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IMPROVED OPTICS FOR AUTOMATIC
STORED-SEAM TRACKING ON AN
ELECTRON-BEAM WELDER

K. A. Kitzke

November 1978

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OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

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IMPROVED OPTICS FOR AUTOMATIC STORED-SEAM TRACKING ON AN ELECTRON-BEAM WELDER

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ABSTRACT

A commercial 7.5-kW electron-beam welder has been optically upgraded. The viewing system has been replaced by high-resolution optics [36 line pairs per millimeter (36 l/mm)] with video option. A high-intensity arc lamp provides illumination of the weld region. The upgraded optical system provides the capability for making accurate and repeatable welds with computer-automated seam tracking.

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SUMMARY

A commercial 7.5-kW electron-beam welder at the Oak Ridge Y-12 Plant^(a) has been upgraded with two improved optical systems. One system, which is predominantly for operator viewing, replaces the original telescope, modifies the optical assembly in the lower column below the electron gun, and provides a three-fold increase in resolution to 25 vertical line pairs per millimeter (25 vertical l/mm) and 32 horizontal line pairs per millimeter (32 horizontal l/mm). The second system, which is designed for operator viewing and video acquisition of beam/seam data, utilizes two new ports in the top of the welder vacuum chamber. A telescope attached to one port provides resolution of 36 vertical or horizontal l/mm. A one-kilowatt xenon arc lamp was attached to the other port to illuminate the weld region.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the Department of Energy.

INTRODUCTION

The objective of this study is to produce a modified/upgraded electron-beam (EB)-welder optical system which can provide the illumination and resolving power which is necessary to repeatably and accurately locate the weld seam for precisely controlled stored-seam welding. Deep-penetration, narrow-melt-zone, electron-beam welds require precise beam/seam alignment during welding. Incorrect alignment will displace the root of the weld, causing a weak joint. Many applications require alignment of the beam and seam within ± 0.05 mm. The need for high-resolution viewer/data acquisition optics (ie, optics with simultaneous data acquisition of the weld-seam and electron-beam weld-pool positions via a closed-circuit television camera and viewer/operator use) require an optical system which is beyond the capability of currently available EB-welder systems.

PROBLEMS WITH THE ELECTRON-BEAM-WELDER VIEWING SYSTEM

The Hamilton Standard viewing configuration is illustrated in Figure 1. The University of Arizona's Optical Sciences Center evaluated the performance of the original optical system and presented the following results. The spatial frequency cutoff at normal working distances was 9 line pairs per millimeter (9 l/mm), measured with a USAF 1951 three-bar

Figure 1. ORIGINAL OPTICAL VIEWING CONFIGURATION.

resolution target which was used for all resolution tests. The actual resolution values are well below the theoretical diffraction limit of the system imposed by the 10 x 35 mm "half moon" aperture located in the lower column beneath the electron gun. The half-moon aperture represents the physical limitation on the angle of viewing acceptance in a lower-column optical system for the following reasons: (1) The aperture is a segment of a

37.5-mm-diameter circle resulting from a 17.5-mm-wide target tube which bisects the circle (see Figure 2), and (2) the maximum diameter of the circle (37.5 mm) is determined by the inner diameter of the deflection and focusing coils located between the half-moon aperture

Figure 2. OPTICAL CONFIGURATION OF THE ORIGINAL ILLUMINATION SYSTEM.

and the heat shield. Even at the longest working distance, which is the worst case for resolution, the theoretical diffraction limit is 26 vertical l/mm and 78 horizontal l/mm, indicating that there are inadequacies in design or component quality. A star test identified coma and astigmatism images as image-degrading aberrations by their characteristic cross-bow shape. The predominant cause of coma and astigmatism was traced to the two very strong achromats (low f number), because large amounts of residual spherical aberration are characteristic of simple achromats with high speeds. In addition, several other problems were identified. The optical axis of the telescope is horizontally displaced 17.4 mm from the center of the half-moon aperture which causes coma, the result of an eccentric pupil condition indicated in Figure 5 (Page 10). The metal pentamirror configuration introduces astigmatism because of the inadequate flatness characteristics (several-wave irregularity at 632.8 nm) of the metal folding flats. The vapor shields (replaceable glass windows which prevent metallic vapor deposits from reaching the pentamirror and lead-glass

window) and lead-glass window (an X-ray shielding optical window) were adequate for the original system, although higher-quality (one-eighth wavelength) components would be desirable for a diffraction-limited system. The limited optical performance of this system makes it unsuitable for the precision required in beam/seam alignment.

PROBLEMS WITH THE ELECTRON-BEAM-WELDER ILLUMINATION SYSTEM

The Hamilton Standard illumination system is completely enclosed in the lower column beneath the electron gun. The system uses a strong ($f/0.7$) aspheric condenser lens to image a 75-watt tungsten halogen lamp with spherical reflector onto the object through a 10 x 35-mm half-moon aperture located symmetrically opposite the viewing half-moon aperture (see Figure 2).

The large magnification associated with a single-lens-condenser illumination system ($\sim 15X$) is undesirable because of the loss of luminance associated with the large area illuminated at the workpiece. The luminance (the power which leaves the workpiece per unit solid angle and unit projected area of the workpiece) of the workpiece surface is inherently limited by the following conditions: (1) luminance of the light source, (2) transmission of the illumination system optics, and (3) surface preparation of the workpiece (ie, specular or diffuse reflector). Luminance of the tungsten lamp is insufficient to permit the seam and beam to be viewed simultaneously. Sometimes the lamp luminance will not allow precise positioning of the seam even without the beam, a result of poor surface reflectivity of the weld specimen.

OPTICAL UPGRADE OF AN ELECTRON-BEAM WELDER

GOALS OF THE OPTICAL UPGRADE

Limited optical performance of the Hamilton Standard viewing/illumination system, as well as the need for precision beam/seam alignment, prompted the effort toward welder optical upgrading (see Figure 3). It was necessary to provide an improved viewing system to make it easier for the operator to manually locate the seam to be welded.^(b) An improved

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Figure 3. UPGRADED ELECTRON-BEAM-WELDER OPTICAL SYSTEM.

illumination system was also essential so that both the weld-seam and electron-beam weld pool could be viewed simultaneously. A closed-circuit television system was required for data acquisition to determine the location of the center of the weld-seam and the electron-beam weld pool in addition to recording the weld pool. The upgraded optical system provides the capability for making accurate and repeatable welds with computer-automated seam tracking.

(b) Welding specifications at the Oak Ridge Y-12 Plant require the optical system to have the ability to clearly resolve 50- μ m features on an object. This requirement corresponds to a resolution of 20 l/mm.

SYSTEM 1

System 1, outlined in Figure 4, replaces the Hamilton Standard telescope in the lower column beneath the electron gun. This system is designed primarily for operator viewing because of the diffraction limit on the resolution imposed by the half-moon aperture.

Figure 4. IMPROVED OPTICAL VIEWING SYSTEM THROUGH THE LOWER COLUMN.

High-quality optics (a minimum of one-eighth wavelength distortion for individual components) are substituted for the metal folding flats, vapor shields, and lead-glass window. The center of the 10 x 35-mm half-moon viewing aperture is aligned with the telescope's optic axis, Figure 5. Constant 1X magnification is provided over the entire range of working distances to eliminate the dimensional ambiguity which results when the working distance changes. Worst-case resolution is improved to 25 vertical l/mm and 32 horizontal l/mm. A beamsplitter port for attaching a closed-circuit television camera is provided for weld monitoring and recording, although use of a video system in conjunction with System 1 is undesirable because of the 30% vignetting (dimming of the image near the edges) which occurs as a result of the noncircular half-moon aperture.

Figure 5. RELOCATION OF THE TELESCOPE APERTURE TO ALIGN THE HALF-MOON VIEWING APERTURE WITH THE OPTIC AXIS OF THE TELESCOPE.

SYSTEM 2

System 2, shown in Figure 6, is designed for operator viewing and television-data acquisition of weld-seam and EB-weld-pool positions. A telescope assembly similar to the one used in System 1 with a pentamirror assembly is attached to one of the two 51-mm clear-aperture viewing ports located in the top of the welder vacuum chamber. The circular shape of the viewing aperture eliminates vignetting from the system, and the increased size of the aperture improves the worst-case resolution of this system to 36 vertical or horizontal l/mm, which is approaching the visual acuity of the average observer.

VIDEO SYSTEM

The television camera and associated optics, Figure 7, can be attached to either optical system at the camera port. The television scene can be displayed on a monitor, recorded on video-cassette magnetic tape, and transmitted to the data acquisition equipment.^(c) The beamsplitter can be changed for optimum performance of the optical system. A broadband 50% transmission-50% reflection beamsplitter can be used to meet normal viewing/positioning requirements associated with EB welding. A hot-mirror beamsplitter can be used to reflect the infrared wavelengths to the camera for enhanced examination of infrared phenomena, such as weld pools, while the operator views the visible wavelengths which are transmitted by the beamsplitter. Magnification of the video system can be varied from 1.6 to 2.7X by moving the position of the Barlow lens with respect to the vidicon tube (Figure 7). A magnification of 1X can also be obtained by removing the Barlow lens. The illumination and video filters can be adjusted manually or automatically^(c) to prevent "blooming" (a condition which occurs when high light levels cause the light which hits a

(c) Burkhardt, J. H., Jr, Bowers, G. L., Davenport, C. M., Turner, P. C., and Greene, L. M.; *Computer Automation of an Electron-Beam Welder With Automatic, Stored Seam Tracking*, Y-2114; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; May 10, 1978.

VIEWING SYSTEM

ILLUMINATION SYSTEM

Figure 6. IMPROVED ILLUMINATION/VIEWING SYSTEM THAT UTILIZES VIEWING PORTS IN THE TOP OF THE WELDER CHAMBER.

particular diode on the silicon vidicon wafer to sensitize adjacent diodes) and obtain maximum contrast of the television scene. Optical resolution of the video leg is on the order of 36 l/mm. Unfortunately, the electronic processing (ie, bandwidth and noise level of the camera electronics), reduces the video-system resolution to 11 l/mm at a magnification of 1X, but this resolution is sufficient to track a seam and beam within approximately $\pm 50 \mu\text{m}$. Increased magnification can be used to increase the resolution by a factor equivalent to the magnification increase. For example, a 2X magnification increases the resolution to 22 l/mm, but decreases the field of view to 3.17 by 4.77 mm. The limited field of view associated with increased magnification restricts the allowable part runout which can be tracked with the automated seam-tracking equipment.

ILLUMINATION SYSTEM

A one-kilowatt xenon arc lamp (used for weld-region illumination with System 2) is attached to a second port in the top of the welder chamber (Figure 8). The filtered output of the arc lamp provides a luminance that is 1.5 to 150 times larger than the 75-watt

Figure 7. VIDEO LEG OF THE IMPROVED OPTICAL SYSTEM. (Porro Prism Path Folding has been Omitted)

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Figure 8. XENON-ARC-LAMP ILLUMINATION SYSTEM.

tungsten halogen lamp. The arc lamp is sufficient to permit a seam to be viewed simultaneously with a weld pool for most metals and alloys (except for those metals with a very high melting point or a very poor surface reflectivity).

OPTICS INTERNAL TO THE WELDER VACUUM CHAMBER

Parallax or tilt adjustment of the final, flat, diagonal mirror in both the illumination and viewing systems can be made to allow for proper alignment of the workpiece at various working distances (0.13 to 0.51 m below the heatshield, see Figure 9). Since this mirror (one in each system, a viewing mirror and an illumination mirror) is exposed to welding

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Figure 9. PORT SYSTEM VIEWING/ILLUMINATION ASSEMBLY WHICH IS INTERNAL TO THE WELDER VACUUM CHAMBER.

vapors, a deposition of vapor from the workpiece is accumulated at a rate which depends upon the workpiece composition, working distance, and electron-beam power. These mirrors can easily be changed out and the deposits removed with a mild etch solution which does not attack the protective overcoat on the mirror surface. A spring-loaded grounding clip is also installed on each mirror to prevent capacitive charge buildup on the mirror surface which will deflect the beam erratically when it discharges to the chamber.

RESULTS AND CONCLUSIONS

Vacuum ports are provided for a high-resolution optical/video system and a high-intensity arc lamp. The new optics provide a fourfold increase in resolution to a value of 36 l/mm. A target value of 20 l/mm was set for seam-tracking applications with the video system. Optically, this goal has been exceeded, although electronic processing reduces the resolution to 11 l/mm.

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