Process Control of 3D Welding as a Droplet-Based Rapid Prototyping Technique

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Abstract

Three-dimensional welding is investigated as a rapid prototyping technique for the production of real metallic parts using gas metal arc welding principles. A high speed machine vision system is used to study the correlation between droplet transfer parameters and resultant weld penetration characteristics. Experimental work is conducted to determine how droplet transfer frequency, droplet size, and number of passes affect the geometrical and metallurgical properties of the weld penetration. A finite element analysis is performed in order to study what influence additional layering has on the cooling characteristics and resultant penetration profile.

Introduction

Current rapid prototyping techniques such as stereolithography, laminated object manufacturing, fused deposition modeling, and selective laser sintering can produce parts made from wax, plastic, nylon, and polycarbonate materials. The processes are useful for creating 3D models for visualization purposes or feasibility studies, however, industry has expressed interest to expand the current rapid prototyping techniques or create new ones to enable the direct production of metallic parts. With this goal in mind, much effort has been focused on using the principles of traditional welding processes for the direct fabrication of metallic parts. For many years welding techniques have been used to repair damaged components or to build up surfaces to resist wear and abrasion, but it was only during the last three decades that scientists began investigating the possibility of manufacturing complete metal parts using the controlled deposition of filler metal. The use of welding for creating free standing shapes was established in Germany in the 1960's. This led to companies such as Krupp, Thyssen, and Shulzer developing welding techniques for the fabrication of large components of simple geometry, such as pressure vessels which could weigh up to 500 tons. Other work in this area has been undertaken by Babcock and Wilcox who have been working mainly on large components produced in austenitic material. Also, work by Rolls-Royce has centered on investigating the technique as a means of reducing the waste levels of expensive high performance alloys which can occur in conventional processing. They have successfully produced various aircraft parts of nickel based and titanium based alloys. Work on 3D welding has also been in progress at the University of Nottingham, United Kingdom [1]. All of these attempts to use 3D welding for building metal parts failed to incorporate a feedback control system between the robot controller and the welding system. Sensory feedback is a necessary requirement for improvement of the system quality through process monitoring and for post inspection purposes. Attention must also must be given to the use of sensors to prevent possible collapse of the part caused by temperature build-up as well as to avoid build-up of metal along the layer caused by the change in the welding speed. Recently, a sensing system based on machine vision and high speed image processing has been developed for controlling the metal transfer process in a 3D welding operation [2,3]. Production of complete parts using welding principles can offer the following major advantages over conventional techniques: 1) A wide variety of shapes and sizes is possible when the torch is robotically controlled., 2) The produced parts have good isotropic characteristics., 3) The process is very fast so development lead times are significantly shorter., 3) There is very little material waste., and 4) A very highly automated system can be developed.

While initial work in the area of 3D welding has already shown that complex shapes can be formed, the results are not perfect. The problems associated with rapid prototyping metallic parts can be attributed to many different factors. Heat build-up due to the welding processes can cause part malformation or collapse of the structure. Inaccuracies in the welding and robot parameters can cause cumulative errors, resulting in the torch being too close or too far away from the surface. Solid layers cannot be formed accurately enough to form a smooth surface. This means that gaps can occur inside solid objects. It is evident from these problems that some form of sensing is required to control the process. In conventional gas metal arc welding, the manner in which metal is transferred from the consumable electrode into the weld pool plays a major role in the formation of the bead and penetration characteristics, as well as the final microstructure of the solidified metal. Thus, developing a sensing system based on the metal transfer process should advance the potential for applying GMA welding principles to a rapid prototyping process capable of producing metallic parts.

Experimental Setup

The welding power supply used for the experimental work uses a 24 V constant voltage wire feeder capable of providing wire feed speeds in the range of 127-1981 cm/min. A high speed digital camera is used for acquiring images of the metal transfer process. The images have a resolution of 128X128 pixels and a gray scale range of 0-255. The maximum possible frame rate of the camera is 800 frames per second with a data transfer rate of 16 MHz. The images are captured by a frame grabber capable of on-line image acquisition and real-time image processing. The frame grabber is equipped with its own DSP chip which allows for asynchronous processing so the time required for image acquisition and processing can also be used for monitoring other process parameters. A laser backlighting technique is used to filter out the arc light and produce shadowgraph images of the metal transfer process. The lighting source and optical components are shown in Fig. 1. During welding, the welding torch and machine vision components remain stationary and the workpiece traverses along a linear path beneath the torch. A photograph of the experimental setup can be seen in Fig. 2.

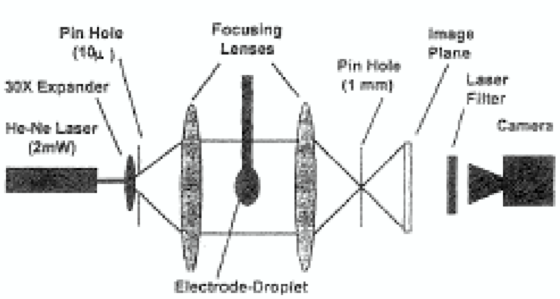


Fig. 1 Schematic presentation of the laser optics and high speed camera system.

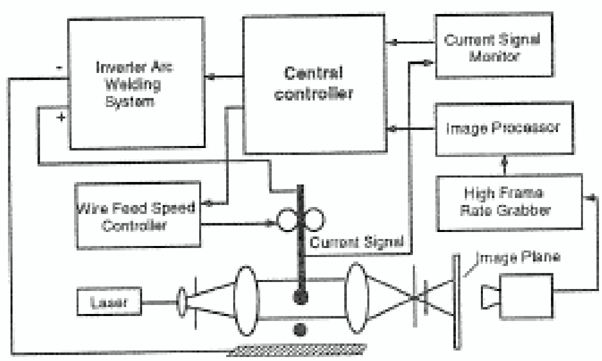


Fig. 2 Experimental setup.

Experimental Work

The welding experiments are performed with direct current-electrode positive (DCEP) gas metal arc welding. Coupons of 1015 mild steel with dimensions of 7.62 X 25.4 X 0.3 cm are used as workpieces. An ER 70S-6 automatically fed electrode wire with a diameter of 1.2 mm serves as the filler material. The contact tube-to-workpiece distance is 25 mm for all welds. A constant electrode extension of 20 mm is used for all experiments. A mixture of 95% argon and 5% carbon dioxide is employed as the shielding gas, and traverse speed is fixed at 6.4 mm/sec.

Controlling the Metal Transfer Process

Regulating the metal transfer process can best be accomplished by controlling the total heat input. The process parameter that is primarily responsible for heat input is the average welding current. Once a droplet reaches a desired size, switching the current from the peak level to the base level will initiate an oscillation of the droplet at the tip of the electrode. When the droplet is on a downward stroke, a signal is sent to the power source controller to raise the current to the peak level, which increases the electromagnetic force. The downward momentum of the droplet in combination with the increased electromagnetic force generates a large enough detachment force to detach the droplet from the electrode. Fig. 3 shows an idealized shape of the current waveforms employed in this work for controlling the metal transfer process. In addition to detaching the droplet, the welding current must be controlled to achieve the desired heat input. In order to allow a certain degree of control over the average current level, the current waveform in the droplet growth period, i.e., the interval between the detachment instant of the previous droplet and the oscillation initiation of the present droplet, should be designed based on the desired average current and the required drop in current necessary to initiate the droplet oscillation. (See Fig. 4.) Immediately following the detachment instant, the current should be returned back to the base level for a pre-set duration, and then smoothly increased back to the peak level. Using this approach, the height to width ratio of a bead layer generated by GMA welding can be controlled.

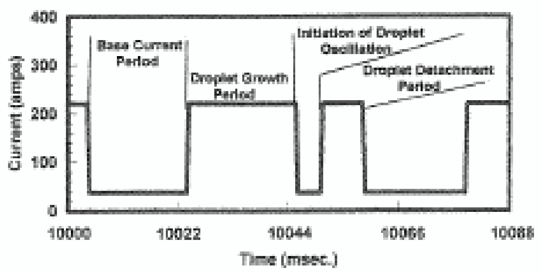


Fig. 3 Idealized shape of pulsed current waveform.

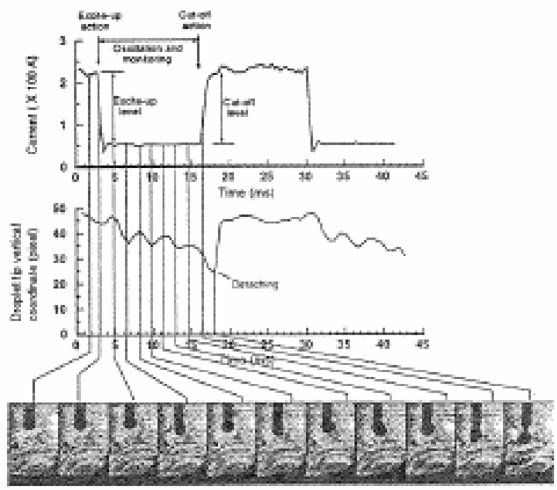
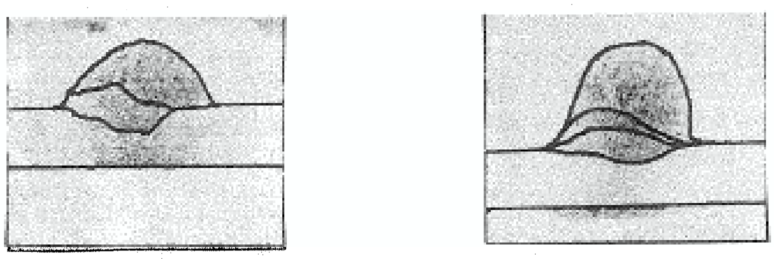


Fig. 4 Experimental observation of the excited droplet oscillation and detachment.

When building a layered structure it is required that the heat input be much less than the amount required for a welding process. Important factors in the production of high quality layered structures are the creation of metallurgical bonding through substrate remelting, the control of cooling rates of both the substrate and deposited material, and the minimization of residual stresses. Figs. 5(a and b) respectively show cross-sectional views of the double and triple layering results produced with an average current of 170 A and a long droplet growth period. Use of a larger droplet size will contribute more heat to the substrate and result in a more pronounced finger-shaped penetration. This is supported by the bead cross-sections, and is especially evident for the triple-layer case represented in Fig. 5(b). Excessive remelting of the previously deposited layers will also occur. Applying additional layers will introduce more heat into the substrate and make it more difficult to provide the conditions for building a straight wall layered structure. By shortening the droplet growth time period and by decreasing the level of average current to 150 A, the amount of heat contained in the deposited droplets will be reduced, and the depth of layer penetration into the substrate can be controlled as illustrated in Figs. 6(a and b) for the case of double and triple layer deposition. The photographs of the bead cross-sections depict much smoother penetration boundaries free of the central finger-like penetration that is inherently characteristic of a GMA welding process.

(a) (b)

Fig. 5 Bead cross-sections of a double-pass (a) and triple-pass (b) weld formed with an average current of 170 A.



(a) (b)

Fig. 6 Bead cross-sections of a double-pass (a) and triple-pass (b) weld formed with an average current of 150 A.

Finite-Element Modeling of 3D Welding

Almost as quickly as welding emerged as one of the most popular and widely used joining processes, engineers and physicists began their theoretical journey into the field of welding to understand the physics of the process and the interactions of the different phenomena involved. Efforts in this area were strongly motivated from the start by the clearly visible and rapidly growing potential for the application of the welding processes. To avoid the tedious approach of endless trial-and-error experimentation for establishing reliable data bases, accurate theoretical models were needed to predict the critical welding results, such as weld bead width and depth of penetration. However, after decades of intense research in this area, precisely predicting process results for such a complex process as welding has proven to be a very difficult task. Regardless, these models have saved both time and resources by serving as tools for narrowing the ranges of feasible operating parameters. Likewise, if a rapid prototyping process is to be developed based on the principles of welding, theoretical models must be developed which provide information pertinent to the layered fabrication of metallic parts. The mathematical models previously developed for the welding processes are not applicable for droplet-based rapid prototyping due to the many different requirements of the two processes. The finite element technique is employed to perform a thermal analysis of a droplet-based rapid prototyping operation and model the depth of bead penetration into the base plate.

Designing a feasible 3D welding operation requires a thorough understanding of how the part will respond to the repeated heating and cooling cycles. The maximum and minimum temperatures play a major role in determining the final microstructure, as do the heating and cooling rates of the process. Important factors in the production of high quality layered structures are the creation of metallurgical bonding through substrate remelting, control of cooling rates of both the substrate and the deposited material, and the minimization of residual stresses. For building a layered structure, it is required that the heat input will be much less than in the case of a welding process. In the layer building process the bonding thickness between two layers has to be large enough to provide sound bonding mechanical strength. However, excessive remelting of the previously deposited metal can disrupt the geometry of the earlier formed layers. Therefore, it is critical that the selected heat input level be suitable for the given part geometry and process conditions. Also, the cooling rate must be considered since it affects not only the microstructure, but also the shape of the solidified bead. If the newly deposited molten metal cools rapidly, a high and narrow bead will form. Whereas, a low cooling rate will allow time for the molten metal to spread over the previously deposited layer before solidification occurs. The resultant bead will be wide and more flattened.

The finite element model for 3D welding is designed based on the welding conditions and experimental parameters employed for the experimental work. They include the geometrical dimensions of the workpiece and newly formed weld bead, fixturing, composition of the workpiece and filler metal, weld path, traverse speed, initial temperatures, ambient conditions, composition and flow rate of the shielding gas, welding current, voltage, and properties of the metal transfer process such as droplet size and transfer rate.

The outcome of any welding process is predominantly determined by the heat that is input to the workpiece to produce melting. Simulating the heat source is a critical step in the development of a numerical model designed to predict the outcome of a welding operation. Both the magnitude and distribution of the heat source are of significant importance, and thus can have a profound effect on the process results. The finite-element method has developed into a powerful tool to solve complex thermal analysis problems [4,5]. While the technique has been fairly successful in simulating the gas tungsten arc welding process [6-11], very few attempts have been made to model a gas metal arc welding process [12] owing to the additional complexity caused by the introduction of filler metal during the operation.

Due to the nature of the energy transfer to the workpiece, analytically modeling the welding heat source is complex. For numerical modeling purposes, heat input to the weldment can be represented as a distribution of surface flux, but this approach introduces some arbitrariness into the defined heat source. In a few works, major simplifications have been made and the thermal energy supplied by the heat source is assumed to be input at a point or line source, depending on the geometry of the weldment [13]. These types of idealized solutions are only valid for simple geometries and for regions far away from the fusion and heat affected zones.

Determining the losses that occur between the solid electrode and the workpiece is extremely difficult. A portion of the arc heat is spent to melt the continuously fed filler wire. Part is lost to the environment before it ever reaches the base plate. Heat from the arc and heat contributed by the molten metal droplets deposited onto the workpiece induces heat flow in all directions in the workpiece. In an attempt to quantify the portion of arc energy that is actually absorbed by the workpiece, a term referred to as the arc efficiency (η) has been developed. Compared to GTAW, radiation and conduction from the arc plasma make much more minor contributions to the total amount of heat input to the weldment [14]. The major source of heat energy is the mass of molten material provided by the consumable electrode to the workpiece in the form of metal droplets. Therefore, two sources of thermal energy should be included when modeling a GMAW heat source, i.e., the energy from the arc generated at the workpiece and the heat energy contained in the metal drops transferred from the filler wire. It has been shown that the energy contribution from the arc primarily affects the width of the weld pool while the amount of energy contained in the molten metal droplets primarily controls the melting rate of the workpiece material [15]. Consequently, the depth of pool penetration into the base material is predominantly governed by the amount of heat energy supplied to the workpiece by the molten droplets. Also, it has been reported that the degree of weld penetration can be influenced by the impingement of the metal droplets on the weld pool [16].

Idealistically, in order to accurately model a GMAW heat source, effects from the following phenomena should be included: radiation and conduction from the arc, positive ion impingement on the workpiece, heat input from the filler metal droplets, influence of the additional mass of material from the consumable electrode, and effects of weld pool indentation caused by the impinging metal drops. Numerically representing any one of these phenomena would be a very complex task. Furthermore, attempting to quantify the cumulative effect of these factors coupled together would be even more challenging, and nearly impossible to verify.

In an effort to take advantage of the results from previous works and also minimize the chances of making erroneous assumptions, the procedure of modeling the GMAW heat source for the present work is divided into two phases: 1) Evaluate the magnitude of the total heat energy input to the workpiece, and 2) Determine the manner in which the heat energy is supplied to the workpiece.

Calculating input thermal energy will be based on an estimated arc efficiency (η). The works that have addressed the topic of arc efficiency for the GMAW process have reported values ranging from 66% up to 71% [17,18]. Since it is known that very small changes in the welding parameters can significantly alter the arc efficiency, estimating an exact value for η is unrealistic given the knowledge available to date. However, a reasonable estimation for η can be assumed by comparing the current experimental conditions with those in previous studies. For this work, an efficiency value of η=74% is assumed for modeling the GMAW heat source. The amount of energy supplied by the arc to the base plate is calculated using the formula: $q = \eta \cdot V \cdot I$ where q(Watts) is heat transfer rate, η is arc efficiency, V(volts) is voltage, and I(amperes) is welding current.

Before the heat transfer rate can be incorporated into the finite-element model, it needs to be converted into a heat flux q'' having units of W/m^2. Thus, phase II of modeling the heat source must be completed in order to determine over what surface area the heat will be input and how it will be distributed over the area. Various approaches have been taken to simulate a GMAW heat source, including input at a point or line [14], input over a circular area having a uniform, ramped, triangular, or Gaussian distribution [19], and supplying the heat internally within a spheroidal or ellipsoidal region [20]. Recent works have shown that in a GMAW process, the majority of the heat energy supplied to the workpiece comes from the mass of molten material deposited into the weld pool, and that radiation and conduction from the arc plasma contribute very little thermal energy to the weldment [20]. Based on this information, the molten droplet is selected as the object of focus for modeling the heat source. It will be assumed that the weldment receives heat energy solely from the molten droplets depositing into the weld pool. An average maximum droplet diameter value of 1.82 mm has been calculated for the range of process parameters values employed for the experimental work. Taking 1.82 mm as the diameter, a projected area for droplet impact on the pool is calculated and used to convert the heat transfer rate q (Watts) into a value for heat flux q'' (W/m^2).

The finite-element results for modeling a double- and triple-layer 3D welding process are presented in Figs. 7-8 for average welding currents of 170 A and 150 A. It can be observed that the higher current yields a slightly deeper penetration depth. However, melting of the original base plate, distinguishable by the larger mesh elements, does not occur in either case.

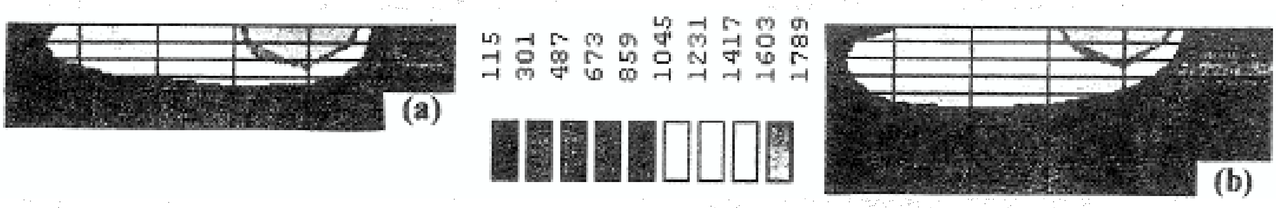


Fig. 7 Isotherm plot of an FEM simulated double (a) and triple (b) pass weld formed with an average current of 170 A (view of the weld path cross-section)

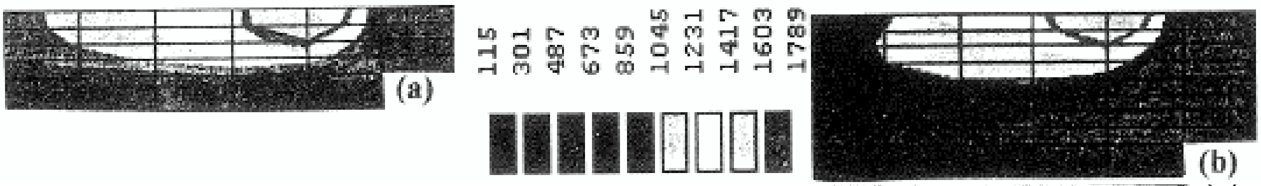


Fig. 8 Isotherm plot of an FEM simulated double (a) and triple (b) pass weld formed with an average current of 150 A (view of the weld path cross-section)

Conclusions

Machine vision sensing can be used for monitoring and controlling the metal transfer process in a 3D welding operation. By precisely controlling the droplet growth process and instant of detachment, the maximum depth of weld penetration as well as the shape of the bead penetration profile can be controlled. Isotherm plots of simulated bead cross-sections demonstrated that the finite-element modeling technique can accurately predict the weld penetration results of a 3D welding operation.

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