MACHINE VISION BASED CONTROL OF GAS TUNGSTEN ARC WELDING FOR RAPID PROTOTYPING

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Abstract

A machine vision system, based on CCD camera, is used to control the molten pool size during the gas tungsten arc welding (GTAW) process. The technique is tested by making a metallic part with a complex 3-D network of conformal channels on a hybrid rapid prototyping machine based on welding and milling. The test part demonstrated manufacturing flexibility and new technological opportunities required for prototyping injection mold tools. The real metallic part made in a layered fashion had good surface quality, dimensional accuracy, and high density.

Introduction

In the last decade, production industry has been under growing pressure. Products have shorter life cycles and so industry must have shorter product development times [1]. Changing requirements have prompted the need for making prototypes of all kinds fast. Also, how fast the industry is able to develop a new product depends heavily on how fast the industry is able to produce a prototype. This demand has led to the development of new prototyping techniques.

For many years prototyping techniques have been based almost exclusively on polymers, waxes, or paper materials. The rapid prototyping parts had limited dimensions, and they had a tendency to distort due to shrinkage and lack of support. The mechanical properties were also poor since metallic materials could not be used. It is obvious that the production of metallic prototypes is the important goal in the field of rapid prototyping.

In the hybrid rapid prototyping machine for metallic parts fabrication [2], welding process provides depositing material and energy to fuse the added material. In order to generate uniform and fairly flat layers, metal deposition rate and molten pool size should be invariant of the alterations of the welding conditions. Closed loop control of the welding process, with the information of the molten pool size as a feedback, is a necessity. Machine vision system, based on a CCD camera as a sensor, is used to address that problem.

Machine vision systems have been used extensively for seam tracking and the adaptive control of welding conditions, mostly with the idea to simulate the eye sensing and process actuation of the human welder. Richardson et al. [3, 4] positioned the optical system to be coaxial with an electrode and used a vision system to obtain a digitized image of the weld pool. Focused and diffused argon laser were used as light sources and a CCD camera with a telephoto lens was used to monitor and record the weld-pool image [5]. A vision system for monitoring the weld-pool geometry using a high shutter speed camera combined with structured light that involved a nitrogen laser is described in [6]. The commonly used method for off-line analysis is high-speed photography [7, 8, 9, 10] in which a high-speed camera is used to film the metal transfer process.

Combining GTAW with milling, instead of gas metal arc welding (GMAW) [2], showed some advantages. In GTAW, the wire feeding rate does not depend on the welding current as is the case with GMAW. It is even possible to completely stop the metal deposition process while keeping the arc on, move the work piece, and start the wire feeding again at the new location. Another important advantage is that in GTAW, the wire can be fed directly into the molten pool. In such a way, the surface tension is evenly spreading the liquid metal, and possible irregularities inherent to the droplet-wise metal transfer are avoided. The disadvantage of the GTAW is related to the problem of multi-directionality. An additional mechanism is necessary to ensure that the wire is always fed in front of the moving arc.

The objective of this research is to develop a control system for the GTAW process, suitable for rapid prototyping, based on the real-time image processing. The controlled welding process, combined with the milling operation, presented a new technological opportunity for making complex 3-D network of conformal channels. The test part had good surface quality, dimensional accuracy, and high density.

Control system and Experimental Setup

The essential requirement for controlling the metal deposition process is controlling the size of the molten pool. Small irregularities in the previous layer are amplified in subsequent layers. Because of that the flattening of a new built layer by milling is necessary. Keeping the molten pool size approximately constant results in an even and fairly flat deposited layer, therefore, significantly reducing the need for milling operation. Up to 10 layers can be deposited without intermediate milling.

A closed loop control of the welding current is established in order to keep the molten pool size and the average temperature of the molten pool vicinity within a certain range. The molten pool size is extracted by a real-time processing of the images obtained from the high-frame rate camera. The average temperature of the molten pool vicinity is estimated from the images acquired by the infrared camera. In order to ensure that the welding current will be kept within the allowed range of values, a limitation is performed after the calculation of the new current value (Fig. 1).

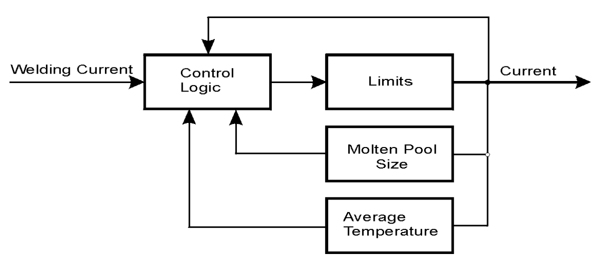


Fig. 1. Feedback signals in the closed loop control.

The experimental setup consists of the central controller (PC, Pentium III, 500 MHz, 128 MB), the CNC milling machine, an inverter-type DC-welding power source, a high-frame rate CCD camera and an infrared camera as it is shown in Fig. 2. Two additional computers, equipped with the frame grabbers, are used for image acquisition and image processing. In this way, extensive and time consuming image processing was performed in parallel with the central controller's program.

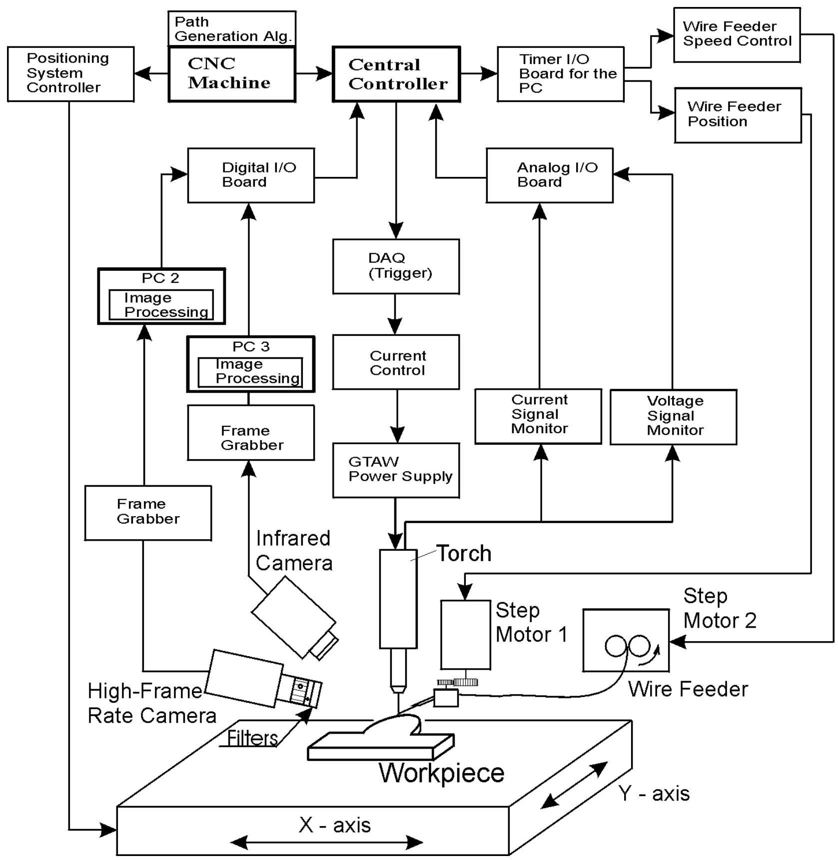


Fig. 2. The experimental setup.

Image Processing

Using the high frame-rate CCD camera as the sensor, the weld-face shape of the molten pool is monitored. The arc makes a very complex illumination and irradiation of the weld specimen and the weld pool. The light incoming into the camera is filtered through the cold mirror and neutral density filters, and as a result, most of the frequencies originating from the Argon plasma are canceled and only the infrared radiation passed through, and entered the camera (Fig. 3). Consequently, the arc light was attenuated while the infrared part of spectrum, originated in the molten pool, remained unchanged. All of the CCD cameras are very sensitive in infrared range of the spectrum; therefore, fairly clear images of the molten pool are obtained regardless of the mutual position of the arc, molten pool or camera.

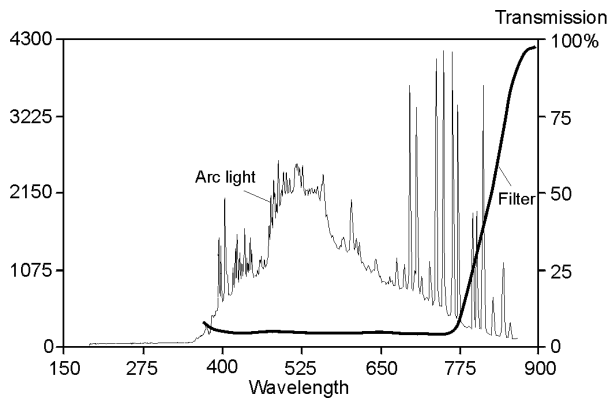


Fig. 3. Arc spectrum and filter characteristic.

Extensive processing is performed to extract the molten pool size from the original image. The Laplacian method with a structuring element of 5x5 pixels, that searches for zerocrossing in the second derivative of the image, is used. The Laplacian operator is represented by Eq. 1 as:

$$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2}; \qquad f = f(x,y); \quad f = 0...255; \quad x, y = 1...128 \qquad (1)$$

where $f = f(x,y)$ is the functional representation of the image. As a second-order derivative, the Laplacian operator is typically very sensitive to noise. In order to reduce the noise, erosion is applied, that removes pixels not surrounded by the pixels of the same value. Finally, a closed convex curve (envelope) is constructed around the molten pool. A number of white pixels within the envelope represents the molten pool size. Fig. 4 shows the original image and the images obtained after each processing sequence when the molten pool was “hidden” behind the arc; i.e., the molten pool was moving toward the camera. Even in this most difficult case, the proposed image processing sequence successfully extracted the molten pool size.

Fig. 4. The original image and the images after each processing step.

Building a test part

The GTAW combined with the CNC milling operation is used to produce 3-D metallic parts in a layered fashion. The GTAW process provided depositing material and energy to fuse added material while the CNC milling machine provided motion in X,Y-plane so that the material could be added at the desired position, and the possibility to make new features by removing material.

The first step in part making procedure was to create a CAD model (Fig. 5). CAD model had to be sliced into layers, and NC code (Main NC program) had to be generated for each layer. New software, capable of automatically generating the Main NC program directly from the CAD model is developed. The software "understands" cross-section geometry and generates the correct torch path with the accompanying control signals for the welding process and NC subroutines the for milling operations. The Main NC program, which resides in the milling machine's memory, controls the workpiece motion, sends the information of the torch position to the central controller, and controls the metal deposition process.

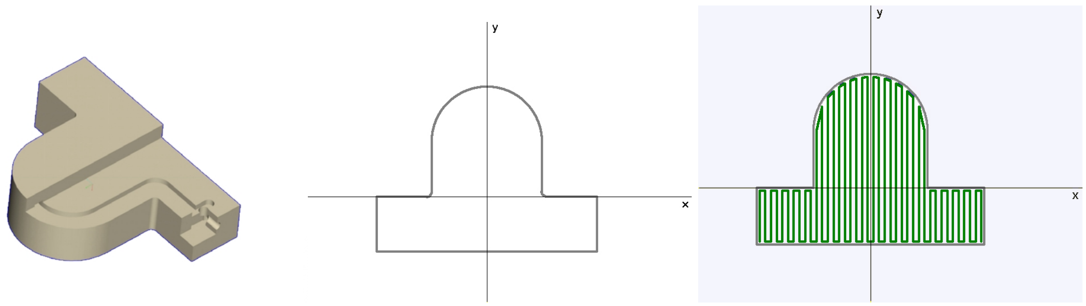


Fig. 5. CAD model, the layer cross section, and generated torch path.

The material added to the molten pool requires time to melt, overheat, and spread by the surface tension force. For that reason, wire should be fed in front of the moving arc. To address the problem of multi-directionality, a wire tip positioner with a step motor is constructed, as shown in Fig. 6. Information about the arc direction is embodied in the Main NC program. When the arc changes direction, the appropriate signal is generated and step motor moves the contact tip to the new position providing that the wire is fed in front of the arc.

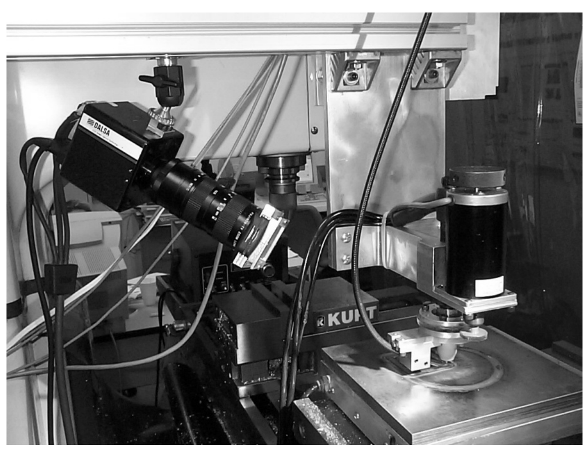


Fig. 6. CCD camera and wire tip positioner.

Building a metallic part in a layered fashion offers a new technological opportunity for making the confomal channels in a convenient and efficient way. The experimental procedure of making a metallic part with a 3-D conformal channel network consisted of:

1. building a 3-D part layer by layer until the top of the channel is reached,
2. milling the channel, Fig. 7,

3. filling the channel with support material (e.g. casting sand), Fig. 8,
4. covering the channel with a sheet metal of the same shape as the channel in order to provide the conditions for an electrical arc to form, Fig. 9,
5. building a 3-D part until the top of the new channel is reached,
6. milling a new channel and, if needed, making a connection between the previous and new channel,
7. filling the channel with support material and covering it with sheet metal

Steps 5 - 7 are repeated for the each additional channel. Before the last channel is filled with the support material, all of the vertical connections between channels should be made by drilling the holes.

8. building the remaining layers of the part until the top is reached,
9. removing support material to open the 3-D channels,
10. milling 3-D part in order to achieve wanted surface accuracy, Fig. 10.

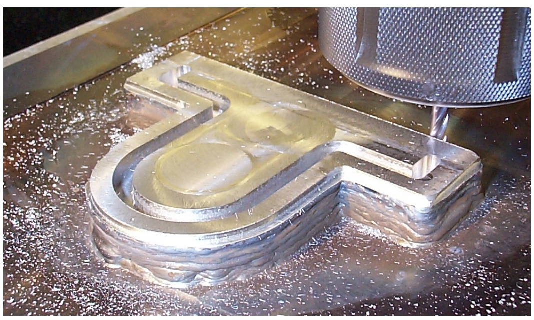


Fig. 7. Milling a channel.

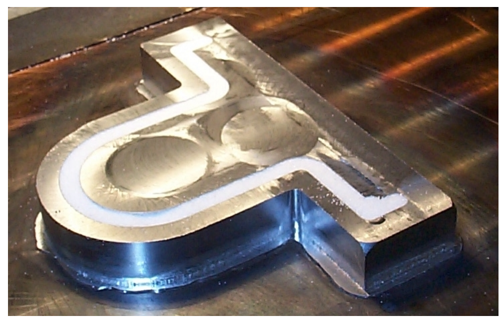


Fig. 8. Channel filled with support material.

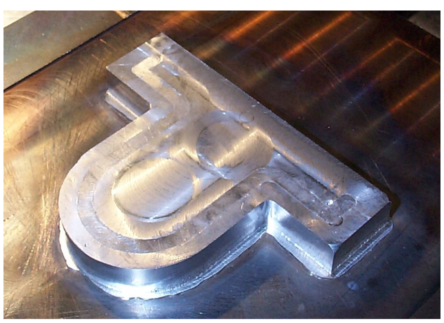
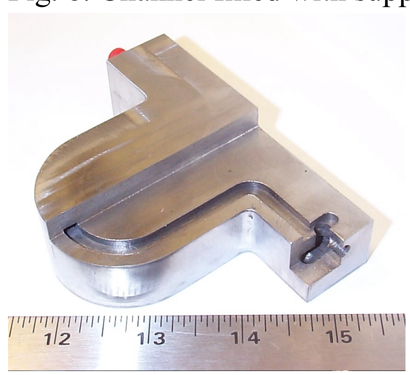


Fig. 9. Channel covered with sheet metal.



10. Finished 3-D part.

Conclusion

A machine vision system, based on a CCD camera, is used for controlling the molten pool size during the GTAW process. Cold mirror filters are used to reduce the arc illumination and pass the infrared radiation. Images of the molten pool were clear enough to allow the extraction of the molten pool size by a real-time image processing consisting of Laplacian edge detection, thresholding, erosion, and convex envelope construction. The control technique is tested by making a metallic part with 3-D network of conformal channels on a hybrid rapid prototyping machine based on welding and milling. New technological opportunities and the manufacturing flexibility necessary for prototyping injection-mold tools are presented. The test part had good surface quality, dimensional accuracy and high density.

Acknowledgements

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