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DEVELOPMENT OF LASER WELDING TECHNIQUES FOR JOINING ARMOR, (U)

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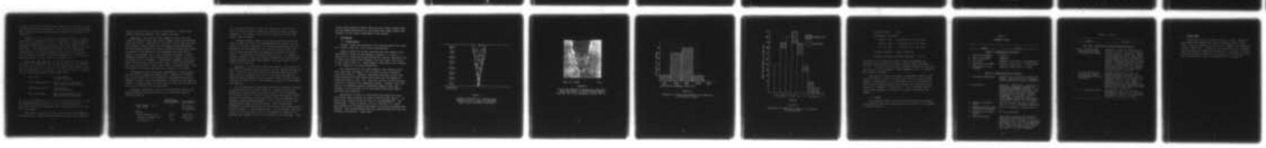

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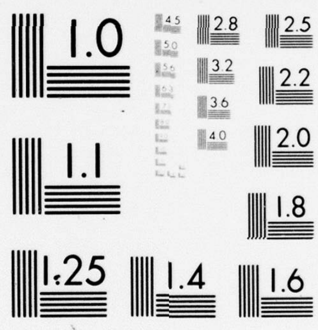

MICROCOPY RESOLUTION TEST CHART

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(6) DEVELOPMENT OF LASER WELDING TECHNIQUES FOR JOINING ARMOR,

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1. INTRODUCTION

The multikilowatt laser as an industrial tool in the production line has now been accepted for over three years. Recently, the laboratory feasibility of heavy-penetration laser welding was demonstrated in low strength steel by the IITRI Laser Center.

1.1 Objective

The objective of this program is the establishment of laser welding process parameters that will produce a sound, cost-effective joint with ballistic potential of 1 1/2 in. armor plate. Sufficient production, test, and operational data will be prepared to permit a detailed analysis of the achievement of this objective and repeatability of the process. Ballistic testing is not within the scope of this initial work.

1.2 Material

The program material is MIL-A-12560C(MR) (Mn-Mo) 1 1/2 in. armor plate. The program welding electrode is MIL-E-19822. A 20° V-joint configuration is being used for laser filler wire welding. The reported composition (in weight percent) of these two materials is as follows:

	Plate	Wire
C/Mn	0.26/1.43	0.06/1.37
P/S	0.008/0.010	0.005/0.017
Si	0.25	0.55
Ni/Cr	--/--	1.31/0.10
Mo	0.5	0.4
Al	0.43	--
B	0.003	--
V	--	0.12

1.3 Equipment

The program will be conducted at the IITRI Laser Center on a 15 kW CO_2 laser facility. The overall layout of the station is shown in Fig. 1. The cylindrical telescope at the top of the picture focuses the beam and aims it horizontally at the 45° downhand flat (copper) mirror in the upper left-hand corner of the picture. The downhand mirror directs the converging beam downward at the point as it moves on the mechanical table shown in the lower left-hand corner. During this period the scheduled substitution of a second telescope for the one shown in Fig. 1 was accomplished. A comparison of the two systems in terms of the geometry of the welding beams produced illustrates the purpose served by the substitution:

Taper of Beam (included angle)

F/18: 6-8°
F/7: 16-18°

Ratio of Tolerance for Vertical Placement (focus)

$$\frac{F/18}{F/7} = \frac{6.6}{1}$$

Nominal Spot Diameter

F/18 = 0.1 in.
F/7 = 0.04 in.

Concentration of Energy in Spot (12 kW)

F/18 = 1.5×10^6 watts/in.^{2}
F/7 = 9.5×10^6 watts/in.^{2}

From the above comparison, it appears that the F/18 telescope substitution provided valuable latitude because its narrower beam can work more deeply in the groove (or in a narrower, more cost-effective groove). At the same time, its broader spot and greater tolerance for vertical placement suggest a much easier process to use (or to automate).

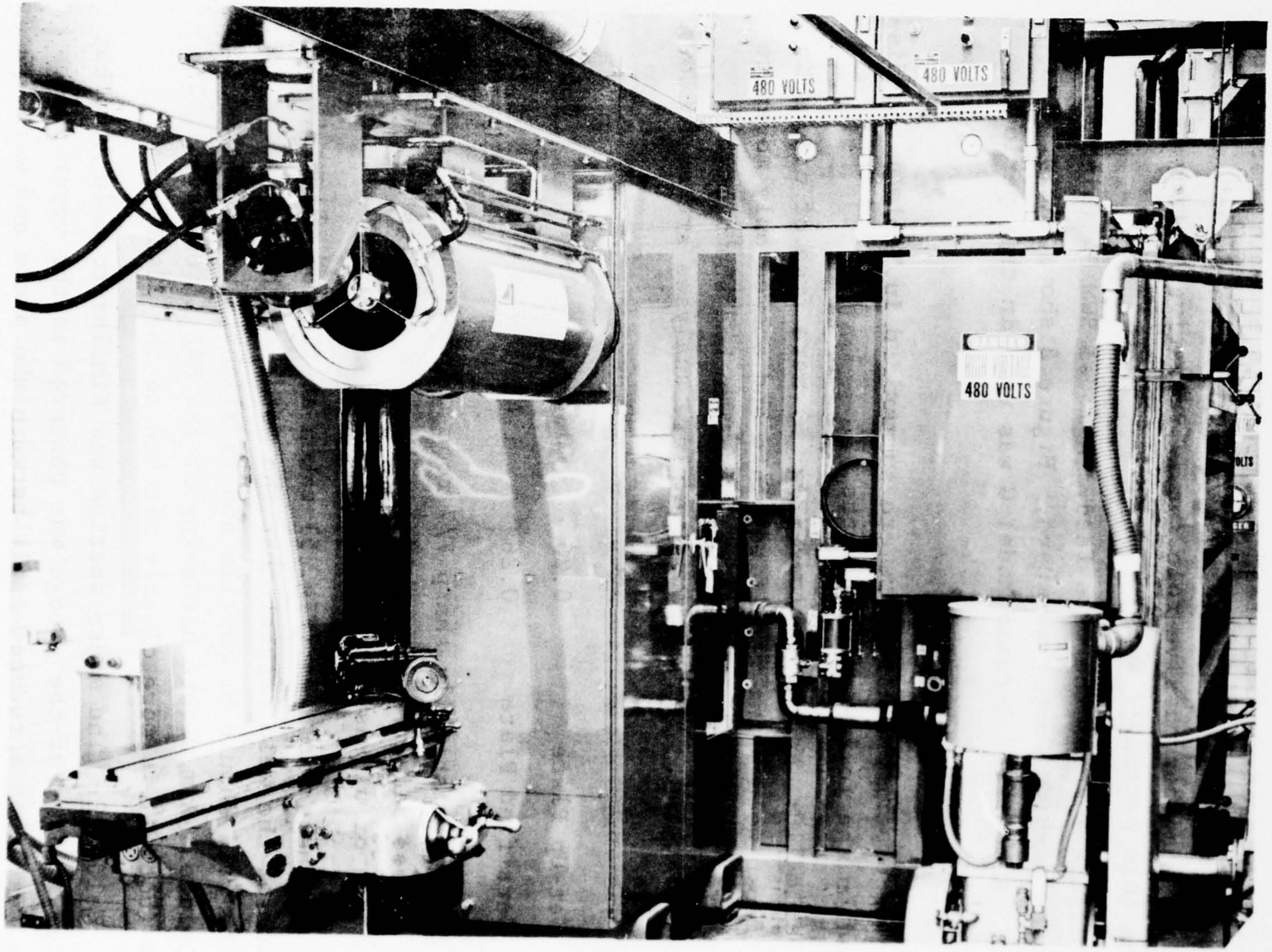


Figure 1

Laser Welding Station

The role of the wire feed equipment is becoming more important as experience with process stability increases and as the wire plays a less passive role (as in resistive heating tests during this period.)

Figure 2 shows the wire feed. A model SWM 34 (Linde Div. of Union Carbide Corp.) was used. Figure 3 shows the wire guide. A modified Bernard Model G was used in this period.

2. EXPERIMENTAL RESULTS

The experimental results are summarized in Table 1 and discussed in the following paragraphs.

Weld 110: Macro sections (Fig. 4) were free of cracks in this first weld using certified plate and showed only moderate porosity. Previous welds on set-up plate had shown severe center cracking. The comparative plate analyses are as follows:

	C	Mn	S	Mo
Set-Up Plate	0.26	0.25	0.018	0.5
Certified Plate	0.26	1.43	0.010	0.29

The characteristically sharp F/7 root reinforcement is a potential stress raiser under rapid loading and complicates interpretation of ultrasonic test data.

Hardness profiles (Fig. 5) taken at the top, middle, and bottom of the weld suggest that the metal at the top and middle of the weld should be ductile and is slightly undermatched to the plate. A moderate hardening of the HAZ is observed. The root (bottom) is more closely matched to the plate.

Weld 112: The macro section was similar to weld 110, but better filling of the groove was observed in the upper passes as a result of a reduced angle between the plate and wire. A pipe-like jet shield that could be lowered into the groove to

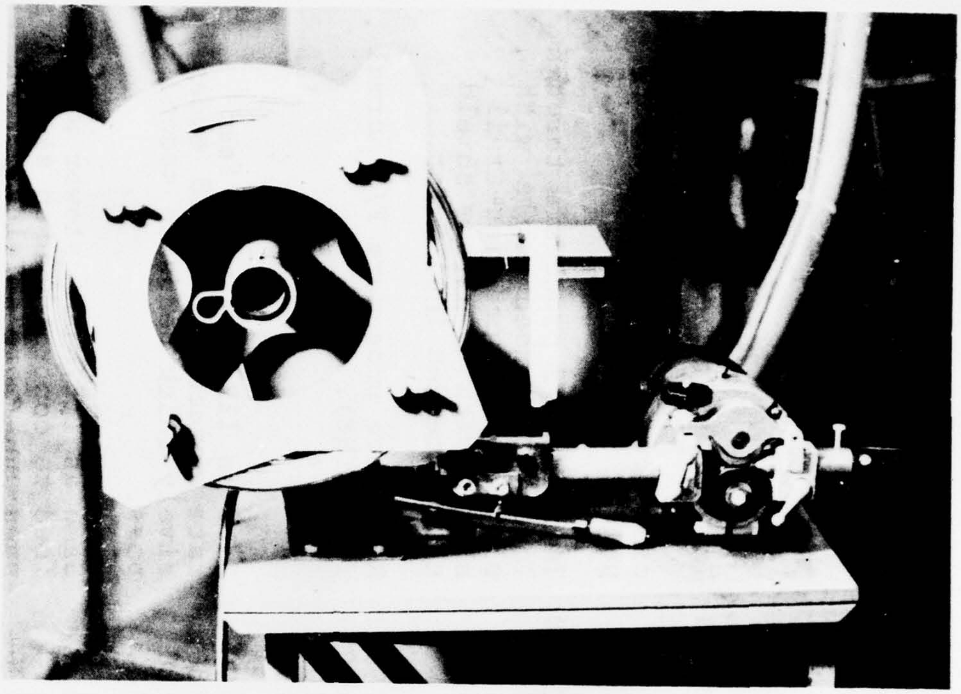


Figure 2

Wire Feeder

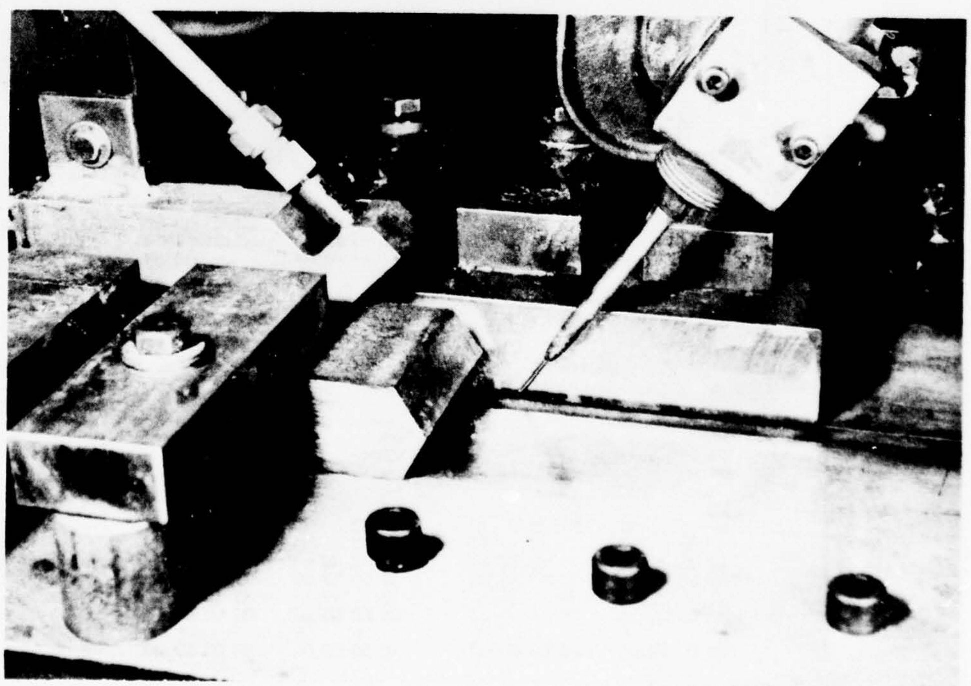


Figure 3

Torch Arrangement

Table 1

EXPERIMENTAL PROCEDURE SUMMARY

Joint No.	Pass Sequence (root gap, in.)	Wire Feed Speed, ipm	Welding Speed, ipm	Beam Conf.	Gas Flow, cfh	Comments
			F/7 Welds, Part I			
110	A Root (N.R.)	60	15	CF	150/100	Initial F/7 concentrated focus (CR). Procedure: initial use of as-cut joint with no root pass.
	B-C Span	120	15	CF		
	D Span	120	10	CF		
	E-K Side	120	10	CF		
112	A Root (N.R.)	60	15	CF	150/100	Improved F/7 procedure through lower wire feed angle with plate. Replaced jet-trail shield with a narrow shield that extended into joint.
	B-C Span	120	15	CF	150	
	D Span	60	15	CF	150	
	E-L Side	60	15	CF	150	
113	A Root (1/16)	60	15	NF	100	Reference procedure F/7 normal focus (NF).
	B-D Span	120	15	NF	100	
	E Side	120	15	NF	100	
	F-L Side	120	15	NF	150	
114	A Root (N.R.)	60	15	NF	100	Same as 113, but with feed rate reduced to avoid excessively thick beads in second pass.
	B Span	90	10	NF	100	
	C-D Span	120	10	NF	100	
	E-J Side	120	10	NF	100	
115	A Root (3/32)	60	15	NF	100	Same as 113, but slower wire feed to control bead on second pass and more shield gas on upper passes to improve top bead contour.
	B Span	60	10	NF	100	
	C-D Span	120	10	NF	100	
	E Side	120	10	NF	100	
	F-K Side	120	10	NF	150	

Table 1 (cont.)

Joint No.	Pass Sequence (root gap, in.)	Wire Feed Speed, ipm	Welding Speed, ipm	Beam Conf.	Gas Flow, cfh	Comments
116	A Root (3/32)	60	15	NF	100	Started same as 113, but 3/32 in. gap caused root pass drop-thru. Repaired acceptably by speeding D pass and adding three finish passes.
	B Span	60	15	NF	100	
	C Span	120	10	NF	100	
	D Span	120	15	NF	100	
	E-F Side	120	10	NF	100	
	F-N Side	120	10	NF	150	
117	A Root (1/16)	60	15	NF	100	Same as 115, but with slower last pass (to improve top bead contour.
	B Span	60	15	NF	100	
	C-D Span	120	10	NF	100	
	E-F Side	120	10	NF	100	
	G-M Side	120	10	NF	150	
	N Top	60	15	NF	150	
	F/18 Welds, Part II					
119	A Root (N.R.)	60	15	NF	100	Reference F/18 procedure. Oxide removed from preparation for one half of joint length (this weld only).
	B Span	60	15	NF	100	
	C-D Span	120	10	NF	100	
	E-H Side	120	10	NF	100	
	I-M Side	120	10	NF	150	
121	A Root (1/16)	60	15	NF	100	Reference F/18 mechanical test weld interpass cleaning.
	B Span	60	15	NF	100	
	C-D Span	120	10	NF	100	
	E-M Span	120	10	NF	100	
	N-P Top (Partial bead)	60	10	NF	100	
123	A Root (1/8), no H.W.	60	15	NF	6He4A 100	Reference hot wire trial with interpass cleaning and gas mixes that induce some plasma.
	B Span, no H.W.	60	15	NF	6He4A 100	
	C-D Span with H.W.	180	15	NF	6He4A 100	
	E-I Side with H.W.	180	15	NF	CO_2 100	
	J-L Top	180	15	NF	CO_2 90	

Basic process: 1-1/2 in. thick plate; narrow (20°) V-joint with no root and as-flame cut; no pre- or post-heat; 12 kw; 1/16 in. dia A632 wire feed lowered to 30°; helium shielding gas. Shield type: Jet/trail for 110 and 112; changed to pipe for remainder.

Neg. No. 50017 2.5X

Figure 4

Narrow Gap Laser Weld in 1-1/2 Inch Armor Plate. Weld 110; F/7 telescope; as-cut (20° V).

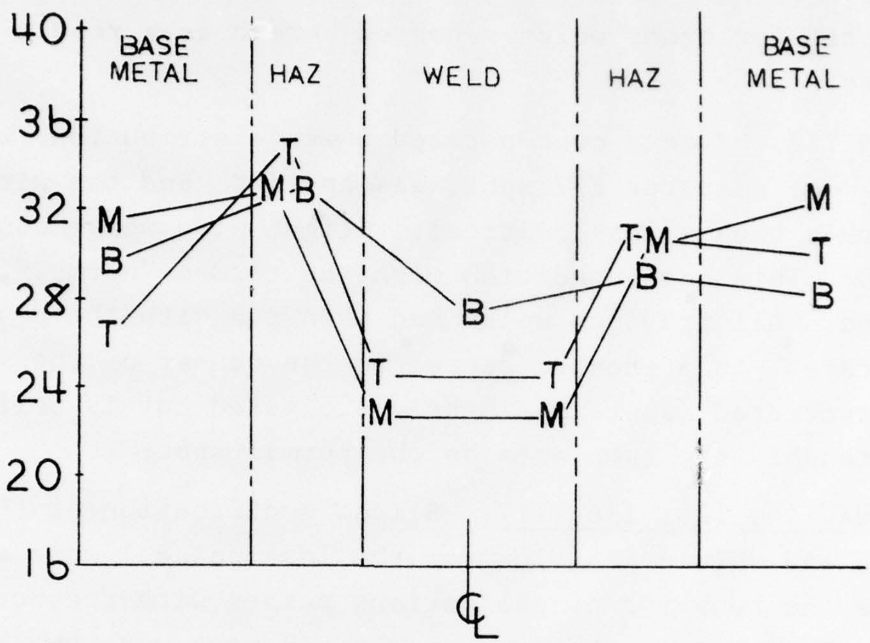


Figure 5

Hardness Profile for F/7 Laser Weld in Armor Plate

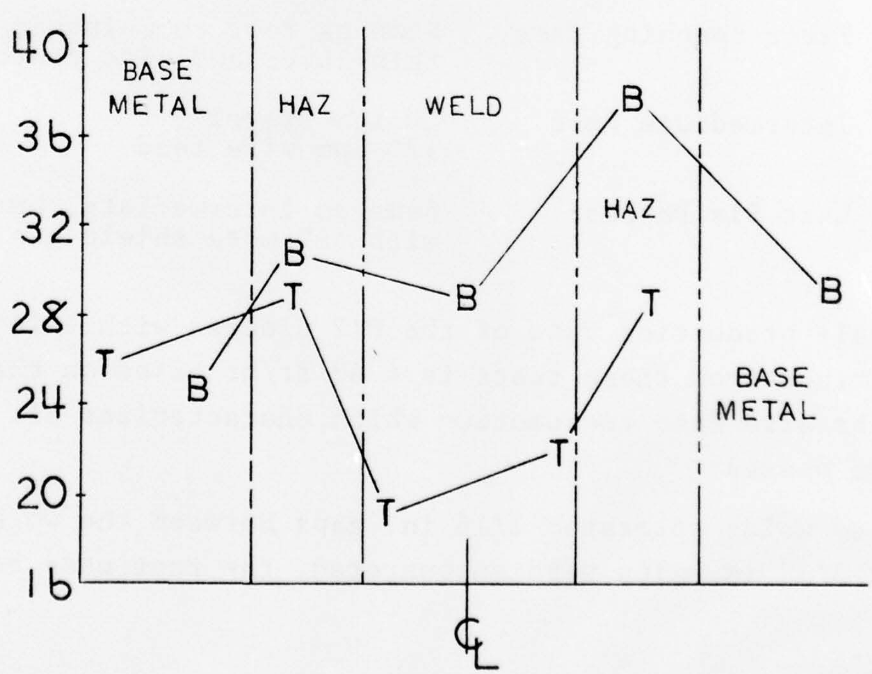


Figure 6

Hardness Profile for F/18 Laser Weld in Armor Plate a point just above the layer being deposited is believed to have contributed to this improvement. This shield and wire feed angle were adopted for other welds reported herein as a result of this experience.

Weld 113: A less concentrated power distribution, within the 0.042 in. diameter F/7 spot, was applied, and the wire/beam relationship became less critical. Slight wire weave could be tolerated. This beam condition might be termed "normal" for the laser used. All previous welds had been run with the power "concentrated" to a greater degree in the center of the spot. The "concentrated" spot is slightly elongated but is believed to involve roughly the same area as the normal spot.

Welds 114, 115, 116, 117: Slight modification of the wire feed rate and shield gas flow (on the last passes) were applied to refine the behavior of the various passes with respect to contour and placement in the groove. The changes were not striking, but the following general pattern seemed best:

Root Pass:	15 ipm travel 60 ipm wire feed
First Spanning Pass:	Same as root to maintain thin layer and flat contour
Intermediate Pass:	10 ipm travel 120 ipm wire feed
Last Six Passes:	Same as intermediate, but with 50% more shield gas

The overall production rate of the F/7 process with 1/16 in. wire as determined from these tests is 4.62 ft/hr based on the 6.25 lb/hr wire feed consumption which characterizes all but the first two passes.

These welds tolerated 1/16 in. gaps between the workpieces, but when 3/32 in. gaps were encountered, the root pass tended to drop out of the joint in one of two instances. A repair was readily effected, however, when dropout occurred.

Weld 119: This was the first complete weld to use the 0.018 in. diameter focal spot (with "normal" power distribution) from F/18 optics. Additionally, one half of the joint face was belt sanded to remove oxide from the flame cutting operation. The F/18 greatly reduced wire/beam placement problems and tended to produce a less sharp root reinforcement than did the F/7. However, the broader spot is not completely tolerant of wire placement because the vapor concentration of energy is sited at the midpoint of the diameter. Significant movement of the wire under the point-like energy source tends to flip the beam from one side or the other of the round, nearly horizontal wire. Stabilization of the wire location still appears to be needed.

Radiographs show a detectable improvement in quality when the side wall is sanded to remove oxide. However, the difference is not great and a more extensive investigation would be required to make a final determination. Because of its inherent economy, the development of a process that uses the side wall in the as-cut condition will be continued.

Weld 121: Mechanical tests of all-weld-metal tensile and impact specimens were carried out on this material with the following results:

	Reference (MIL-E-19822A)	Experimental
Charpy Impact, ft-lb (at -60°F)	20	43; 41.5; 41.0; 33.5; 22.5(Defect)
Tensile		
Yield Strength, ksi	88.0	88.9-92.0
Ultimate Strength, ksi	NA	108.9-121.0
Elongation, %	14.0	15-25

For the specific batch of wire the vendor has reported (see First Quarterly Report) values with similar ultimate strength, elongation, and impact, but his yield strength (110 ksi) was higher than the above.

Hardness profiles taken at the top and bottom of the weld (Fig. 6) show the weld to be undermatched with respect to the plate at the top of the weld, but closely matched near the root. The HAZ is not pronounced at the top of the weld so that the entire upper portion might be expected to perform well upon impact. A harder HAZ is observed near the root. It appears to be quite narrow so that the selected hardness test intervals apparently missed the left-hand maximum, but came closer on the right side of the weld.

Weld 123: In this weld, power was added to the process in the form of resistance heating from a current flowing through the wire. This hot wire (H.W.) process increased deposition rates 50% so that a finishing rate of 6.7 ft/hr might be expected. There was some evidence in set-up passes (weld 122) that finishing rates as high as 8-10 ft/hr could be achieved if the process were refined.

The introduction of resistance heated wire greatly increases the absorption of the beam on the wire. Smooth contours are difficult to achieve when the beam is almost totally absorbed. In the final passes of weld 123, gas mixtures were applied which enhance the formation of the plasmas that often accompanies conventional laser welding processes. It was felt that heat from plasmas would smooth the bead contour. Both helium/argon (60%/40%) or carbon dioxide form such plasmas, but neither improved bead contour. A spot diameter that is even greater than the 0.018 in. F/18 spot might also be considered as a means of improving bead contour, but is not available in this program. Such a spot would normally reflect from the work without penetrating, but the added absorptivity of the heated wire might offset this tendency to the overall advantage of the process.

3. DISCUSSION

3.1 Observations

Figure 7 shows the location of the various passes that make up a typical weld (No. 121 in this illustration).

Figure 8 shows the actual cross-section and several crack-like defects located in the region of passes C, D, and E. A review of all other welds made during this quarter indicated that if crack-like defects were present, they were most often found in this region (Fig. 9). Additionally, such defects are oriented at 45° (approx.) to the weld centerline.

The orientation of the crack suggests that characteristic weld centerline cracking is not the cause of the occasional crack-like defects. However, centerline cracking is also most often observed in those passes associated with the region of crack-like defects (Fig. 10). The wide shallow centerline crack is easily re-fused in the subsequent passes. However, the location of the maximum observed occurrence suggests very high stresses in that portion of the weld where crack-like defects have also been observed.

Radiographs of weld 121 (from which the mechanical tests were taken) were evaluated in terms of MIL-R-11468, Table I. No cracks were visible in the 1T hole in a 1% penetrameter. Two indications of lack of fusion, 3/16 in. long and 9 in. apart, were observed in the region from which the tensile specimens were removed. Only scattered cavities were observed when the part was reviewed for porosity. These were:

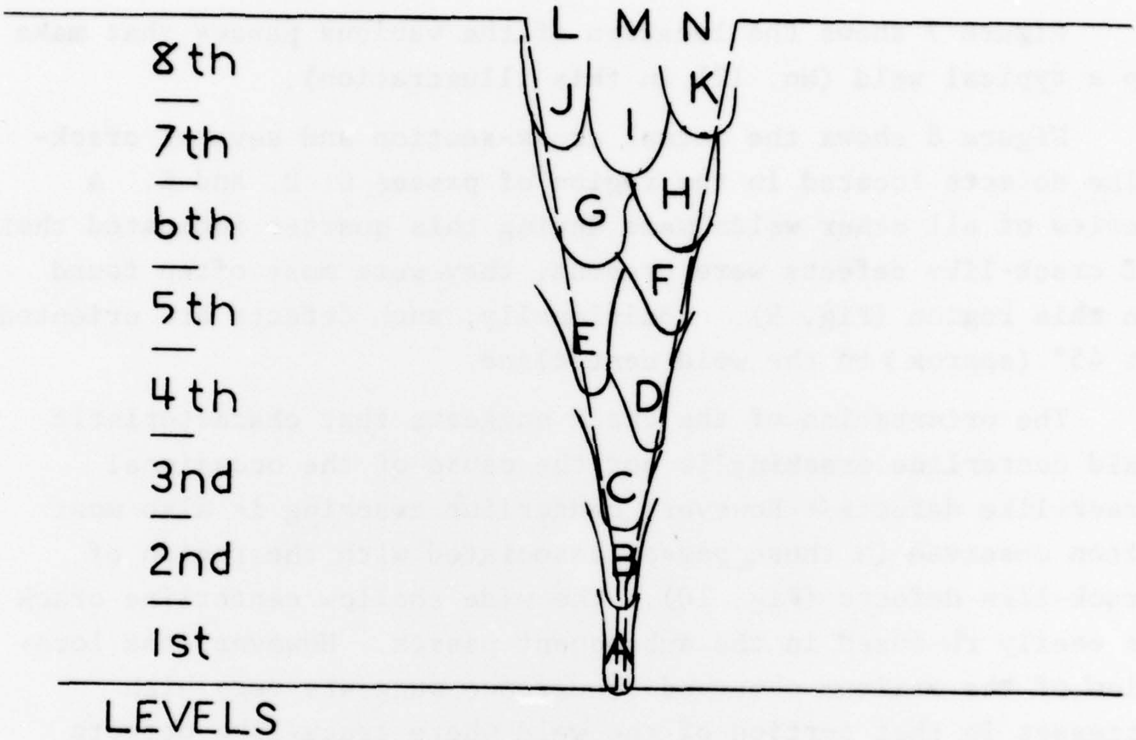
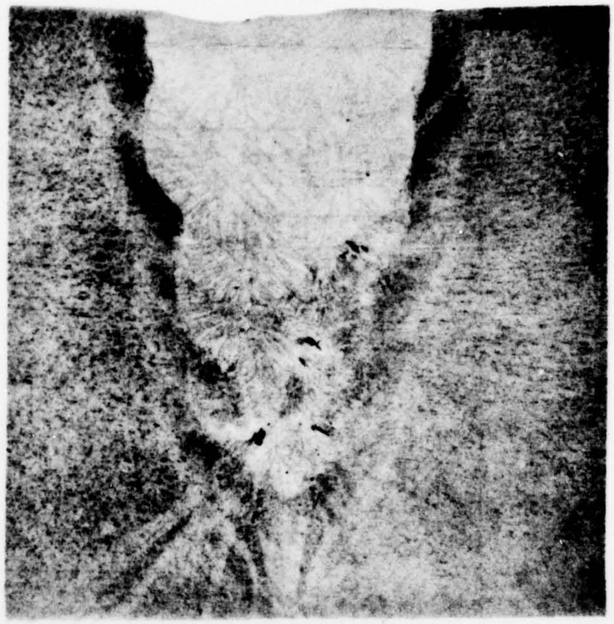


Figure 7

Location of Passes in a Typical Weld
(Scale at left is used for recording defect data from macro sections.)



Neg. No. 50016 2.5X

Figure 8

Crack-like Defects in Narrow Gas Laser Weld
Cross Section of 1-1/2 Inch Armor Plate.
Weld No. 121; F/18 telescope; as-cut (20° V)

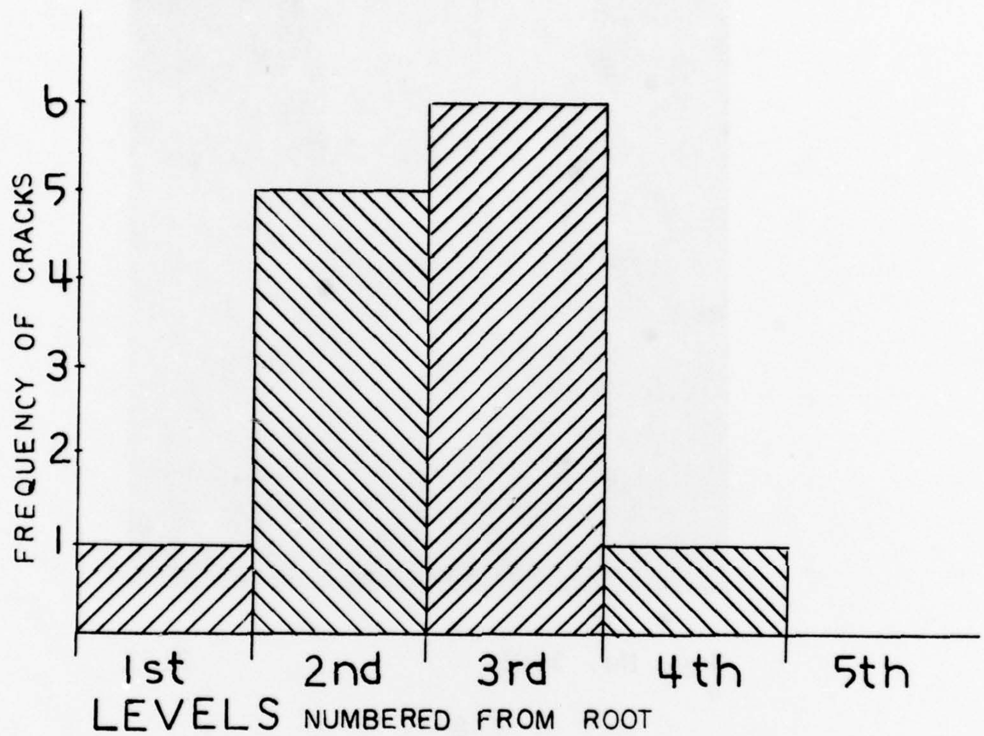


Figure 9

Frequency of Crack-like Defects as a Function of Location in Weld

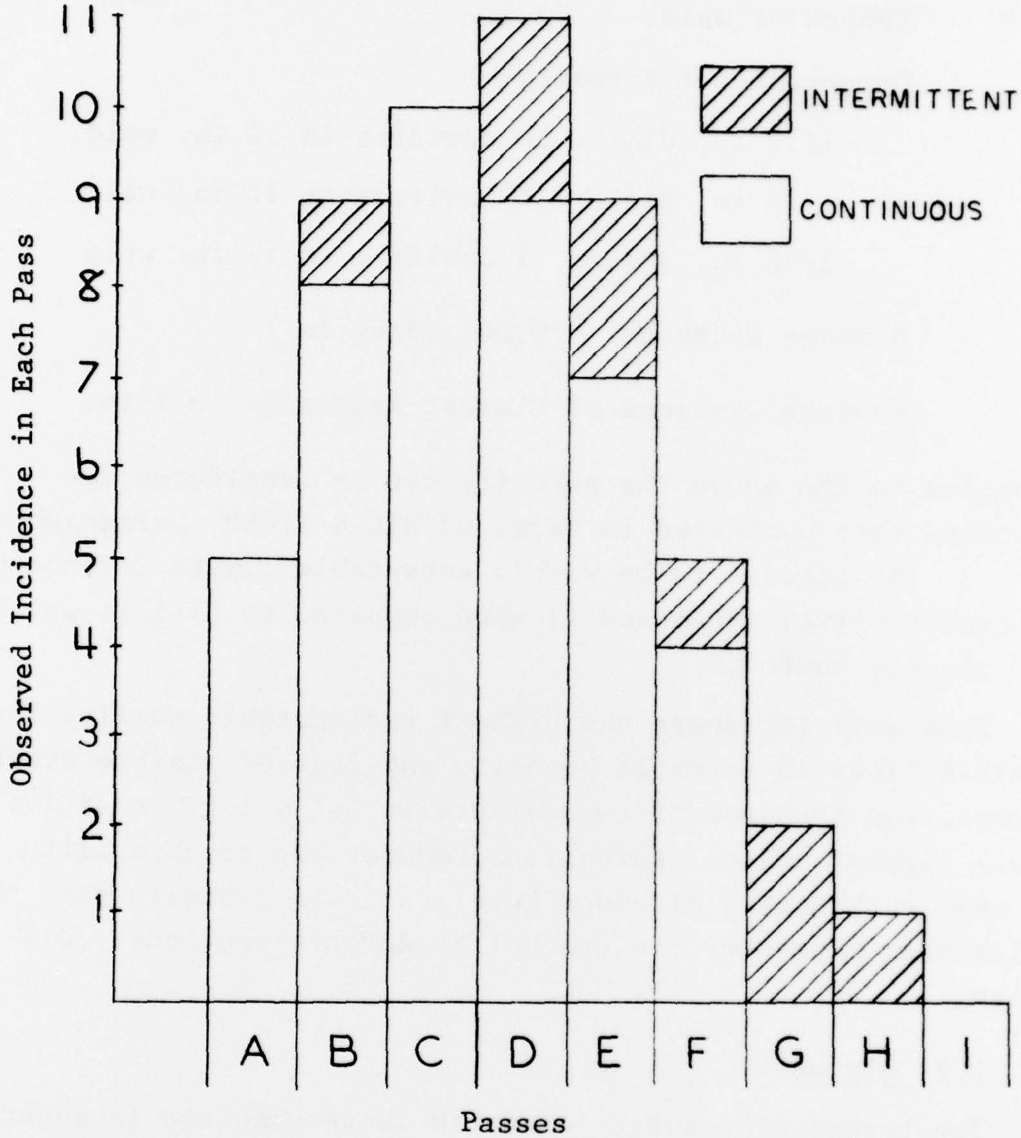


Figure 10

Frequency of Centerline Cracks as a Function of Welding Pass

Length of Weld: 12 in.

Occurrence of Porosity:

1/32 in. dia. - 10 cavities in 12 in. weld

1/16 in. dia. - 6 cavities in 12 in. weld

3/32 in. dia. - 1 cavity in 12 in. weld

Average Diameter: 0.045 (3/64 in.)

Average Distance of Closest Approach: 0.7 in.

According to the above, the porosity can be considered as scattered when evaluated in terms of MIL-R-11468, paragraph 4.1.3.2. It appears to be within acceptable limits for the highest quality level (Standard I) when compared to C1-1 to which it most closely conforms.

Thus weld 121 meets the highest radiographic quality level in MIL-R-11468 in terms of porosity and lack of visible cracks. However, the presence of two detectable (at a 1-1T sensitivity level) lack-of-fusion indications reduces the acceptability of the weld to Standard II under Rule 1. It is probable that the indications represent the crack-like defects previously discussed.

3.2 <u>Status</u>

The technical results set forth above resulted in substantial progress along the planned course of action of this program, as shown in Table 2.

Table 2

PROGRAM STATUS

Task	Status
Part I - Adaptation of Process	
1 - Plate Procurement	Complete
2 - Wire Procurement	Complete
3 - Cut Plate	Complete (for Phase I requirements)
4 - Adaptation to Armor	Complete (using Part II techniques)
5 - Evaluation of the Process	Complete (using Part II welds)
Part II - Optimization of Process	
1 - Increased Deposition	Complete for F/18 and Hot Wire techniques. Large-wire tests deferred until quality of welds is stabilized.
2 - Evaluation	Complete. Mechanical properties of weld metal acceptable per MIL-E-22200/6C ELECTRODES, WELDING. Small intermittent crack-like defects observed in macro sections require interpretation in terms of MIL-R-11468(ORD). Otherwise, Part II welds demonstrated that acceptable radiographic quality was obtainable.
3 - Welding at Reduced Power	Will be run next period if quality level at 12 kW procedure stabilizes.
4 - Demonstration of Cost-Effective Techniques	Not yet scheduled-- pending Task 3.
5 - Evaluation of Task 4 Welds	Not yet scheduled.
6 - Data Collection	Substantial progress has been made regarding effectiveness of F/18, ability of hot wire feed to increase deposition rate, and the intermittent occurrence of a small crack-like defect. Data from large wire-tests and Tasks 3, 4, and 5 pending.

Table 2 (cont.)

Task	Status
Part III - Applications Engineering Parameters	
1 and 2 - Prepare Test Specimens with Manufacturing Variations	Complete. Welds can consistently tolerate 1/16 in. fit-up variances, but not 3/32 in. variances. There is insufficient quality improvement from machined joints as opposed to as-cut joints to continue with the expensive machined (ground) configuration. Hardness tests in the vicinity of the capping pass indicate very little HAZ. The root appears, in hardness surveys, to more completely warrant attention.
3 - Test and Evaluation of Specimens Representing Manufacturing Variations	Partially complete in that the mechanical tests completed this period represented a weld that was produced from as-cut specimens containing a 1/16 in. gap. These specimens met the requirements of MIL-E-22200/6C, and the radiographic quality of the weld appeared to meet MIL-R-11468, Standard II.
4, 5, 6 - Long-Weld Tests	Deferred for the final process adjustments in Part II to eliminate intermittent defects that have been observed in macro sectioning.

4. FUTURE WORK

In the next reporting period welding of Task 4 demonstration welds will complete the Part II welding effort, since 1/8 in. wire for large-wire tests is not commercially available in MIL-E-19822 wire. Instead of the large-wire tests, emphasis will be placed on optimizing the process to eliminate the small crack-like defects observed in this period, and thus raise the MIL-R-11468 quality level from Standard II to Standard I.