IN-PROCESS RADIOGRAPHY OF ARC WELD

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INTRODUCTION

In-process nondestructive evaluation of welds is of major importance for automated weld processing. Real-time evaluation of defect formation makes possible on-line rewelding and adjustment of process parameters. Measurements of physical parameters related to weld quality may also give information important for understanding the weld process and for improvements of weld quality. In this study we implement industrial radiography for real-time weld process monitoring and testing. 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 study of metal fusion and filler metal-base metal interaction, metal transfer and mass flow in the welding pool. This technique may also be used for post-service real-time remote testing of weld quality. By integrating automatic nondestructive inspection with an automatic process control system, unified manufacturing control and testing procedures can be developed. In this unit approach, the nondestructive system may be included as a part of the sensing system in the feedback loop of the process control. Research and development of such general concepts for remote weld process control using real-time radiography as a vision system was initiated in our laboratory under the sponsorship of the Edison Welding Institute. The discussion of this concept will be published elsewhere [1].

This paper summarizes some of our results for in-process evaluation of weld penetration for submerged arc welding. Submerged arc welding is distinguished from other welding techniques in that the welding pool is covered by a thick layer of special powder which is called "welding flux." During welding this flux melts and shields the arc while the molten metals pool preventing metal oxidation. Due to this situation, it is impossible to observe the pool by optical means. X-ray penetrating radiation can be effectively used for pool observation, weld path tracking, and observation of volume defects. Some preliminary results of this work were previously published in the proceedings of the 16th NDE Symposium [2].

EXPERIMENTAL PROCEDURE

The schematic diagram of the experimental system is shown in Fig. 1. The real time x-ray and welding units are integrated as a single set-up in
Fig. 1. Schematic of the experimental system.
an exposure room. The radiographic system consists of exchangeable 160 kV and 300 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 or a horizontal position depending upon the mode of operation. The welding part is mounted on a 5-axis manipulator. The x-ray tube may be translated by the independent linear mechanical positioner. Both x-ray tube and image intensifier can be tilted and aligned relative to the welding part at the required angle of observation.

The arc welding unit consists of a 600 amp, DC welding power source and a continuous wire feeding system. The welding power supply, manipulator and x-ray source are remotely controlled from the control room. A TFI Gemini II control unit is used for the 160 kV ceramic tube and a Phillips control unit is used for the 300 kV tube. The radiographic image from the output of the image intensifier is picked up by a Vidicon television camera for observation and recording at the rate of 30 frames per second. Simultaneously, the television image is fed to a Quantex QX-9000 Real Time Image Processor. It is used for image enhancement and for the extraction of quantitative information on weld quality. The real-time data on weld penetration, lack of fusion, cavities, etc. are important for in-process adjustment of welding parameters, for example, welding current and speed of travel for improvement of welding quality. Currently work is in progress to close the loop between the image processor and the weld power supply for process control.

A series of butt welds were made in the flat position by using the mechanized submerged arc welding process which was simultaneously monitored with the real-time radiography system. Prior to welding, the welding flux was placed at the top and bottom of the base metal, as shown in Fig. 2. All the samples were prepared from 356x50x6.35 mm mild steel. The welding wire used was a continuous bare steel electrode, 2.38 mm in diameter. A granular compound with a density of about 1.38 g/cm³ was used as the welding flux. The density of the welding slag, which is melted and solidified flux, was about 2.89 g/cm³.

Complete joint penetration is required to assure a proper joint. Inadequate weld penetration and lack of root fusion are the most frequent weld defects. During welding, the welding current was varied between 340 A and 390 A in order to obtain different depths of weld penetration. The arc voltage was about 30 V, and the welding travel speed was about 6 mm/sec. The depth of penetration was determined from the radiographic images. To find the actual weld penetration, the welds were cross-sectioned and microphotographed after welding. The width and thickness of the weld reinforcement and depth of weld penetration were measured and

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Fig. 2. Schematic illustration of set up for submerged arc welding process. Points indicate the flux powder. The welding pool covered by the molten slag is also shown.
compared with radiographic data. During the experiments the radiographic exposure was begun prior to welding to adjust the radiographic parameters (tube voltage and current) for optimal contrast. After the tube parameters were set, the welding was begun and radiographic images of the welding process were observed and recorded. The 160 kV x-ray tube was used in these particular experiments. 150 kV for the tube voltage and 5 mA for the tube current were selected for process observation. The x-ray source and object were kept at a distance of about 180 cm. The distance between the object and the image intensifier was about 19 cm.

The real-time radiographic images were digitized and analyzed. Space averaging, histograms, and image profiling were the image processing techniques used most. An image profile is a distribution of the radiance value (value of gray level of the pixel) along a particular horizontal line of an image. From the image profiles of a weld in different cross-sections, the weld geometries were calculated. They were the width and thickness of reinforcement of the weld and the width and the depth of inadequate weld penetration. The calculated weld geometries measured from the image profile were compared, as mentioned above, with the actual weld geometries measured from the weld cross section.

RESULTS AND DISCUSSION

Changes of welding conditions such as current, voltage, and/or speed of welding can affect the thickness and width of the weld reinforcement and penetration. They also determine the existence and depth of incomplete weld penetration. The lack of weld penetration lowers the weld bearing capacity, and hence, is considered as a weld defect. From the weld cross section, dimensions of both the welding reinforcement and inadequate joint penetration were actually measured. They were compared with the calculated values found from the real-time radiographic images.

An example of a frozen image (one frame) from sequences of real-time radiographic images taken during submerged arc welding is shown in Fig. 3. The image is represented in negative form similar to the film image. The base metal, the weldment and the melted pool are shown in the image. The weld and the pool are covered by the welding flux and by molten flux.

Fig. 3. An example shows one frame of real-time radiographic image of the submerged arc welding.
(slag). However, the flux only slightly affects an image because of its low density. The center light region in the image is the weld. The upper part of this region corresponds to the weld with complete penetration. The lower part corresponds to the weld with inadequate penetration which is characterized by a long gray strip along the joint. The lower white area with the semi-circular shape is the welding gun; also the welding wire can be seen. In front of the welding gun is the joint gap which is a totally dark area. The surrounding gray area of the weld is the base metal. The radiographic images were digitized in real time at the speed of 30 frames per second.

![Diagram](image)

Fig. 4. Logarithm of the normalized gray level value versus depth of the slot and thickness of the shim given in the deviation ($\Delta h$) from the original plate thickness ($h$).

To establish a relation between a gray level value of a pixel and the actual thickness of the material, the transfer function of the complete measuring system is required. This was done by taking radiographic images of steel plates with slots of various depths and shims of various thicknesses. Steel plates of the same thickness as the base metal of the weldments were used. The slots simulate insufficient weld penetration and the shims simulate weld reinforcements. The results of the measurements are summarized in Fig. 4, where the logarithm of the normalized gray level value is plotted versus depth of the slot and thickness of the shim given in the deviations ($\Delta h$) from the original plate thickness ($h$). $B_2$ is the
value of the gray level in the image of the slot or shim and B1 is the gray level in the image of the plate. The data are well fitted by the straight line showing high dynamic range.

In this same way, an example of data from a real-time radiographic image (as in Fig. 3) is shown in Fig. 5. The points corresponding to the weld reinforcement are in the upper part of the figure (increasing thickness) and the data for incomplete penetration are in the lower part of the figure (decreasing thickness). The straight line in Fig. 5 is the least square fit of the experimental data from Fig. 4 (sample with slot and shims). The data from the actual weld is quite well fitted by this calibration curve. In this way the depth of weld penetration and thickness of weld reinforcement may be easily measured in real time.

Fig. 5. The same as in Fig. 4 only for weld penetration and weld reinforcement. The straight line is the least square fit of the experimental data from Fig. 4.

The digital information on depth of weld penetration received from real-time radiographic images may be used for process control of the weld. For this the welding current must be adjusted in such a way that full penetration will occur. The results of such an experiment are summarized in Fig. 6. In the upper part of the figure, the welding current is shown. In the middle, the image profiles are shown. These profiles show the
Fig. 6. Example illustrates the process control. Using information received from image profiles, the welding current is readjusted in such a way that full penetration occurs.
changes of the values of the gray levels along a particular horizontal line of the digitized image. The deep, wide minimum of the profile corresponds to the increased thickness of the weld due to weld reinforcement. The lower part of the figure shows the microphotographs of the weld cross-sections corresponding to the image profiles in the middle part. At a welding current of about 390 A, full weld penetration is observed. This follows from the image profile and is supported by the photograph of the weld cross-section, both shown in the right column. When the current is reduced to 340 A, there is incomplete weld penetration, indicated by the peak A on the image profile. The depth of the weld penetration was calculated from the height of this peak as was discussed above. The corresponding weld cross-section is shown below in the middle column. The information on incomplete weld penetration may be easily extracted from the appearance and height of peak A by computer. If this occurs, the welding current must be increased. This is illustrated in the left column of Fig. 6. When the current is increased above 360 A, the peak A disappears indicating full penetration, as also shown on the microphotograph of the corresponding weld cross-section.

CONCLUSION

It is shown that real-time radiography can be successfully used for in-process monitoring of arc welding. In the case of submerged arc welding, radiography is the only method which can be used for observation of the welding pool. By digitizing the image, useful quantitative information on weld reinforcement and weld penetration may be extracted. This information is used for control of welding current to achieve full weld penetration. Further development of this technique will lead to on-line quality and process control of arc welding.

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REFERENCES

