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Characterization of a Laser-Beam Spinning Technique

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Abstract

The objective of this study was to evaluate the beam spinning technique for bridging gaps in butt joints that are CO₂ laser-welded. A device was designed and built to circularly oscillate a CO₂ laser beam on the plane of a work surface. A series of welds was made using a continuous-wave output power of 805 watts, and the resultant weld bead profile was characterized as a function of three process parameters. From the experimental results, predictor equations were derived for laser-beam spinning speed and amplitude of the beam spinning pattern on the work surface. The data collected in this experiment indicate that the width of the weld bead is increased by oscillating the beam and that this increase may be made without significantly reducing the weld penetration. The increased width of the weld may offer a solution to variable gaps in weld joints, which has been a recurring production problem.

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Characterization of a Laser-Beam Spinning Technique

Introduction

Our objective was to develop a way to accommodate gaps in the joints of connector-to-housing welds. These gaps, which may be up to 10 mils wide, are a result of normal machining tolerances in the racetrack-shaped welds of the W88 and other firing sets. Typical materials are 17-4PH stainless steel for the housing and 304L stainless steel for the connector. An edge-flange joint design is used with the edges 60 mils high and 20 mils thick. The required penetration is 30 mils minimum; the close proximity of glass-to-metal seals limits the maximum temperature during welding.

This application is typical of Allied-Signal Aerospace Company, Kansas City Division (KCD) production items. KCD is CO₂ laser-beam welding the firing set housings using a Photon Sources V1200 laser operating at 500-W constant wave power, sharp focus, and 80 ipm travel speed. At these welding parameters, which are dictated by the penetration requirement and the limited heat input, the random joint gaps sometimes fail to fuse.

Mike Cieslak, Process Metallurgy Division 1833, observed the gap closure problem and discussed machining tolerances with KCD. After concluding that tighter machining tolerances were not economically feasible, the Process Development Labs in the Metallurgical Process Division 7473 was asked to look into possible solutions.

The primary KCD contacts were:

J. Samayoa, staff engineer, D/844

J. Daumeyer, engineer, D/844

R. Obenchain, senior project engineer, D/844

The SNL Albuquerque personnel involved were:

M. Cieslak, KCD technical liaison, Process Metallurgy, Div.

J. Jellison, Supervisor, Process Metallurgy Div.

P. Wilson, Special Projects Div.

D. Sheldon, Statistics, Computing, and Human Factors Div.

E. Brandon, welding development, Metallurgical Processes Div.

M. Reichenbach, Mechanical Process Engineering Div.

We first tried oscillating the beam in a circular pattern to accommodate the joint gap during welding. As a conceptual aid, the path of a circularly oscillated beam traversing a surface is shown schematically in Figure 1. Circular oscillation may be accomplished by offsetting and rotating the focus lens, as with a boring head attachment used for drilling holes, or by tilting and rotating a bending mirror. We decided to pursue the latter—tilting and spinning the final bending mirror, which is located at the top of the workstation. This approach is not without precedent. C. J. Davies at The Welding Institute in Cambridge, England, describes a similar device in The Welding Institute Report No. 269/1985, dated March 1985. Figure 2 shows a photo of a beam spinner built by The Welding Institute; Figure 3 shows a schematic of same.

Figure 1. Schematic of beam path showing effect of travel speed at a constant 3000 rpm spin speed (from Report No. 269/1985, The Welding Institute)

Figure 2. Beam spinner built by The Welding Institute in Cambridge, England (from their Report No. 269, 1963, dated March 1963)

Figure 3. Schematic of beam spinner built by The Welding Institute (from their Report No. 269/1985, dated March 1985)

Experimental

We designed and fabricated a "beam spinner" to rotate the final bending mirror that consisted of an Electro-Craft E586 motor with the mirror clamped in a mirror holder mounted on the output shaft of the motor. An O-ring in the mirror holder cushions the mirror and allows the clamping pressure to adjust the offset of the mirror (Figures 4, 5, and 6). With this device the mirror offset can be varied from 0 to 6 mils and the rotational speed from 0 to 5000 rpm. The beam spinner is a relatively simple apparatus. It occupies little space in the workstation, is capable of

traversing a closed-loop path on the workpiece, and requires minimal development.

To analyze the effect on depth of weld penetration and width of weld bead, we set up a fractional factorial design of three variables, each at three levels. As shown in Figures 7 and 8, the variables and levels were

X_1 , mirror offset*	2, 4, 6 mils
X_2 , spin speed	2000, 3500, 5000 rpm
X_3 , welding speed	40, 60, 80 ipm

*The low-to-high measurement at 3 in. diameter on the surface of the mirror

Figure 4. Beam spinner built at SNL. From left to right are the motor attached to a mounting block, the mirror, and the clamping ring.

Figure 5. SNL beam spinner assembly

Figure 6. SNL beam spinner installed on top of workstation

Figure 7. Schematic of fractional factorial design

Figure 8. Schematic of fractional factorial design showing combinations of parameters

We made bead-on-plate welds, sectioned the weld segments, measured the two response variables (depth of penetration and width of weld bead), and analyzed the data. Using a least-squares analysis technique, we arrived at predictor equations for the depth and the width. To establish a level of confidence, I made multiple welds at zero spin speed and zero offset at the three levels of welding speed, and multiple welds at the midpoint of the design (at 4-mil mirror offset, 3500 rpm spin speed, and 60 ipm welding travel speed).

The bead-on-plate welds were made on 0.056-in.-thick mild-steel sheet using a Photon Sources V1200 CO₂ laser operating at a constant continuous wave power of 805 W using argon lens gas, a 5-in. focal-length lens, and sharp surface focus. A random sequence was used to make the welds in order to negate any time or sequence dependency. Four welds were made at each combination of parameters.

Figure 9 shows one of two workstations of the SNL Albuquerque Photon Sources V1200 CO₂ laser. Figure 10 is a closeup view of the nozzle-workpiece. The workstation was used to make the coupons for this experiment.

Figure 9. SNL CO₂ laser workstation

Figure 10. Coupon in position for laser welding

Results

The resultant predictor equations were:

$$\begin{aligned}\text{Width, } W &= 0.717 + 0.012(X_1) \\ &+ 1.29 \times 10^{-6}(X_2) \\ &- 100 \times 10^{-6}(X_3) \\ &+ 1.54 \times 10^{-6}(X_1)(X_2) \\ &+ 3.16 \times 10^{-6}(X_1)^2\end{aligned}$$

and

$$\begin{aligned}\text{Depth, } D &= 0.0319 + 0.003(X_1) \\ &+ 1.35 \times 10^{-6}(X_2) \\ &+ 1.20 \times 10^{-6}(X_1)(X_2)\end{aligned}$$

where

- W and D are in inches
- X_1 = mirror offset in mils
- X_2 = spin speed in rpm
- X_3 = welding travel speed in ipm

The standard errors of these predictors are 3 mils for the width equation and 1 mil for the depth

equation. This means that the actual measured values will be accurately predicted within 3 and 1 mils, respectively, for the width and depth about 68% of the time.

Table I illustrates the beneficial results of the beam spinner. An examination of the predictor equations and these data shows that, in the range of parameters tested, the depth of penetration was unaffected by the welding travel speed; also, an increase in welding speed decreased the weld width. More specifically, doubling the welding speed caused a 30% reduction in weld width. The decrease in weld width happened to be linear in the range of welding speed tested.

The ultimate question is, of course, at what welding parameters are the depth and width maximized? According to the equations, this is predicted to occur at the maximum values of spin speed and mirror offset and is independent of travel speed. To maximize the depth and width of the weld bead at minimum heat input, we would choose parameters of 6 mils for mirror offset, 30000 rpm for spin speed, and 50 ipm for welding speed.

Table 1. Results of Laser-Beam Spinning

	X ₁ Mirror Offset (mils)	X ₂ Spin Speed (rpm)	X ₃ Welding Speed (ipm)	D Depth (in.)	W Width (in.)
	0	0	40	0.035	0.056
	0	0	60	0.035	0.048
	0	0	80	0.035	0.040
(Maximum)	6	5000	80	0.035	0.200
(Midpoint)	4	3500	60	0.026	0.141

Typical cross sections of welds are shown in Figure 11. These welds illustrate the increased width of the weld bead as the mirror offset is increased. At the same time, the depth of penetration does not change significantly.

Several coupons were fabricated to simulate the KCD production hardware. The rectangular insert-in-socket coupons were fabricated with a 10-mil gap on two sides when the opposing sides are abutting (Figure 12). The parts were Nd-YAG laser spot-

welded in that offset position to simulate a "greatest gap" condition and were then CO₂ laser-welded using the beam spinner and the parameters from the midpoint of the experimental plan matrix (4-mil mirror offset, 3500 rpm spin speed, and 60 ipm travel speed). The laser power was 805 W.

A typical welded coupon is shown in Figure 13. The joint gap was closed without skips. Metallurgical examination showed the penetration to be 0.030 to 0.035 mil.

(a)

(b)

(c)

(d)

Figure 11. Effects of amplitude of oscillation: (a) no oscillation, (b) 2 mil mirror offset, (c) 4 mil mirror offset, (d) 6 mil mirror offset.

Socket with insert in place for welding: Socket without insert:

Insert spot-welded to maintain a 10-mil gap for CO₂ laser seam weld:

Figure 12. Socket-and-insert mockup of header/housing weld

Figure 13. CO₂ laser welded (a) and unwelded (b) coupons

Conclusions

The data collected in this experiment indicate that the width of the weld bead is increased by oscillating the beam, and that this increase may be accomplished without a significant sacrifice in weld

penetration. Therefore, the concept of laser beam spinning offers a solution to accommodating gaps in weld joints; and, it is possible that the gap can be bridged without an appreciable increase in heat input.

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