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ABSTRACT

The Gas Metal-Arc (GMA) welding process is explained and the equipment used described with an analysis of power supply function and the action of the arc, followed by discussion of general applications and problems. GMA braze welding of beryllium is then described, as is the development of a special high purity filler wire and a narrow deep groove joint design for improved weld strength in beryllium. This joint design and the special wire are applied in making high strength welds in high strength aluminum for special applications. High speed motion pictures of the welding operation are shown to illustrate the talk.

INTRODUCTION

This paper will describe the development of a narrow groove Gas Metal-Arc (GMA) welding technique for welding beryllium, and its application to making welds in high strength aluminum without severely reducing the strength of the base metal. I will first describe the GMA process, the equipment used in this development, and the technique for making narrow groove welds on beryllium; then describe the use of a high purity extruded wire for making quality welds and the modification of a contact tip to allow this extra soft wire to be used; and show how the narrow groove weld has been applied to aluminum. To conclude my talk, I will show some of the high speed movies we have taken at LLL to illustrate some of the points I have made, and to help you understand the welding process better.

BACKGROUND

The GMA or Gas Metal-Arc process was originally developed to weld aluminum, a material that is quite difficult to weld by other than the inert gas processes. Since its introduction in the 1950's, it has been improved greatly and found to be quite useful in welding a number of other materials, especially steels. It is a process that can weld metals very quickly, efficiently, and economically; and also is very useful in manufacturing processes because it can be easily automated and controlled to make quality welds in an efficient manner. When used to weld aluminum, it is operated as a high speed, high current density process; but can also be operated at lower current densities and with different arc action for welding other materials. Various gases and gas mixtures can be used, as well as wires with a flux core for additional shielding when welding steels and other non-aluminum materials.

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DESCRIPTION OF PROCESS

Gas Metal-Arc welding is the term used by the Welding Society to designate an arc-welding process wherein coalescence is produced by heating with an electric arc between a filler metal (consumable) electrode and the work. Shielding is obtained from a gas, a gas mixture, or a mixture of a gas and a flux. In this process, the welding current flows from the power supply, through a welding lead to the welding torch, where it is transferred to a small diameter, rapidly moving wire which passes through the center of an inert gas blanket into the arc zone. The current transfers from the end of the wire to the workpiece, through the arc, and returns to the power supply through the ground lead. The heat of the arc melts the base metal in the welding groove, and also the end of the rapidly moving wire. The molten metal from the end of the wire flows into the groove, where it unites with the molten base metal and solidifies in the weld joint.

The GMA (Gas Metal-Arc) process is similar to the submerged arc process because the filler metal is a continuously moving electrode, and is melted in the arc in both processes. Since the filler metal melts as it enters the arc, it must be fed into the arc at the same rate it melts in order to maintain a constant arc gap. This feed rate can vary from 423 mm/s to 3400 mm/s, depending upon the filler wire diameter and the current level desired. Generally speaking, the smaller the electrode wire, the higher the feed rate. The process is a high current density process with high deposition rates in aluminum which allows high welding speeds and gives welds with less distortion, a narrower heat affected zone, and lower costs. The high current density arc eliminates the preheating of aluminum in all but the thickest joints. The arc is somewhat more penetrating and narrower than the arc in covered electrode-arc welding; therefore, in making groove welds, smaller root faces and root openings can be used with GMA than with covered electrode-arc welding. Less weld metal is required with lower heat input and lower costs.

The process is considered semiautomatic even when used in the manual mode, because once the wire feed is started and the arc struck, the welding conditions are automatically controlled by the machine settings. The operator is thus free to concentrate on placing the weld bead. It lends itself quite well for full automatic welding where the torch is held by a machine and programmed to follow a predetermined path or sequence.

The GMA process has many advantages over other processes in the welding of aluminum. A tenacious refractory oxide of aluminum forms on the surface on exposure to air, and this oxide must be removed before a fusion weld can be made. With processes other than inert gas or electron beam, this oxide is removed by the use of a flux and a corrosive residue may be left if this flux is not completely removed. With inert gas processes, such as GMA or GTA (Gas Tungsten-Arc), the arc has a self-cleaning action and no flux is necessary. The power normally used for welding aluminum is usually direct current reverse polarity. This means that the electrode or filler wire is positive and the workpiece negative, so that the electrons flow from the workpiece to the electrode. When argon is used as the shielding gas, the direct current reverse polarity breaks up the tenacious surface oxide on the base metal ahead of the weld pool. This cleaning action is believed to be a result of the electrons leaving the workpiece, the inert gas ions striking the workpiece, or a combination of both. It does not occur when helium gas is used as a shield, probably because of the difference in electrical characteristics.

EQUIPMENT

The equipment used in the GMA process consists of the welding torch or gun, the torch and ground current leads, the water and gas lines, the wire drive mechanism and controls, and the power supply. The wire drive mechanism and the power supply make this process different from other processes.

Welding Torch

The welding torch or gun forms one side of the welding arc. Here the welding current is transferred to the rapidly moving wire, and the gas blanket is formed around the wire and the welding arc. Guns are designed for either hand-held operation or machine-held operation, and the design differs depending upon the intended use. Although the hand-held gun is light weight, all the gas, cooling water, welding current, and wire supply lines are attached to it and these make it bulky and hard to handle. Its use is usually limited to small diameter wires.

The guns for automatic or machine use are larger and sturdier, and can handle much heavier wires and larger currents. They are designed to operate for long periods of time in adverse environments without mechanical difficulties. The wire drive mechanism is usually mounted on the gun so the wire is pulled from the supply spool and must be pushed only a short distance through the current contacts in the gun. The machine-mounted gun used by LLL is a modified commercial Gas Tungsten-Arc welding torch that is mounted on a commercial wire drive mechanism. We use this unit because the distance from the drive rolls to the contact tip is less than four inches, and this allows us to drive soft aluminum wire of .75 mm diameter at speeds up to 420 mm/second. This torch will be used in the demonstration.

Welding Leads

The leads that come into the gun are the conventional leads for inert gas welding; the inert gas lines, the cooling water supply and return lines, and the welding current leads. Since the process can use very high currents, the current leads are usually of 500 ampere capacity.

Wire Drive

The wire drive mechanism consists of a set of drive rolls, one usually knurled and the other smooth with a central groove, and the knurled roll is driven by a variable speed motor that will run at any selected constant speed. Speeds will vary from 42 mm/s to 420 mm/s, and will depend upon the wire size being used. A new wire drive system recently placed on the market uses three drive rolls that are each set at an angle to the line of travel of the electrode wire through the rolls. A hollow armature electric motor rotates the rolls around the electrode, and the skewed rollers impart a force to the wire which moves it smoothly through the center of the motor to the gun. Early GMA units used a variable speed drive motor with a speed dependent upon the voltage drop across the welding arc in order to maintain a constant arc gap with the conventional constant current generator used at the time. New units use a constant speed wire drive and a constant voltage power supply to maintain the welding arc gap, as I will explain later. The drive mechanism usually has two speeds: a slow inching speed to move the wire into contact with the workpiece and establish the arc, followed by a high velocity welding speed as soon as the arc is established. The motor speed is usually kept constant by an electronic feedback loop.

As I mentioned before, the wire drive mechanism is usually at the gun for machine welding equipment. It pulls the wire from a large supply spool, and feeds it through the contact tip and into the arc. The wire drive mechanism and the supply spool are usually together for a hand-held operation about three meters away from the gun. The wire must then be pushed for this distance. Soft aluminum wires of small diameter are very difficult to push this far, and sometimes the wire drive mechanism is mounted on the gun to pull the wire from the spool or to assist a push mechanism at the spool. The new linear wire drive system is small enough to be placed in the handle of the gun, and the drive characteristics are such that two or more placed in a line will automatically adjust the load without complicated electronic sensing and regulating circuits.

Power Supply

When GMA welding was first introduced in the early 50's, conventional constant current generators with variable voltage and drooping volt-ampere characteristics were used. It was necessary to vary the wire feed speed to maintain a constant length arc gap. This constant changing of the motor speed to vary the wire feed speed created maintenance problems, and it was difficult to keep the motors operating properly. The advent of constant voltage power supplies allowed the wire to be driven at a constant speed because the power supply characteristics maintain the arc gap constant. With a constant voltage power supply, if the arc gap decreases for any reason, the arc voltage also tries to decrease. The constant voltage power supply will not let the voltage drop, so the current increases because of the lower resistance of the arc gap. The increased welding current melts the electrode wire faster, lengthening the arc gap until the original length is reached and the gap stabilizes. Conversely, if the arc gap length increases, the wire melting rate is decreased and the gap shortens until equilibrium is again established.

The major control on a constant voltage machine is the open circuit voltage control. Open circuit voltage is the voltage across the leads before the arc is struck. When the arc is struck, there is a voltage drop along the welding leads and across all the connections with the greatest voltage drop occurring across the welding arc. This value is called arc voltage. Since the other voltage drops are relatively constant, a change in the open circuit voltage will change the arc voltage. When the arc voltage changes, the only way to maintain electrical equilibrium is for the arc gap to change in the opposite direction. This is how the length of the arc gap is controlled.

The power supply may have one or two other controls, slope and/or inductance. Slope is a term that describes the static electrical characteristics of the power supply, and refers to the decrease in voltage as the current increases. This is a function of the internal resistance in the circuit. It is used to limit the maximum current drawn under short circuit conditions. Without slope control, the welding current during short circuiting would be extremely high; the molten metal would be violently heated and would literally explode, creating excessive spatter. With slope control, the maximum welding current reached during short circuiting can be limited to the amount necessary to clear the short circuit with the least amount of spatter. Since slope control is obtained by changing the resistance in the welding circuit, usually through a device called a reactor, the open circuit voltage must be changed whenever the slope is changed in order to maintain the same arc gap.

Inductance is the electrical property which slows down the flow of current through a coil, and it is used to limit the rate of current rise through the circuit when short circuiting occurs. Inductance is most important in dip transfer where it is used to lengthen the time it takes the current to reach short circuit values and it increases the arc "on" time. This provides what is known as a "soft" arc which increases puddle fluidity, improves penetration, makes the bead flatter and smoother, and reduces spatter. A change in inductance does not affect the arc voltage so no adjustment is necessary when it is used.

You may wonder why we can't adjust our equipment to avoid short circuits, except in starting. In the beginning this was done, but as our knowledge increased, it was found that a properly controlled short circuiting arc could be a very valuable tool in GMA welding. There are three ways in which the molten metal transfers to the workpiece through the arc, depending upon welding conditions. In an argon atmosphere with the welding current above a certain value, called the transition current for that electrode diameter, the molten metal comes from the end of the wire in a number of individual drops at a very rapid rate. These drops are propelled through the arc in a free-fall mode without causing shorting between the electrode wire and the workpiece. This is called spray transfer.

If we reduce the welding current below the transition current value, or use CO_2 shielding gas on steel, the molten metal comes off the end of the electrode in large drops with diameters larger than the diameter of the wire. These drops often bridge across the gap between the electrode and the workpiece and cause a short circuit. This type is called drop transfer.

A recent development permits the electrode metal to be transferred entirely by contact between the molten tip of the electrode and the molten base metal or puddle. This type of transfer is called dip transfer or short arc. In this dip transfer method, low open circuit voltages, small diameter wires, low currents, and judicious use of slope and inductance is required. Because this is a low-heat input method, it can be used to weld much thinner metals than can be welded with conventional GMA. All three types of transfer will be shown in the high speed motion pictures which comprise the final part of this talk.

A more recent development combines the advantages of a spray arc with the advantages of a dip transfer arc, and is called Pulsed Arc Welding. This type of arc action is possible because of the development of a new type of power supply that can be set to alternate between two current levels at a regular rate. When the current is at the high or peak level, which has been set slightly above the transition level for the particular conditions being used, metal droplets come off the end of the wire in spray form. When the current level drops to the lower value, called the background or base level, drops form quite slowly on the end of the wire and the workpiece cools slightly. In operation, the current is kept below the transition current for a short time (less than required to form a massive drop at the electrode tip) and raised above the transition current for a time sufficient only to transfer the molten tip as one drop. The current then returns to the base level, and the cycle is repeated. Spatter-free transfer is obtained at low average currents, and the excessive penetration and high deposition rates of regular GMA welding are controlled and reduced. With this power supply, the GMA process can now be used to weld aluminum sheets down to 1.5 mm thick and to weld aluminum joints in other positions than flat without difficulty.

BERYLLIUM WELDING

Beryllium is a metal that is used primarily in the nuclear industry with special applications in the aircraft and missile industry. It is used in the nuclear industry because of its combination of unusual physical and mechanical properties, with its properties as a moderator and reflector. It is useful as a structural material in the aerospace industry because of its combination of low density, high elastic modulus, high strength-to-weight ratio, high heat capacity, low thermal expansion, and good thermal conductivity. One difficulty with beryllium is that the ductility is low, and it is very notch-sensitive. The strength and ductility are markedly dependent upon grain size; fine grained material is stronger and more ductile than coarse grained material. Fusion welding is detrimental to the mechanical properties of beryllium because the molten beryllium solidifies in long columnar grains that are very brittle, and because the heat of fusion causes excessive grain growth in the heat affected zone of the base metal and reduces the small amount of ductility present from 2% to almost zero.

Since we could not make ductile fusion welds in beryllium, we searched for another joining method and found we could join beryllium successfully to itself by braze welding, using an aluminum - 12% silicon eutectic composition braze alloy. This alloy is now designated as 4047. Braze welding was first done with the Gas Tungsten-Arc process, but we found that the heat input with GTA was too great and caused grain growth in the heat affected zone with corresponding brittleness. We found that we could make the braze weld with GMA because we could keep the heat input down and do less damage to the base metal by using dip transfer and welding at high rates of travel speeds from 30 to 40 mm/s. We also use .75 mm diameter filler wire, both because it fits in the groove better and because the smaller wire allowed us to use lower currents. Aluminum wire is softer than steel wire and there is a problem in pushing it any distance, so we devised an adaptation to a commercial GTA torch, as I mentioned earlier.

One problem we found when we operated this aluminum-silicon wire in the dip transfer mode (with the lowest voltage and current we could use) is that the hydrogen in or on the wire dissolves in the molten metal. It does not have time to escape because of the rapid freezing rate. This gives us porosity in the weld. We tried many things to eliminate this porosity, and finally Batelle, Columbus came up with the answer: use a wire made by Cominco from high purity materials and extruded to the .75 mm diameter wire instead of relying on conventional drawing techniques. This procedure eliminated hydrogen in the wire and any formed by the decomposition (in the arc) of any drawing lubricants left on the surface. Unfortunately, the extruding operation left the wire very soft with a number of small burrs on the sides of the wire. We experienced difficulty in driving this wire through the torch because it would hang-up and arc-out in the contact tip. The contact tip we were using had about .18 mm clearance around the wire because it was thought that more clearance than this would give poor electrical contact. Our operator-supervisor took a very radical approach, and enlarged the hole in the tip to give .38 mm clearance. He also bent the end of the tip 5°, and placed the tip so that the cast in the wire (as it came off the drive rolls) would force the wire against the bend. In order to prove to skeptics that this would work, we cut away the side of the tip opposite the bend and left the wire exposed. This proved that the wire was picking up the current at the end of the tip. There were objections that the wire would wander in so large a hole and not stay centered in the welding groove, and objections that there would be starting difficulties after the first start. We took high speed motion pictures of the wire going through the tip during welding, and I will show them at the end of the talk. You will be able to see that the wire stays in the middle of the groove and doesn't wander. We also started and stopped the welding arc for 24 consecutive times without a misfire. This wire and tip is used for all our beryllium welding at LLL. It gives strong, porosity-free welds, and that is why we used it on the high-strength aluminum work I will describe later on.

The first welding grooves we used in beryllium braze welding were typically 1.5 mm root radius, 60° included angle, and 2 to 3 mm deep. This groove was used for seal welds and other welds where little strength was required. After we had made these welds for some time, new designs called for strength welds and we decided that this joint could not be used satisfactorily for deeper welds because of the large amount of low-strength filler metal required. The large mass of higher density material in the weld was not desirable, either.

We then went to what we call a narrow deep groove with a root radius of 1 mm, an included angle of 11°, and a groove depth of up to 9.5 mm. This groove requires less than half as much metal to fill as the wide groove when both grooves are 6 mm deep. Less than half as much heat is required to fill this groove, and we have less distortion and less thermal shock and grain growth in the base metal. Since the side walls of this groove are almost vertical, the strong base metal has a restraining action upon the narrow band of weaker weld metal, increasing the apparent strength of the joint. In addition, some base metal beryllium is dissolved in the aluminum-silicon filler metal, and this has a significant strengthening action on the weld. With less filler metal present, but with the same amount of beryllium base metal dissolved in the weld, the percent concentration is increased with a corresponding increase in weld metal strength. All these factors add up to a stronger joint. These advantages also apply to the welding of high-strength aluminum, specifically solution treated 5083.

ALUMINUM WELDING

Pure aluminum is a low-strength, ductile material with tensile strengths of 69 MPa in the annealed condition. By alloying with other elements, aluminum alloys with tensile strengths approaching 350 MPa can be obtained in weldable compositions. The strengthening mechanisms used can be classified in two ways: heat treatable and non-heat treatable. A typical heat treatable alloy is 6061, an alloy that derives its strength from the addition of Cu, Si, Mg and Cr which are dissolved in the aluminum by a solution heat treatment at approximately 530°C and then precipitated out by heating for 8 hours at 175°C. It has a tensile strength of 125 MPa in the annealed condition and 300 MPa in the T6 condition. When welded by conventional methods, the heat affected zone is softened to near the annealed condition and must be re-heat treated to obtain properties close to the T6 condition.

A typical non-heat treatable alloy is 5083, an alloy which derives its strength from the addition of Mn, Mg, and Cr which strengthen by solid solution mechanisms and by the effects of cold work. Typical annealed strengths for 5083 are 275 MPa with yield strengths of 135 MPa, while cold-worked strengths can be as high as 345 MPa tensile and 275 MPa yield.

We had an application at LLL that required the use of high yield strength aluminum that had to be welded, and could not be heat-treated after welding. The alloy selected was 5083 in the solution treated condition that was formed into final shape by cold-working to give a yield strength of over 275 MPa. The proof stress approached this value, and the design required that no yielding occur during testing. An additional complication was that there was low melting materials adjacent to the root side of the joint, and the heat of welding had to be kept as low as possible. A composite joint was used with a heavy land of about 3 mm that was first welded by electron beam, a process with even higher power density that could make the weld with very low heat input. After the electron beam weld was made, a narrow groove 6 mm deep with a 1.25 mm root radius and a 12° included angle was filled in three passes. A test unit was taken to failure and failed at a calculated value of 296 MPa, and strain gages showed the yield strength to be in excess of 250 MPa.

The question arises -- why didn't we use the filler alloy normally used for this material, namely 5183? We made some welds with wire from one lot of 5183 we had on hand, and we tried to get some high purity 5183 (without success), so we ordered another lot of commercial 5183. We found excessive porosity in samples from both weld wires made using the dip transfer parameters we used to keep the heat input low. If we had been able to use a large groove, high-heat input, and spray transfer, the porosity in this 5183 wire might have been reduced enough to be acceptable. We were able to meet the special requirements of the application by using our high purity 4047 wire, so we did not investigate the use of 5183 further.

The procedure for making the final weld was:

	Open Circuit Volts	Arc Volts	Amps.	Travel Speed
1st pass	28	23.8	150	21.2 mm/s
2nd pass	30.5	25.5	170	16.9 mm/s
3rd pass	31.0	26.5	170	21.2 mm/s

Bare Rod Length (Stockout) 9.5   Cup Gap 3.1 mm   Wire Diameter .076 mm

The rod was made in two interrupted passes, the craters ground out and the weld completed, followed by a third continuous pass.

CONCLUSIONS

Narrow deep groove welding, using the GMA welding process and high purity extruded wire, will maintain the maximum properties in the weld and heat affected zone of high strength aluminum because the low porosity filler wire in the narrow groove gives maximum strength and ductility in the weld zone, and the low heat input minimizes the extent of the heat affected zone. These characteristics make it useful for special applications where high yield strength is required in the weld and heat affected zones, especially where post weld heat treatment is not possible.

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