技術解説

Technical Review

Adaptive Control of Hybrid Laser-Arc Welding

C.M. Allen, G. Shl, P.A. Hilton and J.G Wylde

TWI Japan/UK Dodwell, 03-5826-7375, dodwell@d1.dion.ne.jp, http://www.twi.co.uk

はじめに

不断な産業界の技術革新は溶接の分野も同様で，コスト削減，生産性／品質向上への開発努力は溶接機器，材料，開発，生産技術，自動化など多岐に亘り，その実現の為にはより緻密な制御が求められつつある。

多くの利点を持つ自動溶接は既に一部の産業分野で使われているが，現場の溶接局部はギャップの変化，目違い等により溶接条件が刻々変わり，これ等の変化に瞬時に対応し溶接品質を安定的に確保するには課題も少なくない。従来レーザー／アークハイブリッド溶接は熟練を要するマニュアルシステムが多いが，本稿はレーザーセンサーを用いたハイブリッド溶接におけるアダプティヴ制御について，TWI における近年の研究成果の一部を下記に紹介し自動化の普及に資する。

1. Introduction

Technology in every field is continually developing and welding is no different. In addition to developments in conventional welding processes such as arc and resistance welding, newer approaches involving frictional techniques and the use of power beams are finding more applications. There are many reasons for this. Industry is continually seeking to reduce costs while increasing productivity and maintaining or improving quality. Most traditional welding processes are manual and require skilled operators. In many markets skilled welders are becoming hard to find as fewer young people see welding as an attractive profession.

This has fuelled a drive towards more semi - or fully automated welding systems. For certain applications, e.g. circumferential pipe welding, this can be more readily achieved because the joint geometry is relatively simple. However, for general fabrication introducing automated welding systems is more complex. In addition to these trends, developments in equipment, both for arc and power beam welding, are continuing. Thus providing additional opportunities for automation.

One area which has attracted a lot of interest is laser welding. This has been used for many years for high speed, low distortion and/or thicker section applications where cost savings can be realized. However, the use of a laser has certain limitations. Not least of these is the limited ability to cope with variable fit-up between work pieces, which is all too common in the fabrication environment. As mentioned above, laser power sources are developing rapidly, and the relatively recent Yb-fibre and Yb:YAG disk lasers offer a significant step forward in terms of power and penetration potential, but the very high inherent beam quality exacerbates the issue of improving existing tolerances to variable fit-up.

One way of overcoming this issue, enabling us to take advantage of laser power source developments, has been hybrid laser-arc welding. Here, an arc welding power source, typically MIG, can be combined with the laser power source in the same welding head to provide increased fit-up tolerance while still maintaining good weld profile characteristics and welding speed. This all represents excellent progress, but a key issue still facing the application of hybrid laser-arc welding in a production environment remains the ability to cope with changes in fit-up. Thus, if we have a fixed gap, we can modify the hybrid welding parameters (within certain limits) to cope. However, if the gap varies, perhaps due to distortion of work pieces, or variation in positioning and fixturing, this creates a problem.

Recent work at TWI on adaptive control of the hybrid laser-arc welding process[1] has shown that this approach offers the potential to cope with variable gaps. In adaptive control, a second scanning laser is used ahead of the welding head. This identifies the position of the joint, the gap and any hi-lo mismatch between the work pieces. This information is fed back into the welding controller which selects appropriate parameters from a database of pre-determined conditions covering the range of variables within the capacity of the process. This is shown diagrammatically in Fig. 1.

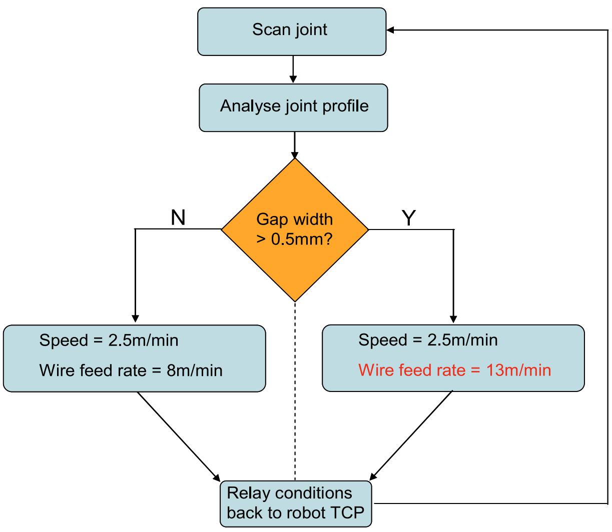


Fig. 1. Example of adaptive control algorithm.

In order to develop the basic data, a range of trials are carried out looking at the optimum welding parameters for a range of gaps and hi-lo variations. This short paper summarises some of the recent work at TWI.

2. Experimental

2. 1 Equipment and Materials

An IPG YLS-5000 Yb fibre laser was used in welding trials, with a calculated focused spot diameter of 0.28 mm. The beam focusing optics were mounted on a Kawasaki FS-060L robot. The optics were protected from fume and spatter using an air-knife and an appropriate cover slide. All trials were performed in the flat position, with the laser beam at 90° to the workpiece surface. A measured laser power of 4.8 kW at the workpiece was used.

When hybrid welding, an ESAB PSF 410 MW metal active gas (MAG) welding torch was also used, with an AristoFeed 30 wire feeding unit, U8 controller and AristoMIG 450 arc power source. All welds were made using a laser-leading configuration. The separation between the laser and the arc was set to 2 mm. A contact tip to workpiece distance of 15mm was used, with a work angle of 60° (pushing) for the MAG torch. A synergic pulsed metal transfer mode was also used, with a 1.2 mm diameter A18 grade solid wire consumable. The weld top bead was shielded by 20 l/min of argon through the torch. The weld under bead was shielded by 2 l/min of argon.

All trials were carried out on 8 mm thick S355 grade structural steel plates. These were laser cut to size, acetone degreased, disc ground back to bright metal, and then degreased again before welding.

2. 2 Experimental Procedure

Initially, laser only butt welding trials were carried out at a range of welding speeds (0.9-2.2 m/min) to determine a suitable joint preparation and welding speed for the hybrid trials that followed. Optimum hybrid welding conditions to produce ISO 13919-1:1997 Class B quality welds (the most stringent weld quality class in this standard) were then determined for close fitting joints.

A series of trials were then carried out to establish the tolerance of these hybrid conditions to joint mismatch or joint gap. Further trials were then carried out on a range of samples in which a range of gaps were deliberately introduced, as well as a range of hi-lo mismatch. In each case, the welding conditions were varied to establish suitable parameters to produce class B welds.

The above conditions were then used as control points for the adaptively controlled trials. A Servo-Robot Digi-I/S laser vision sensor with V300 control unit, communicating with a Kawasaki D+ robot controller, was used. Welds were made over joints with either varying amounts of joint gap or joint mismatch, with welding conditions being changed in real time.

Changes in welding (robot) speed and robot position were effected by relaying joint fit-up information from the V300 unit to the D+ controller, then referencing a look-up table written within the D+ controller software. For example, this table may call for a reduction in robot speed and the introduction of an offset of the robot tool centre point off of the joint line, when a joint mismatch over a given height is detected. Changes in wire feed rate were effected using an ADAP software module in the V300 unit. Thus the wire feed rate was adjusted in real time as a function of the joint gap. A suitable time delay between the generation of the signal and its transmission to the arc welding power source was used, to allow the robot tool centre point to catch up with the point at which the laser vision sensor had collected the information on joint gap.

3. Results

Initial hybrid trials were carried out on close fitting, flush plates, using a V butt joint preparation with a 6mm root face and a 60° included angle. A visually acceptable weld top bead appearance was achieved, with slightly convex profile and minimal undercut, using a wire feed rate of 7 m/min and a -3V arc voltage trim. Radiography indicated internal porosity contents to Class B. Fig. 2 shows a cross-section of a weld made with these conditions. The weld cap had minimal undercut (0.16 mm) and an excess penetration of 0.5 mm, i.e. conforming to class B.

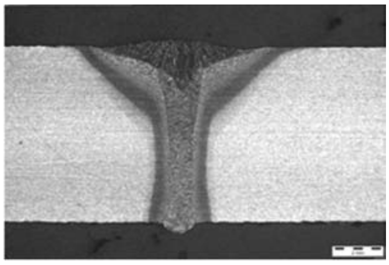
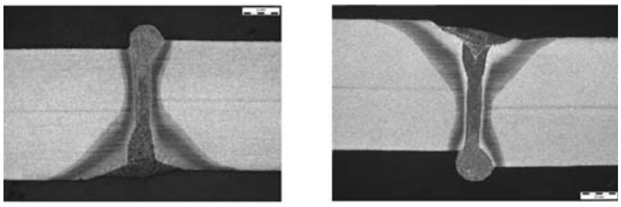


Fig. 2. Cross-section through hybrid weld made over flush, close fitting V butt joint. 2 mm scale bar.

The same conditions were also used to weld joints with up to 2 mm hi-lo mismatch. Figs. 3a and 3b show sections from such welds with 0.6 and 1.0mm mismatches. This shows that a Class B root and cap profile were achieved to a mismatch of 0.6mm (Fig. 3a), with the root toe blend angle becoming re-entrant on the higher plate when the mismatch increased to 1.0mm (Fig. 3b).



a) 0.6 mm mismatch b) 1.0 mm mismatch

Fig. 3. Cross-section s through hybrid weld made over joint. with hi-lo mismach. of 0.6 mm a) and 1.0 mm b).

At higher hi-lo mismatch values, the weld root was both re-entrant and also undercut. Radiographs of these welds indicated that class B quality was achieved to mismatch values of at least 0.6 mm, with chain or clustered porosity and lack of penetration defects present at higher values of mismatch. These trials showed, therefore, that the conditions suitable for welding flush, close fitting joints, could also be used to produce Class B welds for a hi-lo mismatch up to 0.6 mm.

Trials were also carried out on joints with various gaps between the plates using the same welding parameters. These trials showed that the base conditions could also be used to weld joints with gaps up to 0.3 mm.

A range of other welding conditions were then examined, to improve the weld profiles for a range of hi-lo mismatch and gaps. In terms of coping with increased hi-lo mismatch, one or more of the following changes were introduced:

- A reduction in welding speed.
- Deliberately offsetting the laser beam off of the joint line (by offsetting the welding head).
- Using different laser focus positions.

These results suggested that a change in laser focus position was the best way to achieve a modest (<25%) improvement in mismatch tolerance (Figure 4).

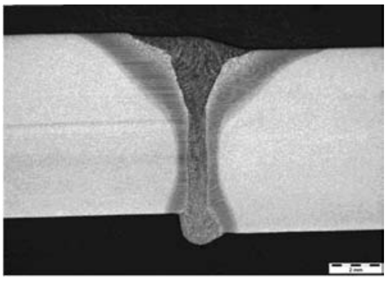


Fig. 4. Cross-section through hybrid weld made over joint. with 0.8 mm of mismach, focusing laser 2 mm below top of root face.

In terms of coping with increased gap, one or more of the following changes were introduced:

- Increasing the wire feed rate and/or arc voltage trim.
- Reducing the welding speed.
- Focusing the laser 4mm above the top of the root face.

The results from these trials suggested that adaptive changes in both welding speed and wire feed rate would be the best option, and allowed for a ～ 200 % improvement in gap tolerance (Fig. 5).

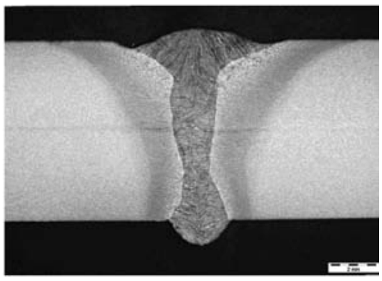
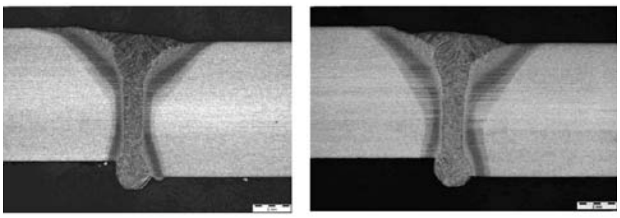


Fig. 5. Cross-section through hybrid weld made over joint with 0.5 mm wide gap, welding at 1.2 m/min with wire feed rate of 9 m/min.

Adaptive trials were then carried out as described above, the welding controller selecting the appropriate welding conditions, for the joint geometry as determined from the laser scan. Trials were performed using joints with hi-lo mismatch, a tapering joint gap and with a combination of the two. The welding speed, wire feed rate and laser focus position and/or laser beam offset were varied in real time during the welding.

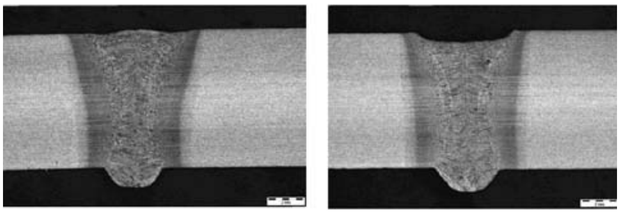
In terms of coping with hi-lo mismatch, the most successful results were achieved by adaptively reducing welding speed. Figs. 6a and 6b show the weld profiles achieved from the same weld, over joint mismatches of 1.0 and 1.2 mm, by adaptive reduction of welding speed from 1.6 to 1.2m/min. As Figs. 6a and 6b show, an acceptable weld root profile has been achieved with this approach, to a mismatch of at least 1.0 mm.



a) 1.0 mm mismatch b) 1.2 mm mismatch

Fig. 6. Cross-section through adaptively controlled hybrid weld made over joint with hi-lo mismatch of 1.0 mm a) and 1.2 mm b).

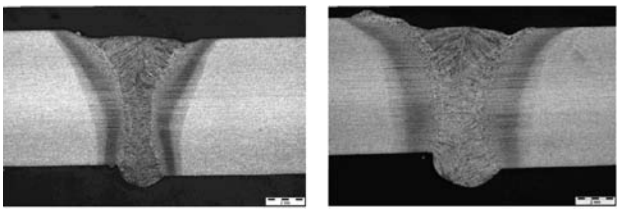
In terms of coping with a tapering joint gap, the most successful results were achieved by adaptively reducing the welding speed and increasing the wire feed rate. Figs. 7a and 7b show the weld profiles achieved at joint gaps of 0.6 and 0.9 mm, from the same weld. As Figs. 7a and 7b show, an acceptable weld cap profile is achieved to a gap width of at least 0.6 mm, twice that achieved without adaptive control. An ISO class C weld was achieved over a 0.9 mm wide gap, but at gaps >1 mm, weld cracks and lack of sidewall fusion defects were detected.



a) 0.6 mm mismatch b) 0.9 mm mismatch

Fig. 7. Cross-section s through adaptively controlled hybrid weld made over joint with gap of 0.6 mm a) and 0.9 mm b).

The most effective approach for joints with a combination of both hi-lo mismatch and gap was achieved via adaptive control of the welding speed and wire feed rate (Fig. 8)



a) 0.65 mm mismatch, 0.5 mm gap. b) 1.0 mm mismatch, 0.85 mm gap.

Fig. 8. Cross-section s through adaptively controlled hybrid weld made over joint with both mismatch and gap.

0.65 mm mismatch and 0.5 mm gap a)
1.0 mm mismatch and 0.85 mm gap b)

4. Discussion

In the current work, the gap tolerance of the hybrid process with a high brightness Yb fibre laser without using adaptive control is 0.3mm, to produce class B welds over broad root face V butt joints in 8mm steel plate. This has been doubled by using adaptive control. However, this maximum is still only 0.6mm. This more modest result can be attributed to the 60 ° V butt joint configuration used, necessitating the use of high wire feed rates to achieve a weld profile with acceptably low levels of underfill. With an alternative choice of joint configuration, weldable with higher output power levels, a greater maximum gap tolerance for class B welds would be anticipated.

Tolerance to joint mismatch has also been increased through the use of adaptive control and class B welds can be achieved across a hi-lo mismatch value of at least 1 mm.

The individual tolerance limits to either gap or hi-lo mismatch are reduced when both are present. The limits are 0.5 and 0.65 mm for class B welds, respectively, compared with 0.6 and 1 mm, if only gap, or mismatch, is present. Nevertheless, class C welds can be achieved over combinations of 0.85, and 1 mm, respectively, with adaptive control.

5. Conclusions

Hybrid welding using a 5kW fibre laser can produce ISO 13919-1 class B butt welds in 8mm thickness steel with a 60° V butt joint configuration when either joint gaps of 0.3 mm width, or mismatches of 0.6mm height, are present.

With adaptive control of welding parameters, the tolerance limits for class B welds can be extended to 0.6 or 1 mm, respectively.

Hybrid welding can also be adaptively controlled to cope with combinations of gap / hi-lo mismatch, to 0.5/0.65 mm (class B) or 0.85/1 mm (class C).

Reference

1) C.M. Allen, G. Shi and P.A. Hilton:Adaptively controlled hybrid welding using a high brightness laser, ICPBT, 2010

Appendix

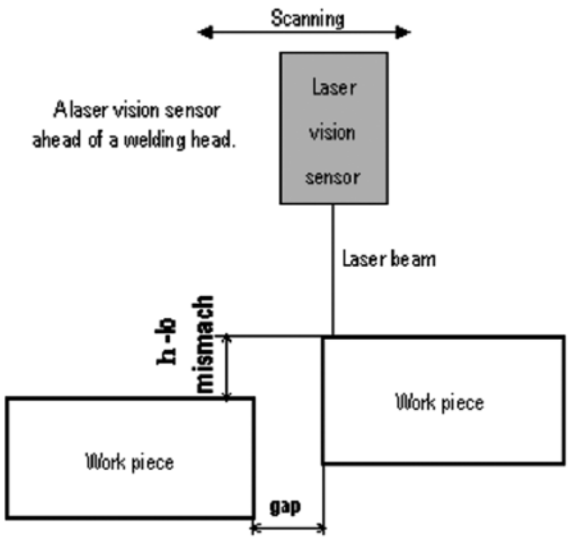


Fig. 9. Difinition of hi-lo mismatch and gap.