Controlling Heat Input, Spatter and Weld Penetration in GMA Welding for Solid Freeform Fabrication

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Abstract

Two new approaches for metal transfer control during the GMA welding process, one based on a laser beam placed through the arc and the other based on real-time image processing, allow lower heat input, reducing spatter and weld penetration. The controlled welding process and CNC milling operation are combined together to form a hybrid rapid prototyping process. Test parts obtained in this procedure show better surface quality, dimensional accuracy and high density, while demonstrating new technological opportunities in rapid prototyping of real metallic parts.

Introduction

It has been recognized by several research teams [1, 2, 3] that the principles of the GMAW process could be used in the development of a cost effective method for layered deposition manufacturing or rapid prototyping (RP) of full dense metallic parts and tools. These attempts to use 3-D welding for building metal parts failed to incorporate a feedback control system between the controller and the welding system. Sensory feedback is a necessary requirement for improving the stability of the welding process [4]. Another way to stabilize the welding process is to use a milling operation to prepare the surface for a new layer. In several SFF techniques currently under development, a CNC milling operation is used to remove the metal build-ups in order to secure constant height of the generated layer [5].

The primary barrier to achieving quality welds in GMAW is the irregularity of the metal transfer process, i.e. the irregular growth and detachment of the droplets. Our interest is to develop a 3-D welding process for RP of real metallic parts using GMAW principles. 3-D welding process for RP requires low heat input and low weld penetration which is the exact opposite of the conventional welding process. Low heat input and weld penetration require low values of welding parameters such as current and wire feeding speed. On the other hand low values of the welding parameters provoke arc instability because associated short circuiting metal transfer or globular metal transfer mode can cause significant spatter [4]. This paper presents two new approaches for metal transfer control, one based on a laser beam placed through the arc and the other based on real-time image processing. Welding and milling are combined together to form a hybrid rapid prototyping process. Test parts obtained in this procedure show better surface quality and new technological opportunities in producing real metal parts.

Techniques for Low Current GMA Welding

The characteristics of the GMAW are best described in terms of the three means by which metal is transferred from the electrode to the workpiece: short circuiting, globular and spray transfer. With low values of welding current and wire feeding speed, short circuiting or globular metal transfer will take place [6].

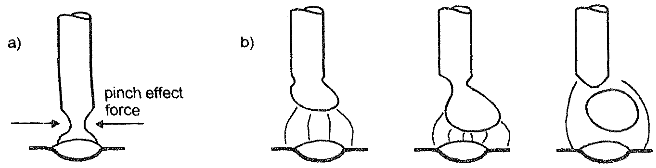

Figure 1. Short circuiting and globular metal transfer mode

With short circuiting transfer, the molten weld metal necks down from the end of the electrode and touches the weld pool. During the shorting phase, the voltage drops and the amperage increases. The increased amperage produces what is called a pinching effect that causes the molten metal to detach (Figure 1a). As it separates from the electrode end, the arc reignites. If the pinch force current is too high, the weld metal will detach violently, creating spatter. The globular transfer is likely to produce the most spatter. With this transfer mode, a molten drop is formed on the end of the electrode, growing in size until it is detached by the force of gravity (Figure 1b). The droplet is usually larger than the diameter of the electrode and it separates in a nonaxial direction, which can result in metal droplets falling outside the weld pool. The droplet might even touch the weld pool before it detaches creating a mini-explosion that spews spatter.

Pulsed mode has been introduced to address problems with globular transfer mode. In pulsed mode, a power source provides two levels of current: one a constant, low background current which sustains the arc without providing enough energy to cause drops to form on the wire tip, and the other a superimposed pulsing current with an amplitude greater than the transition current necessary for spray transfer [6]. However, to guarantee one droplet per pulse, intensity and duration of the pulse current has to be carefully adjusted. Because of narrowness of the optimal range of welding parameters, such an open-loop selection of the pulse intensity and duration is often not robust with respect to the welding conditions. If the instant of detachment can be detected, the current may be switched to the base current to prevent multiple drops in a single pulse [7].

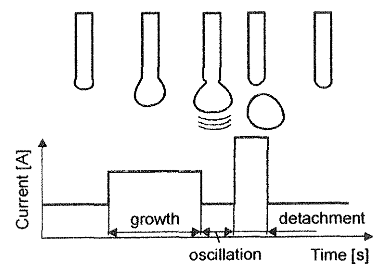

Figure 2. Droplet growth and droplet detachment pulse

Active metal transfer control has been used to achieve one droplet per pulse [8]. A pulse cycle is divided into two periods: growth period and detachment period shown in Figure 2. In the growth period, a current level below the transition current is used. When the growth period ends, the current is switched to the base level and the process enters the detachment period. Sudden change in the welding current causes the droplet to oscillate vertically. When the droplet moves down, the current is changed to the high level above the transition current for a very short time. The sudden increase of current provokes a high pinch force and together with the downward momentum it detaches the droplet. The process utilizes mechanical momentum to reduce the level of electromagnetic force required for the detachment, resulting in a reduction of the overall heat input.

Heat input is calculated as the ratio of the power (i.e., voltage x current) to the velocity of the heat source (i.e., the arc) as follows [9]:

$$H = 6\frac{E\,I}{S}, \quad \left[\frac{\text{kJ}}{\text{m}}\right]$$

where E [V] is the arc voltage, I [A] current through the arc and S [cm/min] arc velocity.

In this paper we present two approaches that allow use of pulsed mode with low average current. These techniques for self-adjusting droplet transfer rate are based on:

a) a signal provided by a laser beam placed through the arc and
b) real-time image processing.

a) GMAW Control Based on Laser Beam Placed through the Arc

In 3-D welding, precise metal deposition is of crucial importance. One way to make metal deposition more accurate is to keep the arc length short so that a detached droplet can not be diverted out of the weld pool. The presented technique manages the arc to any desired length. An arc can be just long enough to avoid short circuiting. The control device consisting of a laser diode and photo diode positioned in such a way that the laser beam passes through the arc, as shown in Figure 3, has been used to control the welding process with wire 1.2 mm in diameter.

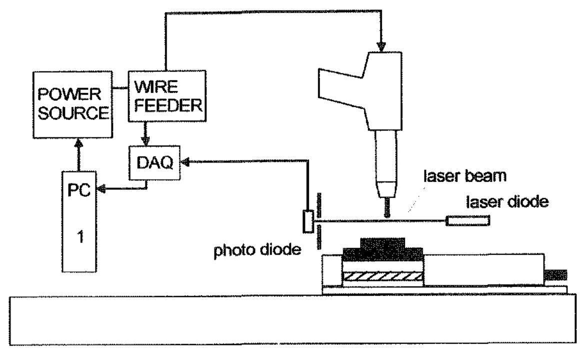

Figure 3. GMAW controlled by feedback signal from laser beam placed through the arc

While the wire tip is above the laser beam, background level current flows through the arc (Figure 4). Background current is very low and only keeps the arc on. Although wire tip melting should be avoided or at least minimized during the background current period, a droplet of molten metal slowly grows because of very low wire feed speed (~100 cm/min) and a relatively long duration (~ 65 ms, Figure 5). When the wire

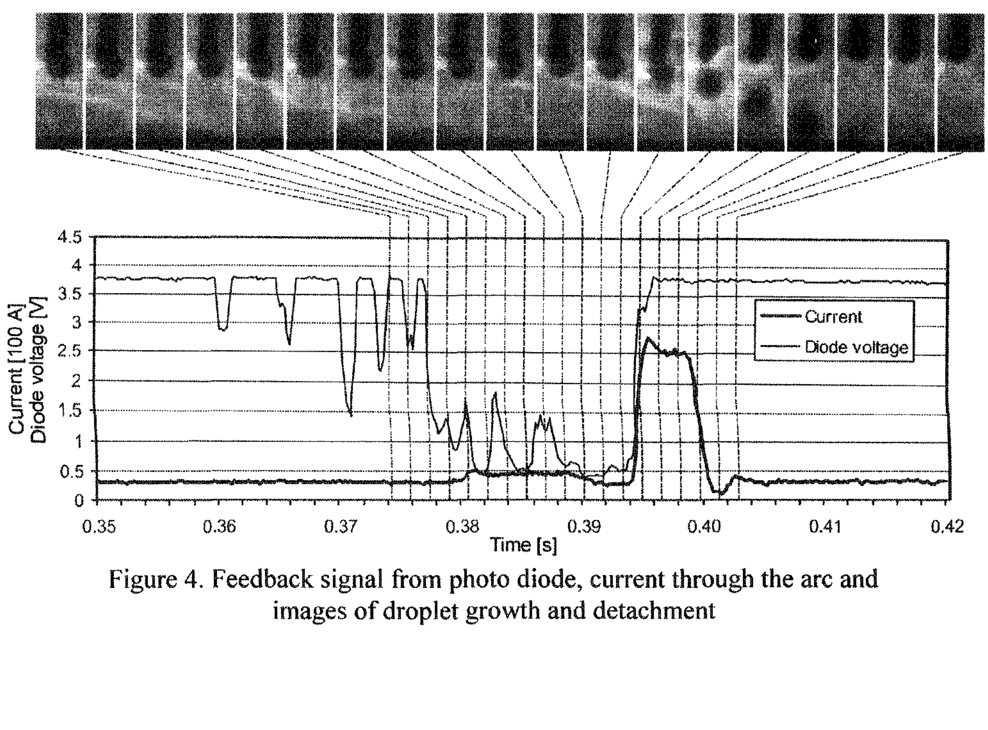

Figure 4. Feedback signal from photo diode, current through the arc and images of droplet growth and detachment

c) Short circuiting mode with thin wire (0.6 mm in diameter)

Short circuiting encompasses the lowest range of welding currents and smallest electrode diameters associated with GMAW [6]. This type of metal transfer produces a small, fast-freezing weld pool and is preferred in production of small parts and thin walls in 3-D welding. Metal is transferred from the electrode to the workpiece only during a period when the electrode is in contact with the weld pool. No metal is transferred across the arc gap, and this ensures precise metal deposition directly to the weld pool.

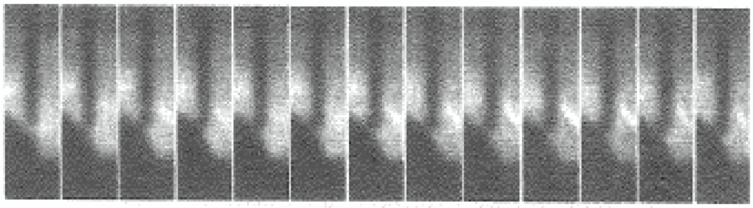

Figure 11. Short circuiting metal transfer mode

With wire of 0.6 mm in diameter, the welding current was 40 A, voltage 23 V, wire feed speed 290 cm/min (0.82 cm^3/min), workpiece speed 36 cm/min, heat input 155 kJ/m. Shielding gas was a mixture of 95 % Argon and 5 % CO_2. Short circuiting metal transfer mode has the lowest heat input and the lowest possible metal transfer rate, but it is not the appropriate technique for welding with thicker wire (1.2 mm) because of significant spatter. The lowest values of welding parameters with 1.2 mm thick wire (globular metal transfer mode) were: average current 48 A, wire feed speed 90 cm/min (1 cm^3/min), workpiece speed 36 cm/min, heat input 200 kJ/m.

Hybrid Rapid Prototyping Process Based on Welding and Milling

In spite of our success in controlling the welding process, the rapid prototyping process based on 3-D welding alone does not provide satisfactory dimensional accuracy and surface quality. Because of complete melting, the accuracy as well as the surface quality of parts are generally lower than that of machined parts. To overcome this difficulty, a combination of welding as an additive process with a subtractive technique such as milling can be an appropriate solution [3, 5]. This computer-controlled hybrid rapid prototyping system integrates the controlled GMAW process, which provides the controlled heat and mass transfer and precision depth control of bead penetration with a 2-1/2 axis CNC end and face milling operation (Figure 12).

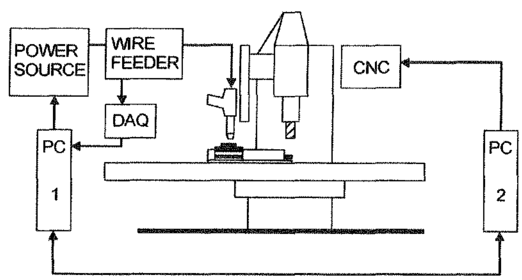

Figure 12. 2½ axis CNC hybrid rapid prototyping machine

The control system consists of two parallel microprocessors. The first processor (PC 1) controls the welding process and simultaneously acquires data from four channels. The first two channels are reserved for voltage and current measurements and the other two for acquiring signals from an infrared pyrometer and the light sensor. The second microprocessor (PC 2) controls the CNC milling machine. These two processors communicate, providing synchronization between the welding process and workpiece motion. This system offers a new way of building metallic parts in layered fashion with full density, high mechanical and metallurgical properties, high dimensional accuracy and good surface quality with complex geometrical features and sharp edges.

a) Building a wall

Building a metal wall consisting of single weld beads placed on top of each other is one of the basic procedures in 3-D welding. Poor surface quality and low dimensional accuracy are obtained by depositing metal layers without the milling operation because of small defects in the previous layer that become more and more amplified in subsequent layers. Using milling to prepare the surface for a new layer significantly improves surface roughness as shown in Table 1:

Table 1. Surface quality in dependence of layer thickness and milling operations

Layer thickness	Face milling	End milling	Roughness
1.5	No	No	~ 1.3 mm
1.0	Yes	No	~ 0.9 mm
0.5	No	No	~ 0.6 mm
0.5	Yes	No	~ 0.3 mm
0.5	Yes	Yes	< 0.2 mm

End milling can be used together with combined welding and face milling for further surface quality improvement. Additional milling operation increases time necessary to complete the layer, although the milling operation can be significantly shortened if high cutting speed machining is used due to small amounts of material that need to be removed. Also, surface quality is improved by making thinner layers. With face milling only, better surface quality was found in case when 0.5 mm thick layers were deposited comparing to the case with 1 mm thick layers.

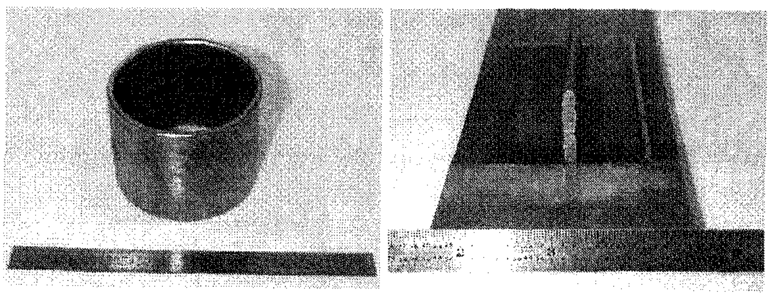

Figure 13. Samples

b) Path planning for multiple beads layer

There is a number of commercially-available software for tool path planning for a subtractive milling operation, but we are not aware of the software that can generate the path plan suitable for an additive welding operation. Previous research [10] shows that it is of highest importance to provide symmetric weld bead geometry and temperature conditions in order to have uniform metal flow. We tried to make multiple bead layers with various torch path plans and the best results were obtained with the path plan shown in Figure 14. A circumference bead is necessary to fill gaps created by irregular arc ignition and lower metal deposition at the end of the weld bead.

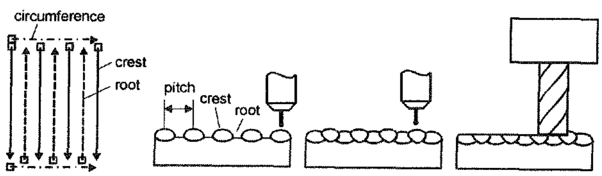

Figure 14. Correct weld trajectory

c) Making conformal channels

Making conformal channels is another basic technique in 3-D welding RP. The procedure of making conformal channels consists of the following steps: the part is built up layer by layer (every welded layer is face milled) to the point reaching the top of the channel, end milling is used to mill the conformal channel into the layered part (any shape in x-y plane), the milled channel is filled up with the support material (e.g. casting sand) covered on top with a thin sheet of metal in order to provide conditions to form an electrical arc, continue applying layers by welding and with successive face milling until part is finished, and finally, remove the support material in order to open up the channel.

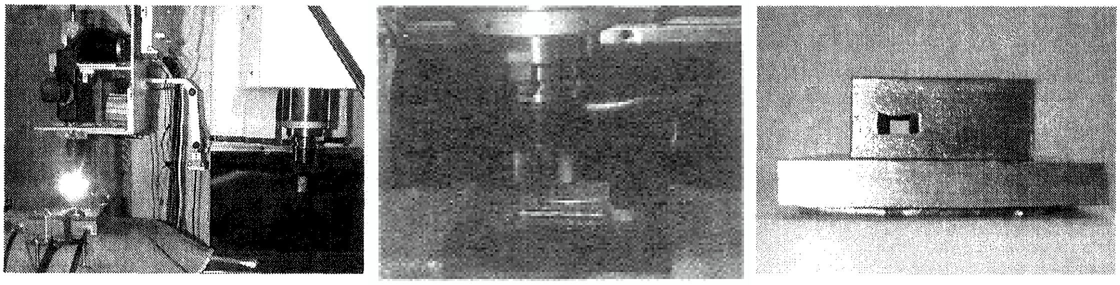

Figure 15. Making channel by Hybrid RP

Conclusion

Sensory feedback is a necessary requirement to accommodate the welding process to suit 3-D rapid prototyping needs. Two new approaches for globular metal transfer control, one based on a laser beam placed through the arc and the other based on real-time image processing, allow welding with low heat input, reduced spatter and shallow weld penetration. Test parts produced on the hybrid rapid prototyping machine, consisting of controlled welding and CNC milling, showed better surface quality, dimensional accuracy and high density demonstrating new technological opportunities and manufacturing flexibility in producing real metal parts in a layered fashion.

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