HENRY GRANJON PRIZE COMPETITION 2005 Winner, Category A "Joining and fabrication technology"

NOVEL WAYS OF USING ND:YAG LASER FOR WELDING THICK SECTION AUSTENITIC STAINLESS STEEL

T. Jokinen
VTT Industrial Systems (Finland)
E-mail: tommi.jokinen@vtt.fi

ABSTRACT

Hybrid welding has been introduced as a process that combines one laser and one arc welding process to work together. These advanced joining processes are effective and outweigh several drawbacks of mere single methods. Hot spots, made by laser to the joint, have been reported to stabilise the arc and change the way of material transfer in the arc. The arc is also attracted and constricted by the hot spot. This phenomenon has been utilised in this study in order to get the process adaptable inside very narrow grooves. This novel approach, combined with multi-pass techniques, enables a considerable increase in the thickness of the parts to be welded. Welding continues to employ rather low total heat input levels and, consequently, results in very low thermal distortions in joining thick sections. As the process retains a keyhole typical of high energy density welding, the process is also very effective for joining thick sections. Based on the above argument, the process further developed in this study should be considered when evaluating welding processes for joining vacuum vessel sectors of ITER. The same certainly applies to many other demanding thick sections and hence heavy high precision components.

IIW-Thesaurus keywords: *Laser welding; Photon beam welding; YAG lasers; Lasers; Radiation welding; MIG welding; Arc welding; Gas shielded arc welding; GMA welding; Combined processes; Austenitic stainless steels; Stainless steels; Steels; Filling passes; Process parameters; Process conditions; Reference lists; Practical investigations.*

1 INTRODUCTION

Hybrid welding means the coupling of the energy of two different energy sources into a common process zone. This means that laser beam and arc interact simultaneously in the same region (plasma and weld pool) and mutually influence the accomplishment of welded joint. Synergistic effects from coupling incorporate the increase of penetration and hence welding speed. There are, however, further reasons for experimenting and introducing this hybrid technology to applications. Major advantages originate from the gap bridging ability of the process. Mere laser welding sets high demands on tolerances in groove manufacturing and fixturing to control the constancy of the tight fit necessary. Also, movements of the work-pieces that stem from thermal distortions during welding can adversely affect mere laser welding by increasing the root gap. Hybrid welding is much less sensitive to these kinds of problems. On the other hand, traditional arc welding often requires costly postweld treatments such as flame straightening to compensate thermal distortion. By hybrid welding, distortions can be reduced due to significantly lower heat input compared to arc welding. Hybrid welding is also more of a keyhole process than conduction process. Thus, thermal deformation of the work-piece mainly takes place in the plane with minimal angular distortions. These advantages of hybrid welding open technically and commercially interesting possibilities for a multitude of applications e.g. in workshops that handle large plates and structures. One shipyard and one car manufacturer have already successfully utilised this opportunity, for example [2-10, 12, 13].

Hybrid welding has mainly been introduced in applications where thicknesses allow single pass welding. Likewise, experimental work has focused on single pass welding. According to the published data, this means plate thicknesses up to 12, 16 mm. The limiting factor for increasing plate thickness in single pass welding is the power of the laser. Naturally, it has become possible to exceed the above weld thicknesses using expensive high power lasers. Medium power lasers enable,

Doc. IIW-1702-05 (ex-doc. IV-884-05) recommended for publication by Commission IV "Power beam processes".

however, the welding of very thick steel plates applying two alterations to the high power approach:

(i) a bevelled groove preparation in between the plates to be welded, and

(ii) a multi-pass welding technique.

Here, hybrid welding shares the excellent opportunity to use medium power lasers for thicker sections with laser welding with filler wire. Reduction in necessary laser power means capital cost reductions, but still allows more effective joining than multi-pass arc welding [1, 5, 11].

VTT Industrial Systems has been involved in several EU-ITER tasks in which suitable joining processes have been examined and considered for manufacturing a vacuum vessel of a fusion reactor, c.f. Figure 1. The ITER vacuum vessel sectors, made of 60 mm thick stainless steel, have to be welded together on site and hence cost, welding time and distortion issues become critical. The necessity of site welding, together with the complicated geometry of the vessel, set a prerequisite for excellent position welding capabilities. Therefore, Nd:YAG -laser based solutions were judged as potential due to the flexible transmission of laser light via optical fibre.

VTT subjected a hybrid process comprised of a combination of Nd:YAG -laser and MIG welding to a closer experimental study. The aim was to reveal the key controlling parameters of the process and via their optimisation to demonstrate the feasibility of hybrid welding the walls of the vacuum vessel.

2 EXPERIMENTAL PROCEDURE

2.1 Laser and auxiliary equipment

Welding experiments were performed by 3 kW Nd:YAG laser using fibre optic beam transfer (HAAS-LASER GmbH model HL 3006 D). The diameter of the optical fibre was 0.6 mm. The beam parameter product of 25 mm*mrad derives from this figure and the focusing system of the resonator. The full 3 kW laser light power was used in the experiments and it was measured at the surface of the work-piece. A focusing optic with a focal length of 200 mm was used in each test run and this resulted in a focus point diameter of 0.6 mm and a focusing angle of 6,12°.

The MIG welding machine used was built with inverter technology and incorporated a fully synergetic control.

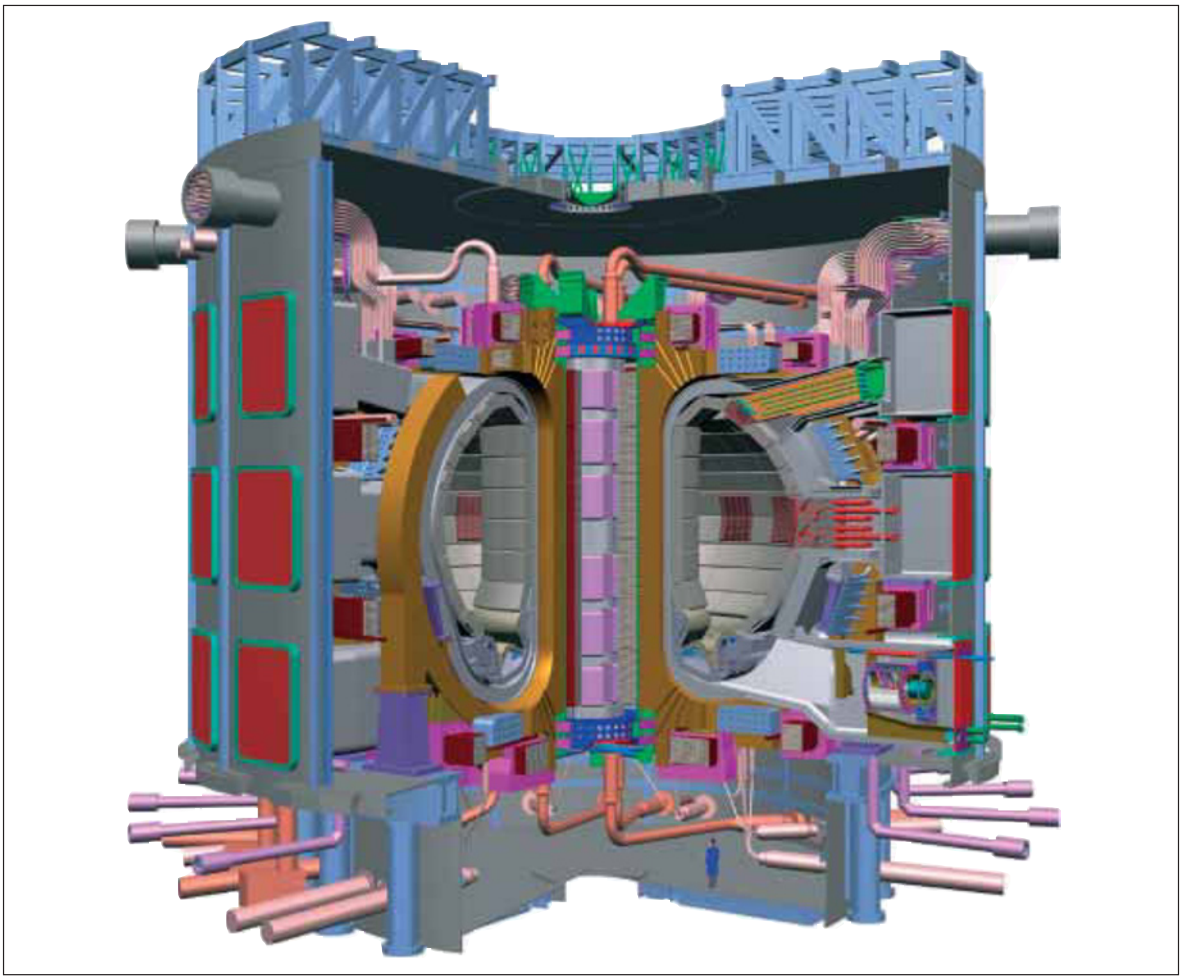


Figure 1 – Schematic picture of the ITER (International Thermonuclear Experimental Reactor)

Filler wire feed rate varied from 7 to 14.5 m/min with a corresponding range of 18 to 26 V in arc voltage and of 36 to 125 A in arc current. In the experiments, the MIG torch was placed towards the laser-welding head and the handling system allowed the movements necessary to change interaction parameters. Both leading and trailing torch orientation were used. The inclination angles of the torch were 40 and 50 degrees (forehand). The distance between arc impingement and laser spot, D_{LA}, varied from 1 to 3 mm. The process is illustrated in Figure 2.

2.2 Materials

The test material used in the experiments was an austenitic stainless steel, EN 1.4307 (AISI 304L), Table 1. The filler wire used in the experiments, AWS 5.9 ER 308LSi (ESAB mark name, OK Autrod 16.12), was chosen in accordance with the base material. The diameter of filler wire was kept at 0.8 mm for each experiment. Both argon and helium were used as a shielding gas. The shielding gas was introduced to the process via an extra nozzle, (He, 16 l/min) and also via MIG torch (Ar, 7 l/min), Figure 2.

Table 1 – Chemical composition of the materials used in the experiment (%)

Material	C	Si	Mn	P	Cr	Ni	N
AISI 304L	0.017	0.33	1.52	0.025	18.2	8.2	0.07
OK 16.12	0.025	0.8	1.8		20	10	

Figure 2 – Hybrid welding process

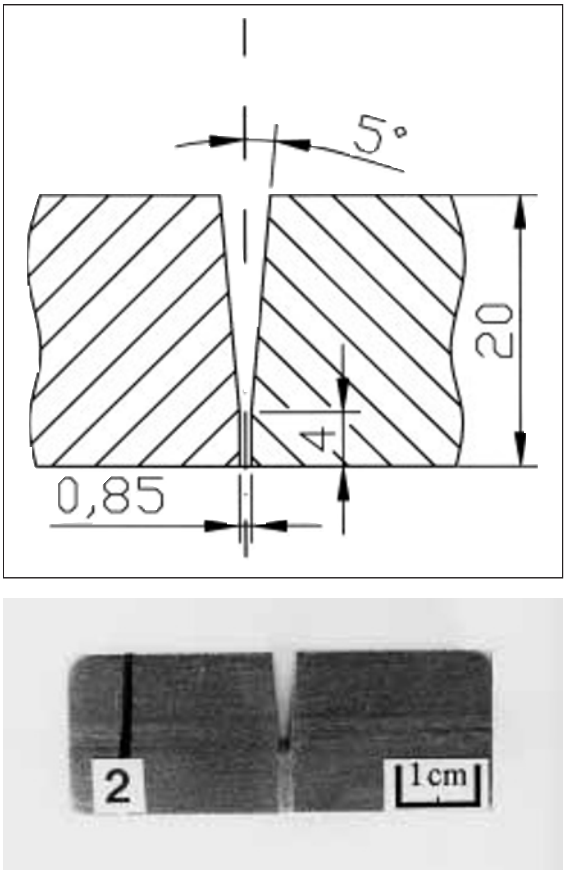


Figure 3 – Example of groove geometry and test piece used in the multi-pass hybrid experiments

The hybrid experiments were made with plate thicknesses of 20 and 30 mm. Single V-preparations with a root face of 4 mm were used in butt joints, see Figure 3. Groove angle was varied at three levels: 8, 10 and 12 degrees. Root welds of the test pieces were welded using laser welding with filler wire (i.e. without an arc). Depending on the stage of the experiments, first, second or even third filling passes were also made with laser welding with filler wire.

2.3 Experiments

The experiments were started with the test pieces shown in Figure 3, to study the applicability of hybrid welding for the first filling pass. In order to receive the optimal parameter combination and the combined effect of the parameters, TAGUCHI technique was applied to the designing and performing experiments. The orthogonal matrix used was Taguchi array L9. In this matrix, four different factors are varied on three levels. The four factors in the present case were:

– wire feed rate (and hence related MIG parameters),
– focal point position according to the root weld,
– distance D_{LA} between the laser and arc, and
– welding direction for which naturally only two different values could be given,

see Table 2.

Table 2 – Factors and their values in the first filling weld TAGUCHI experiment

Factor			Levels		
			1	2	3
A	Wire feed rate	m/min	40 % v_L	50 % v_L	60 % v_L
B	Focal point position	mm	5	7	9
C	Distance D_{LA}	mm	0	1.5	3
D	Direction of torch	-	Leading	Leading	Trailing

The output parameter in the TAGUCHI experiment was filling effect, H_{Fill}. It means the filling [mm] of the pass welded and it was measured from the groove. From that value, taken as an equivalent amount of score points, minus points were taken off if a lack of fusion or other defects were detected in the macrographs. Lack of fusion between the root pass and the first filling pass halved the points. If poor adhesion was revealed, one point was taken off from the measured filling value.

3 RESULTS AND DISCUSSION

3.1 TAGUCHI experiments for the first filling pass

According to the nature of the specific output parameter developed, individual welds were subjected not only to the determination of the filling effect, but also to a visual inspection of the cross-sections. The results of experiments in terms of the filling effect (i.e. how much the weld height is raised in the groove by the first filling pass) and the quality assessment of the welds are given in Table 3. The same applies to the points achieved by each test weld.

Following that, the calculation routine shown in Table 4 provided the optimum combination of input parameters changed in the experiments.

According to Table 4, the best parameter combination is then:
A2 = Wire feed rate 50 % from calculated groove volume
B2 = Focal point position 7 mm up from the root pass
C3 = Distance D_{LA} 3 mm
D3 = Trailing edge arc torch

This optimum setup of the parameters can be seen in Figure 4 a) together with a corresponding macrograph of the weld. According to the observation of the process during the experiments, the trailing edge adjustment of the arc was more sensitive to disturbances in the process, leading to weld defects or poor adhesion between the passes. Due to this reason, the same parameter combination was used with leading edge adjustment, Figure 4 b).

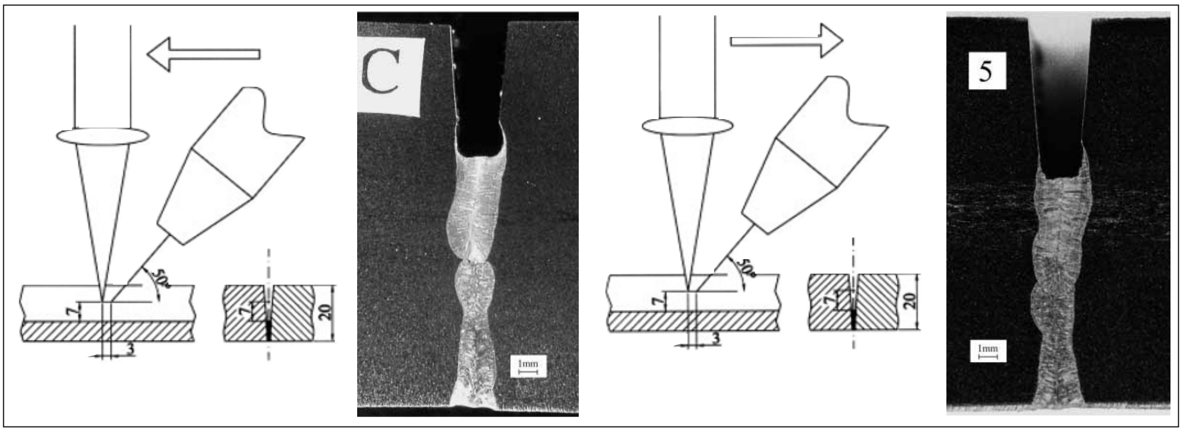
The TAGUCHI calculation routine was also used to reveal the significance of the input parameters varied.

Table 3 – Points of individual hybrid welds in the TAGUCHI experiment for the first filling pass

Nro	Filling effect H_{fill} [mm]	Visual inspection	Points achieved
1	2.6	-	**2.6**
2	4	-	**4**
3	6	Poor adhesion	6 – 1 = **5**
4	4.4	-	**4.4**
5	5.3	-	**5.3**
6	4	Lack of fusion	4 / 2 = **2**
7	3.1	-	**3.1**
8	6	Lack of fusion	6 / 2 = **3**
9	7.7	Lack of fusion	7.7 / 2 = **3.85**

Table 4 – Calculation routine of the TAGUCHI experiment for the first filling pass

Parameter		Calculation	Best result
A	Wire feed rate [m/min]	A1 = 1/3. (2.6 + 4 + 5) p = 3.87 p A2 = 1/3. (4.4 + 5.3 + 2) p = 3.90 p A3 = 1/3. (3.1 + 3 + 3.85) p = 3.32 p	**A2 ⇒ 50 %V_LB**
B	Focal point position [mm]	B1 = 1/3. (2.6 + 4.4 + 3.1) p = 3.37 p B2 = 1/3. (4 + 5.3 + 3) p = 4.10 p B3 = 1/3. (5 + 2 + 3.85) p = 3.62 p	**B2 ⇒ 7 mm**
C	Distance D_{LA} [mm]	C1 = 1/3. (2.6 + 2 + 3) p = 2.53 p C2 = 1/3. (4 + 4.4 + 3.85) p = 4.08 p C3 = 1/3. (5 + 5.3 + 3.1) p = 4.47 p	**C3 ⇒ 3 mm**
D	Welding direction or torch direction [leading / trailing]	D1 = 1/3. (2.6 + 5.3 + 3.85) p = 3.92 p D2 = 1/3. (4 + 2 + 3.1) p = 3.03 p D3 = 1/3. (5 + 4.4 + 3) p = 4.13 p	**D3 ⇒ Trailing**



Groove angle 10 °, welding speed 0.7 m/min, wire feed rate 9,9 m/min

a) Trailing torch orientation **b) Leading torch orientation**

Figure 4 – Optimal setup of the parameters received from TAGUCHI experiments and macrograph of the weld

The distance DLA between the arc and laser impingement point was found to be clearly the most significant factor affecting the output parameter comprising of the filling effect and the quality of the weld, see Figure 5. The second factor, in order of importance, was the torch orientation. To a lesser degree, the output parameter was found to depend on the focal point positioning and the wire feed rate.

3.1.1 Wire feed rate

The preliminary experiments preceding the TAGUCHI exercise clearly demonstrated that the filler wire feed rate must be kept well below the theoretical value calculated from groove volume. Otherwise the process becomes unstable resulting in various imperfections. This finding may at least partly be attributed to the transverse shrinkage, though it is rather small when compared to the same in arc welding. Consequently, values of 40, 50 and 60 % of the calculated amount of filler wire feed were used at the three levels in the TAGUCHI experiments. The best value was received for 50 %, but the difference from 40 % was marginal, only 0.03 points. The influence on the output parameter was small, explaining only 14.9 % of the regression, which ranks as the lowest among the parameters. This finding clearly demonstrates that too much filler metal should not be fed in unit time to the narrow groove, in order to accomplish high quality welds. In particular this applies to the first passes. If the deposition rate is too high, the filler metal interferes in the laser keyholing. The process becomes unstable and an insufficient amount of energy is concentrated on the surface of the previous pass that leads to incomplete fusion.

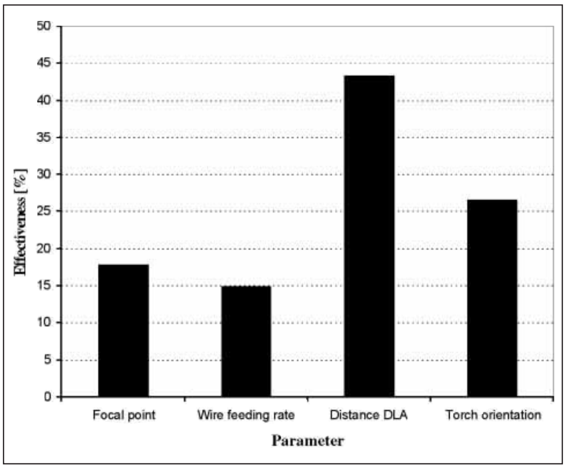


Figure 5 – The significance of the parameters varied in TAGUCHI experiments for the first filling pass

3.1.2 Focal point position

Focal point position defines the geometry of the laser beam and its energy distribution. The optimum value obtained from the TAGUCHI experiments was 7 mm above the weld face of the first pass. The level of 5 mm was even better for the quality, but resulted in a smaller filling effect. 9 mm was too much and this comes from the excessive filler metal feed because it was calculated from the area between the first pass, groove surfaces and bevel in the plane of the focal point position.

3.1.3 Distance D_{LA} between laser focus point and arc

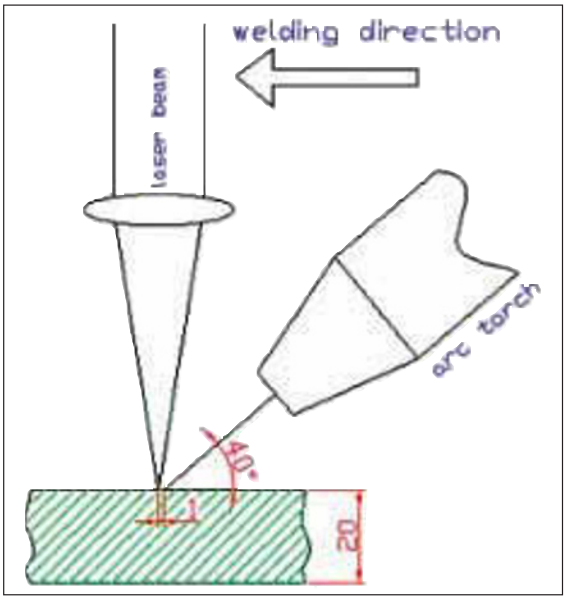
The TAGUCHI test runs revealed that the process is more stable resulting in fewer defects, and the filling effect becomes better, if a certain distance is allowed between the laser focus point and the discharge point of the arc. The optimum value for the D_{LA}- parameter was found to be 3 mm. The difference was, however, small when compared to 1.5 mm. The distance DLA explained 43.4 % of the regression and, hence it was the factor exhibiting the highest significance among the input parameters. According to VTT's experience, smaller distances can be used in single pass welding. In particular this applies to cases when the arc comes from the trailing edge. Then even distance of zero was used without quality problems.

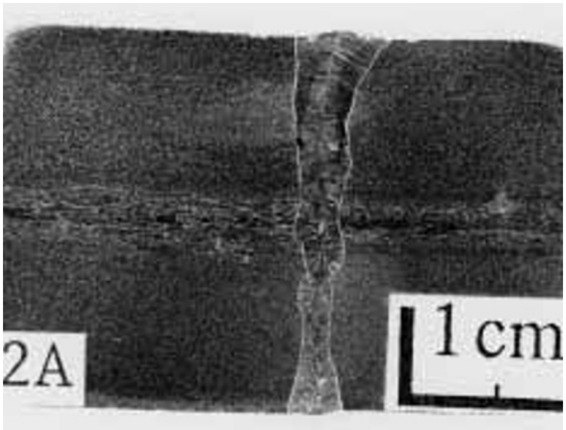
In the narrow groove, the situation is somewhat different. The keyhole is less stable and rather prone to disturbances if too much filler metal is fed into the time unit. Reasoning of the proper value for distance D_{LA} can thus obviously be based on the narrow groove itself. Providing that it is too small, there is no place for the filler to go and it wanders above and to the keyhole. In such a case, the laser beam cannot reach the bottom of the root.

3.1.4 Welding direction / arc torch orientation

The trailing edge feed direction of the arc was found better for the filling effect in the TAGUCHI exercise performed for the first filling pass. Quality wise, however, this direction is more sensitive to disturbances especially when increasing the deposition rate. Unstable processes associated with severe spattering stems obviously from the fact that arc pressure focuses on the molten metal. When high arc parameters are used, the arc pressure is high enough to cause spattering. Also, the pressure can impel the molten metal towards the keyhole. However, if filler wire feed was adjusted correctly and there was some distance between the laser focus point and the arc, a sound and stable process and, hence high quality, welds were achieved.

After the calculation routine of TAGUCHI, high value was received for the arc orientation in the mean of effectiveness to the process, 26.6, but no big difference was calculated towards the leading edge feed. The value of the leading edge was 3.92 and, as for the trailing edge, it was 4.13. Although the TAGUCHI exercise suggests the optimum for the arc orientation to be the trailing edge, it is more reliable in terms of process stability to feed the arc from the leading edge.





Groove angle 10°, welding speed 0.5-0.7 m/min, wire feed rate 9.7 m/min

Figure 6 – Cross-section of the hybrid weld with thickness of 20 mm filled with 4 passes, and its set-up

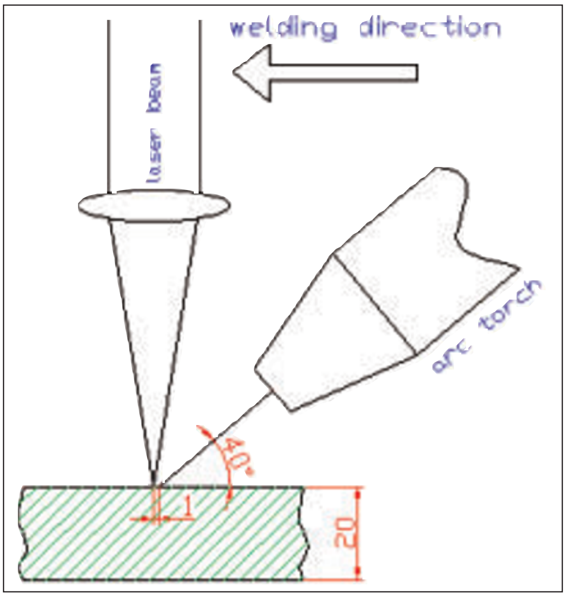
3.2 Experiments for the filling passes for thicker sections

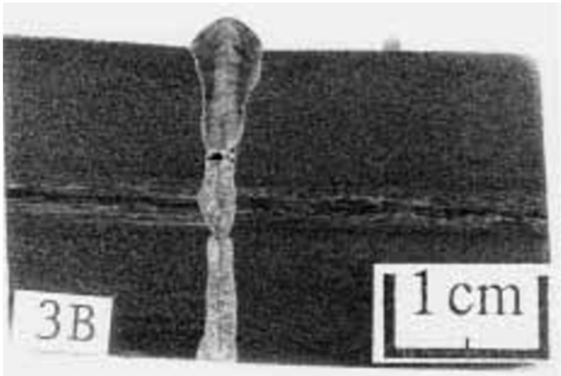
By using knowledge of the hybrid process in a very narrow groove shown in chapter 3.1, some experiments were performed in order to fulfil the requirement for welding thicker sections. These experiments for the filling passes were started with a plate thickness of 20 mm using hybrid welding after the first filling pass. Additionally, in some test pieces, a few filling passes were made with filler wire welding before hybrid welding.

Figure 6 exhibits a weld with four passes. The weld beads follow the opening of the groove and no excessive amount of base material has been melted. It is clearly seen that welding has taken place in the keyhole mechanism. As further proof, the width/depth ratio of the first filling pass is 0.39. The adhesion is also proper in the most critical point, i.e. between the root pass and first filling pass. Still the overlap between those passes should be more than 0.7 mm when measured from the test piece. The more pronounced overlap between the first and second filling pass (1.8 mm) ensures a better acceptable adhesion. The overlap between the third and last filling pass (3.8 mm) is too much from the total heat input point of view.

Figure 7 illustrates the critical defects that can occur in adhesion between the passes. In this case, the first filling pass was made using laser welding with filler wire. Even then the penetration of the weld is incomplete and thus adhesion poor to the root weld. Neither has the penetration of the first hybrid pass been deep enough to accomplish a sound adhesion. The second and last hybrid passes have penetrated the preceding bead indicating that the parameters and adjustments have been adequate for the welding task. Comparison to the weld in Figure 6, which has been made using the same parameters, implies that the reason for the poor adhesion is the narrower groove angle (i.e. 8°).

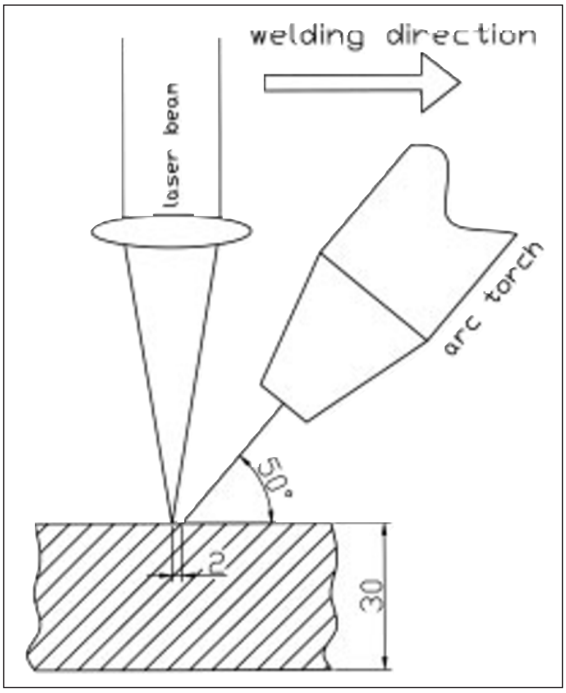
In the welding of 30 mm thick plates, the same kind of groove geometry was used as in the welding of 20 mm:

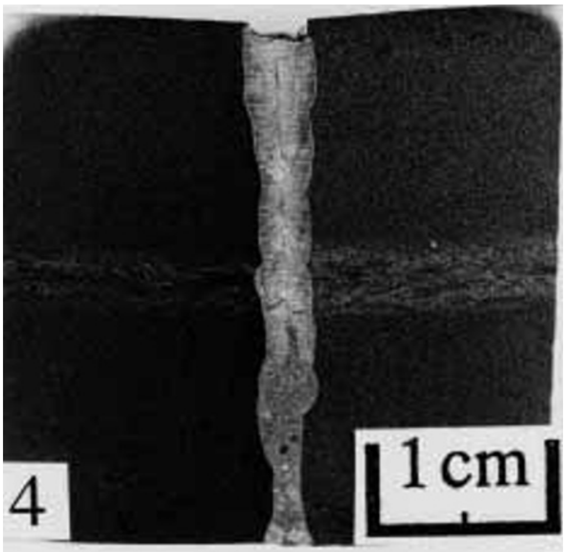




Groove angle 8°, welding speed 0.5-0.7 m/min, wire feed rate 9.7 m/min

Figure 7 – Cross-section of the hybrid weld with thickness of 20 mm filled with 4 passes, and its set-up





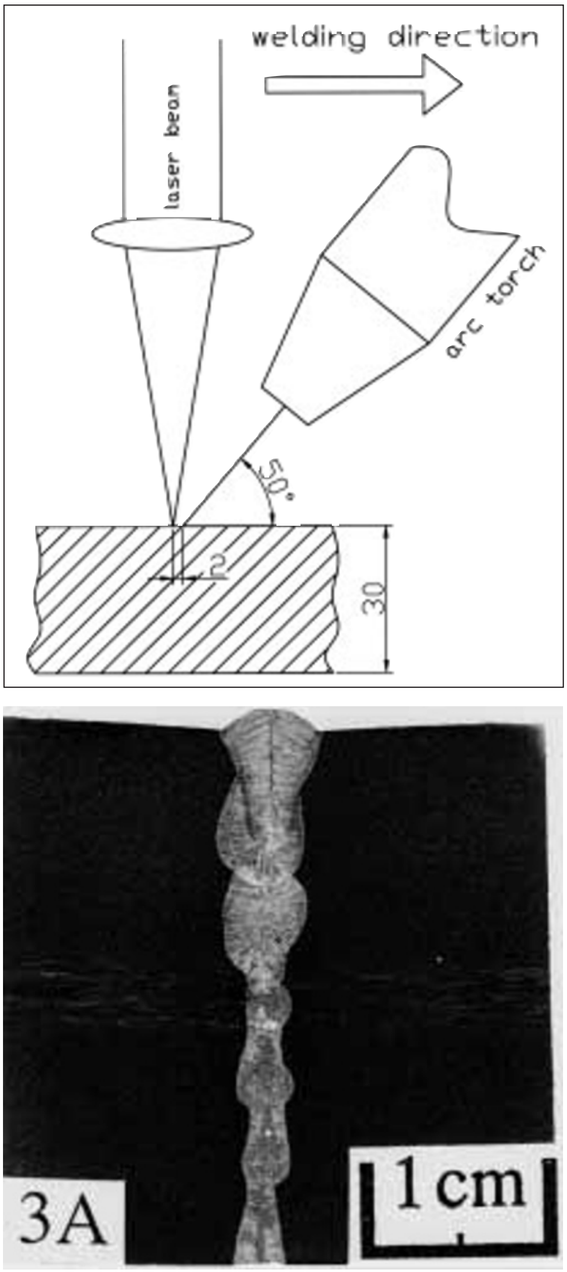
A total of 6 passes, two first using laser welding with filler wire, last four using hybrid welding. Groove angle 10°, welding speed 0.5 m/min, wire feed rate 7-12 m/min

Figure 8 – Set-up for welding the thickness of 30 mm and a cross-section of corresponding weld

single V-groove with root face of 4 mm. Due to the results presented above, the root and at least the first filling pass were welded by a laser with filler wire without an arc. Figure 8 presents a weld, in which the root and first filling pass have been welded with plain laser welding with filler wire. The groove was filled with four hybrid passes and torch orientation was leading. As can be seen, the adhesion between the passes was acceptable in every case. The welds nicely follow the geometry of the groove, and are as narrow as possible in order to penetrate the fusion faces. The final pass, which is the widest one, exhibits the width/depth -ratio of 0.55. This value stands as a clear tribute to keyhole welding. Two small pores can readily be seen in the root pass.

Figure 9 illustrates the experimental arrangement and outcome of another exercise with a 30 mm thick section using the same kind of groove geometry as in Figure 8. In this case, hybrid welding has been employed. As can be seen, the geometry of the individual welds indicates that welding happened in real keyhole mode. The first passes (root + two filling passes) were achieved using laser welding with filler wire and the others with hybrid welding.

Comparison between Figures 8 and 9 reveals the effect of filler wire feed rate and hence the arc parameters. Figure 9 refers to the following filler wire feed rates in the last three filling passes deposited by hybrid welding: 8, 8 and 12 m/min. The corresponding values in the weld shown in Figure 8 were 12, 15 and 10 m/min, respectively. The difference between the geometries of the beads is clear: they are much wider in the test piece in



A total of 6 passes, the first three with filler wire, last with hybrid. Groove angle 10°, welding speed 0.5 m/min, wire feed rate 10-15 m/min

Figure 9 – Cross-section of the weld with thickness of 30 mm and its set-up

Figure 9. Furthermore, Figure 9 highlights an interesting finding: the upper part of the groove allows rather high wire feed rates without serious problems. This is not the case with the lower part of the groove.

4 CONCLUSIONS

Hybrid welding, in which Nd:YAG laser and MIG arc are mutually introduced, can be used for welding thick sections using narrow groove and multi-pass techniques. One controlling factor of a successful process is to ensure sufficient penetration of the bead of the previous pass. This requires a stable process, in which the keyhole generated by the laser beam is not disturbed, and the filler metal introduced by the arc is fluently transferred to the process. The second crucial factor of a stable process is the adequate interaction of laser beam and the arc. This means the optimisation of the main parameters, i.e. the distance D_{LA} between the laser and the arc, suitable filler wire feed rate, focal point position in respect of arc and joint. When a stable process is ensured, the welds exhibiting high quality can be produced in the narrow groove of thick section plates.

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