8306-027

MECHANICAL PROPERTIES AND PHYSICAL METALLURGY OF HSLA STEEL LASER BEAM WELDMENTS

P. E. Denney
U.S. Naval Research Laboratory
Code 6312
Washington, DC 20375

E. A. Metzbower
U.S. Naval Research Laboratory
Code 6324
Washington, DC 20375

ABSTRACT

Laser beam weldments of High Strength Low Alloy (HSLA) Steels, (12 mm (0.5 in.) thick), were fabricated as autogeneous butt welds and with 0.025 mm (0.001 in.) thick Inconel 600 inserts. Their mechanical properties, solidification structure, and microstructure were evaluated. The HSLA steels examined were ASTM A633, A710, A736, and A737. The mechanical properties (YS, UTS, Elong., RA, and Fracture Toughness) of the base plates and weldments were measured. The fracture toughness was determined by the Charpy V notch test. Hardness traverses were made across the base plates, heat affected and fusion zones. The solidification structure and microstructure of the autogeneous and Inconel 600 insert welds were identified by optical microscopy. Fractographic analysis was carried out by scanning electron microscopy. A discussion of the differences in structures and mechanical properties of the weldments will be presented.

INTRODUCTION

THE INCREASED USE of high strength low alloy (HSLA) steels in structures is due in part to their high strength, good low temperature toughness, and weldability. Many of these structures require extensive and repetitive welding sequences which are easily automated. The use of a high power laser beam welding system in such an automated system is logical because of the simple joint preparation, high welding speed, ability to be completely computer controlled, and low distortion of the resulting weldment. Also as a result of its low heat input and fast welding speed, the laser beam welding process has rapid solidification and high cooling rates which affect the mechanical properties of the heat-affected zone (HAZ) and fusion zone (1,2). This paper reports on the mechanical properties of laser beam weldments of three HSLA steels (A633, A737, and A710/736).

LASER WELDING

The laser or light amplification by stimulated emission of radiation, has existed for only a little over twenty years but has already found its way into manufacturing (3). In many situations the lasers are low power continuous-wave (CW) or pulsed lasers which are used to weld thin sheet metal. However, a high power CO_2 CW laser rated at 25 kilowatts is presently producing thick section (16 mm(5/8 in) thick) welds in a production line environment (4).

Laser beam welding occurs when the collimated, monochromatic laser beam is focused to a small diameter spot (1.0 mm (.04 in)). This results in a very high power density which impinges on and interacts with the workpiece. This interaction can be considered a combination of reflected and absorbed energy. If the absorbed energy is sufficient, a column or "keyhole" is produced consisting of vaporized metal surrounded by a molten pool both of which extend through the thickness of the material. The vaporized metal, or plasma, that is produced in the keyhole also exist above the interaction site and is a very good absorber of the laser radiation. This results in a decrease in the amount of energy going into the keyhole. A helium gas jet is used to move the plasma away from the top of the keyhole. Helium is also used to blanket the weld area in an attempt to minimize the amount of detrimental gas absorbtion. The depth to which the keyhole will penetrate is determined by the power of the laser beam, the weld speed, and the amount of plasma suppression (5,6). A proper laser beam weldment will have a depth-to-width ratio of 4 to 1 or greater.

MATERIALS AND WELDING PROCEDURES

Three HSLA steels were selected based on their low carbon content, high fracture toughness at low temperatures, and availability The three HSLA steel chosen were A633, Grade E; A737, Grade B; and A710, Grade A, Class 3. Another HSLA steel, A736, Class 3, was also received but because it was the pressure vessel equivalent of the A710, they were both referred to as A710/736 (Table 1). All plates were 12.5 ± 0.3 mm (0.5 ± 0.01 in) and were cut into 152 mm (6 in) X 305 mm (12 in) pieces with the long edge lying in the longitudinal, L, or rolling direction. The longitudinal surface of the edge of the plate to be welded was machined square and flat. The plates were grit blasted to remove oil, scale, and oxides from the surface. Base plate microstructures were determined and the mechancial properties measured. Mechanical properties included Charpy V-notch (CVN) and tensile tests in the L-T (transverse) and T-L (rolling) directions.

In addition to autogenous butt welds, welds with Inconel 600 inserts (0.13 mm (0.005 in) thick) placed in the weld joint prior to welding were made. This was done to alloy the fusion zone material in an effort to increase the fracture toughness of the weld. Similar additions have been made to laser beam welded HY steels with successful results being reported by Moon and Metzbower (7).

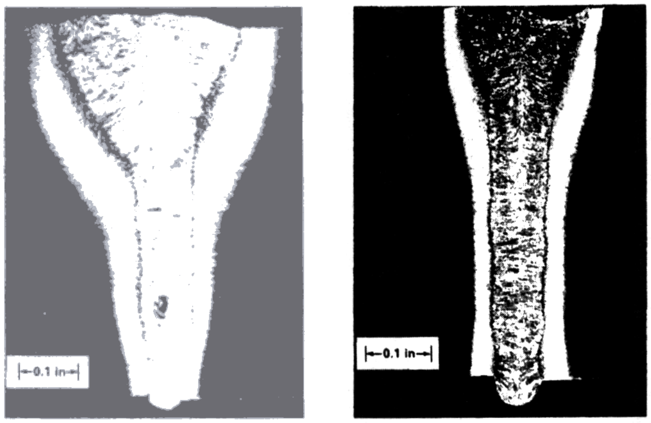
All welds were made using the 15 kW, CO_2 CW laser at the U.S. Naval Research Laboratory (NRL). The power required to weld ranged between 11 kW and 13 kW with some experimental welds being made at 15 kW (Fig. 1). Weld speeds ranged from 11 mm/sec (26 ipm) to 14 mm/sec (33 ipm) with experimental high power welds being made at 20 mm/sec (47 ipm). The laser beam is delivered to the work station by a series of flat metal mirrors with the final mirror being a focussing mirror with a focal length of 0.5 meters (19.7 in). In order to fabricate the welds with the best depth-to-width ratio the focal point of the laser is usually positioned not on the workpiece surface but 2.5 mm (0.1 in) below the top surface of the plate.

Alignment of the weld joint was accomplished by using a low power helium neon (HeNe) laser that is coaxial to the CO_2 laser. Tack welds were made at each end of the weld joint to prevent spreading during the weld pass.

Following the weld pass, the weldments were radiographed to determine internal defects such as porosity and/or cracking. The plates were then cut into the required metallographic and mechanical test specimens.

DETERMINING CHARACTERISTICS OF LASER WELDMENTS

The laser weldments were optically examined for solidification structure and microstructure. The microstructure examination included the base plate material, the HAZ, and the fusion zone. The microstructures were identified using standards and terminology developed by The Welding Institute (8). Microhardness tests were made on the transverse cross-sections of the weld mid-way between the top and bottom of the weld. Fracture toughness of the welds was determined by CVN tests according to AWS specifications. The CVN tests were conducted at 21°C (70°F), -18°C (0°F), and -51°C (-60°F). The tensile tests were also conducted following AWS standards.



11.5kW, 26 ipm

15kW, 47 ipm

Fig. 1 Photo macrograph showing effects of power and travel speed on A633 autogenous weld shape (Nital Etch).

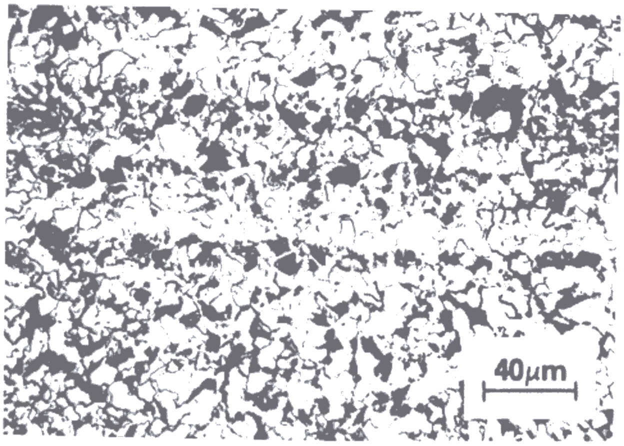
A633, GRADE E -The microstructure of A633, Grade E, is a banded blocky ferrite structure (Fig 2). The microstructure of the HAZ of both the autogenous and Inconel insert welds were identical as was true in all of the other materials. The region of the HAZ nearest the base plate material was a refined structure with what appeared to be a carbide structure (i.e., Fe_3C) conglomerating into large "islands." This resulted in a loss of the banded structure. The area near the fusion zone contained grain boundary ferrite, ferrite-carbide aggregate and aligned martensite-austensite-carbide (MAC). A similar structure was found in the autogenous weld fusion zone with the only difference being that the fusion zone was more refined (Fig. 3). The fusion zone of the weld with an Inconel inserts was a mixture of ferrite with aligned MAC and ferrite-carbide aggregate (Fig. 4). The microhardness of the A633 base plate was approximately 150 Vickers hardness number (VHN) while the autogenous weld reached a microhardness of 400 VHN in the fusion zone and the Inconel insert weld reached a microhardness of 550 VHN in the fusion zone (Fig. 5).

The CVN values of the welds were in all cases lower than the base plate values (Table 2 and 3). The autogenous welds averaged approximately half the CVN values of base plate specimens in the T-L direction while the CVN

Table 1. Compositions, wt%

	C	Mn	P	S	Si	Cr	Ni	Mo	V	Al	Nb	Fe	Other
A633, Grade E	0.19	1.41	0.006	0.025	0.45				0.08			BAL	0.023N
A737, Grade B	0.14	1.27	0.010	0.028	0.23					0.033	0.029	BAL	
A710/736 Grade A Class 3	0.03	0.61	0.010	0.006	0.26	0.86	0.92	0.20		0.029	0.04	BAL	1.20Cu
Inconel 600	0.02	0.22		0.002	0.18	15.14	75.68					8.62	0.14Cu

values of the Inconel insert welds were approximately one third the T-L base plate CVN values. These differences existed at all three temperatures tested.



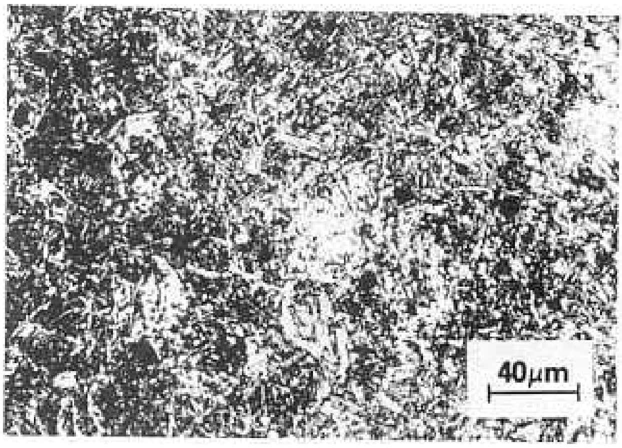


Fig. 3 Fusion zone microstructure of A633 autogenous weld (Nital Etch).

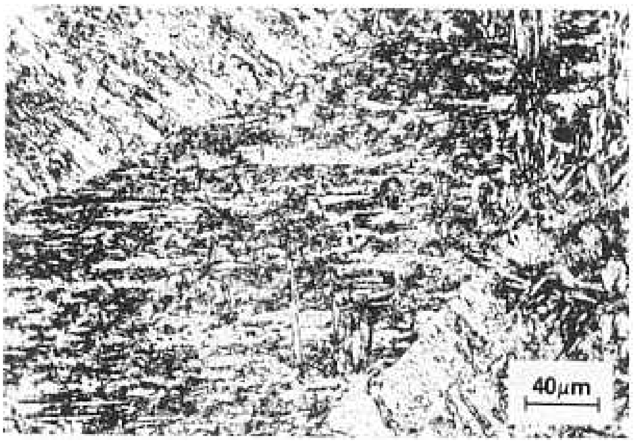


Fig. 4 Microstructure of the fusion zone of A633 Inconel 600 insert weld (Nital Etch).

The A633 welds, both autogenous and Inconel were found to have higher ultimate tensile strengths (UTS) but lower yield strengths (YS), reduction in areas (RA), and elongation (Elong.). Also, all failures occurred outside of the weld areas (Table 3).

A737, GRADE B -The microstructure of A737, Grade B, was similar to that of the A633; blocky ferrite with carbide aggregate regions. However, in the A737 the carbide regions and ferrite structure were more refined plus the carbide aggregate did not form bands (Fig. 6). In the HAZ of A737 the microstructure transformed from that of the base plate to a more refine ferrite with the carbide aggregate becoming spheroidal and conglomerate. The HAZ adjacent to the fusion zone was a mixture of ferrite with aligned MAC and ferrite-carbide aggregate. The fusion zone of the A737 autogenous weld was similar to the HAZ; ferrite-carbide aggregate, grain boundary ferrite, and ferrite with aligned MAC (Fig. 7). The fusion zone of the A737 with the Inconel insert was a mixture of ferrite with aligned MAC structure and grain boundary ferrite. The microhardness of the autogenous and the Inconel insert welds ranged from 150 VHN in the base

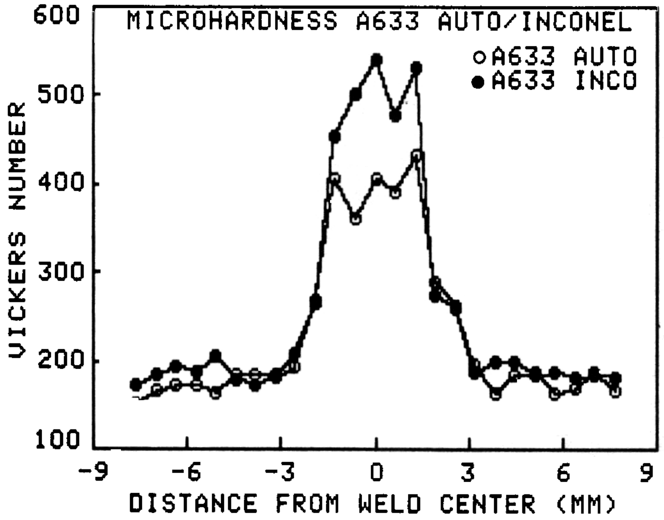


Fig. 5 Microhardness profiles of A633 autogenous and Inconel 600 insert welds (Nital Etch).

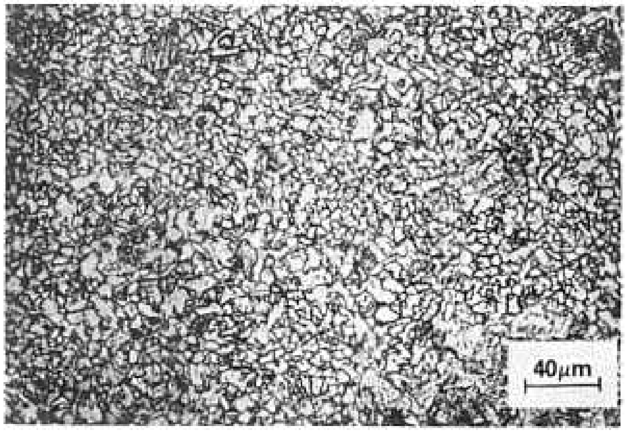


Fig. 6 Base plate microstructure of A737, Grade B. Note the blocky ferrite structure (Nital Etch).

plate of both to 450 VHN and 380 VHN, respectively, in the fusion zones (Fig. 8).

The YS and UTS of the autogenous and Inconel insert welds were approximately 34.5 MPa (5 ksi) higher than that recorded for the base plate properties. The failures in the weld tensile specimens occurred outside of the HAZ. There was no noticeable change in the RA values and only a slight decrease in the Elong. values (Table 2 and 3).

The Inconel insert welds had CVN values that were constant and were approximately 7 Joules (5.1 ft lbs) lower than the T-L direction CVN values from the base plate. This was true at all three temperatures. A similar result was true in the autogenous weld except at -51°C (-60°F) at which the CVN values dropped sharply and were 20.4 Joules (15 ft lbs) lower than the values recorded for the T-L direction of the base plate material (Tables 2 and 3).

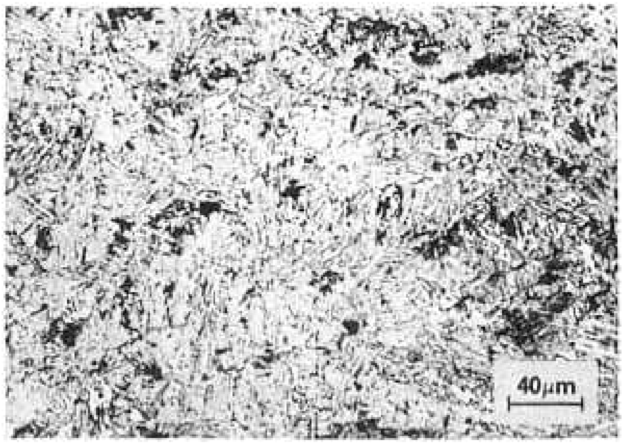


Fig. 7 Fusion zone microstructure of A737 autogenous weldment. Similar to fusion zone microstructure of A633 (Fig. 3) (Nital Etch).

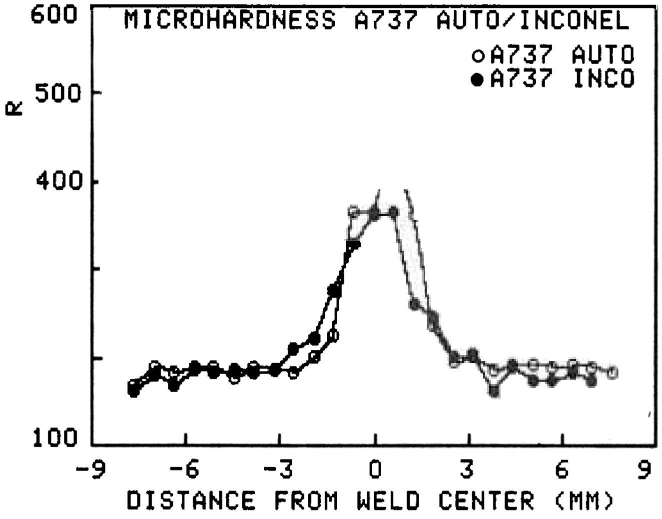


Fig. 8 Microhardness profiles of A737 autogenous and Inconel 600 insert welds.

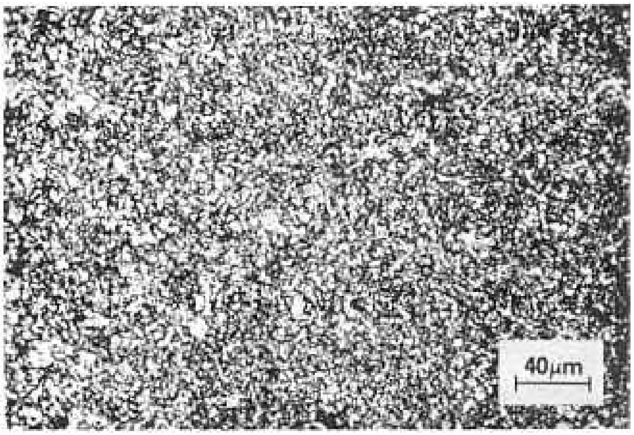


Fig. 9 Microstructure transition of A710/736 from the blocky ferrite base plate structure (left) to the refined structure at the beginning of the HAZ (right) (Nital Etch).

Table 2 Base Metal Average Properties

							Charpy V-Notch	Joules
	Direction	UTS, MPa	YS, MPa	%RA	%Elong	21°C (70°F)	-18°C (0°F)	-51°C (-60°F)
A633	T-L	604 (87.6 ksi)	451 (65.3 ksi)	67	31	44.9 (33 ft lbs)	44.9 (33 ft lbs)	25.8 (19 ft lbs)
	L-T	606 (87.8 ksi)	451 (65.4 ksi)	47	30	101 (74 ft lbs)	107 (79 ft lbs)	46.2 (34 ft lbs)
A737	T-L	601 (87.1 ksi)	458 (66.3 ksi)	41	28	31.3 (23 ft lbs)	35.3 (26 ft lbs)	32.6 (24 ft lbs)
	L-T	598 (86.7 ksi)	453 (65.6 ksi)	58	27	105 (77 ft lbs)	105 (77 ft lbs)	107 (79 ft lbs)
A710/736	T-L	709 (102.8 ksi)	630 (91.3 ksi)	75	29	204 (150 ft lbs)	216 (159 ft lbs)	221 (163 ft lbs)
	L-T	720 (104.3 ksi)	647 (93.8 ksi)	69	28	265 (196 ft lbs)	262 (193 ft lbs)	271 (200 ft lbs)

Table 3 Weld Metal Properties

					21°C (70°F)		Charpy V-Notch -18°C 90°F)		-51°C (-60°F)	
	UTS,MPa	YS,MPa	%RA	%Elong	Joules	ft-lbs	Joules	ft-lbs	Joules	ft-lbs
A633 Autogenous	610 (88.4 ksi)	396 (57.4 ksi)	43	20	25.9	19	15.0	11	13.6	10
A633 Inconel Insert	608 (88.1 ksi)	387 (56.1 ksi)	42	25	34.0	25	12.3	9	12.3	9
A737 Autogenous	618 (89.6 ksi)	484 (20.1 ksi)	46	19	23.1	17	35.3	26	12.3	9
A737 Inconel Insert	641 (92.9 ksi)	509 (73.7 ksi)	54	24	23.1	17	29.9	22	24.5	18
A710/736 Autogenous	670 (97.2 ksi)	562 (81.5 ksi)	59	23[1]	208[2]	153	109[2]	80	37.6[2]	28
A710/736 Inconel Insert	690 (100 ksi)	599 (86.8 ksi)	62	18[1]	168[2]	123	87.7[2]	65	21.8[2]	16

[1] Includes results from specimens that failed in the weld.

[2] Includes CVN results from specimens with solidification cracking and/or incomplete fusion.

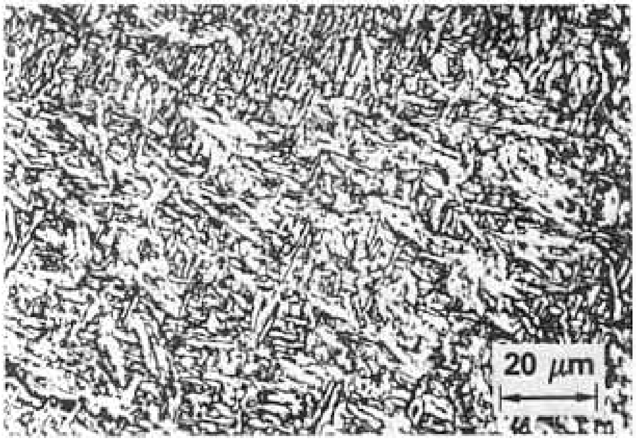


Fig. 10 Region of acicular ferrite structure in the fusion zone of A710/736 autogenous weld (Nital etch).

A710, GRADE A, CLASS 3 AND A736, CLASS 3- The microstructure of the A710/736 base plate was a very fine blocky ferrite with some small carbide aggregate regions located along the grain boundaries (Fig. 9). The HAZ near the base plate was similar to the base plate microstructure except the blocky ferrite was more refined and the carbide aggregate regions larger. The HAZ near the fusion zone was a mixture of martensite and ferrite with aligned MAC. The fusion zone of the autogenous A710/736 weld was a combination of acicular ferrite, ferrite with aligned MAC, and grain boundary ferrite (Fig. 10). The microstructure of the A710/736 Inconel insert weld fusion zone was a large grain martensite structure (Fig. 11). The microhardness of the A710/736 base plate was approximately 200 VHN whereas the autogenous weld fusion zone was 300 VHN and the Inconel insert weld fusion zone was slightly higher at 350 VHN (Fig. 12).

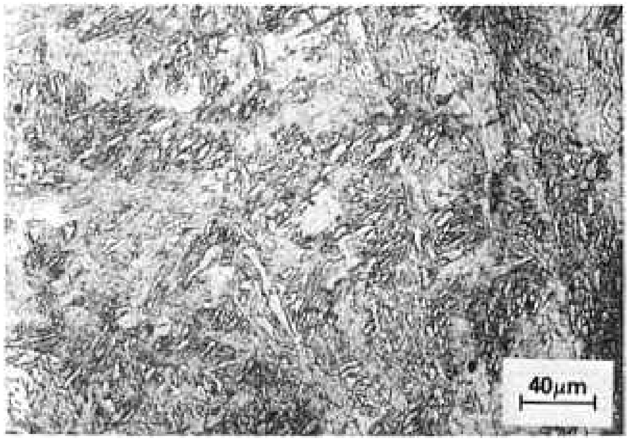


Fig. 11 Fusion zone microstructure of A710/736 weld with Inconel 600 insert (Nital Etch).

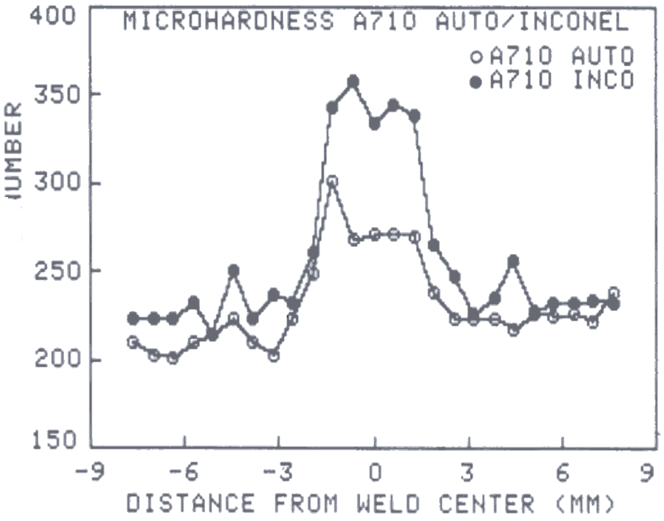


Fig. 12 Microhardness profiles of A710/736 autogenous and Inconel 600 insert welds.

The CVN results for the A710/736 welds were quite scattered. At 21°C (70°F) the autogenous welds ranged from 90 Joules (66 ft lbs) to 351 Joules (258 ft lbs) whereas the base plate T-L direction averaged 204 Joules (150 ft lbs) and the L-T direction averaged 265 Joules (195 ft lbs). At -18°C (0°F) the range of CVN values were 253 Joules (186 ft-lbs) to a low of 16 Joules (12 ft-lbs) and from 76 Joules (56 ft-lbs) to 11 Joules (8 ft-lbs) at -51°C (-60°F). The fracture surfaces of specimens with low CVN values were examined by the scanning electron microscope. The fracture surfaces of the specimens were found to have features associated with solidification cracking and/or incomplete fusion. The fracture surface of a specimen with a CVN value near that of the base plate was examined by SEM The surface was found to be covered with microvoid coalescence.

The mechanical properties of the A710/736 autogenous and Inconel insert welds were slightly lower than the base plate properties (Table 2 and 3). Three A710/736 (one autogenous and two Inconel) welds failed in the weld itself with the result being a significant drop in UTS and Elong. and in two of these three cases the R.A.

LASER WELDING EFFECTS ON HSLA PROPERTIES

The results of the CVN and mechanical tests of laser welded HSLA steels were not totally unexpected. Numerous papers have been published on the effects of alloy elements and/or cooling rates on the mechanical properties (8,9,10,11,12). In laser welding the solidification and quenching rates are much higher than that of conventional welding and therefore the use of most mechanical property plots as they relate to the nature of the material require some extrapolation for their use with laser welding. Such extrapolation would indicate a substantial decrease in the CVN values of the welds. However, in the case of A737 autogenous welds the results were not significantly lower than the results from the T-L direction of the base plate material. It appears that the composition of A737 is such that the rapid solidification and rapid cooling rate produces a microstructure with an acceptable fracture toughness or at least a fracture toughness comparable to the base plate material. Bernard examined a steel similar to A737 (13) and presents a continuous-cooling transformation (CCT) diagram that when extrapolated upon, agrees with microstructure observations made on the A737. He also presented diagrams relating cooling rate to hardness and impact toughness that are similar to the laser welded results.

Unlike A737, welds of A633 had a noticeable drop in the CVN values. This could be related to the difference between the composition of A737 and A633 which is that A633 has higher carbon, manganese and silicon levels. The increase in alloys in the A633 apparently produces an untempered martensite that is more brittle than that of the A737.

Along these same lines, the addition of the Inconel 600 to the weld metal appears to change the cooling rate/microstructure relationship very little since the CVN values are approximately equal between the Inconel and autogenous welds. However, in the A633 welds the Inconel lowers the CVN values even further. This again appears to be related to the composition/cooling rate/microstructure relationship which would affect the CVN results. In both the A737 and A633 the effects of Inconel additions to the toughness of the welds differ from results reported by Moon and Metzbower (7) and their work with Inconel additions to HY steel. It should be noted that the HY steels have lower carbon and manganese levels than either the A737 or A633.

The large range of CVN values for the autogenous welds of A710/736 at 21°C (70°F) and -18°C (0°F) indicated a possible weld defect related problem. This was supported by the observation of fracture features on the CVN specimens that were associated with solidification cracking and incomplete fusion which went undetected by radiography. The incomplete fusion is similar to the misaligned joints and resulting defects reported by Russell, Brown, and Adams (14) and their work with deep penetration electron beam welds. The solidification cracking, as in conventional welding, is associated with the heat input, weld pool shape, and solidification rate, all of which can be altered to eliminate the defect.

The higher CVN values of the autogenous A710/736 welds were comparable to the CVN values for the parent material. These values appear to be related to the acicular ferrite present in the fusion zone. The presence of the acicular ferrite in the fusion zone is somewhat unexpected because of the rapid solidification and high rate of cooling. Why acicular ferrite, normally formed by slow cooling, should be present in a rapid solidification and quenched system is unknown but could be related to the extremely low carbon levels (~0.03%) in the A710/736.

The average of the CVN values for the A710/736 autogenous welds decreased at lower temperatures (Table 3). Because of the large range of CVN values, a determination as to whether this decrease was related to a transition from upper to lower shelf fracture toughness was not possible. The decrease in the average CVN values with temperature and the wide range of CVN values were also common in the A710/736 welds with Inconel 600 inserts. However, the average CVN values for the Inconel insert welds were approximately two-thirds the averages of the autogenous A710/736 welds.

The extremely large increase between base material hardness and fusion zone hardness in the autogenous and Inconel insert A633 and A737 welds and also the fact that all tensile tests failed outside of the HAZ would indicate that the HAZ and fusion zone had higher UTS than the base plate material. In the A710/736 the mechanical properties (YS, UTS, RA, and Elong.) were all slightly lower than the base plate properties for both the autogenous and Inconel insert welds. This decrease and also the appearance of a fracture toughness transition temperature in the CVN results could be related to the fact that the A710/736 is a quench and precipitation heat treated steel. Since the precipitates go back into solution during the welding operation and are then rapidly cooled an additional heat treatment may be required for precipitate formation.

CONCLUSIONS

The results of microstructure observations and mechanical testing indicate that A633, A737 and A710/736 can be successfully laser beam welded autogenously and also with Inconel 600 inserts. The A633 and A737 autogenous and Inconel 600 insert welds had higher UTS values than base plate materials. The CVN values of autogenous A737 welds were comparable to base plate L-T CVN values except at -51°C (-60°F) whereas with an Inconel insert the CVN values were comparable at all temperatures to the base plate L-T CVN values. In A633 both the autogenous and Inconel insert CVN values were below those of the base plate material.

The mechanical properties of the A710/736 autogenous and Inconel insert welds were slightly lower than base plate properties. The autogenous weld CVN had a wide range of values but the higher values were equal to those of the base plate except at -51°C (-60°F). These higher values appeared to be related to the presence of acicular ferrite in the fusion zone. The lower values were associated with weld defects. A decrease in the average fracture toughness occurs with a decrease in temperature. Similar results were observed in the Inconel 600 insert welds.

These preliminary results indicate that three HSLA steels, A633, A737, and A710/736, can be successfully laser beam welded with only slight deterioration of the mechanical properties. With further work on the welding parameters and/or procedures, possibly welds with higher fracture toughness values can be achieved.

ACKNOWLEDGMENTS

The authors would like to thank and acknowledge the contribution of materials by Mr. R. Smith of ARMCO Steel Corporation and Mr. B. Moore of Phoenix Steel Corporation. We also thank Mr. E. Pierpoint for his technical assistance.

REFERENCES

1. Davies, G.J. and Garland, J.G., I. Met. Reviews, 20, 83-106 (1975)

2. Savage, W.F., Proc. of the Fifth Bolton Landing Conf., "Weldments: Physical Metallurgy and Failure Phenomena," Pub. General Electric Co., Schenectady, N. Y., 1-18 (1978)

3. Watson, M. N., The Welding Institute, private communication

4. Weber, J., AWS Weld. J., 62, 2, 22-26 (Feb 1983)

5. Metzbower, E.A., Naval Eng. J., 93, 4, 49-58 (Aug 1981)

6. Mazumder, J., J. of Metals, 34, 7, 16-24 (July 1982)

7. Moon, D.W. and Metzbower, E.A., Proc. from the Second Inter. Conf. on Application of Lasers in Mat. Processing, Jan 1983, "The Effects of Inconel 600 on the Toughness of HY Steel Laser Welds," to be published

8. The Welding Institute, private communication

9. Glover, A.G., McGrath, J.T., Tinkler, M.J. and Weatherly, G.C., AWS Weld. J., Welding Research Supplement, 56, 9, 2675-2735 (Sept 1975)

10. Hill, D.C. and Levine, E., Proceedings of The Metallurgical Society of AIME, Oct 1980, St. Louis, MO, "Physical Metallurgy of Metal Joining," Pub. of the Metal. Soc. of AIME, Warrendale, PA, 36-52

11. LaFrance, M.L., Canon, F.A., Launant, G.R. and Leclere, J., Proceedings of the Int. Symp. on HSLA Steels, "Microalloying '75," Pub. of ASM, Metals Park, OH, 367 - 374 (Oct 1975)

12. Meyer, L., Heisterkamp, F., Mueschenborn, W., Proceedings of the Int. Symp. on HSLA Steels, "Microalloying '75," Pub. of ASM, Metals Park, OH, 153-67 (Oct 1975)

13. Bernard, G., Proceedings of the Int. Symp. on HSLA Steels, "Microalloying '75," Pub. of ASM, Metals Park, OH, 552-66 (Oct 1975)

14. Russell, J.D., Brown, K.W. and Adams, M.J., Metal Construction and British Welding Journal, 4, 11, 131-39 (Nov 1972)