CLOSED-LOOP RADIOGRAPHIC PROCESS CONTROL OF ARC WELDING

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INTRODUCTION

Two different approaches may be applied to the nondestructive evaluation of welds. The conventional one consists in the application of nondestructive inspection after welding. The second, new, approach is in-process nondestructive evaluation where the production and testing operations are integrated into a single procedure. In this combined approach information received from nondestructive evaluation may be used in feedback with other process parameters for process control. Such a concept gives a significant cost saving [1]. Because the nondestructive system is included as a part of the sensing system in the feedback loop of the process control the quality control is integrated with the process itself.

In this paper, the implementation of real-time radiography for in-process control of arc welding is discussed. X-ray penetrating radiation is used for volume observation in the welding pool and the heat-affected zone during the weld process. The advantages of such a technique are on-line testing of defect formation in the weld and the availability of this information for feedback control of weld quality. A general discussion of this concept is published elsewhere [2]. The results for manual remote control of arc welding using real-time radiographic observation may be found in reference [3].

EXPERIMENTAL SYSTEM AND CONCEPT

The real-time radiographic unit may be used for on-line quality control and as a vision system in feedback control of the welding power supply. This can be done in manual or in automatic mode. In the manual mode, welding is observed on a TV monitor and evaluated by the operator who remotely controls the welding manipulator and the welding power supply, maintaining appropriate welding quality.

The radiographic monitoring method is distinguished from optical monitoring in two ways: 1) there is no effect of the welding arc on visibility, and, more important, 2) internal defects of the weld and weld penetration are visible and therefore complete information on weld quality is available for weld control. Also, welding processes such as submerged arc welding are accessible by this technique.

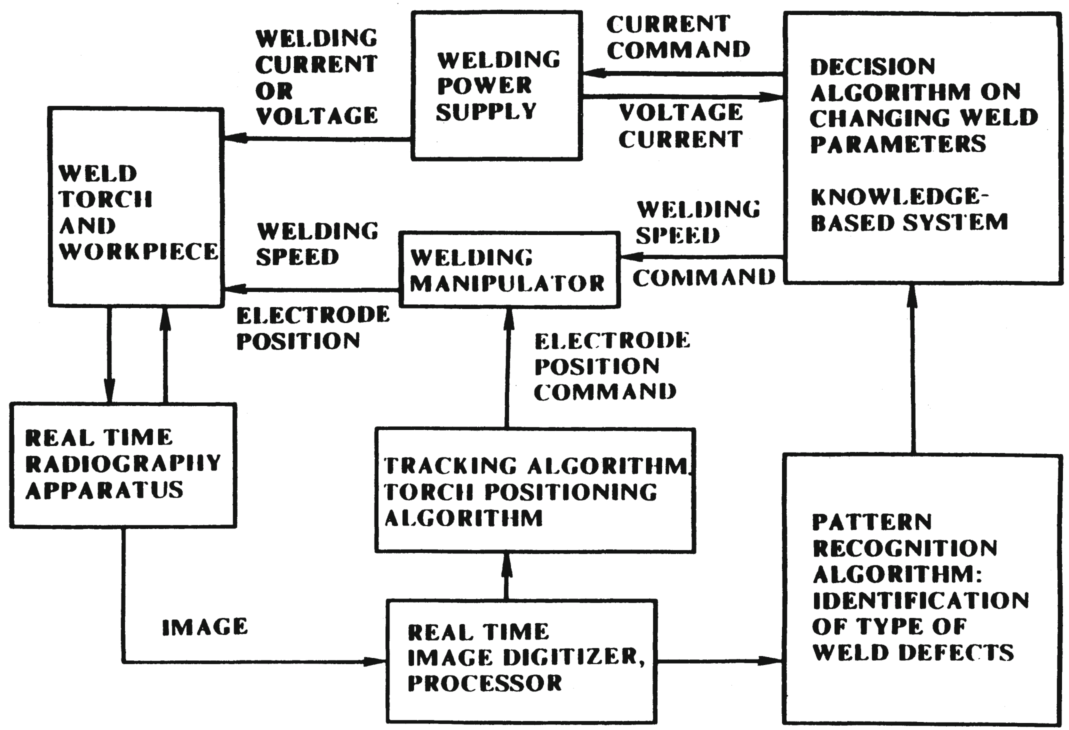


Fig. 1 Schematic diagram for intelligent automatic weld quality and process control with radiographic system.

Automatic weld quality and process control is also possible in the framework of the radiographic method. A schematic diagram for such control is represented in Fig. 1. In this approach the real-time radiographic image is digitized and analyzed by computer. The welding electrode position can be observed in the image together with the depressed welding pool and the welding gap, and therefore one branch of control may include tracking and torch positioning algorithms which will control the welding manipulator.

A second branch of control is weld quality control. Here the digitized image is analyzed by different pattern recognition algorithms for identification of weld quality and type of weld defects (if they exist). Next, information on weld characteristics is fed to the decision algorithm. Information from other sensors is also accumulated in this unit for analyzing weld current, voltage and other parameters. Here the appropriate schedule for changing the welding parameters should be established; for example, appropriate current and weld speed to eliminate lack of weld penetration. The knowledge-based system for different kinds of welding should be a major part of the decision algorithm.

The aim of our study was to demonstrate the possibility of using real-time information from radiographic images for on-line feedback computer control of the welding power supply to maintain weld quality. To control the welding power supply the IBM-AT computer with analog-to-digital (ATD) and digital to analog (DTA) boards were added to our monitoring system, which was described in ref. [1].

The schematic diagram of the measurement and control system is shown in Fig. 2. Several elements of the setup are not shown here for simplicity. The real-time x-ray and welding units are integrated as a single set-up. The radiographic system consists of 160 KV x-ray sources and a Machlett Lab Image Intensifier. The x-ray sources and the image intensifier have remote control x-y lead shutters to reduce the effect of scattered radiation on the image. The welding torch with the welding part is placed between the x-ray source and the image intensifier, in a vertical position. The image from the image intensifier is fed to the digital image processor, where the image is digitized and analyzed in real-time. Specific features are extracted from the image and decisions on weld quality are made (for example complete or incomplete weld penetration). A packet of special programs was developed to operate the image processor for this purpose. Details of the algorithms are given in the next section.

The decision on weld quality is sent through an IEEE-488 interface to an IBM-AT computer equipped with ATD and DTA boards and used as a welding power supply controller.

To control the welding power supply, the dial potentiometer used for manual remote control was replaced by a voltage-controlled potentiometer. This potentiometer was integrated on a special board controlled through a D/A converter by computer. The current and the voltage from the welding power supply were fed through a specially made signal conditioning and isolation board to the computer. The signals were digitized by a 12-bit A/D converter. In the computer the current and voltage were smoothed to extract the DC component.

It is important to stress that in this method the information on weld quality received from the radiographic image was used in system feedback to control the welding current and weld quality, as will be discussed in later sections.

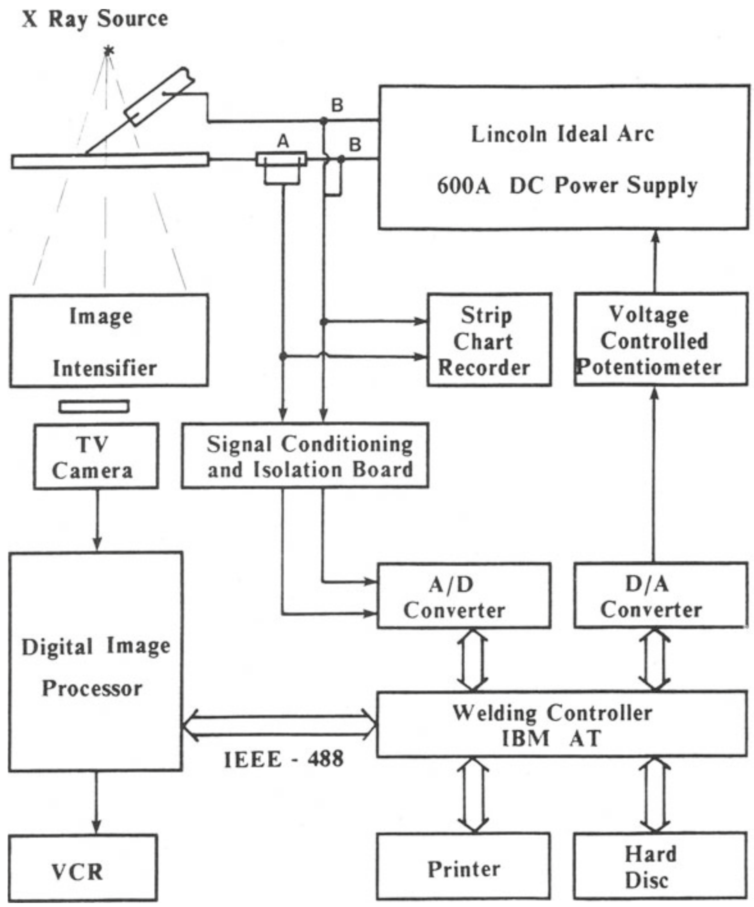


Fig. 2 Schematic diagram of experimental arrangement for intelligent process control of weld.

OUTLINE OF ALGORITHM FOR COMPUTER CONTROL OF WELD PENETRATION AND EXPERIMENTAL RESULTS

Incomplete weld penetration (lack of weld penetration) appears on a radiographic image as a narrow strip in the middle of the weld with a gray level different from that of the weld. In the case of a positive image it is visible as a bright line (in film radiography it will appear as a dark line). Recognition of lack of weld penetration may be based on the shape of the brightness profile in the digitized image. Lack of weld penetration as shown in Fig. 3 appears as maximum B_1 in Fig. 3(a). We will describe an on-line computerized decision making process to extract this feature. The difficulties of doing this lie in requirements for high speed processing and noise reduction.

Brightness profiles were analyzed from the image at a distance of about 25mm (1") behind the welding torch to avoid the molten area which is "noisy" due to pool oscillations. This distance is still small enough for a quick response on the weld quality and for corrections. One of the problems revealed in this early stage of the development was a high noise level in the profile traces. The noise complicates the finding of the profile maximum (Fig. 3) which should be done automatically by computer.

To reduce the noise level significant space averaging and smoothing (low-pass filter) were done. First, four consecutive TV raster lines were digitized and averaged. The width of the digitized lines (window) was 120 pixels which is equivalent to a line of width about 23mm across the weld. Next, five neighboring pixels were averaged for additional smoothing.

The profile obtained represents smoothed brightness changes through the weld image. An example of such a profile in the part of the weld lacking penetration is shown in Fig. 3(a). The value Bo corresponds to an increase of weld thickness relative to the base metal area. The brightness B1 characterizes the value of the lack of penetration. The value of the ratio B1/Bo is taken as one of the criteria for computer recognition of lack of weld penetration. It is compared to the threshold level which is determined by the value of background noise. Full penetration is counted when B1/Bo is less than the threshold level. A typical image profile for complete weld penetration, after the above averaging procedure, is shown in Fig. 3(b).

The second criterion selected for determination of weld penetration is based on the ratio of the area of the cross-sections A1 and Ao as shown schematically in Fig. 4. This value characterizes the cross-sectional area of the lack of weld penetration. Based on these data the thickness and width of weld reinforcement, and depth and width of lack of weld penetration, may be calculated from the radiographic image. Both the amplitude and the area criteria give information on depth and width of lack of weld penetration.

The threshold levels were set either by radiographically examining previously made fully penetrated and incompletely penetrated welds or by calculation from the brightness-thickness ratio and pixel size. In this experiment, the threshold values were set to 0.1 for the brightness ratio, $18mm^2$ for the minimum reinforcement area and 0.1 for the area ratio. When any one of the above criteria was fulfilled, the weld penetration was counted incomplete.

To demonstrate the work of the complete system, the following approach was taken. It was decided to force the system into the region of incomplete weld penetration and afterwards to lock it on automatic control and observe its recovery to the region of full penetration. For

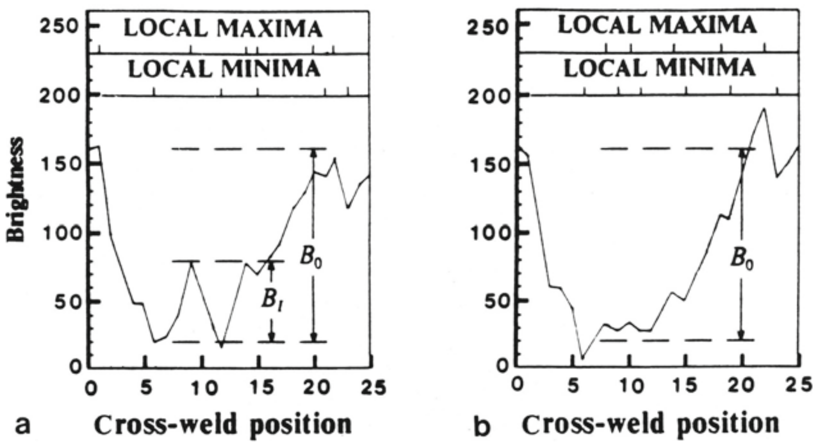
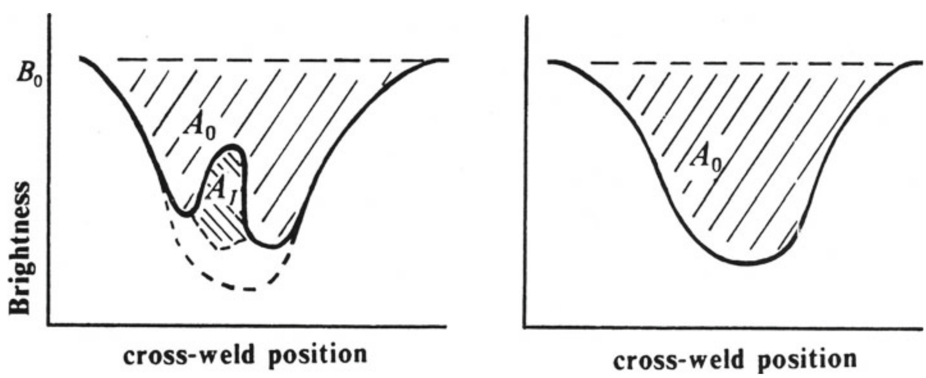


Fig. 3 Brightness profile across image of weld (a) incomplete and (b) complete welds. Bo is difference in brightness levels between base metal and weld reinforcement. B_I is brightness difference between brightness levels of complete and incomplete weld.



(a) Incomplete penetration weld profile.

(b) Full-penetration weld profile.

Fig. 4 Schematic showing area of profiles taken into account in second criterion on weld penetration.

this purpose, in the initial stage of welding the change of welding current was preprogrammed in the computer. Welding started in normal conditions. Then the computer decreased the current and when an indication was received from the image analysis of incomplete weld penetration, the feedback locked on and the computer began to increase the current in the power supply until the message "full penetration" was received.

Fig. 5 shows in the bottom row three typical cross-sections of the above weld sample. In the top row the corresponding brightness profiles of the image are shown. The decision on weld penetration was made by analyzing these profiles as discussed above. Cross-section #85, a full penetration weld, was taken shortly after starting the welding with welding current 385A. Cross-section #106 was at the point where the lack of weld penetration was detected with welding current about 350A. Cross-section #124, a full penetration weld again, was the weld cross-section after welding current increased.

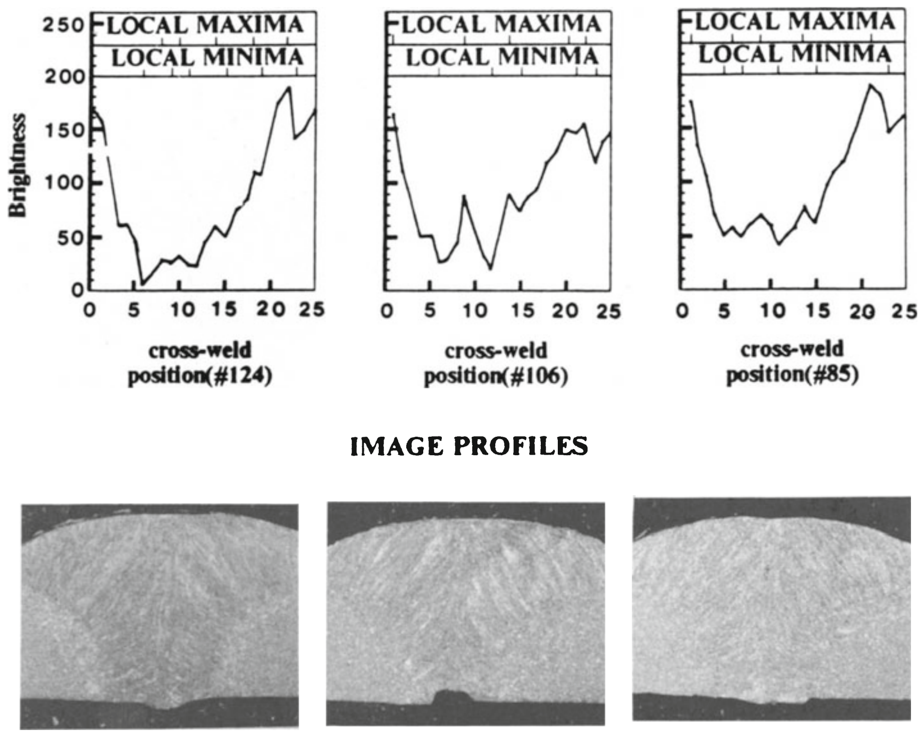


Fig. 5 Top row: Brightness profiles of images with computer decision: Complete (left and right) and incomplete (middle). Bottom row: Corresponding photographs of weld cross-sections.

Because of noise in the radiographic images, the threshold values of area ratio, and brightness ratio are important in the detection of weld quality by this method. In order to have optimal control of weld quality, they must be selected carefully. It will be difficult to detect a small lack of penetration using a very high threshold value. But a very low threshold will make the penetration control system very sensitive to radiographic noise. Several careful trial tests of weld penetration were needed to determine these threshold values.

The window of the image was selected at a distance (25mm for the above particular case) behind the welding torch to avoid the "noisy" weld pool region. At this distance, the weld may be near to solidification, and increasing the welding current may not be able to restore full weld penetration although it may decrease the lack of penetration. A closer distance will help to give better control of weld penetration but the effect of the noise from weld pool motions and gas bubbles must be considered. Another solution which overcame this disadvantage is under development in our laboratory. It includes analysis of the shape of the welding pool.

CONCLUSION

A new concept of arc weld process control was developed for computerized control and maintenance of the appropriate weld quality. According to this concept information extracted from real-time radiographic images about weld quality, supplemented by sensor data on weld current and voltage, is used for weld power supply control. The major difference from other welding control approaches is that here intelligent closed-loop radiographic control, based on direct information on weld quality, is used. The concept was demonstrated for closed-loop intelligent process control of weld penetration in submerged arc welding. The special software packages for on-line pattern recognition of lack of arc weld penetration and control of the welding power supply were developed in the framework of this task.

ACKNOWLEDGMENT

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