 WELD POOL STIRRING

Close observation of the resulting weld beads indicated two distinct patterns. Some welds showed patterns consistent with the weld pool stirring down at the top centerline, and towards the root of the weld (negative capillarity driven fluid flow). Other welds showed evidence of stirring radially outward at the centerline (positive capillarity driven fluid flow). Negative stirring tends to form deep, narrow weld beads. Positive stirring forms shallow, wide weld pools.

The effect of minor elements on weld pool stirring and weld bead morphology has been well documented (10, 11, 44-46). These minor elements influence the surface tension temperature coefficient. High concentrations (>150 ppm) of elements such as oxygen and sulfur promote negative convective flow, forming deep narrow weld beads. In the absence of these elements, fluid flow is positive, resulting in shallow, narrow weld beads.

Magnesium additions of three and six percent to the flux coating of SMAW electrodes have been shown to produce very low weld metal oxygen and sulfur contents. Magnesium and magnesium/aluminum alloy additions clean the weld pool of sulfur more effectively than the aluminum reactive additions. This surface cleaning would explain the differences in weld area sizes and shapes formed by the three types of fluxes.

It has been shown by others that weld metal oxygen can influence weld bead morphology (11). At currents less than approximately 150 amperes, weld pool stirring is controlled by surface tension gradients which in turn are influenced by weld metal sulfur and oxygen. It has also been suggested that oxygen rich weld pools may increase arc stability and thus increase weld penetration depth. For exothermic welding consumables, the data indicates that heat input from the molten droplets is controlling weld bead area and penetration. Chemical heat generation during exothermic welding is controlled by the reaction of a metal with oxygen. Thus, a measure of the weld metal oxygen should, in some fashion, reflect the measured heat input, weld bead area, and penetration depth.

Figure 6 shows how weld metal oxygen changes with the type and amount of the reactive addition. For each type of reactive addition weld metal oxygen decreases with increasing weight percent reactive component. Also, a minimum exists for all three types of addition at around 25 weight percent reactive addition. Recalling the measured heat input curves in Figure 1, it is apparent that these minima occur at the same concentration of reactive addition as the maxima in the heat input curves.

This correspondence indicates that the plateau in heat input may be due to exhaustion of available oxygen to react. Additionally, excess hematite (oxygen source) produced the greatest measured heat input and a stable weld pool oxygen content and measured heat input at each of the two levels of reactive addition tested. This result may indicate a saturation point in which the size of the molten droplet controls the amount of reactive addition (metal plus oxide) which can react.

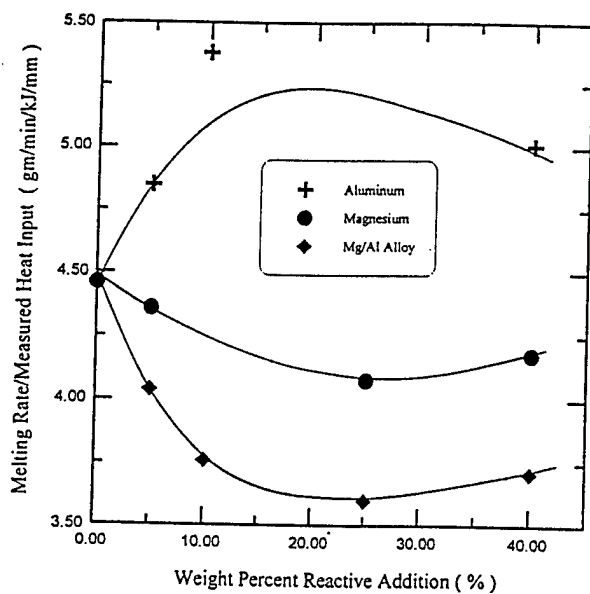


Figure 5. Melting Rate Normalized with respect to Measured Heat Input for the Three Types of Exothermic Additions.

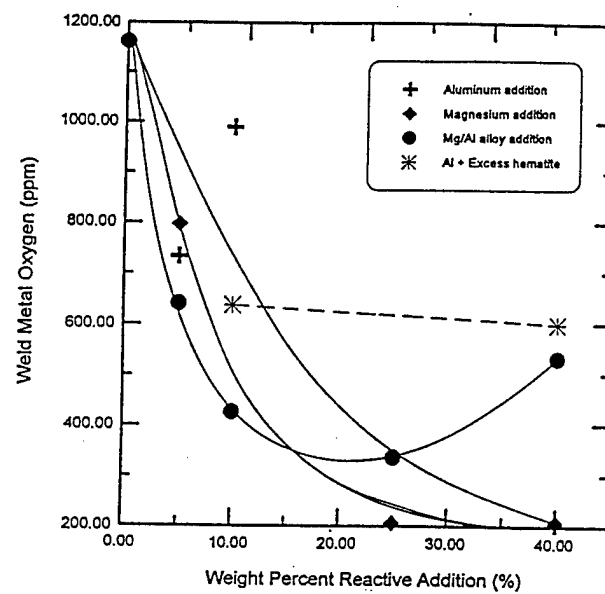


Figure 6. The Effect of Type and Amount of Reactive Addition on Weld Metal Oxygen.

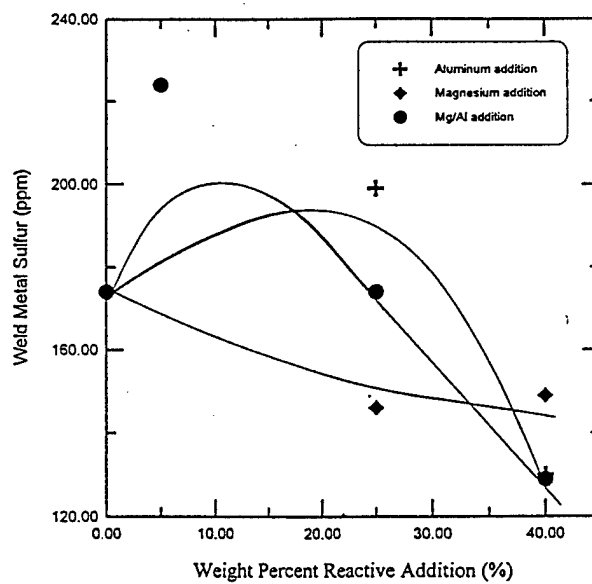


Figure 7. The Effect of Type and Amount of Reactive Addition on Weld Metal Sulfur Content.

Figure 7 shows how weld metal sulfur changes with type and amount of reactive addition. The aluminum and the magnesium/aluminum alloy additions increase weld metal sulfur at low concentrations and then sulfur content decreases at the higher concentrations of these types of additions. The pure magnesium reactive addition lowers weld metal sulfur at each concentration of the addition. At the forty weight percent level of reactive addition the weld metal sulfur content ranges from 130-150 ppm for the different types of additions. This level of sulfur is very near the transition value for positive and negative weld pool stirring reported in the literature (10,11).

The amount of free sulfur in the weld metal produced by the magnesium rich rods is probably lower than indicated in Figure 7 because the interstitial analyzer measures the total sulfur content. The total sulfur content would include sulfur tied up as magnesium sulfides which would not be available to change the surface tension temperature coefficient of the weld pool. Therefore, the amount of free sulfur in the magnesium rich case would be significantly lower than 150 ppm transition level. This level would produce weld pool stirring conducive to forming small, shallow weld beads.

2.2 EXOTHERMICALLY ASSISTED FLUX CORED ARC WELDING CONSUMABLES

The significant increases in weld deposition achieved with exothermically assisted SMA welding were found to be related to the enhanced melting of the welding consumable (20). Increases in the deposition rate of up to 50 percent were achieved with the proper exothermic additions to the flux. Increased exothermic additions, however, accelerate the burn velocity in the covered electrode flux coating, and the burn velocity can outrun the melting rate of the electrode to limit the maximum level of exothermic addition agent.

One solution to the problem of premature reaction was to fill a hollow tube (flux cored) with the reactive flux. Upon reaction, a flux-cored rod would better contain the exothermic heat being generated and may enhance the melting characteristic of the electrode. The extra heat imparted to the electrode would then be transferred to the base plate. These rods might also be more stable because the cored housing would act to shield the hot electrode from the oxygen-rich atmosphere, preventing spontaneous propagation and promoting reaction near the wire electrode tip.

The experimental flux cored wire consumables are being made at CSM from flat strip using a drawing bench and non-driven forming rolls. The strip was formed into a U-shaped channel, filled with the exothermic flux addition, and rolled to form a tube. The welding and evaluation procedures include calorimetric analysis, metallography and chemical composition analysis. The nature and effect of the pyrochemical reactions involved is presently being analyzed and modeled.

2.2.1 RESULTS

Experiments to systematically evaluate the influence of the flux composition, electrode configuration and welding process parameter on the heat generation, weld penetration, and electrode performance has been performed. The preliminary results show the promise of enhanced heat generation through the use of FCA welding (48).

Studies performed with FCA electrodes precisely fabricated with various amounts of magnesium and hematite show conclusively the beneficial effects of such additions in the increase in measured heat input (48). Figure 8. shows the flux formulations used where exothermic addition refers to a stoichiometric mixture of magnesium and hematite. Figure 9. shows the heat input, measured with a computerized liquid nitrogen calorimeter, as a function of weight percent exothermic addition (magnesium and hematite mixture) to the flux for several melting rates. Similar to the case with the SMA electrodes, a maximum effect is noted at about 20 weight percent addition, most pronounced at the lowest melting rate studied. Higher melting rates (wire feed speeds) gradually reduce the relative measure of the noted increase in heat input and displace the peak to lower weight percentages.

Beyond this maximum radiation and spatter losses due to excess superheating of the molten droplets may be a significant contribution to the subsequent reduction in measured heat input. Another cause may be due to the fact that conventional wire feed power supplies self regulate to a preset voltage so that the true effects of the exothermic additions are masked out at higher wire feed speeds. The electrical power input goes up with increases in the wire feed speed.

Also of note is the wire density decrease with the addition of the magnesium mixture. Iron powder is displaced from the flux formula by the exothermic additions resulting in less heat content (mass) per linear inch of wire for the various weight percent reactive additions studied. In all trials the fill densities were held constant at twenty weight percent fill. The magnesium thermite combustion and reaction temperature is much higher than the melting point of iron. This situation may contribute to the problem of excess spatter and the resulting loss of heat input. The ongoing investigation is now utilizing the aluminum exothermic reaction which may be more likely to prove successful in that the combustion temperature for this reaction is just slightly higher than the melting point of iron, such as the case with the SMA electrodes.

The ongoing work will continue the present effort of evaluating aluminum (exothermic reagent) as a heat generator. Then a thorough characterization of the influence of welding process parameters, including welding out of position, on the performance of the consumable that contains the exothermic addition (Al or Mg) which has demonstrated the most promise to reduce the need of a power source.

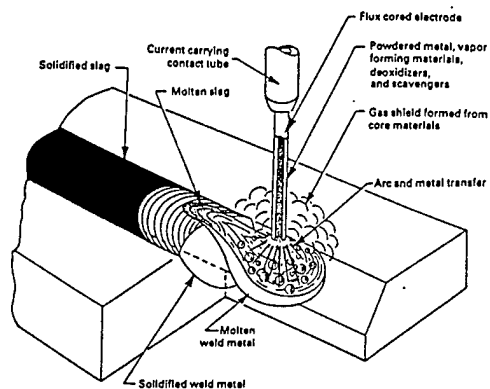
2.2.2 FINITE ELEMENT HEAT FLOW MODEL

Further study incorporating a mathematical finite element heat flow model is in progress and will allow for the rational optimization of this exothermic flux design concept. Ideally, the burning rate of the flux components will be adjusted to match the melting rate of the filler metal tube as the electrical power is minimized. Experimentation with aluminum thermite additions in the FCA flux is in progress. A composite one dimensional finite element heat flow model with a moving boundary and a phase change (a one phase Stefan problem) is being constructed using the ABAQUS language system. Arrangements have been made with the National Institute for Standards and Technology (NIST) to use their high speed laser interferometer for precise real time electrode stickout measurements deemed necessary for model verification and adaptation. It is anticipated that several experimental wires operating within optimized welding parameter regimes will result.

Flux Formulations

Ingredient	0 wt% exothermics	10 wt% exothermics	20 wt% exothermics	30 wt% exothermics	40 wt% exothermics	50 wt% exothermics
CaF ₂	15	15	15	15	15	15
CaCO ₃	6	6	6	6	6	6
SiO ₂	4	4	4	4	4	4
TiO ₂	15	15	15	15	15	15
Fe	60	50	40	30	20	10
Mg	0	6.7	13.4	20	26.6	33.4
Fe ₂ O ₃	0	3.3	6.6	10	13.4	16.6

Flux-Cored Arc Welding



Shielded Metal Arc Welding

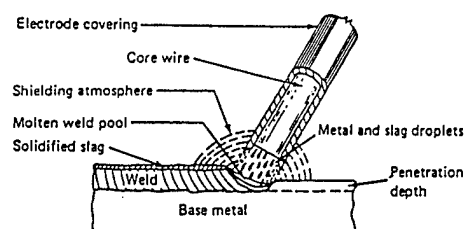


Figure 8. Flux Formulations for FCA Steel Welding

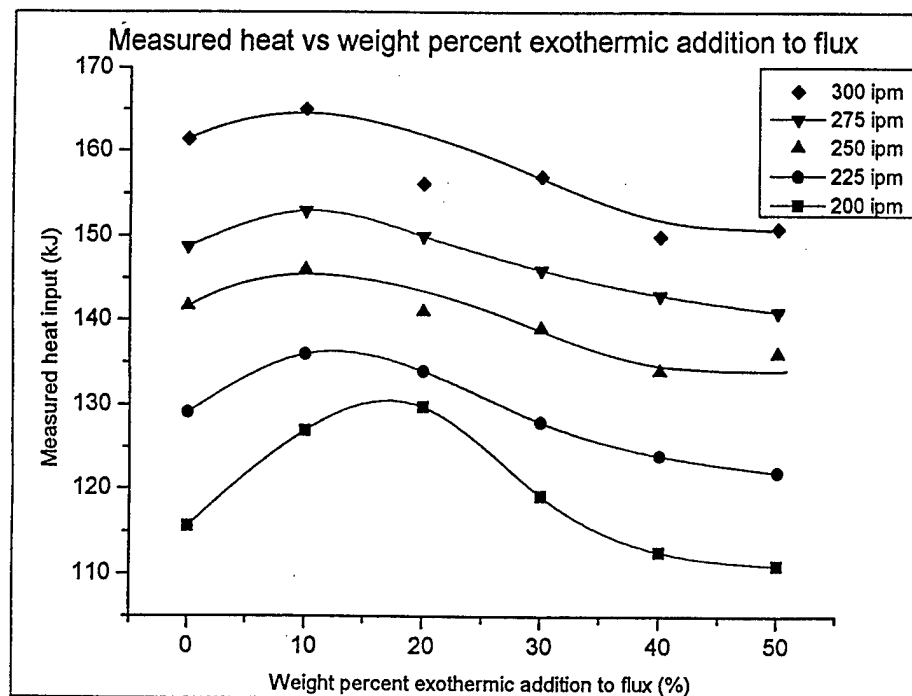


Figure 9. Measured Heat Input for various Compositions and Melting Rates

2.3 ALUMINUM WELDING CONSUMABLES

The CSM results show that the intermetallic grain refining particles (Al_3Ti and Al_3Zr) are susceptible to dissolution during the thermal experience of the welding process. The intermetallic particles present in the first pass provided nucleation sites for the formation of new grains to produce a refined solidification structure. After the second pass, however, these particles dissolve to a large extent. This dissolution leaves the second-pass weld metal deficient in nuclei and produces a large grained columnar dendritic structure. Once dissolved, these intermetallic particles have difficulty reprecipitating at the high cooling rates observed in the solidification of welds. Kerr, et. al. (38) noted that at high cooling rates it is possible to suppress the formation of the intermetallic phase in the aluminum-titanium alloy system. This effect is probably caused by the difficulty with homogeneous nucleation at high cooling rates. The inability of the intermetallic phase to form in the weld pool during the welding cycle means that the intermetallic phase particles must be present in the welding consumable prior to welding. The presence of titanium or zirconium as a weld metal constituent is not a sufficient condition for grain refinement of the weld deposit. The elemental additions must be present as an intermetallic phase in the welding consumable.

The dissolution and difficult precipitation of the nucleating intermetallic particles emphasize the importance of the influence of weld pool solidification kinetics on the grain refining response achieved by the addition of nucleating agents. Two useful parameters can be used to characterize weld pool solidification conditions using the thermal gradient (G) and the growth rate of the solidification front (R). The product of the thermal gradient and the solidification velocity GR ($^{\circ}\text{C}/\text{sec}$) represents the cooling rate during solidification. The cooling rate is an indication of the residence time in the liquid state before solidification. A low cooling rate gives a long residence time in the weld pool and a high cooling rate gives a short residence time. The G/R ratio represents the undercooling that results from the rejection of solute at the solidification interface. The G/R ratio is, thus, an indication the tendency for constitutional supercooling and nucleation in the liquid ahead of the interface. As the G/R ratio changes from high to low values the nature of solidification changes from plane front solidification to cellular to columnar dendritic to equiaxed dendritic.

The influence of heat input and welding speed on the G/R ratio and the cooling rate (GR) were evaluated using six different current and weld travel speed conditions to provide G/R ratios ranging from 5.6 to 50.5 ($^{\circ}\text{C sec}/\text{mm}^2$) and cooling rates ranging from 227 to 908 ($^{\circ}\text{C}/\text{sec}$). A low current and a low weld travel speed produced welds with a slow cooling rate and a high G/R ratio. A high welding current and a high weld travel speed produced welds with a high cooling rate and a low G/R ratio. Thus, a low experimental cooling rate is achieved at a high G/R ratio, and a high experimental cooling rate is achieved at a low G/R ratio.

The effects of the G/R ratio and the cooling rate on the grain refining response was determined by metallographic evaluation of the solidification structure for welds with unalloyed aluminum, 0.1 wt. pct. titanium and 0.1 wt. pct. zirconium. The results showed that welds produced with unalloyed aluminum provided little grain refining over the whole range of cooling rates and G/R ratios. Welds with 0.1 wt. pct. titanium or 0.1 wt. pct. zirconium additions showed substantial grain refinement because of heterogeneous nucleation at high cooling rates (GR) and low G/R ratios (high undercooling). These alloys showed little grain refinement at the low cooling rates and high G/R ratios.

It was expected that a change in the grain refining response caused by altering the G/R ratio would cause a change in the weldability of the specimen. Weldability tests were performed using a Varestraint test apparatus, which subjected the test samples to an applied strain of four percent. The results of this test showed that the same trend occurred for the weldability as occurred for the grain size. Better weldability (smaller total crack length) was achieved for welding conditions that gave a higher cooling rate and a lower G/R ratio. The effect of welding variables on the weldability was found to be stronger for the welds containing titanium than for those containing zirconium. Both the grain size and weldability tests confirm the strong dependence of grain refinement on the solidification conditions that exist in the weld pool.

Verification of the influence of welding variables which control the cooling rate and the G/R ratio can be found from a comparison of calculated particle dissolution times with their weld pool exposure times for the various welding conditions used in the welding study. Many investigators have reported on their experiences concerning the dissolution times for the TiAl_3 intermetallic crystals in molten aluminum. Dissolution times have ranged from less than 30 seconds (39), to several minutes (40), and in some cases a period of several hours (41). Thus, for the case of a weld pool environment where the intermetallic size and distribution will be much finer owing to the welding consumable processing route, a theoretical analysis was performed to represent the particle size range and dissolution environment found in the weld pool environment. The analysis is similar to one presented by Amberg, Backerud and Klang (42), adjusted for the particle size and thermal conditions observed in the experimental welds. The theoretical dissolution times were calculated for an intermetallic particle size range that was experimentally observed to occur in the alloy insert strips used to make the titanium and zirconium additions. The calculated dissolution times show that for a temperature of 700°C , particles of a size equal to or less than a micron will dissolve in a matter of a few seconds. The dissolution rate is even greater at a temperature of 800°C at which particles equal to or less than about 5.0 microns are dissolved in a few seconds. The significance of this theoretical result becomes apparent when an estimate is made of the time a particle spends in the weld pool. A simple way of finding the minimal time a particle spends in the weld pool is to assume it remains stationary as the weld pool moves past. The residence time is calculated by dividing the length of the weld pool measured at the centerline by the travel speed.

The analysis of these residence times shows the minimal weld pool exposure times for an intermetallic particle to be on the order of one to several seconds. These results are significant since the residence times are of the same magnitude as the calculated dissolution times for the particles contained in the welding consumable. This comparison provides a reason for using welding conditions with higher cooling rates and lower G/R ratios in order to enhance grain refinement and subsequent weldability.

Comparison of the theoretical dissolution times and the theoretical residence times shows that the several weld pool exposures in a multiple-pass weld test are sufficient to dissolve the intermetallic particles, which decreases the grain refinement. Weld parameters that provide high cooling rates and low G/R ratios decrease the exposure time, which limits the dissolution of the intermetallic particles. This result implies the use of high welding currents and higher welding speeds to reduce the dissolution of smaller particles. The retention of smaller particles by limiting the exposure time increases the number of heterogeneous nucleation events. This procedure yields better grain refinement for a given concentration of a grain refining addition, as demonstrated in the experimental evidence. In addition to decreasing the exposure of the intermetallic particles to the weld pool environment, an increase in the undercooling (lower G/R ratio) enhances the driving force for heterogeneous nucleation as defined within the classical heterogeneous nucleation rate theory. The

increase in the driving force for nucleation will also aid the grain refinement achieved for a given concentration of the added element.

2.4 WELD METAL OXYGEN

One of the compositional variables that strongly influence low-carbon structural steel weld metal microstructure and mechanical properties is the weld metal oxygen content. As the weld metal oxygen content varies, a change in microstructure occurs. At low concentrations of oxygen, ferrite with aligned or nonaligned second phases may become predominant, slightly higher oxygen levels may result in the formation of the desired acicular ferrite, and further increases in the oxygen content promote the formation of grain boundary ferrite.

The start of austenite decomposition and ferrite nucleation are very sensitive to variations in the amount of oxygen present in the weld metal. Consequently, for a given cooling rate and chemical composition, the final weld metal microstructure can be fine-tuned by proper control of the weld metal oxygen concentration. Thus, in gas metal arc welding, adjusting the shielding gas oxygen potential provides a means of controlling the weld metal oxygen content.

Bead-in-groove gas metal arc welding experiments were performed on HSLA steel coupons using three different welding wires and two heat inputs. A total of 17 different argon-based oxygen and carbon dioxide shielding gas mixtures was used. Complete metallographic and chemical analyses were carried out to evaluate the weld specimens. Sub-size Charpy V-notch toughness testing was performed on selected welds.

The effect of shielding gas composition on the chemical composition, microstructure and mechanical properties of the fusion zone of HSLA steel weldments has been studied. Based on the results obtained in this investigation the following main conclusions can be drawn:

- (1) The shielding gas oxygen equivalent developed in this research is a powerful parameter to describe the oxidizing potential of a shielding gas mixture. Good correlations on weld metal chemical composition, microstructure and toughness were obtained for welds made with both oxygen- and/or carbon dioxide-containing shielding gases.
- (2) The final weld metal chemical composition is strongly affected by the gas-metal reactions that take place during welding. The shielding gas oxygen equivalent plays an important role in controlling the pyrometallurgical reactions that occur during welding.
- (3) Weld metal microstructure is significantly influenced by the shielding gas used during welding. For the base metal-welding wire (ER70S-3 and ER70S-6) combinations investigated, a shielding gas equivalent of two to three volume percent gave the highest amounts of the desired acicular ferrite microstructural constituent in the weld metal.
- (4) The weld metal hardness was observed to decrease with increasing shielding gas oxygen equivalent. The decrease was due to loss of hardenability elements from the weld metal. A hardenability parameter P_{cm} that includes the effect of weld metal oxygen on the hardenability was developed. The adjusted P_{cm} called P_{cm}' is given by the equation

$$P_{cmo'} = C + \frac{Si}{30} + \frac{Mn + Cr + Cu}{20} + \frac{V}{10} + \frac{Mo}{15} + \frac{Ni}{60} + 5B - \frac{3}{4}O$$

- (5). For the weld metals investigated in this research program, the Charpy V-notch transition temperature at 35 j absorbed energy was observed to reach a minimum when the shielding gas oxygen equivalent was around two to three volume percent, which corresponded to the welds with the highest amount of acicular ferrite in the weld metal.

2.5 ALLOY PHASE ANALYSIS FROM BULK MAGNETIC MEASUREMENT

The ability to characterize alloy properties and phase stability through correlation with electronic measurements may allow significant improvements in the non-destructive evaluation of advanced alloy properties and the prediction of service life. In this work measurements of bulk electronic and magnetic properties were investigated to evaluate whether they can be used to reveal the microstructure and phase stability of alloys. An alloy of aluminum with 4 wt. pct. copper was selected as a model system. The magnetic susceptibility was selected as the measured property, based on its known relationship to the electron concentration and the electronic nature of a metal. The magnetic susceptibility measurements were used to follow phase transformations in the aluminum-copper alloy and exhibited three distinct regions corresponding to different alloy microstructures: 1) metastable GP1 phase refinement, 2) formation of metastable GP2 and initiation of θ' phases, and 3) θ' phase refinement and θ phase formation. The results suggest that bulk electronic and magnetic measurements (magnetic susceptibility) can be used to predict microstructure and thus properties of alloys (aluminum-copper system).

This investigation considered a binary alloy. Engineering alloys are typically more complicated, having several alloying elements that will contribute to the electronic measurements. Characterization of these alloys may require additional analysis. Two or more electronic and magnetic measurements, sensitive to different attributes of the microstructure, may provide additional insight to the alloy state. The relationships between bulk electronic properties and alloy state could then be examined using a variety of methods. For example, a neuronet analysis, which allows intricate interactions to be investigated, could be applied for correlating magnetic and electronic properties to mechanical properties and microstructure. More simply, a graphical analysis may provide adequate insight to the connection between electronic state to the alloy state. One measured electronic or magnetic property could be plotted on the y-axis and the second property plotted on the x-axis. For a given alloy system, equal phase condition lines could be depicted on the plot, allowing the microstructure of an unknown sample to be determined from the coordinate of plotted properties. A variety of different electronic and magnetic quantities could be used to develop such plots for many different alloy systems and the plots could then be used to metallurgically characterize alloy components, providing significant improvements in the nondestructive evaluation of advanced alloy properties and the prediction of service life.

3 SUMMARY OF THE MOST IMPORTANT RESULTS

1. Exothermic additions to shielding metal arc (SMA) welding flux can effectively increase heat input, weld bead cross-sectional area, penetration and deposition rate. The optimum welding process parameter space is being determined.
2. Exothermic additions (Mg) to flux cored arc welding consumables can effectively increase heat input, weld bead cross-sectional area, penetration and deposition rate. Work is in progress to evaluate aluminum as an exothermic addition to a flux cored arc welding consumable.
3. A mill has been put up by modifying an old industrial strip to core wire mill for experimental FCA welding consumables. The mill gives this project the ability to investigate broad variations in consumable compositions. The mill can now produce FCA welding wire in both steel and aluminum in diameters ranging from 0.160 to 0.045 inches (4mm to 1mm) with a flux loading that can be precisely administered over a wide range. A computer data acquisition system maintains a record of the flux filling operation.
4. The ability to make experimental aluminum consumable material quickly and precisely through metal powder additions to the core of a continuous aluminum sheath has been achieved.
5. A fundamental investigation into the influences of specific elemental additions to aluminum weld metal has been performed. Identification and classification of periodic table group behavior, precipitate crystal structure class, that are effective for grain refining, the required phase reactions to allow minimal additions to have significant effects; all were thoroughly analyzed to allow for the best solution of elemental additions to be evaluated for effective aluminum weld metal grain refinement in multi-pass welding.
6. Since knowledge of the oxygen content is basic to the understanding of the behavior of welding fluxes and is important in the transference of knowledge to other consumable processes a weld metal oxygen equivalent expression has been determined.
7. A preliminary investigation using electronic and magnetic measurements to reveal microstructural features and determine the phase stability of alloys was performed. It was demonstrated using magnetic measurements of an Al-Cu alloy that the transition between the various pre-precipitate phases and precipitates can be detected. The growth and transition of specific alloy microstructures can be mapped. A preliminary effort to develop a nondestructive evaluation technique for weld metal microstructural stability.

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5 INVENTIONS

None

6 PERSONNEL

David L. Olson	Principal Investigator
Robert H. Frost	Co-Principal Investigator
Kirk Lindahl	MS (1996) completed
Joe Beach	MS student transferred to Physics Dept.
Steve Malene	PhD Student
Ken Johns	MS Student

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