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Laser Beam Welding of HY80 and HY100 Steels Using Hot Welding Wire Addition

Good impact properties are attained in high-strength steels welded with the laser beam process using a preheated filler metal

BY R. H. PHILLIPS AND E. A. METZBOWER

ABSTRACT. Laser beam welds incorporating a hot welding wire filler metal addition technique have been successfully produced in HY80 and HY100 steels. Plate thicknesses of 13 and 26 mm were welded by this technique in these experiments.

This evaluation included radiographic and metallographic examinations, hardness traverses, Charpy V-notch tests over the temperature range −68° to 20°C and fractographic examinations.

Hardness traverses across the hot wire addition welds showed a significant reduction in weld metal hardness compared to the autogenous welds. The reduction in hardness was greater for the "fast" wire addition welds compared to the "slow" wire addition welds.

The hot wire feed speed also had a concomitant effect on weld metal microstructure. The slow wire feed speed resulted in a mixed martensite-bainite microstructure, whereas fast wire feed speed produced an acicular ferrite microstructure.

Charpy tests showed that hot wire addition significantly improved weldment toughness compared to autogenous welds at the plate sulfur level investigated (0.012 wt %) for both HY80 and HY100 steels. Toughness was further improved using a fast wire feed compared to a slow wire feed.

Introduction

Laser beam welding is a high productivity process that is traditionally used in the autogenous mode (*i.e.*, no filler metal is added to the weld pool). However, it can clearly be perceived that on specific occasions there would be distinct advantages and greater flexibility in deploying laser beam welding in the heterogeneous mode (*i.e.*, by use of filler metal additions to the weld pool). Several examples of laser beam welding incorporating cold welding wire feed have been reported in the literature in recent times (Refs. 1–3).

KEY WORDS

Feed Speed
Hardness Testing
Hot Welding Wire
Hot Wire Additions
HY80
HY100
Laser Beam Welding
Metallography
Microstructure
Steel Plate

The main advantages of laser beam welding in the heterogeneous mode compared to the autogenous mode can be considered as follows:

1) Confers the ability to alter the chemical composition and thus the microstructure of the weld metal. This in turn can result in improved mechanical properties of the weld metal, particularly notch toughness. It can also result in improved resistance to weld metal solidification cracking.

2) Results in larger fit-up tolerances.

3) Affords the opportunity for depositing high-quality multipass welds with reduced porosity, compared to autogenous weldments.

In the specific cases of HY80 and HY100 steels, the relatively high carbon (0.15–0.18 wt-%) and alloy content of the steels, together with the fast cooling rates associated with autogenous laser beam welding, ensures the formation of untempered martensitic microstructures in the weld metal. This can lead to the formation of weld metal with poor notch ductility (Refs. 4, 5).

By way of comparison, the weld metal deposited using conventional arc welding of HY steels characteristically has a relatively low carbon level ranging from 0.05 to 0.08 wt-%. Under appropriate welding conditions, this leads to the formation of an acicular ferrite microstructure with a concomitant high toughness profile.

The two methods of filler metal addition that appear to have the best potentials for use with laser beam welding are

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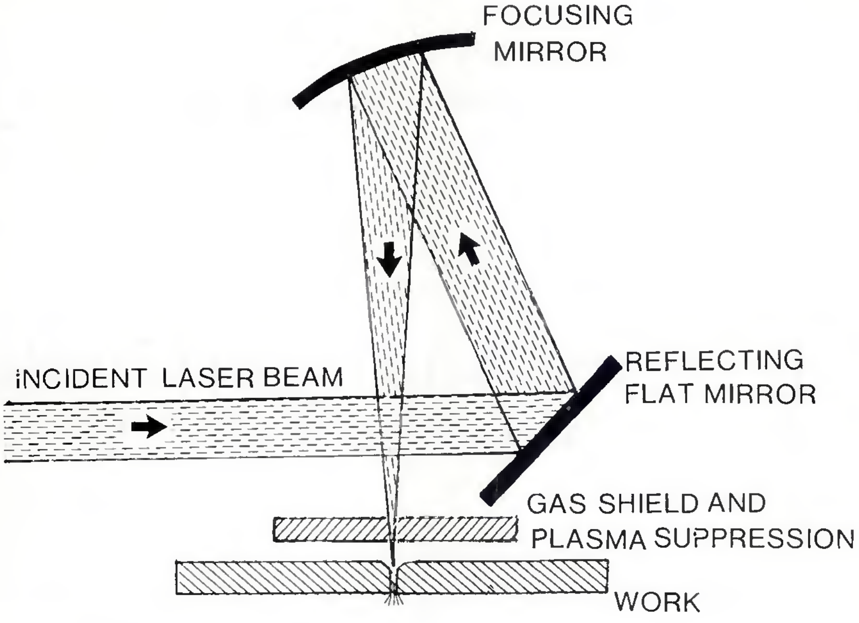


Fig. 1 — Schematic diagram of beam focusing arrangements and workstation.

welding wire addition or metal powder addition.

Of these, welding wire addition appears to hold the best potential, both from the viewpoint of metallurgical quality of the weld and also productivity. For instance, oxygen and hydrogen pickup in the weld metal would be far more of a problem for welding with metal powders than for welding with wire.

In the experimental work reported, a hot wire addition technique was used so that most of the energy from the laser beam was used to establish and maintain the keyhole rather than being partially dissipated in melting the filler metal.

The paper concentrates on the Charpy V-notch specimens since it has been demonstrated that the attainment of weldments with adequate mechanical properties in laser beam welds of HY80 and 100 is not a problem (Refs. 5, 6).

Experimental Procedure and Materials

A 15-kW continuous wave, carbon dioxide laser in the unstable resonator mode was used for these experiments (Ref. 7). A schematic diagram of the laser beam focusing arrangements is shown in Fig. 1. The horizontal output beam from the laser was reflected upward by a plane mirror into a downward-facing concave mirror with a focal length of 750 mm (29.5 in.) to provide welding conditions in the flat position. The plates to be welded were 150 X 300 mm (6 X 12 in.) thick, resulting in a 300 X 300-mm (12 X 12-in.) thick weldment.

A schematic diagram of the workstation including the hot wire feed unit is shown in Fig. 2A and in greater detail in Fig. 2B. The welds were made by moving the workpiece on a traversing table under the stationary laser beam. The angle between the normal to the plate and the laser beam was approximately 3 deg. Helium gas was used for plasma suppression as well as general area shielding of the weld.

Plasma suppression was achieved by directing a jet of helium gas through a 2-mm (0.08-in.) diameter stainless steel tube (hypo tube) at the point where the focused laser beam would impinge upon the plate surface. The hypo tube was set behind the laser beam at an angle of about 45 deg and was coplaner with the welding direction. The flow rate of the helium gas was approximately 3 L/min (1.4 ft^3/h)as determined by a gas flow meter calibrated for air.

Precise alignment of the joint to be welded was made using a helium-neon (He-Ne) laser, which was coincident with the CO_2 laser beam. Prior to welding, tack welds were made at both ends of the plate to be welded, which prevented relative movement between the two plates due to expansion and contraction of the plates during welding.

A longer focal length mirror of 750 mm was used for the hot wire addition experiments compared to a 500-mm (20-in.) focal length mirror for the autogenous laser beam welding experiments (Ref. 4). It was necessary to use the

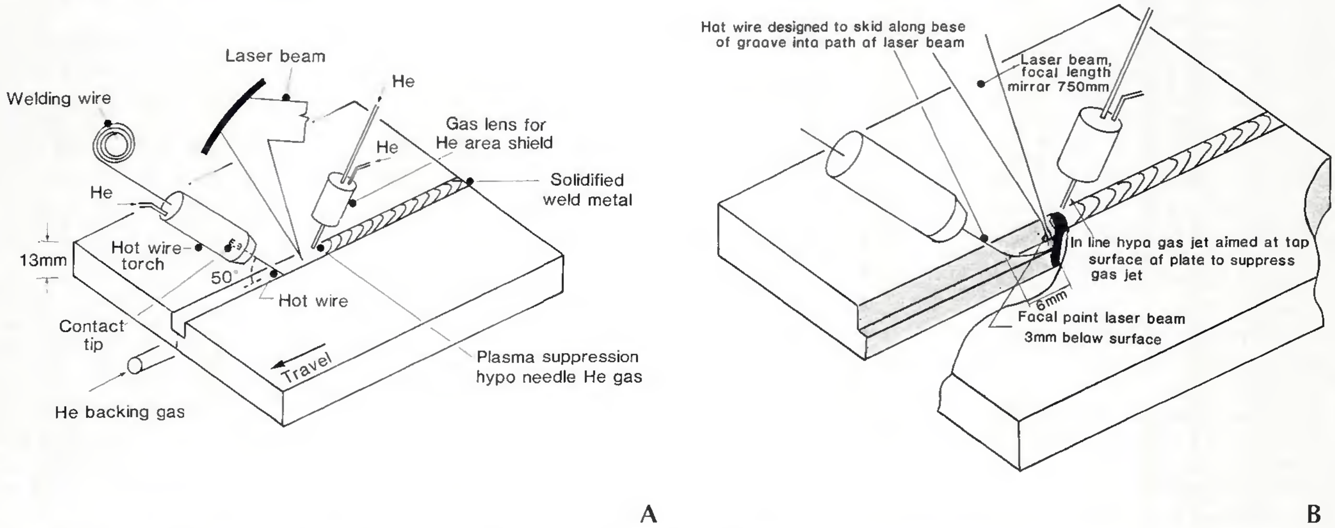


Fig. 2 — A — Schematic diagram of experimental setup for laser beam welding with hot welding wire feed; B — detail of hot wire filler metal addition.

Table 1—Composition of Experimental Materials

		Chemical Composition wt-%									
		C	S	P	Mn	Si	Ni	Cr	Mo	Cu	Al
Plate	13-mm-thick HY80	0.16	0.014	0.0007	0.32	0.18	2.32	1.41	0.29	0.13	0.03
	13-mm-thick HY100	0.16	0.016	0.005	0.26	0.21	2.66	1.47	0.41	0.15	0.02
	26-mm-thick HY80	0.15	0.002	0.005	0.31	0.31	2.24	1.37	0.28	0.17	0.05
Welding Wire	1.2-mm-diameter Airco AX90	0.065	0.004	0.006	1.50	0.21	2.10	0.10	0.47	0.04	
As-Deposited Weld Metal	13-mm HY80 with HWA[(a)] at 145 mm/s	0.10	0.009	0.007	0.63	0.29	2.18	0.94	0.36	0.09	0.02
	13-mm HY100 with HWA at 145 mm/s	0.10	0.009	0.006	0.87	0.28	2.16	0.70	0.47	0.10	0.03
	13-mm HY80 with HWA at 425 mm/s	0.06	0.005	0.008	1.08	0.26	2.28	0.37	0.47	0.08	0.02
	26-mm HY80 with HWA at 425 mm/s	0.07	0.003	0.006	1.16	0.40	2.02	0.35	0.45	0.09	0.03

(a) HWA is hot wire addition.

longer focal length mirror to enable the physical location of the hot wire so that the incoming laser beam would not impinge upon it. Although the longer focal length mirror has the advantage of having a greater depth of field, it has the disadvantage of having a larger spot diameter at the focal point and hence a somewhat reduced power density.

The hot wire feed unit consisted of a power transformer, a variable speed wire feed unit and the hot wire torch. The welding wire used in these experiments was 1.2-mm (0.045 in.) diameter Airco AX90 to MIL 100 S1 specification, and of the composition shown in Table 1. The wire was heated resistively with the extension from the contact tip being set at 40 mm (1.6 in.). Before commencing laser beam welding experiments, the power settings on the hot wire feed transformer were adjusted so that melting was just occurring at the wire tip and a molten bead would be deposited on the plate surface but not welded to it.The hot wire torch was set at an angle of 55 deg to the plate so that the wire intersected the bottom groove of the plate 6 to 8 mm (0.24 to 0.31 in.) ahead of the laser beam and then skidded into the beam path as shown in Fig. 2.

The experimental work was conducted in two stages:

1) Single-pass welds in 13-mm (0.5-in.) thick HY80 and HY100 plates incorporating the hot wire addition.

2) Multipass welds incorporating the hot wire addition in 26-mm (1-in.) thick HY80 plate.

In Stage 1 of the work, two edge profiles and two wire feed speeds were utilized. These are illustrated in Fig. 3.

Only a limited amount of work was carried out in Stage 2 and this was primarily directed at establishing the most appropriate edge preparation and welding conditions for the root pass.

The compositions of all experimental steels and the welding wire are shown in Table 1.

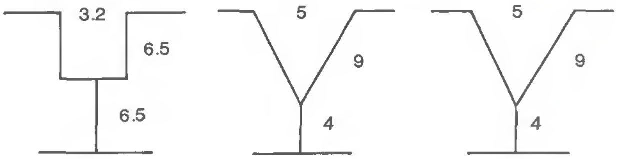
Two edge profiles were used in the experimental work (stepped and V-groove). In addition, two wire feed speeds were also used, (a slow speed of 145 mm/s, 5.7 in./min, and a fast speed of 425 mm/s, 16.7 in./min). Full penetration welds were produced in both HY80 and HY100 steels. The laser beam welding parameters used in these experiments were as follows: 1) a power input of 13 kW; and 2) a travel speed of 8.5 mm/s (20 in./min).

Results and Discussion

Welding Parameters and Characteristics

Good quality welds with acceptable penetration and top and bottom bead formation were produced at the slow wire feed regardless of whether a stepped or V-groove preparation was used. Radiographic inspection of the welds showed that both weld metal solidification cracking and porosity were markedly reduced compared to autoge-

EDGE PROFILES TRIALLED : 13mm THICK PLATE HY STEELS



EDGE PROFILE	STEPPED	V	V
hot wire feed speed	145mm/sec	145mm/sec	425mm/sec
plasma control	good	good	poor
weld appearance	acceptable top & bottom bead formation	acceptable top & bottom bead formation	acceptable top bead, unacceptable bottom bead lack of penetration
valid CVN	YES	YES	NO

Fig. 3 — Summary of edge profiles used.

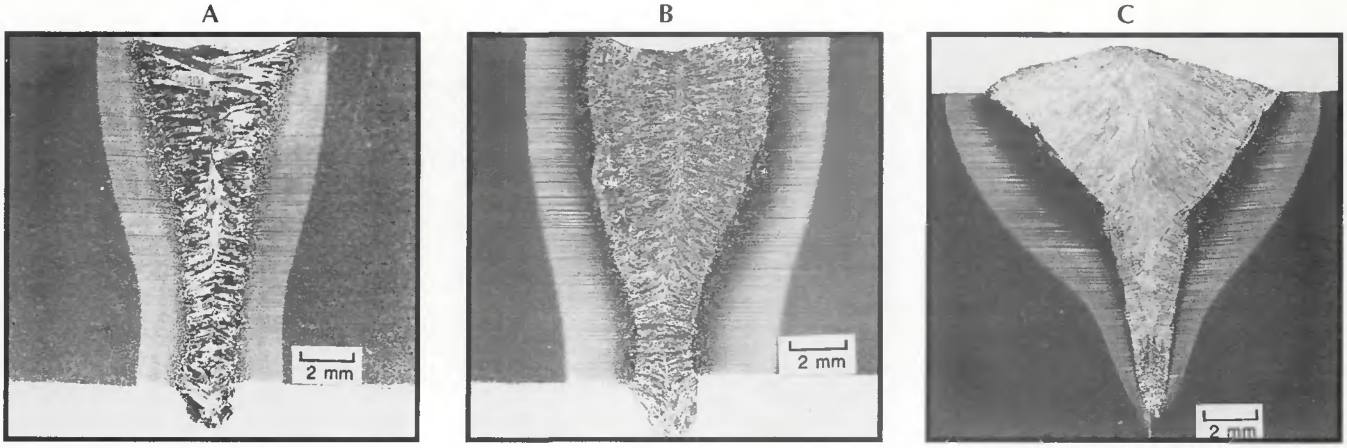


Fig. 4 — Comparison of weld bead profiles for laser butt joint welds in 13-mm-thick HY80. A — Autogenous; B — hot welding wire addition at 145 mm/s; C — hot welding wire addition at 425 mm/s.

nous welds with a similar sulfur level (Ref. 8). From an operational viewpoint, the plasma plume above the plate surface was readily controllable during welding although it was somewhat more sensitive to procedural variations than for autogenous welding.

At the fast wire feed speed, however, significant problems were encountered with plasma control, and poor quality welds usually resulted. In this case, although top bead formation was generally acceptable, there was frequently incomplete joint penetration and unacceptable bottom bead profile. This was probably a result of an incorrectly designed edge preparation. In particular, it appeared there was insufficient volume designed into the weld groove and weld overfill resulted, which in turn made plasma control more difficult.

In order to obtain valid Charpy-V notch (CVN) results for the fast wire feed situation, a further series of welds was made in 26-mm (1-in.) thick HY80 plate. During these experiments, the weld metal was generally constrained within the weld groove and good plasma control was observed with weld quality the result.

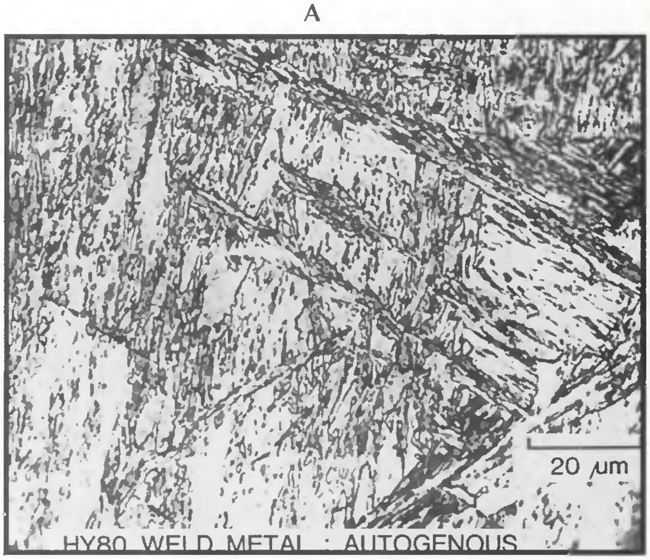
A comparison of weld bead profiles obtained for autogenous laser beam welding and laser beam welding with the slow and fast wire feed speed is shown in Fig. 4A, 4B and 4C. As expected, it can be seen that the weld nugget size progressively increases from autogenous welding through to the slow and fast wire feed speeds. It can be seen from Fig. 4C that the fast wire feed has resulted in the formation of an undesirable wine glass weld nugget profile. This problem would probably be alleviated by using a different weld groove configuration, e.g. a stepped profile with a greater volume capacity.

Chemistry

The chemical compositions of all plate materials, welding wire and resultant weld metal is shown in Table 1. Previous work (Ref. 8) has indicated that the composition of the fusion zone of autogenous weldments is essentially that of the base plate. It can be seen that the carbon, chromium and sulfur content of the weld metal decreases with increasing wire feed speed while the manganese and silicon content is increased. This is a result of the mixing of the weld metal and the base plate. At the higher wire feed, more welding wire is incorporated into the fusion zone.

The weld metal carbon level is of particular importance and is progressively reduced with increasing wire feed speed. From a plate carbon level of 0.16 wt-% C, the weld metal carbon level drops to 0.010 wt-% C for the slow wire feed and further to 0.06 wt-% C for the fast wire feed speed. This level is similar to that usually encountered with the conventional arc welding of HY steels. In a similar manner, the sulfur level is progressively reduced with increasing wire feed speed from 0.014 wt-% for the HY80 plate to 0.009 wt-% for the slow wire feed speed and further to 0.005 wt-% for the fast wire feed speed. It can thus be seen that carbon and sulfur content of the fusion zone is progressively decreased with increasing wire feed speed through the dilution effect of the filler metal.

Fig. 5 — Comparison of weld metal microstructures. A — Autogenous; B — hot welding wire addition at 145 mm/s; C — hot welding wire addition at 425 mm/s.



Microstructure

Clear differences are evident in the photomicrographs of the weld metal microstructures shown in Fig. 5. For the autogenous laser beam weld (Fig. 5A), the microstructure is primarily untempered martensite. The slow wire feed weld (Fig. 5B) results in a mixed martensite/bainite microstructure, and the fast wire feed weld (Fig. 5C) results in a microstructure that is primarily acicular ferrite. The differences are the same for both the HY80 and HY100 weldments. It should be noted that acicular ferrite is the preferred weld metal microstructure for optimum toughness when HY80 and HY100 are welded by conventional arc processes. Clearly, there is a critical parameter, based on the volume fraction of consumable wire in the weld metal and the cooling rate, that must be attained before an acicular ferrite microstructure is produced.

Hardness Profiles

The results of hardness traverses along the weldment cross-sections of the three laser beam welds are shown in Fig. 6. For the autogenous welds in HY80 and HY100, it can be seen there is a high hardness plateau of about 450 HV across the HAZ and weld metal. For the hot wire addition welds, the hardness profile alters significantly to become bimodal, with the maximum hardness of about 450 HV being achieved in the coarse-grained HAZ but reducing to lower levels in the weld metal. The biggest reduction in weld metal hardness occurs for the fast wire feed speed where the average weld metal hardness was 290 HV compared to a weld metal hardness of 350 HV for the slow wire feed speed and 450 HV for the autogenous weld.

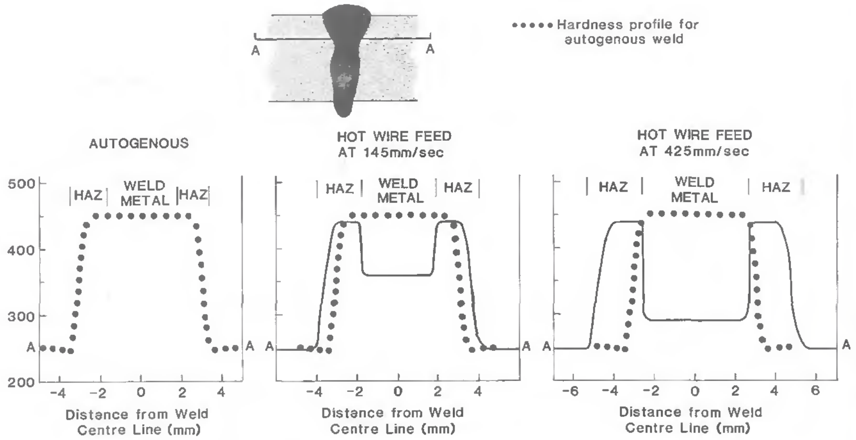


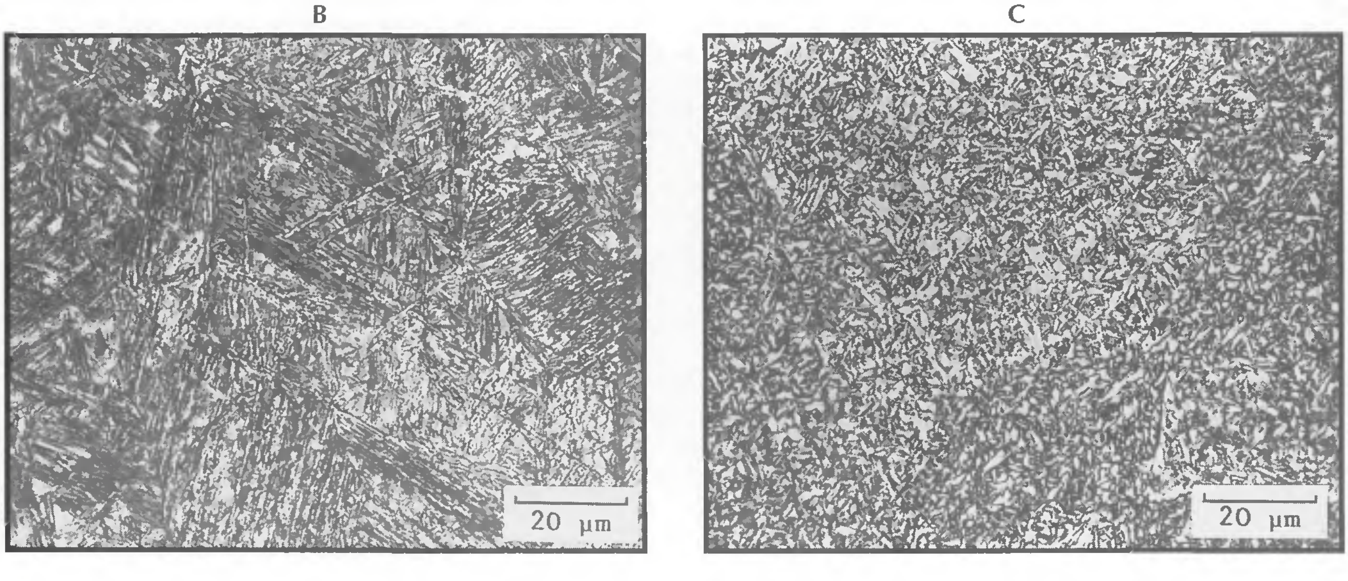
Fig. 6 — Comparison of hardness profiles across HY80 laser beam weldments.

Charpy V-Notch Results

Charpy V-notch (CVN) tests were conducted on slow wire feed speed welds (145 mm/s) made in 13-mm-thick HY80 and HY100, and fast wire feed speed welds, (425 mm/s) made in 26-mm-thick HY80 steel, covering the temperature range –68° to 20°C (–90° to 68°F). The notches were located in the fusion zone. These results are shown in Fig. 7 along with previous autogenous laser beam weld results in high-sulfur (0.012 wt-%) HY80 and HY100 steels. Also included for comparison is the U.S. Navy minimum CVN (Ref. 9) requirement for HY80 and HY100 weld metal. All data points are the average value of three tests.

It can be seen from Fig. 7 that the CVN values for both HY80 and HY100 welds produced using hot wire feed at the slow wire feed of 145 mm/s are very similar over the entire range tested and show a significant improvement compared to autogenous welds in these steels with sulfur levels of 0.012 wt-%. It can be seen that the toughness improvement is much more dramatic in the case of the HY100 welds, as the autogenous HY100 weld has a significantly lower toughness than the autogenous HY80 weld. Clearly, the introduction of filler metal has almost completely negated the unknown factor causing the difference in toughness between autogenous HY80 and HY100 welds.

The HY80 welds produced using the slow wire feed speed met the minimum U.S. Navy CVN requirement at –51°C (–60°F), but did not quite meet the requirement at –18°C (0°F), being about 5 J below the requirement. As these results represented the first iteration of experimental work in this area, it could confidently be anticipated that the U.S. Navy minimum CVN requirements would be met with some fine tuning of the experimental parameters. By comparison, the HY80 welds produced using the fast wire feed speed of 425 mm/s in 26-mm plate showed a significant im-



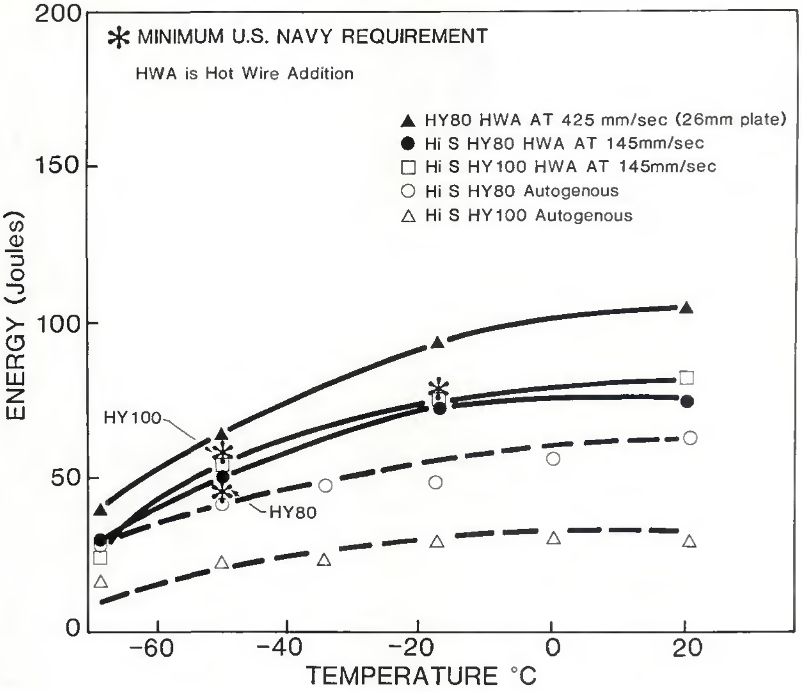


Fig. 7 — Comparison of weld metal CVN results for laser beam welds using hot welding wire addition.

provement in CVN values over the entire temperature range tested. These results comfortably met U.S. Navy toughness requirements.

From the results presented, it is apparent that the improvement in toughness from autogenous through slow wire feed to fast wire feed is primarily due to the changes in weld metal microstructure from untempered martensite through a mixed martensite bainite microstructure to acicular ferrite.

Fractographic Examination of Broken CVNs

The fracture faces of all CVN specimens broken at –51°C were examined using scanning electron microscopy (SEM) and are shown in Fig. 8A, B and C. The most outstanding difference between the SEMs is the proportion of microvoid coalescence present on the fracture surface. Autogenous laser beam welds in HY80 and HY100 showed a relatively low proportion of microvoid coalescence; being 25% for HY80 welds (Fig. 8A), and 20% for HY100 welds. For the slow wire feed welds in HY80 (Fig. 8B), the proportion of microvoid coalescence increased to 70% and even higher to 80% for the fast wire feed welds in HY80 — Fig. 8C.

Multipass Welding in 26-mm HY80 Plate

Only a small amount of exploratory work was conducted in this area, and most of it was concentrated on the investigation of root passes.

Welding Sequence and Edge Preparation

The overall concept of sequencing the multipass laser beam welding experiments incorporating hot wire addition into the molten weld pool is shown schematically in Fig. 9. Essentially, this involved depositing a full root penetration pass using a focused beam and hot wire addition, *i.e.*, a standard keyhole-type weld. It was proposed that subsequent passes would involve "out of focus" welding and hot wire addition. The main reason for attempting out of focus welding was to substantially reduce excessive porosity problems, which are traditionally encountered when using a focused beam in a non-penetrating situation. The objective was to obtain a U-shaped weld pool, as opposed to the spike profile which characterizes focused beam welding.

Two edge preparations were employed in these experiments, namely a stepped edge profile and a double V-groove profile. Both profiles incorporated butting root faces for the root pass. These are shown in Fig. 10.

Welding Characteristics and Weld Bead Profiles

First pass root welds incorporating a focused laser beam and the fast wire feed speed of 425 mm/s were deposited in 26-mm-thick HY80 plate using both the stepped and double V-groove profile. The laser beam welding parameters used in these experiments were 1) a power input of 15 kW, and 2) a travel speed of 8.5 mm/s.

The welding characteristics for the stepped profile groove weld were excellent, and plasma control presented no problem. During these experiments, the plasma appeared to be confined within

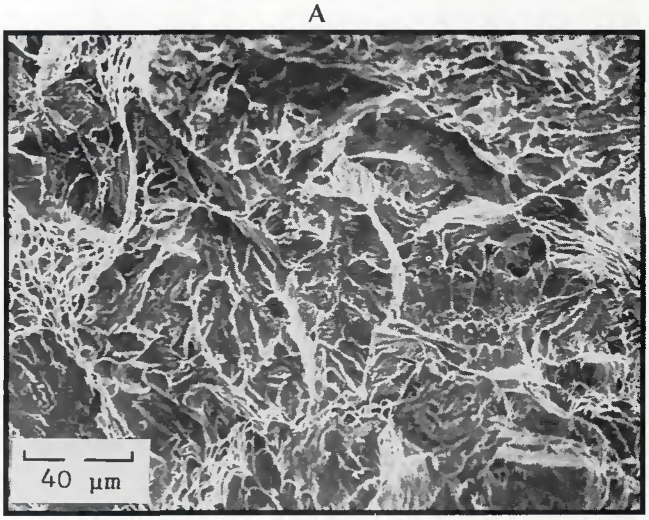


Fig. 8 — SEM comparison of weld metal fracture appearance (HY80 CVNs broken at –51°C) A — Autogenous; B — hot welding wire addition at 145 mm/s; C — hot welding wire addition at 425 mm/s.

the walls of the weld groove, a factor which probably assisted the plasma control greatly.

A visual inspection of the root pass showed a very good bead appearance, with the root surface in particular being very uniform. Radiography of the weld however showed extensive centerline weld metal solidification cracking although porosity was minimal. Metallographic sections were taken of both cracked and uncracked sections and these are shown in Fig. 11A and 11B. In an attempt to overcome the solidification cracking, further experiments were conducted using a preheat of 150°C (302°F). However, radiographic inspection of these welds showed that extensive solidification cracking was still present and that preheating did not appear to significantly reduce the problem.

It was deduced that weld metal composition was not the most important factor promoting cracking as both the carbon level (0.08 wt-%) and the sulfur level (0.003 wt-%) were relatively low. The main detrimental factors promoting cracking were probably the relatively high strain imposed by the 26-mm plate on the 12-mm-deep weld, the high depth-to-width ratio of 2.2:1, the primary solidification direction, and finally, the amount of low melting point segregates. In this latter respect, it can be seen from Fig. 10B that in the top section of the weld where cracking occurs, the weld metal solidification front sweeps laterally toward the centerline with no upward sweep so that all low melting point segregates are concentrated along a plane of weakness in the centerline. Lower down the weld, however, the solidification front tends to sweep upward, which probably has the effect of dispersing the low melting point segregates to some extent.

In the case of the double V-groove, acceptable full penetration welds were

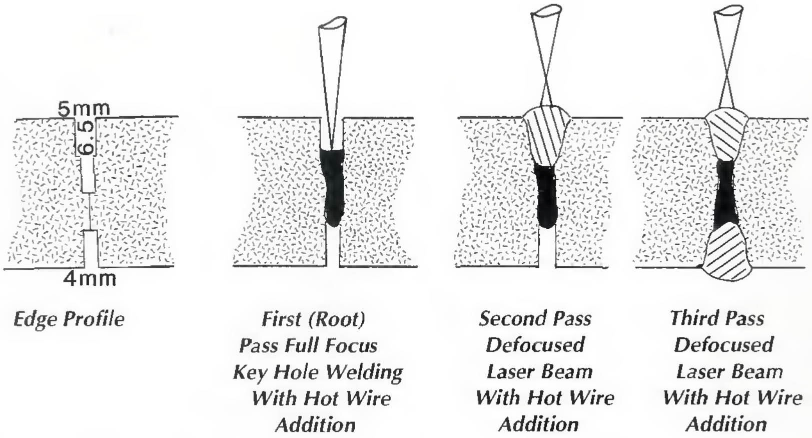


Fig. 9 — Concept of sequencing multipass laser beam welding experiments incorporating a hot welding wire addition.

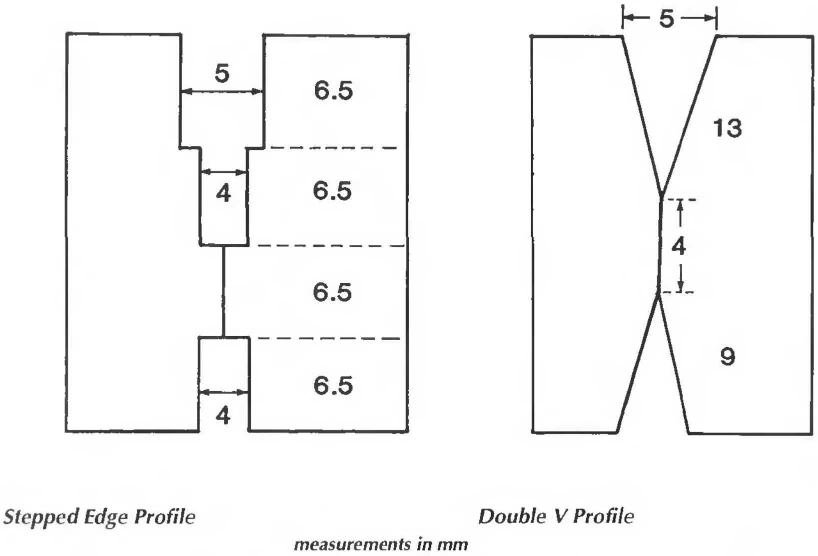
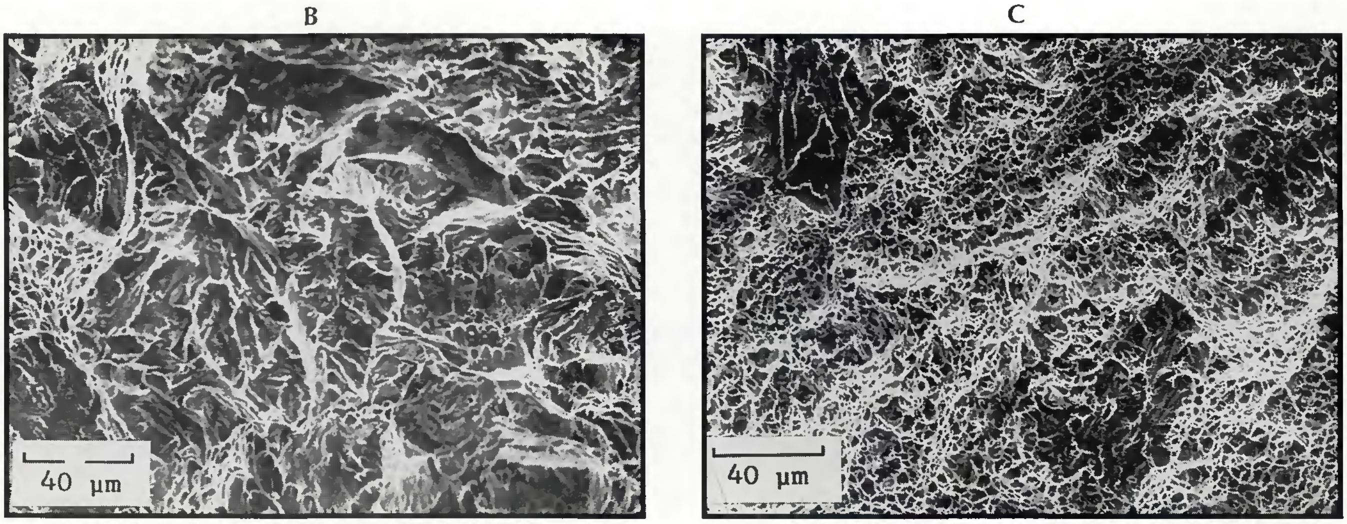


Fig. 10 — Edge preparations used for root pass experiments in 26-mm HY80 plate.



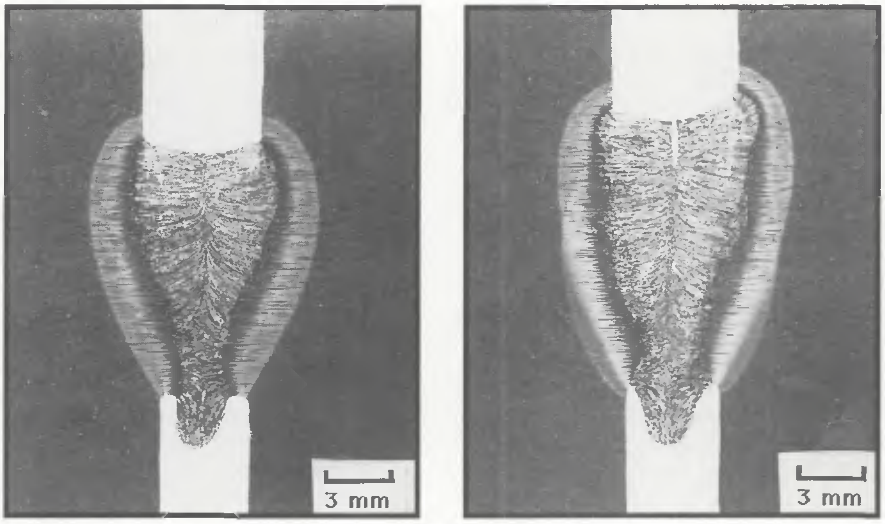


Fig. 11 — Left — Weld bead profile for root pass in stepped weld groove in 26-mm plate using a hot welding wire addition at a feed rate of 425 mm/s, no solidification cracking; right— weld bead profile of root pass in a stepped square-groove in 26-mm plate using a hot welding wire addition at a feed rate of 425 mm/s, centerline weld metal solidification cracking is evident.

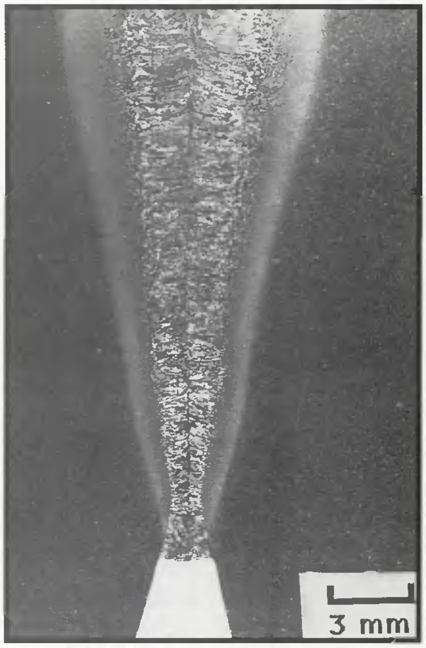


Fig. 12 — Weld bead profile for a root pass in a double V-groove on 26-mm plate using a hot welding wire addition with a feed rate of 425 mm/s.

produced, although the welding characteristics were not as stable as for the stepped square-groove. Since plasma control was somewhat more difficult, radiographic examination showed only minor porosity, although some intermittent weld metal solidification cracking was present. A macrosection of a completed weld is shown in Fig. 12. It is particularly interesting to note that the single-pass cross-section is 20 mm deep not counting the extra 2 mm of weld metal with no sidewall fusion at the bottom of the bead. It can be seen that a completed weld in 26-mm plate could easily be made in two passes and that a low-penetration, high-speed weld could be used for the second pass.

Conclusions

Single-pass laser beam welds incorporating a hot wire filler metal addition technique have been successfully produced in 13-mm-thick HY80 and HY100 plate.

The level of weld metal solidification cracking and porosity in the single-pass hot wire addition welds in 13-mm HY80 and HY100 was significantly less than that encountered in autogenous laser beam welds in HY80 and HY100 plates at similar sulfur levels (0.014 wt-%).

Weld metal CVN values for the hot wire filler metal addition welds in both HY80 and HY100 were significantly higher than those obtained for autogenous laser beam welds at similar sulfur levels. Toughness was further improved using a fast wire feed speed of 425 mm/s compared to a feed speed of 145 mm/s.

For the welds investigated, the weld metal microstructure was the most important factor determining toughness. The weld metal microstructure was itself primarily determined by the wire feed speed as it affects dilution. In this respect, welds produced using the fast wire feed speed resulted in an acicular ferrite microstructure, whereas welds produced using the slow wire feed speed resulted in a mixed martensite/bainite microstructure. By contrast, autogenous laser beam welding of HY80 and HY100 resulted in an untempered martensitic microstructure.

In the multipass laser beam welding of 26-mm-thick HY80 incorporating hot wire filler metal additions, weld metal solidification cracking was found to be the main problem encountered in depositing the root pass.

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