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An Integrated Optical Sensor for GMAW Feedback Control

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Abstract

The integrated optical sensor (IOS) is a multifunction feedback control sensor for arc welding, that is computer automated and independent of significant operator interaction. It is based on three major "off-the-shelf" components: a charged coupled device (CCD) camera, a diode laser, and a processing computer. The sensor head is compact and lightweight to avoid interference with weld head mobility, hardened to survive the harsh operating environment, and free of specialized cooling and power requirements.

The sensor is positioned behind the GMAW torch and measures weld pool position and width, standoff distance, and postweld centerline cooling rate. Weld pool position and width are used in a feedback loop, by the weld controller, to track the weld pool relative to the weld joint, thus allowing compensation for such phenomena as arc blow. Sensor stand off distance is used in a feedback loop to control the contact tip to base metal distance during the welding process. Cooling rate information is used to infer the final metallurgical state of the weld bead and heat affected zone, thereby providing a means of controlling post weld mechanical properties.

AUTOMATED WELDING requires a welding system capable of adapting to changing conditions encountered during the welding process. Many sensor systems have been developed to give automated welding systems the capability to adapt to variations in one parameter, e.g., laser striping for joint tracking [1], through the arc sensing [2], coaxial viewing of the weld pool [3], and infrared sensing [4]. The integrated optical sensor (IOS) is a multifunction feedback control sensor that has three distinct near-real-time measurement functions: weld pool position and width, sensor to work piece distance, and weld bead centerline cooling rate. The pool position and width are used to control the welding torch position relative to the to the weld pool, allowing the host control system to compensate for such phenomena as arc blow. The host welding system uses the sensor stand off distance in a feedback loop to control the contact tip to work piece distance. Cooling rate information is used to infer the final metallurgical state of the weld bead and heat affected zone therefore, post weld mechanical properties can be controlled.

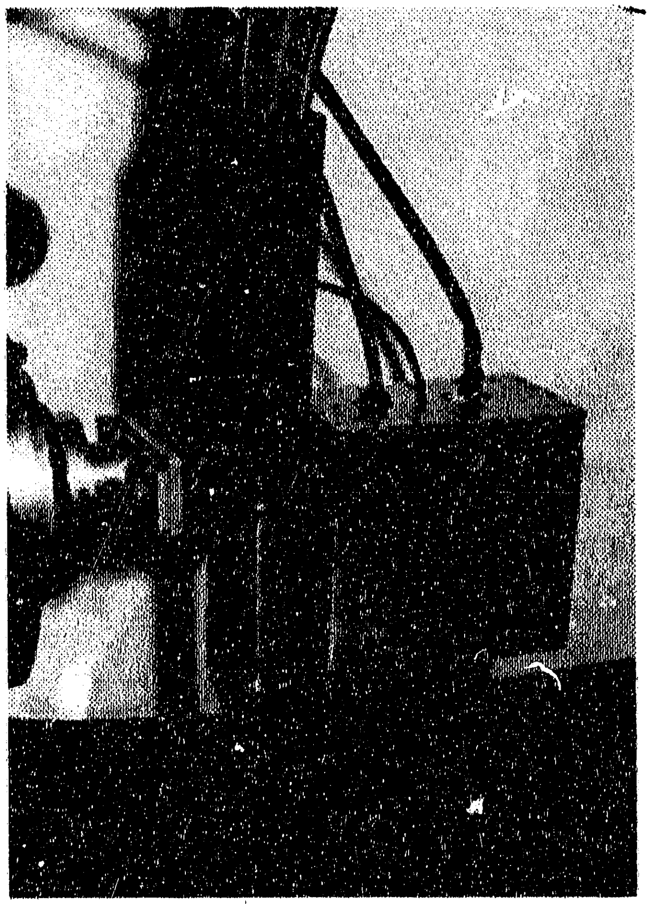

Fig. 1 Integrated optical sensor mounted to GMAW torch.

The IOS consists of three major components: a remote head CCD camera with lens and filter pack, a continuous wave Ga Ar diode laser, and a remotely located computer data acquisition and processing unit. The sensor head is mounted just behind the welding torch as pictured in Figure 1. The sensor's camera and laser are mounted in an industrially hardened case, allowing the sensor head to withstand harsh operating environments without any specialized cooling or power requirements. A single cable attaches the sensor head to the computer data acquisition system. The computer processing system uses an industrial PC AT compatible 80486 to acquire images from the sensor's camera and analyze them for weld pool width/position , standoff, and weld bead centerline cooling rate. Data are transmitted to the host welding system via an RS-422 serial interface at a rate of approximately 10 Hz. The sensor is computer automated, independent of significant operator interaction.

Sensor Operation

The IOS is a stand-alone system, that is, it operates with minimal operator assistance. When the power is turned on the sensor computer is activated and boots the operating system, which then automatically starts the sensor software. The camera and laser power are activated and, after a short period, both are ready to operate. Once this has taken place the sensor waits for an input command from the RS-422 serial communication port. The commands are listed in Table I. When the sensor has received an on-line command it is ready to be calibrated.

Calibration consists of centering the calibration block, shown in Figure 2, underneath the IOS and then sending the calibrate command and the sensor to work piece distance to it. The sensor then calibrates the image intensity and the scales of measure in the x and y image planes. The calibration procedure ensures that the level of illumination received by the camera is correct so that the temperature measurements made for the cooling rate calculation will be correct. The x and y calibrations ensure that the coordinate data is correct. The sensor to work piece distance is used to ensure the correct distance values are reported. As long as the sensor to torch relationship is constant, the calibration need not be re-performed. When the calibration process ends, the sensor sends the calibration complete command to the host controller and is then ready to run.

When the sensor has received the temperature set point and the travel speed, it goes into the sensor hold mode and waits for the host to send a sensor continue command. When the sensor continue command is received, the laser shutter is opened and the sensor begins taking data for the host welding controller. Images are obtained with the frame grabber in the processing computer and the output data are determined and sent to the host computer at a rate of up to 10 Hz. During sensor operation the host can exercise various commands to control the sensor. For example, the sensor may be paused and then continued. While the sensor is paused the laser shutter is closed and the sensor stops collecting data. The data output rate can be changed. If the host computer does not wish to received data at 10 Hz it can request that the IOS send data at a lower rate. Also, the temperature set point (the point at which the weld bead cooling rate is determined) may be changed, as well as the weld travel speed. A diagnostics command is available for the advanced user to troubleshoot the system should a problem arise. The diagnostics mode makes the processed images available for the operator to view, as well as the raw and processed data. The off-line command readies the sensor to have its power turned off.

Table I. Sensor command list.

Command	Description
IOS Commands	
ON	On line
OL	Off line
SD	Set sensor-to-work-piece distance
TS	Set travel speed
ST	Set temperature at which to report cooling rate
SH	Sensor hold
SC	Sensor continue
DG	Set diagnostic mode level 0-All diagnostics off 1-Processed image output 2-Terminal display on 3-Both 1 and 2 activated
SU	Sensor setup (data output rate)
IOS Responses	
A	Output Data Cooling rate Confidence level Left pool edge distance from center Right pool edge distance from center Left bead edge standoff distance Right bead edge standoff distance
CD	Calibration complete
ER	Error and description number
RB	Watch dog has rebooted sensor computer

Sensor Hardware

The sensor head carries the camera and laser behind the welding torch. Figure 3 shows the sensor head, which is approximately 117 mm (4.6 in.) wide, 127 mm (5 in.) high, and 73 mm (2.9 in.) thick, with the cover plate removed to display the remote head camera on the right and the diode laser on the left. The sensor head is mounted on the welding torch at a slight angle so that the edge of the welding torch gas cup becomes visible at the right side of the image as shown in Figure 4. This viewing angle ensures that the camera does not receive to-much light from the welding arc. The camera view is approximately 63 x 45 mm (2.5 x 1.8 in.) at a sensor to work piece distance of 140 mm (5.5 in.). The diode laser supplies an infrared beam that is spread into a line with a cylindrical lens in the lower portion of the laser housing. At the bottom of the laser housing is a shutter mechanism for controlling the laser beam. Underneath

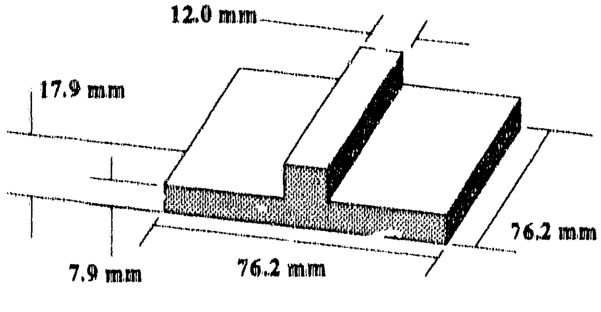

Fig. 2 Calibration Block

the laser are two mirrors that reflect the beam out of the IOS housing at the proper angle. Although the laser is a class IV laser, it has a nominal hazard zone of 355 mm (14 in.) and only people within this distance must wear laser goggles. The sensor head is capable of withstanding the welding environment without any external cooling. All power, control, and video signals are carried in a single umbilical cord from the sensor computer and laser control system. A diagram of the system is shown in Figure 5.

The IOS uses an industrial IBM PC AT clone with 8MB of memory using an Intel 80486 CPU operating at 25MHz for data processing. The computer system is designed for stand-alone operation and does not require the use of a monitor or keyboard. The computer sends and receives data via an RS-422 serial communication port connected to the host computer. A Data Translation frame grabber is used to translate NTSC video images into arrays of pixel data. An analog and digital output board is used for interfacing with the laser shutter and camera gain controller. A watch dog timer and temperature monitor board is also installed in the computer. The watch dog timer will reboot the system in the event the computer should "lock up" and no longer be processing data. The temperature monitor measures the internal temperature of the computer's case and can be used to send warning to the operator in the event of overheating. An electronic disk stores the software, thus avoiding the use of a more delicate hard disk. A floppy disk is required only for loading the software on to the electronic disk.

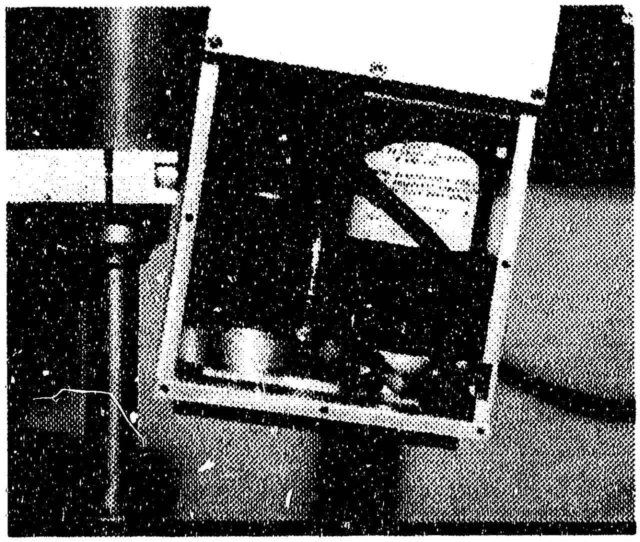

Fig. 3 Sensor head with cover plate removed.

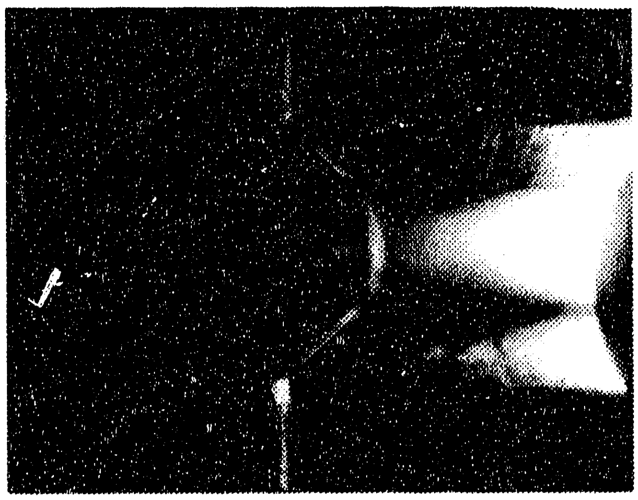

Fig. 4 Unprocessed image from sensor camera.

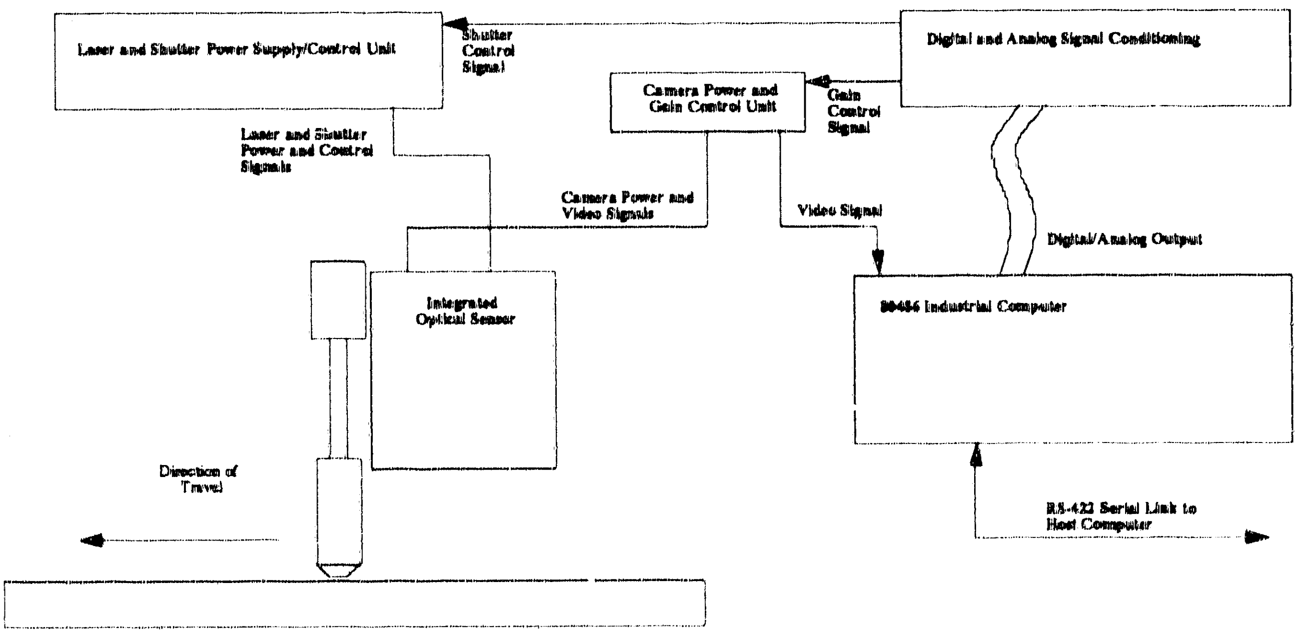

Fig. 5 Diagram of sensor system components.

Sensor Software

The sensor software makes all the calculations for data output as well as controls the camera gain and laser shutter. To obtain the desired data output rate, the software was written using a 32 bit C compiler, which produces code that, with the help of a DOS extender, allows the software to take advantage of the protected mode of the Intel 80486 CPU [7]. Protected mode allows the software to access all the memory installed in the machine and run approximately twice as fast as the same software would run in the typical real mode used by DOS [8].

To calculate output data the computer obtains images, like the one pictured in Figure 4, of the weld pool from the camera and converts them into an array of numbers ranging from zero to 256 using a computer board called a frame grabber. The frame grabber plugs into the computer's input/output bus. The array of image data is made available to the computer as if it were a part of the computer's memory. Each number in the array represents one pixel or picture element. The size of the array of pixels is 512 wide by 480 high with the 0,0 location in the upper left hand corner. The x image axis runs from 0,0 to the right and the y image axis runs from 0,0 downward. The array of pixels in memory can then be analyzed for intensities and object locations in the image using common image processing techniques [9,10].

The process of gathering data for calculations is divided into three operations. Each operation uses a newly obtained frame of image data. The first operation locates the molten weld pool edges and stores them for later use. Then the location of the center of the weld pool is calculated and passed on to the second operation. The second operation makes a scan of the image at the center location passed from the previous operation. The pixels along the center of the scan, which is also the center of the weld bead, are stored for later reference. The edge of the gas cup is located in the x direction and stored for the first frame to use so that its scan will be a set distance from the gas cup. The location of the laser line is determined and passed on to the third operation. The third operation scans two areas of the image in the x location given by the second operation and in the y locations of the edges of the molten weld pool. The two scans determine the location of the laser line in the x direction and store them for later use. The three scans are shown in Figure 6.

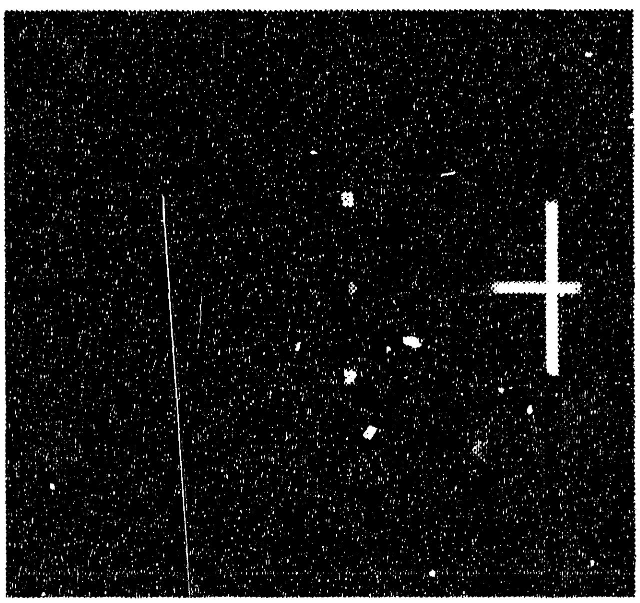

Fig. 6 Processed image output.

After the data have been obtained and stored, calculations are performed to convert the data into real world measurements. The edges of the molten weld pool are determined as distances in millimeters from the center of the camera's view. An exponential or linear equation is fit to the data stored from the second operation. The slope of the curve at the requested temperature is then calculated, and with the travel speed data, converted into a cooling rate in Centigrade degrees per second. The data from the third operation is used in calculation of the sensor to work piece distance, along with data from the calibration sequence, to determine the sensor-to-work-piece distance for each edge of the weld bead in millimeters. When the calculations are complete the data are sent to the host computer. The complete processing time for one set of data is approximately one tenth of one second.

Sensor Calibration

The IOS must convert data from the image it reads into output data in the form of real world measurements. In order for the measurements to be accurate, the sensor has to be calibrated. Two types of measurements are made from the image data, linear and temperature. Calibration of the linear measurements takes place during the calibration procedure. Calibration of the temperature measurements is made partly in the calibration procedure and partly in the laboratory before the sensor is used for real world measurements.

As discussed in the sensor operation section, the calibration procedure allows the sensor to measure the block in Figure 2, which has a step of known width. The measurement of the step is used to develop a scale factor for the y image direction; the scale factor for the x direction is derived using the known aspect ratio of the frame grabber. The sensor-to-work-piece distance is measured using the known height of the step on the calibration block. With the standoff distance sent from the host computer, the sensor can determine the ratio of laser line movement to standoff and develop the appropriate scale factor. The scale factors are then used to convert the raw pixel positions into real-world measurements before they are sent to the host computer.

The temperature measurement function of the sensor is used to determine cooling rate. The sensor uses the camera to detect the infrared radiant energy from the surface of the weld metal. The level of radiant energy indicates the temperature. For the measurements to be consistent, the camera gain setting is adjusted during the calibration procedure. The computer simply evaluates the level of brightness of the image received during the calibration procedure and adjusts it, using the camera gain control, to a predetermined level.

For the infrared energy received by the camera to reflect the real temperature of the material, the camera is evaluated using a black body source. ("A black body, or ideal radiator, is a body which emits and absorbs at any temperature the maximum possible amount of radiation at any given wavelength." [11]) The camera is aimed at the black body source and the pixel levels are recorded for temperatures set throughout the range of the source. The IOS reads temperatures in the range of 982 C° (1800 F°) to 1260 C° (2300 F°) from a Micron black body calibration source.

To reach higher temperatures, an experimental setup was devised using the Gleeble to heat a 12.7 mm (0.5 in.) diameter cold-rolled steel bar. A small hole, 1.59 mm (0.0625 in.) in diameter, was drilled to 7.93 mm (0.3125 in.) in depth

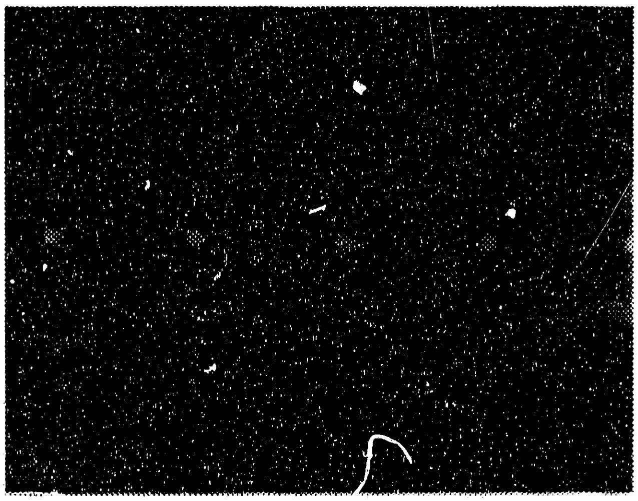

Fig. 7 Image from IOS during Gleeble experiment. The left portion of the image is the center of the bar. The small wires below the holes are the thermocouples. Only a portion of the bar is shown.

providing a ratio of depth to diameter of 5. This ratio produces a near ideal black body [12] when the hole is viewed directly parallel to its sides since steel has an emissivity of greater than 0.2 in almost all cases [13]. The bar has 6 holes drilled along its length about 12.7 mm (0.5 in.) apart. A thermocouple is attached at each hole so that the infrared radiation level can be correlated with temperature. The bar is heated resistively using the Gleeble until the center of the bar is as close to the melting point as possible. The IOS is then positioned over the bar and images are recorded along with the temperatures indicated by the thermocouples. Figure 7 shows the bar as viewed by the IOS. The data are then correlated to create a calibration factor of pixel level to temperature using both the data from the black body calibration source and the Gleeble experiment.

Summary

The IOS is a multifunction feedback control sensor that makes three distinct measurements in near real time: weld pool position and width, sensor-to-work-piece distance, and weld bead centerline cooling rate. Weld pool position and width can be used by the host computer to control the position of the weld pool in relation to the joint. The sensor-to-work-piece distance can be used by the host to control contact tip to work piece distance based upon the distances measured from the sensor to each edge of the weld bead. Cooling rate information is used to infer the final metallurgical state of the weld bead and heat affected zone.

Because of the sensor's small size, it mounts unobtrusively behind the welding torch; previous infrared measurement devices were too large to mount behind the welding torch. Since the IOS uses standard off-the-lab-shelf components, the cost of the sensor is relatively low, enabling the technology to be more readily utilized.

Acknowledgments

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