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**WELDING URANIUM WITH A MULTIKILOWATT,
CONTINUOUS-WAVE, CARBON DIOXIDE
LASER WELDER**

P. W. Turner
A. B. Townsend

June 1977

MASTER

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OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

*prepared for the U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
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WELDING URANIUM WITH A MULTIKILOWATT, CONTINUOUS-WAVE, CARBON DIOXIDE LASER WELDER

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MASTER

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and Development Administration
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ABSTRACT

A 15-kilowatt, continuous-wave, carbon dioxide laser was contracted to make partial-penetration welds in 6.35 and 12.7-mm-thick wrought depleted uranium plates. Welding power and speed ranged from 2.3 to 12.9 kilowatts and from 21 to 127 millimeters per second, respectively. Results show that depth-to-width ratios of at least unity are feasible. The overall characteristics of the process indicate it can produce welds resembling those made by the electron-beam welding process.

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SUMMARY

A 15-kilowatt, continuous-wave, carbon dioxide laser was contracted to make partial-penetration welds in 6.35 and 12.7-mm-thick wrought depleted uranium plates. Welding power and speed ranged from 2.3 to 12.9 kilowatts and from 21 to 127 millimeters per second, respectively. Results show that depth-to-width ratios of at least unity are feasible. The overall characteristics of the process indicate it can produce welds resembling those made by the electron-beam welding process.

INTRODUCTION

High-power, continuous-wave, CO₂ laser (HPL) facilities have demonstrated much of the capability of the electron-beam process. Features that make an HPL facility relatively attractive, in this respect, are as follows: (1) the high-power density of the laser beam makes it applicable to welding, cutting, or heating a variety of materials; (2) work is not enclosed in a vacuum chamber; thus, the productivity and duty cycle exceeds that of the electron-beam welder; (3) visibility is excellent during welding (the CO₂ laser is enclosed in a Plexiglas cage); (4) since electrical circuits and clamps to the work and alignment fixtures are not needed, both metals and nonmetals can be thermally processed and fixtured without hard, electrically conductive tooling that would tend to mar, scratch, or arc the work surfaces; (5) the laser beam is insensitive to magnetism; (6) a single laser facility can service several widely separated (typically, hundreds of feet from the laser) welding, cutting, or material processing stations on a time-sharing basis to maximize its duty cycle and general utility; (7) the HPL beam can be directed a considerable distance to do useful thermal work at locations inaccessible to conventional heat sources (also it can be directed into assembly dry rooms, hot cells, environmental rooms, and the like, which are not conveniently accessible to personnel).

To evaluate the potential of the multikilowatt laser, Purchase Order 73Y-88277V was initiated to weld uranium specimens on the HPL facility at the AVCO Everett Research Laboratory. Uranium specimens were selected for evaluating the HPL facilities so that results could be compared to electron-beam technology for joining uranium at the Oak Ridge Y-12 Plant. (b)

A survey of the manufacturers of multikilowatt laser welding equipment revealed that uranium had not been welded by the CO₂, continuous-wave, high-power laser process. Also, only one of the facilities had a source material license for receiving and welding large amounts of depleted uranium.

(b) Operated by the Union Carbide Corporation's Nuclear Division for the US Energy Research and Development Administration.

WELDING URANIUM WITH A MULTIKILOWATT, CONTINUOUS-WAVE, CARBON DIOXIDE LASER WELDER

EXPERIMENTAL WORK

Material

Wrought, depleted uranium plates, totaling 44.16 kg, were machined to form square edges for welding. Half the plates were 12.7 mm in thickness, the remainder were 6.35 mm in thickness. The length and width of the plates were 76.2 and 50.8 mm, respectively. The level of impurity elements in the depleted uranium was less than 600 ppm by weight, with an iron content of less than 100 ppm.

Laser Facility

Figure 1 gives, schematically, a diagram of the 15-kilowatt laser facility. The optical system directs the beam to two work stations. Only the illustrated F/7 Station was used during this program. The electrical-discharge laser for this facility is located within the vacuum chamber. The laser cavity is shown, schematically, in Figure 2. This type of cavity (referred to as an "unstable oscillator")^(c) transfers a hollow beam at all locations except at the focal point. The lasing CO₂/N₂ gas mixture is ionized by an electron-beam gun. A closed system of blowers and heat exchangers forms a wind tunnel and removes heat from the lasing cavity.

The divergent beam emerges from an aerodynamic window designed to prevent air from entering the vacuum chamber. The first water-cooled copper mirror (Figure 1) collimates the beam; the next three turning mirrors direct the collimated beam to the Cassegrain F/7 telescope shown, schematically, in Figure 3. The focal point is about seven diameters from the large, concave mirror. In Figure 1, the beam is focused to weld in the flat position on the work table which translates the workpiece beneath the beam.

Operators of the HPL facility report that 30% of the power is lost from the beam after it emerges through a beamchopper located between the aerodynamic window and the collimating mirror.

Safety Precautions

The CO₂ laser beam (wavelength, 10.6 μ m) can be safely contained in a Plexiglas enclosure. Interlocks prevent operation of the laser while the door to the work area is open. Warning

(c) Siegman, A. E.; "Unstable Optical Resonators", *Proceedings of the IEEE*, 53, pp 277 - 287; March 1965.

Figure 1. CONTINUOUS-WAVE, CARBON DIOXIDE LASER WELDER, RATED AT 15 KILOWATTS. (Serving the F/7 Station)

lights and horns indicate when the laser station is active. It is the responsibility of the operator to assure that personnel are not within the transparent plastic enclosure during the time the beam is activated. Protection against electrical, noise, and radiation hazards meets standards of the Occupational Safety and Health Administration (OSHA).

Welding Variables

Laser welding variables, relating to thermal conditions, are: power, focal length, and welding speed. It is apparent that the number of operating variables is significantly less than the number the operator must handle in operating most other joining processes.

Power selections ranged from 2.3 to 12.9 kW, and the speed of welding was varied from 21 to 127 mm/s. These parameters were set on a 10-turn potentiometer (the dials were not calibrated directly). The ability to reset the values had an estimated 10% error. A limited amount of welding with the focal point below the surface resulted in erratic penetration. This mode was discontinued, but may prove to be a useful variable with more experimental effort.

Figure 2. LASER CAVITY.

Setup and Preparation for Welding Uranium

Uranium plates were chemically etched to remove oxide within two to three hours before the start of the welding period. Plates were etched in warm nitric acid, rinsed with water,

Figure 3. CASSEGRAIN F/7 WELDING TELESCOPE ROTATED TO THE HORIZONTAL POSITION.

and dried with alcohol. All steps in the welding setup were awkward because welding had to be done in a special, partially evacuated containment vessel designed to prevent the general area from being contaminated with uranium. This enclosure and the setups and tooling for welding in the flat and horizontal positions are shown, schematically, in Figures 4 and 5. A photographic view of the enclosure oriented for welding in the flat position can be seen in Figure 6.

The work base is adjustable, vertically, to provide for variation in the telescope-to-work distance. Also, gas shielding is required to prevent oxidation of the reactive metals and to remove a plume of ionized metal vapor that forms and interferes with the laser beam at a high welding power. A Size 6 gas lens, shown schematically in Figure 7, directed 94 liters/min of helium over the weld zone. A backing gas was not used. A trailing gas was also not employed except for shielding some of the welds requiring high thermal inputs.

Figure 8 provides a view through one of the ports of the uranium containment vessel. It reveals the aluminum fixture on which plates were aligned and the gas-shielding device in position for welding.

Figure 4. SETUP FOR LASER WELDING DEPLETED URANIUM IN THE FLAT POSITION. (System is Enclosed by Plexiglas Walls)

DISCUSSION

Parameters were developed for making 50 and 70% penetration welds in 6.35-mm-thick uranium plates. Length of the welds was 76.2 mm. Welds were made on AISI 304 steel and on uranium to determine what changes in the established parameters for steel should be made when welding uranium. Comparison of the macrographs in Figures 9 and 10 indicate the effect of the focal length on the shape of the fusion zone of stainless steel welds. The same parameters on uranium produced about the same penetration, but with larger fusion zones.

The 12.7-mm-thick uranium plates were welded in the flat and horizontal positions; the 6.35-mm-thick plates were welded in the flat position only. The target penetration was 75%.

Figure 5. SETUP FOR LASER WELDING DEPLETED URANIUM IN THE HORIZONTAL POSITION.

Figure 6. VIEW OF THE CONTAINMENT VESSEL FOR LASER WELDING URANIUM WITHIN THE PLASTIC-SHIELDED WORKING SPACE.

AERL 3735A

Figure 7. OFF AXIS SHIELDING. (Gas Stream is in the Direction of Welding)

Figure 8. FIXTURE FOR WELDING URANIUM PLATES POSITIONED BENEATH THE OFF-AXIS GAS SHIELD.

AERL 3735C

Figure 9. LASER WELD ON AISI 304 STEEL. [Parameters: 6.3 kW, 47 mm/s, and a 710-mm Focal Length (focal point is on the upper surface of the plate); 15X]

Figure 10. LASER WELD ON AISI 304 STEEL. [Parameters: 6.3 kW, 47 mm/s, and an 800-mm Focal Length (focal point is 3.2 mm above the upper surface of the plate); 15X]

Trial welds were broken apart to check the uniformity of penetration and soundness along the joint. The width of the face of the weld was measured prior to fracturing the weld. Attempts were made to measure shrinkage transverse to the weld, but there was sufficient angular distortion to cause the measured values (~ 0.05 mm) to appear too small.

Parameters were selected from trial weld data to join a series of plates that were returned to the Y-12 Plant for metallographic analysis. Figure 11 shows the layout of these plates for metallographic specimens, and Tables 1 and 2 summarize the result of these examinations. The transverse and longitudinal specimens lie within the view of the face of the weld. The transverse specimens were polished and etched; the longitudinal specimens were held in a vise and broken with a hammer.

Measurement of the dimensions of the welds was derived directly from the photomacrographs, using the known plate features to check the magnification. Penetration was determined from transverse sections by measuring from the parent metal surface to the depth of the fusion zone. Thus, this value (more specifically the depth of fusion) does not coincide with the effective penetration on misaligned joints. The width of the weld used in calculating the depth-to-width ratios is the width of the weld face.

Percent spiking was derived from penetration measurements on longitudinal sections:

$$\text{Percent Spiking} = \frac{P_{\max} - P_{\min}}{P_{\min}} \times 100,$$

Figure 11. WROUGHT, DEPLETED URANIUM PLATES, 12.7 AND 6.35 MILLIMETERS IN THICKNESS. (Butt Welded by a High-Powered, Continuous-Wave, Carbon Dioxide Laser; All Dimensions are in mm)

where $P_{\max}$ and $P_{\min}$ are relative to the parent metal surface and do not include weld reinforcement.

All welded joints were radiographed prior to sectioning. Welds 68G and 69E (Table 1) and 74E (Table 2) contained the fewest low-density areas. All remaining welds contained medium to large low-density areas, with Welds 65E (Table 1) and 71C and 74B (Table 2) containing very large low-density areas.

The photomacrographs in Figures 12 through 32 reveal that high-power, CO_2 , continuous-wave laser welds have profiles resembling those of deeply penetrated electron-beam welds. Depth-to-width ratios of at least unity are shown to be feasible.

It is apparent that spiking and root defects are also problems in partial-penetration laser welding. The severity of these defects could be decreased by adjustment of the welding parameters. Figures 13 through 15, showing repeated welds, indicate that 50% penetration in 6.35-mm-thick uranium should be practicable on a production basis. Radiography showed that the repeated welds (Figures 17 to 20) with approximately 75% penetration all contained large root defects, except the one in Figure 19.

Continuous laser welds in 12.7-mm-thick uranium (Figures 24 to 32) contained more spiking and root defects as penetration increased. Horizontal welds (Figures 28 to 32) are well penetrated and have very little undercut. Shielding was not satisfactory on the

Table 1
LASER WELDS MADE IN THE FLAT POSITION ON 6.35-mm-THICK URANIUM PLATE

Specimen	Power to Work ⁽¹⁾ (kW)	Speed		Work Distance ⁽²⁾		Width of the Face of the Weld		Penetration		Spiking (%)	Depth-to-Width Ratio	Specimen Figure Number	Comments
		(ipm)	(mm/s)	(in)	(mm)	(in)	(mm)	(in)	(mm)				
65E	5.0	110	47	28.000	711	0.17	4.3	0.125	3.18	17.5	0.74	12	Problems aligning joint with beam.
68C	7.4	180	76	28.062	713	0.14	3.6	0.150	3.81	12.0	1.07	13	
68D	7.4	180	76	28.062	713	0.14	3.6	0.140	3.56	13.5	1.00	14	
68F	7.4	180	76	28.062	713	0.15	3.8	0.150	3.81	21.0	1.00	15	
68G	8.0	180	76	28.062	713	0.13/0.15	3.6	0.138	3.51	47.5	0.99	16	
69C	8.4	180	76	28.062	713	0.14/0.16	3.8	0.165	4.19	20.5	1.10	17	
69D	8.4	180	76	28.062	713	0.14/0.17	3.9	0.185	4.70	20.5	1.19	18	
69E	8.4	180	76	28.062	713	0.15/0.16	3.9	0.165	4.19	31.0	1.06	19	
69F	8.4	180	76	28.062	713	0.16	4.1	0.180	4.57	23.5	1.13	20	
69G	8.0	180	76	28.000	711	0.15/0.17	4.1	0.170	4.32	21.0	1.06	21	
70C	8.0	250	106	28.000	711	0.13/0.15	3.6	0.120	3.05	103.5	0.86	22	
70D	10.2	250	106	28.000	711	0.12/0.15	3.4	0.188	4.78	76.0	1.39	23	

(1) Loss in the optical path is 30% of the power from the laser cavity.

(2) Minimum beam diameter is at a 711-mm (28-in) telescope-to-work distance.

Table 2
LASER WELDS ON 12.7-mm-THICK PLATE IN BOTH THE FLAT AND HORIZONTAL POSITIONS

Specimen	Power to Work ⁽¹⁾ (kW)	Speed		Work Distance ⁽²⁾		Width of the Face of the Weld		Penetration		Spiking (%)	Depth-to-Width Ratio	Specimen Figure Number	Comments
		(ipm)	(mm/s)	(in)	(mm)	(in)	(mm)	(in)	(mm)				
71E ⁽³⁾	12.6	130	55	28.062	713	0.24	6.10	0.225	5.72	NA	0.94	24	Bead on the plate.
71C ⁽³⁾	12.9	130	55	28.062	713	0.18	4.57	0.393	10.11	28.0	2.21	25	
71F ⁽³⁾	12.6	130	55	28.062	713	0.22	5.59	0.345	8.76	8.0	1.57	26	Used an auxiliary helium shield.
72B ⁽³⁾	9.1	75	32	28.062	713	0.31	7.87	0.345	8.76	14.0	1.11	27	
74B ⁽⁴⁾	9.1	75	32	28.000	711	0.25	6.35	0.263	6.81	9.5	1.07	28	Back-welded plate.
74C ⁽⁴⁾	9.1	75	32	28.000	711	0.20	5.08	0.263	6.81	14.0	1.34	29	
74D ⁽⁴⁾	11.9	130	55	28.062	713	0.14	3.56	0.233	6.05	18.5	1.70	30	
74E ⁽⁴⁾	7.4	175	76	28.062	713	0.12	3.05	0.123	3.25	12.0	1.07	31	
74F ⁽⁴⁾	8.4	175	76	28.062	713	0.10	2.54	0.153	4.04	12.0	1.59	32	

(1) Loss in the optical path is 30% of the power from the laser cavity.

(2) Minimum beam diameter is at a 711-mm (28-in) telescope-to-work distance.

(3) Welds made in the flat position.

(4) Welds made in the horizontal position.

(a) Transverse Section. (13.2X)

MS-76-0292-1

(b) Fractured Longitudinal Section. (4X)

MS-76-0396-1

(c) Face of the Weld. (5X)

MS-76-0235-1

Figure 12. MACROGRAPHS OF WELD 65E. (5.0 kW; 47 mm/s; Sharp Focus)

(a) Transverse Section. (13.2X)

MS-76-0292-2

(b) Fractured Longitudinal Section. (4X)

MS-76-0396-2

(c) Face of the Weld. (5X)

MS-76-0235-2

Figure 13. MACROGRAPHS OF WELD 68C. (7.4 kW; 76 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (13.2X)

MS-76-0292-3

(b) Fractured Longitudinal Section. (4X)

MS-76-0396-3

(c) Face of the Weld. (5X)

MS-76-0235-3

Figure 14. MACROGRAPHS OF WELD 68D. (7.4 kW; 76 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (13.2X)

MS-76-0292-4

(b) Fractured Longitudinal Section. (4X)

MS-76-0396-4

(c) Face of the Weld. (5X)

MS-76-0235-4

Figure 15. MACROGRAPHS OF WELD 68F. (7.4 kW; 76 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (13.2X)

MS-76-0292-5

(b) Fractured Longitudinal Section. (4X)

MS-76-0396-5

(c) Face of the Weld. (5X)

MS-76-0235-5

Figure 16. MACROGRAPHS OF WELD 68G. (8.0 kW; 76 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (13.2X)

MS-76-0292-6

(b) Fractured Longitudinal Section. (4X)

MS-76-0396-6

(c) Face of the Weld. (5X)

MS-76-0235-6

Figure 17. MACROGRAPHS OF WELD 69C. (8.4 kW; 76 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (13.2X) MS-76-0292-7
(b) Fractured Longitudinal Section. (4X) MS-76-0396-7

(c) Face of the Weld. (5X) MS-76-0235-7

Figure 18. MACROGRAPHS OF WELD 69D. (8.4 kW; 76 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (13.2X) MS-76-0292-8
(b) Fractured Longitudinal Section. (4X) MS-76-0396-8

(c) Face of the Weld. (5X) MS-76-0235-8

Figure 19. MACROGRAPHS OF WELD 69E. (8.4 kW; 76 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (13.2X) MS-76-0292-9
(b) Fractured Longitudinal Section. (4X) MS-76-0396-9

(c) Face of the Weld. (5X) MS-76-0235-9

Figure 20. MACROGRAPHS OF WELD 69F. (8.4 kW; 76 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (13.2X)

MS-76-0292-10

(b) Fractured Longitudinal Section. (4X)

MS-76-0396-10

(c) Face of the Weld. (5X)

MS-76-0235-10

Figure 21. MACROGRAPHS OF WELD 69G. (8.0 kW; 76 mm/s; Sharp Focus)

(a) Transverse Section. (13.2X)

MS-76-0292-11

(b) Fractured Longitudinal Section. (4X)

MS-76-0396-12

(c) Face of the Weld. (5X)

MS-76-0235-11

Figure 22. MACROGRAPHS OF WELD 70C. (8.0 kW; 106 mm/s; Sharp Focus)

(a) Transverse Section. (13.2X)

MS-76-0292-12

(b) Fractured Longitudinal Section. (4X)

MS-76-0396-11

(c) Face of the Weld. (5X)

MS-76-0235-12

Figure 23. MACROGRAPHS OF WELD 70D. (10.2 kW; 106 mm/s; Sharp Focus)

MS-76-0396-22
Figure 24. MACROGRAPH OF WELD 71E. (12.6 kW; 55 mm/s; Sharp Focus + 1.6 mm; Weld is in 12.7-mm-Thick Wrought Uranium; 5X)

(a) Transverse Section. (8X)

(b) Fractured Longitudinal Section. (4.5X)

(c) Face of the Weld. (5.5X)

Figure 25. MACROGRAPHS OF WELD 71C. (12.9 kW; 55 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (8X)

(b) Fractured Longitudinal Section. (4.5X)

(c) Face of the Weld. (5.5X)

Figure 26. MACROGRAPHS OF WELD 71F. (12.6 kW; 55 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (8X)

MS-76-0307-3

(b) Fractured Longitudinal Section. (4.5X)

MS-76-U396-16

(c) Face of the Weld. (5.5X)

MS-76-0281-3

Figure 27. MACROGRAPHS OF WELD 72B. (9.1 kW; 32 mm/s; Sharp Focus + 1.6 mm)

(a) Transverse Section. (8X)

MS-76-0307-7

(b) Fractured Longitudinal Section. (4.5X)

MS-76-0306-17

(c) Face of the Weld. (5.5X)

MS-76-0281-7

Figure 28. MACROGRAPHS OF WELD 74B. (9.1 kW; 32 mm/s; Sharp Focus)

(a) Transverse Section. (8X)

MS-76-0307-8

(b) Fractured Longitudinal Section. (4.5X)

MS-76-0396-18

(c) Face of the Weld. (5.5X)

MS-76-0281-8

Figure 29. MACROGRAPHS OF WELD 74C. (9.1 kW; 32 mm/s; Sharp Focus)

MS-76-0307-4

(a) Transverse Section. (8X)

MS-76-0396-19

(b) Fractured Longitudinal Section. (4.5X)

MS-76-0281-4

(c) Face of the Weld. (5.5X)

Figure 30. MACROGRAPHS OF WELD 74D. (11.9 kW; 55 mm/s; Sharp Focus + 1.6 mm)

MS-76-0307-5

(a) Transverse Section. (8X)

MS-76-0396-20

(b) Fractured Longitudinal Section. (4.5X)

MS-76-0281-5

(c) Face of the Weld. (5.5X)

Figure 31. MACROGRAPHS OF WELD 74E. (7.4 kW; 76 mm/s; Sharp Focus + 1.6 mm)

MS-76-0307-6

(a) Transverse Section. (8X)

MS-76-0396-21

(b) Fractured Longitudinal Section. (4.5X)

MS-76-0281-6

(c) Face of the Weld. (5.5X)

Figure 32. MACROGRAPHS OF WELD 74F. (8.4 kW; 76 mm/s; Sharp Focus + 1.6 mm)

horizontal welds. Poor shielding has caused the poor appearance of the face of these welds and may have contributed to the formation of gross defects. With a trailing gas shield, horizontal welding with the laser process offers much potential in welding uranium and other high-density metals that are practically unweldable in the horizontal position. Welding in this position could simplify and considerably decrease the cost of weld tooling.

At high speed and power, the weld-bead width varied in a cyclical manner (Welds 70C and 70D are typical). The penetration tended to vary in a like manner in that welds were deeper where the bead became narrow. The cause is not known, but may have been due to cyclical variation in the welding speed. At slow speeds, the welds began to take on the appearance of arc welds.

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