Variable Polarity GTAW in Rapid Prototyping of Aluminum Parts

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Abstract

This paper reports on a process to build aluminum alloy parts by variable polarity gas tungsten arc welding (GTAW). The relationship between the geometric sizes of the deposited layer and the welding parameters is investigated. A machine vision sensor is used to monitor and control the arc length that is a key welding parameter in the achievement of uniform deposition. By optimizing the depositing speed and the depositing layer thickness, there is no need for a cooling system to cool the part. Three-Dimensional parts with different wall widths and different shapes are successfully obtained. The surfaces of the deposited aluminum parts are smooth and uniform.

Introduction

One challenge for rapid prototyping (RP) is to develop the capability to directly create functional metal shapes that are dense, metallurgically bonded, geometrically accurate, and with a good surface appearance. Weld-based RP is one of the techniques that offer a promising approach to satisfy the requirements of this challenge.

The use of welding to create free-standing shapes was established in Germany in the 1960's (1). This development led to companies such as Krupp, Thyssen, and Sulzer that developed welding techniques for the fabrication of large components of simple geometry, such as pressure vessels that can weigh up to 500 tones (2). Other work in this area was undertaken by Babcock and Wilcox (3) who worked mainly on large components produced in an austenitic material. Also, work by Rolls-Royce (4) centered on investigating the technique as a means of reducing the wastage levels of expensive high-performance alloys that can occur in conventional processing. Rolls-Royce successfully produced various aircraft engine parts in nickel-based and titanium-based alloys. Research work on weld-based RP continues at the University of Nottingham, UK(5), the Cranefield University, UK (6), the University of Minho, Portugal, the University of Wollongong, Australia(7-9), and Southern Methodist University, Dallas, TX(10-11). Two new research groups, one from Korea (12) and the other consisting of researchers from the Indian Institute of technology Bombay and the Fraunhofer Institute of Production Technology and Automation (13) presented their conceptual ideas of combining a welding operation with milling. The Korea research group proposes to combine welding and 5-axis CNC milling for direct prototyping of metallic parts. The other research group from Germany and India proposes to combine welding with $2^1/_2$ -axis milling, where the complex shapes of the layers are obtained by using angle cutters. The brazing process is proposed to deposit the masking material at the edge of each layer in order to allow the formation of overhangs.

It is important to notice that all of the above research work focuses on the rapid prototyping of parts with steel. However, aluminum alloys also have a widespread history of applications in the industry. So, the development of a rapid prototyping technique of aluminum alloys is a very important and valuable research work.

Experiment System

The rapid prototyping experiment system is shown in Fig.1. GTAW technology is used to deposit 5356 aluminum alloy to build part. The diameters of the feed wires are 1.2 mm. A welding power source with a variable polarity property is used to effectively remove the oxidized film on the surface of the aluminum alloys.

The 3-D part is built on a substrate that is fixed on a rotating axis, the R-axis. The R-axis is attached on the Y-axis in the horizontal position. By controlling the movement of the Y-axis in the depositing process, a variable diameter part can be obtained. The substrate is made of a 6061 aluminum alloy with the size of 152 mm _ 152 mm _ 6.35 mm.

There are two axes in the vertical position, the Z-axis and Z'-axis. The Z'-axis is fixed on the Z-axis, and the welding torch is attached on the Z' axis. The Z-axis continuously goes up in the depositing process with a constant speed. There is no stopping between the two sequential layers, and that movement makes the part surface smoother. The speed depends on the substrate rotating speed and depositing layer height. The movement up or down of the Z-axis is controlled to keep the arc length constant in the depositing process according to the acquired signal of the arc length. The arc length is monitored in real time by a machine vision system consisting of a CCD camera, an arc light filter, and an image processing system. The CCD camera is attached to the torch and moves together with the torch.

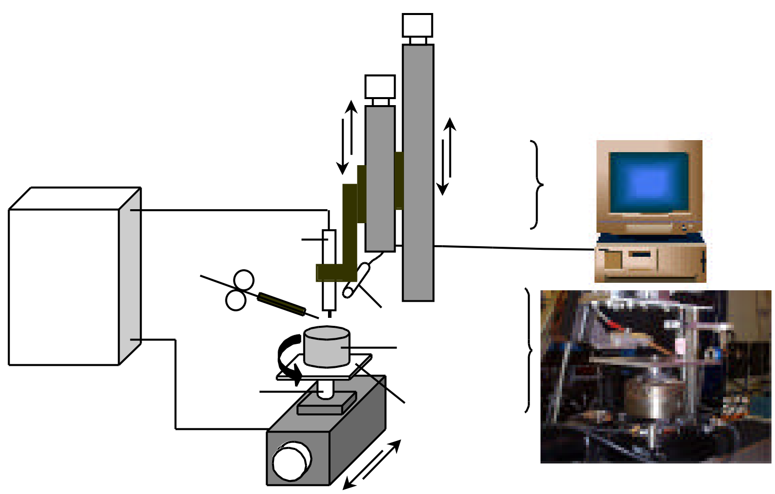


Fig. 1 The schematic diagram of the experiment system

Preheating and Heat Input controlling

When a temperature gradient exists in a body, experience has shown that there is an energy transfer from the high-temperature region to the low-temperature region. We can say that the energy is transferred by conduction, and that the heat-transfer rate per unit area is proportional to the normal temperature gradient:

$$q/A \sim \partial T/\partial x \qquad (1)$$

When the proportionality constant is inserted,

$$q = -kA(\partial T/\partial x) \qquad (2)$$

where q is the heat-transfer rate, A is the section area perpendicular to the direction of the heat flow, and $\partial T/\partial x$ is the temperature gradient in the direction of the heat flow. The positive constant k is called the thermal conductivity of the material.

The heat conductivity of aluminum is almost 6 times that of carbon steel and 12 times that of stainless steel(14). Suppose that q_0 is the suitable heat flow that ensures there is enough arc heat for the depositing process; all other conditions are equal except the materials. When aluminum is applied, the temperature gradient should be 1/6 that of carbon steel or 1/12 that of stainless steel. This result is why the preheating process must be applied in the depositing procedure. The preheating process can reduce the temperature difference between the substrate and the depositing layers.

In addition, as shown in Fig. 2, the first deposited layer L1 has the best heat conducting condition because the heat conducting area, the contacting area between the L1 layer and the substrate is greater, and the routine of the heat flow is shorter. The heat can be conducted to the substrate more quickly and directly. With the height of the part increasing, for example, the heat of the deposited layer Ln must be conducted through the previous deposited layers, then to the substrate. The conductivity of air is less than 0.7 Btu/h·ft·°F and can be neglected. Compared to the L1 layer, the heat-conducting area is smaller and the heat-flow routine is longer at the Ln layer.

According to the equation *(2)*, q decreases with A and $(\partial T/\partial x)$ decreases. So, more heat accumulates at the Ln layer than the first L1 layer. When the heat accumulation is high enough, the previous deposited layers are molten, and the depositing process must be terminated. In order to overcome the problem, the heat input is reduced until a heat balance is established. Most importantly, it is possible to build parts without any additional cooling means.

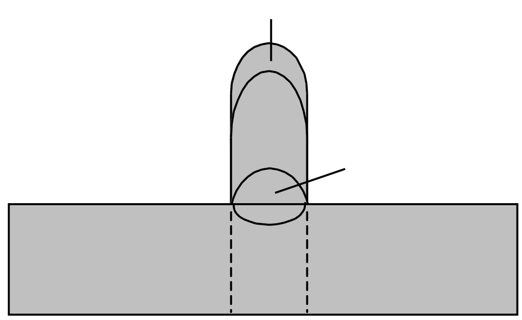


Fig. 2 The sketch of the section of the deposited part and the substrate

Arc Length Monitoring and Controlling

The arc length control is a key in the depositing process. The reasons are as follows:

1). The varying arc length is inevitable especially in a long-time depositing process.

2). The depositing process is not stable if the arc length cannot be kept constant because the varying arc length can result in a change to the heat input from the welding arc. The heat input from the welding arc Q is defined on equation *(3)*:

$$Q = \eta IV \tag{3}$$

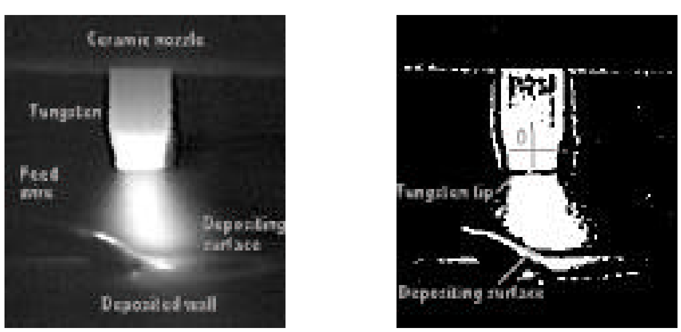
where η is the coefficient of efficiency, I is the welding current, and V is the arc voltage. The welding power source has a constant-current characteristic. So, V will change and make Q fluctuate when the arc length varies.

3). The depositing process is not stable if the arc length cannot be kept constant because the variance of the arc length can result in an unstable transfer of the molten metal from the feed wire. The molten metal from the feed wire can be transferred to welding pool very smoothly when the feed wire touches with a suitable pressure the surface of the substrate or the deposited layer. If the pressure is too high, there is a big friction between the feed wire and the deposited layer surface. The wire-feeding stability is interfered with. If the pressure is too small, the feed wire suspends in the welding arc. The molten metal from the feed wire is discontinuously transferred to the welding pool by droplets. Both cases lead to an unstable transfer from the feed wire of molten metal.

In the experimental system, the wire-feeding guide is fixed to the welding torch so that the feed wire and the torch can be moved together in the direction of the Z-axis. The feed wire pressure interacts with the arc length. To obtain a suitable feed wire pressure, the arc length must be kept constant.

The image of the tungsten, the welding arc, the feed wire, and the deposited wall are shown in Fig. 3. Eleven arc-length-detecting results can be obtained in a frame of image. In order to reduce the detecting error an average value of the results them is taken for the arc length.

By calibration, 12 pixels in the image stand for 1 mm of the arc length. The detecting accuracy is 0.083 mm. During every layer-depositing process, 15 to 30 images are acquired depending on the angular velocity of the part. The arc lengths are detected, and the average arc length is compared to the given arc length. At the beginning of the next depositing layer, the movement of the Z'-axis is controlled to keep the arc length to the given value.



(a) (b)

Fig. 3 Image processing of arc length monitoring (a) original image (b) processed image

Results and Discussion

The welding arc is used as the heat source. An OS523-3 Handheld Infrared (IR) Thermometer is applied to monitor the temperature of the substrate in the preheating process. The temperature is acquired once during a revolution of the substrate at the same position. The sensing area on the substrate is round with a diameter of 20.32 mm. The location of the sensing area is shown in Fig. 4. The distance of O_1O_2 is 64 mm, where O1 is the central point of the depositing path, and O2 is the central point of the sensing area. The acquired temperature is an average temperature of the sensing area and is used to present the temperature of the substrate. The temperature of the substrate is almost constant (118 ˚C) after preheating 52 circles. After 62 circles, there is a very big distortion of the substrate and the influence the temperature detecting; so, the preheating process must be terminated. Therefore 118 ˚C is decided to be the target temperature of the preheating process. The depositing process begins when the temperature of the substrate reaches 118 ˚C.

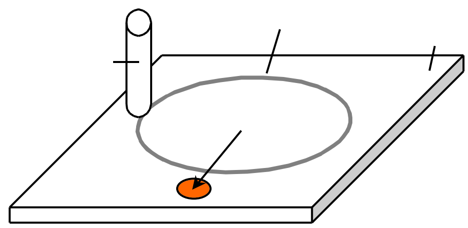


Fig. 4 The sketch of preheating temperature sensing

The shape and dimensions of the weld bead are very important in the use of the rapid prototyping system based on a welding technique, because these factors determine the limits of the wall thickness that can be built and influence the quality of the surface finish.

Numerous experiments are undertaken to build single weld beads for a range of welding conditions. The parameters that are varied include the welding current, the welding arc voltage, the welding speed, and the wire-feed speed. The welding current and arc voltage are monitored. Subsequently, the sizes (height and width) are measured of the built weld bead. The four main welding parameters are the welding current, arc voltage, welding speed, and wire-feed speed. When one of the parameters increases, the others are kept constant. A great amount of data is generated in this way, but the general trends are shown in Table 1.

Table-1 The general relationship of the weld bead sizes and welding parameters

Increasing Variable	Effect on Variables					
	Current	Arc voltage	Welding speed	Wire feed speed	Bead width	Bead height
Current	_	_	=	=	_	_
Arc voltage	=	_	=	=	_	_
Welding speed	=	=	_	=	_	_
Wire feed speed	=	=	=	_	=	_

The first test part consists of a "cylinder" shape as shown in Fig. 5. The part is designed to be built of 300 layers with a layer height of 0.4 mm, a layer width of 4.1 mm, and a diameter of

101.6 mm. The deposited result consists of a part height of 116.0 mm, a width of 4.2 mm, and a part diameter of 102.0 mm. The errors of part height, width, and diameter are 3.3%, 2.4%, and 1.0%, respectively.

The second test part consists of a "cone" shape as shown in Fig.6. The part is planned to be built by two segments: the first segment includes 60 layers with a diameter of 76 mm; the second segment includes 100 layers with a beginning diameter of 76.0 mm and an ending diameter of 46.0 mm. Both of the two segments have the same layer height of 0.4 mm and a layer width of 5.0 mm. The deposited result is: a part height of 66.0 mm high, a width of 4.9 mm at the first segment, a width of 5.3 mm at the second segment, a diameter of 75.5 mm at the first segment, and a diameter of 47.0 mm at the second segment. The errors of part height, maximum width, and maximum diameter are 3.1%, 6.0%, and 2.2%, respectively.

The third test part consists of a "pipe reducer" shape as shown in Fig. 7. The part is planned to be built by there segments: the first segment includes 80 layers with diameter of 76.0 mm; the second segment includes 60 layers with the beginning diameter of 76.0 mm and the ending diameter of 64.0 mm; the third segment includes 20 layers with the diameter of 64.0 mm. All the three segments have the same layer height of 0.4 mm and layer width 4.6 mm. The deposited result is: the part height of 65.1 mm high, 4.5 wide at the first segment, 4.61 mm wide at the second segment, 4.8mm wide at the third segment, 75.5mm diameter at the first segment, 47.0 mm diameter at the third segment. The errors of part height, maximum width and maximum diameter are 1.7%, 4.3% and 2.1% respectively.

The surfaces of the samples are very smooth.

Fig. 5 "Cylinder" shape part

Fig. 6 "Cone" shape part

Fig. 7 "Pipe reducer" shape part

Conclusion

There are three important keys to the success of the process presented in this paper: the preheating of the substrate, the arc-length monitoring and controlling, and the heat-input controlling. This process allows the components to be made directly and successfully with aluminum alloy. Several parts are made with perfectly acceptable quality for the surface finishing, mechanical characteristics, and dimensions.

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