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Effect of welding parameters and the heat input on weld bead profile of laser welded T-joint in structural steel

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The high power fiber laser has become one of the most efficient energy sources for deep penetration welding processes used in heavy manufacturing and marine industries. Combinations of cost-efficient, easily automatable process together with fairly mobile and flexible welding equipment have raised high expectations for improved quality and economic feasibility. In this study, the fillet welding of a low alloyed structural steel was studied using a 10 kW fiber laser. Plates of 8 mm thick AH36 were welded as a T-joint configuration in flat (1F) and horizontal (2F) positions using either an autogenous laser welding or a hybrid laser arc welding process. The effect of heat input on the weld bead geometry was investigated using one variable at a time approach. The impact of single process parameter such as laser power of 4.5–6 kW, welding speed of 0.5–2.5 m/min, beam inclination angle of 6°–15°, focal point position of −2 to +2 mm, and welding positions of 1F and 2F were studied. All welds were visually evaluated for weld imperfections described in EN ISO 13919-1 standard. Penetration depth, geometries of the fusion and heat affected zones, and hardness profiles were measured. Produced joints have a high depth to width ratio and a small heat affected zone; full penetration welds with acceptable weld quality on both sides of the joint were produced. The parameter configurations for optimizing the welding processes are proposed.
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Key words: laser beam welding, low alloyed steel, T-joint, weld penetration

I. INTRODUCTION

Laser and hybrid laser arc welding (HLAW) are high power density processes, making full penetration welds possible in single run at high welding speed and low heat input.[1,2] Up to date, most of the research in laser welding has mainly been concentrated either on butt joint or lap joint configurations. However, the welding of fillet joint is of great importance as well, since most of the welded products having three-dimensional shape require welding of fillet joints.

Welding of fillets in medium thickness steel (4–12 mm) with HLAW has been studied using Nd:YAG laser-MAG hybrid technology; welds with characteristics fulfilling shipyard specifications were produced.[1,3] In the previous studies, it has been noticed, e.g., that welding of a fillet joint is easy due the fact that weld is bending according to the joint, i.e., the effect of the angle of incidence is less severe than in case of butt joint. This is demonstrated in Fig. 1. The phenomena are stronger in case of Nd:YAG laser which has significantly worse beam quality than the CO_2 laser.

Beam quality and output power level of fiber lasers are superior to those of Nd:YAG lasers leading in either deeper penetration or higher speed in practical welding applications. The flexibility of beam delivery by fiber allows accessing difficult joint locations and utilizing novel design solutions in manufacturing of steel structures. This, together with efficiency of laser equipment in case of modern solid state lasers, leads to much higher overall efficiency of the process from wall plug to welding process. The effect of the diameter of the focused beam on welding speed can be noticed very clearly from Fig. 2.

Hybrid welding has additional parameters that influence the process behavior and the properties of the resulting weld. The capability of fiber laser-MIG in welding of fillet welds in 4 mm structural steel has been studied with attention to most influential parameters affecting the weld bead profile.[6] These parameters are laser power, welding speed, focal point position (ffp), air gap, and beam inclination angle.[4,6,7] In addition, focal point position has been shown to have significant effect on the penetration depth and geometry of the weld in butt joint and bead on plate configurations[8] and it should be studied in T-joint arrangement as well. In hybrid welding, typically, the laser process is creating the deep and narrow weld, while arc process aids at the bead geometry formation and brings additional heat to the joint.[1,9,10]

In traditional arc welding processes, the size of the external fillet is considered to be the most important dimension of the joint. The design codes are based on the dimensions and height of the fillet. In arc welding processes, less than half of the plate thickness is penetrated and taken in account in

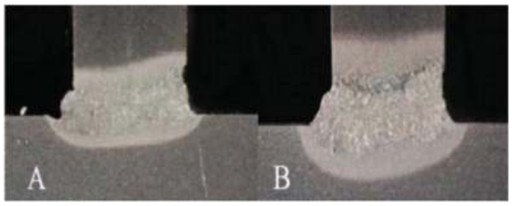


FIG. 1. Welds welded with the highest welding speed to achieve full penetration (a) CO_2 laser weld, $P_L = 5$ kW, $v_w = 0.9$ m/min. (b) Nd:YAG laser weld, $P_L = 3$ kW, $v_w = 0.3$ m/min. S355K2G3 steel with web thickness of 6 mm (Ref. 4).

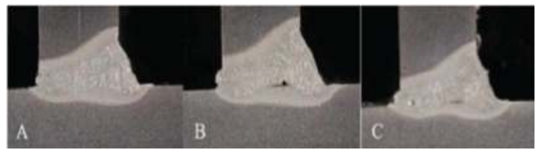


FIG. 3. Illustration of weld flaw caused by misalignment of laser beam in case hybrid welding with CO_2 laser in case of (a) air gap of 0.5 mm, $v_w = 1.3$ m/min, (b) air gap of 0.5 mm, $v_w = 1.1$ m/min, (c) air gap of 0.5 mm, $v_w = 1.5$ m/min. $P_L = 5$ kW, material S355K2G3 steel with web thickness of 6 mm (Ref. 4).

further evaluation of the joint performance. Thus, convex top profile of the bead and high fillet are preferable, because large weld throat means better structural integrity and is advantageous for fatigue life. This regulation cannot directly be transferred to the welds produced with laser based processes, as joints are formed along the interface of the flange and the web throughout the whole thickness. Height of the external fillet is of secondary importance, as weld has usually full penetration with only fraction of the joint situating above the interface of the plates forming a fillet. In laser and HLAW, the concave shape of the top bead is beneficial, as less added filler material means smaller heat distortions and smooth transition from weld bead to base material. In addition, the defects such as undercut are also less likely to appear.

The hybrid welding joint preparation tolerances are less severe compared to requirements of autogenous laser welding. However, the geometrical parameters of the process, such as beam incidence location, are still critical in case of T-fillet joint. Figure 3 shows an example of a case of misaligned beam.

The aim of this study was to investigate the effect of heat input and process parameters on the weld geometry and penetration. Welding position, laser power, welding speed, focal point position, and beam inclination angle, being the most notable variables affecting the shape of the weld bead, were systematically studied. The flat welding position 1F (PA) is the most suitable position for evaluating the capability of the fiber laser based system due to ease of accessibility. The horizontal position 2F (PB) is in practice common for most industrial applications. Figure 4 shows a schematic representation of the welding positions and the cross section of fillet weld produced by either laser welding or HLAW.

Effective throat (t_{eff}) is the shortest distance between the top bead and the end of fusion zone measured along the weld. Penetration depth (d_{pen}) shows the range of the fusion and is measured from the edge of the web to the end of the joint. Width of the weld bead (w_w) is measured across the joint from one toe of the weld to the other and depth of the weld (w_d) is measured from the top surface to the end of the weld.

II. EXPERIMENTAL SETUP

A. Materials

The materials used for this study were 8 mm thick shipbuilding steel AH36 as a base material and G3Si1 as a filler wire. The workpieces were laser cut to dimensions of 350 mm (length) × 100 mm (width) and grid blasted prior to being tack welded in inverted T-position. The chemical composition of the steel and the filler wire are shown in Table I.

B. Laser equipment

A continuous wave fiber laser YLR 10000 emitting wavelength of 1070 nm and having 10 kW maximum power output was used in this study. Focal point diameter of the laser beam was 0.56 mm, resulting from 300 mm focusing mirror, 125 mm collimation mirror, and ø 200 μm process fiber. Kugler LK190 mirror optic laser welding head was used in both test setups. The length of the weld was 165 mm. The main process variables are shown in Table II.

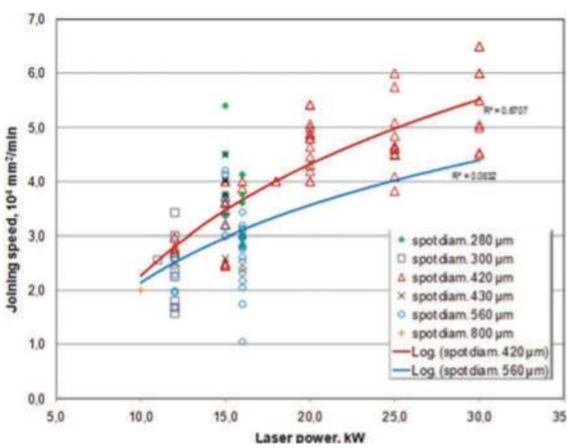


FIG. 2. Joining speeds achieved as a function of laser power for various optical setups and spot diameters used. The lasers used are fiber and disk lasers (Ref. 5).

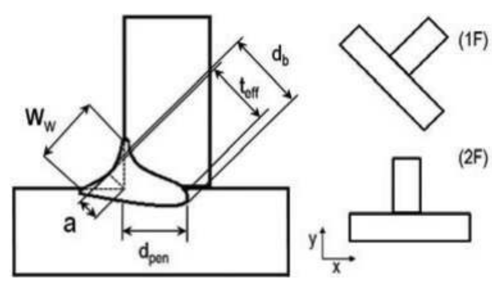


FIG. 4. Schematic illustration of laser/HLAW welded fillet joint (left) and welding positions studied (right).

TABLE I. Chemical composition of the materials.

Material	C	Si	Mn	P	S
AH36	0.18	0.03	0.7	0.035	0.035
G3Si1	0.1	0.9	1.5		

Autogenous laser welding tests were carried out without shielding gas; in HLAW, Ar + 5 CO_2 with flow rate 20 l/min, delivered through the MAG welding torch, was used. In HLAW experiments, the Kugler welding head was combined with a Binzel MAG torch. Kemppi ProMig 530 arc power supply with only pulsed arc setting was used. The synergy setting was constantly on; thus, arc current and voltage were dependent on the welding speed by the feeding speed of the filler wire. The arc was the leading process. Previous experiments have shown that such arrangement generally results in higher quality welds, namely, smoother bead top profile and less root porosity in the joint. The experimental setups are shown in Fig. 5.

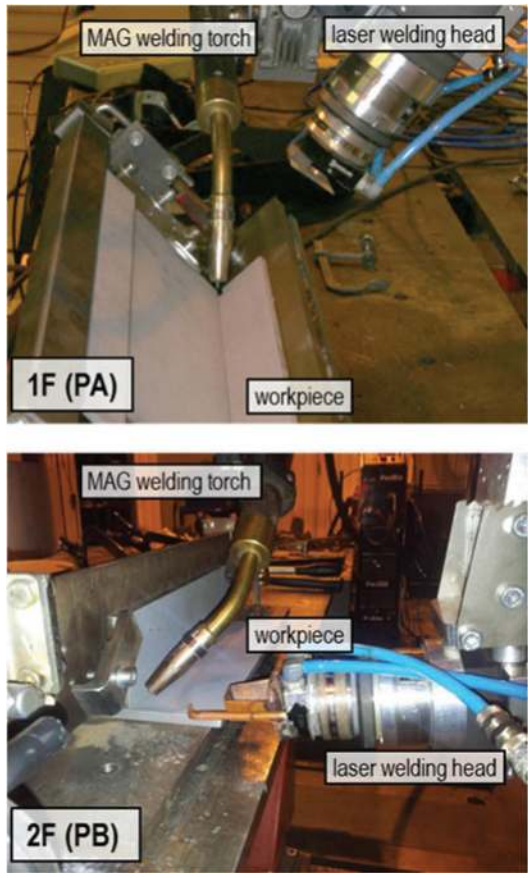


FIG. 5. Experimental setups.

C. Test methods

After welding, a quality of weld beads was visually evaluated to detect common weld imperfections described in EN ISO 13919-1 standard. Special attention was paid to imperfections like undercuts, excessive penetration, and lack of penetration due to their effect on the fatigue properties of the weld, where they act as a notch for crack initiation.

Welds having a good bead quality were cut transverse to the welding direction, polished according to standard procedures, and etched with solution of 5% $HNO_3 + C_2H_5OH$ to obtain the geometry of the weld. Subsequently, macrographs were prepared and critical measurements mentioned in Fig. 1 were taken. Macrohardness was measured along the fusion lines using HV 5 with 0.4 mm intercept between the indentations.

1. Heat input

Line energy was used as a common denominator for a comparison process of the welding positions 1F and 2F. Heat input defines the geometry of the joint and can be controlled by a modification of the welding parameters. The heat input is directly related to the laser (and, if used, arc) power and the welding speed. Heat input for the laser welding was calculated according to the following equation:

TABLE II. Welding parameters.

Material	AH36
Plate thickness (mm)	8 mm
Welding speed (m/min)	0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5
Laser power (kW)	4.5, 5.56, 6, 8, 8.4, 9, 9.5
Focus position (mm)	+2, 0, −2
Beam angle from flange (°)	6, 10, 15
Arc-laser process distance (mm)	3
MAG torch tilt angle (°)	45
MAG torch travel angle (°)	58
Filler wire feed rate (m/min)	Welding speed × 5.2
Filler wire stick out (mm)	15
Filler wire diameter (mm)	1.0
Air gap in HLAW	0.5

$$Q_{laser} = P_L / v_t, \tag{1}$$

where Q_{laser} is the heat input of laser (kJ/mm), P_L is the laser output power (kW), and v_t is the travel speed (mm/s). Heat input of the HLAW is taking into account the additional energy delivered by arc and is calculated by the following equation:

$$Q_T = Q_{arc} + Q_{laser} = (U \cdot I \cdot 60)/v_t + (P_L \cdot 60)/v_t \tag{2}$$

where Q_{laser} is the heat input of laser welding (kJ/mm), P_L is the laser output power (kW), v_t is the travel speed (m/min), Q_T is the heat input of HLAW (kJ/mm), Q_{arc} is the heat input of arc welding (kJ/mm), U is the voltage of arc (V), and I is the current of arc (A).

Laser power used in these experiments was varied between 4.5 and 6 kW and welding speed was varied between 0.5 and 2.5 m/min.

III. RESULTS AND DISCUSSION

A. The effect of the focal point position

Focal point position influences significantly the stability of the welding process, penetration, and quality of the weld. Three focal point positions were tested for studying the

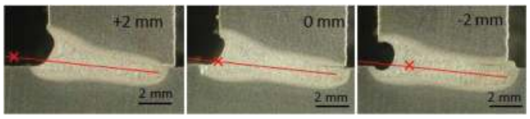


FIG. 6. Cross sections of laser welds produced with focal point positions above, on top, and below the joint. $P_L = 4.56\,kW$, $v_w = 1\,m/min$.

effects on penetration depth and geometry of the top of the weld bead. The tests were made in flat (1F) welding position.

Figure 6 shows the results of three focal point positions tested in autogenous laser welding experiments. The heat input was 270 J/mm for all three welds. Beam inclination angle was 6°; the beam propagation and position of the focal point are illustrated on the macrographs.

Figure 6 shows that the penetration is deepest when the focal point is below the surface. The area of the melt and width of HAZ are similar in all three positions, but the location of the weld with respect to web is shifted inward of the joint along with focusing. Comparing the three focal point positions tested, it can be seen that focusing the beam on top of the joint or inside of the material results in sinking of the weld and formation of the undercut. The width of the weld fusion zones is less than 2 mm; in all cases, the weld has crossed the joint plane and missed the root of the joint, restricting the length of the effective throat. Full penetration was not achieved even in case of fpp of −2 mm, when the melt was pushed through the joint, appearing on the root side (see Fig. 6 right). However, used heat input was sufficient for producing weld throughout the thickness at fpp of −2, in case of correct beam positioning (at smaller inclination angle or higher along the web). Narrow weld width and the beam position with respect to the joint (aiming exactly at the point between web and flange) were limiting the fusion at the root.

Figure 7 shows hybrid welds produced with focal point positions above and below the material.

These welds were made under same parameters with exception of the arc power. Although the welding speed and rate of the filler wire feeding were set to same values, 0.8 kW difference in arc power occurred. The corresponding heat inputs were 462 J/mm (fpp of −2 mm) and 414 J/mm (fpp of −2). Regardless of the smaller arc power that weld produced with fpp of −2 mm received, the trend observed earlier in autogenous laser welding was noticed. fpp inside of the material lets energy to be absorbed in the melt pool more efficiently. This can be seen from the geometry and the surface area difference of resulting joints. The weld obtained with fpp of +2 mm had greater arc energy input than fpp of −2 mm; however, the melt areas of the welds, 14.2 mm^2 (fpp of +2 mm) and 17.3 mm^2 (fpp of −2 mm) show that more energy was available to weld to form when focusing was below the workpiece surface.

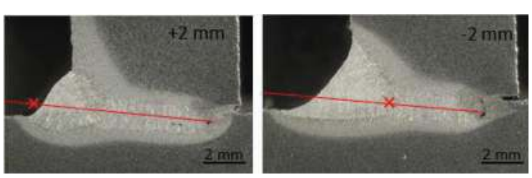


FIG. 7. Cross sections of HLAW welds, fpp of +2 (left) and fpp of −2 mm (right). $v_w = 1\,m/min$, $v_{wire} = 5.2\,m/min$, $P_L = 4.5\,kW$, $P_{Arc} = 3.15\,kW$ (left) and 2.34 kW (right).

The difference in penetration depth, slightly exceeding 6 mm in both fpp's tested, is minor. However, the influence on the top bead geometry is obvious: fpp above the base material results in narrow weld having convex face bead profile, while fpp inside of the joint creates wider weld with concave face bead profile. As mentioned earlier, the filler wire feeding rate was the same for both welds, and yet the weld produced with smaller heat input has larger melt area, and the amount of the base material melted during the welding process is more than it was when the beam was focused above the joint.

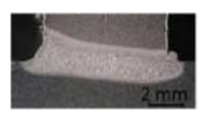
B. The effect of the welding position

Table III presents the welds produced with autogenous laser welding using identical process parameters in positions 1F and 2F.

From figures presented in Table III, it can clearly be seen that the welding position affects the weld geometry and depth of the penetration. The fusion zone of the welds produced in horizontal position is slightly wider and also the penetration is inferior to welds made in flat position.

As expected, the penetration depth and width of the bead lessen with increase of the welding speed in both studied positions. At welding speed of 1.25 m/min, the welds have similar geometry of fusion and heat affected zone, but as welding speed is increased, the differences occur. Weld made in flat position at 1.75 m/min has full penetration with narrow fusion zone and HAZ, while weld made in 2F has partial penetration, 6.2 mm. In the horizontal position, the root of the weld is wider, which, generally, is beneficial from the gap bridging point of view (the beam is more likely to hit the joint plane instead of penetrating the flange). The loss of penetration depth is more noticeable in horizontal position, especially at higher welding speeds. This may be caused by the effect of gravity on the movement of the molten steel,

TABLE III. The effect of the welding position on the weld profile at different welding speeds. Laser welding, $P_L = 6\,kW$, fpp = −2 mm.

Welding speed	Flat (1F)	Horizontal (2F)
1.25 m/min		
1.75 m/min		
2.25 m/min		

because in the horizontal position the melt pool is supported by the flange, while in the flat position the hydrostatic pressure forces the melt to flow rapidly downward. Because of this, an air gap between the plates would increase the penetration depth in flat position.

C. The effect of the inclination angle of the beam

The smallest possible beam inclination angle that was accessible by the equipment used, 6° from the flange, was taken as a starting point. The beam was positioned 0.5 mm above from the joint on the web plate and focused 2 mm below the material top surface in all cases. Sound welds with complete fusion on the root side were produced using 6 kW laser power at welding speeds up to 1.25 m/min, subsequently the beam angle was increased to 10° and 15° to observe whether the penetration is maintainable at higher angles and observe the direction of weld propagation. All welds displayed in Fig. 8 are made in horizontal welding position (2F) with heat input 288 J/mm.

From Fig. 8, it can be seen that the welds are aligned in the direction of the beam. Unlike welds made with CO_2 and Nd:YAG lasers,[4] the welds produced are not bending along the joint plane. The straight and narrow needlelike fusion zone, distinctive to fiber laser welds, was observed.

In the case of 6° angle, full penetration was obtained as adequate amount of melt was pushed through on the root side, forming a sound joint. This phenomenon did not occur in larger beam angles, since the energy was directed linearly and the needle-like weld was formed in the base plate. High density of the beam creates narrow weld, fusion zone does not reach the root region, and under-filling occurs when the beam is missing the joint plane. The area of the fusion zone gradually decreased by change of the beam inclination angles from 10° to 15°, while width of HAZ remained the same. Weld made with the 10° angle had effective throat of 6.8 mm, at 15° angle of 4.3 mm. The penetration depth is also decreasing with increasing beam angles; perhaps the reason is that the beam can be absorbed more efficiently in the melt front when its inclination angle is adjacent to the joint. Small beam inclination angle to the flange is preferable for increasing penetration at any given power and speed combination; however, practical applications may have limitations set by dimensions of equipment and restricted accessibility.

D. Effect of the heat input on weld geometry

1. Laser welding

Figure 9 shows the effect of heat input on the dimensions of the laser welds made in flat (1F) and horizontal (2F) positions.

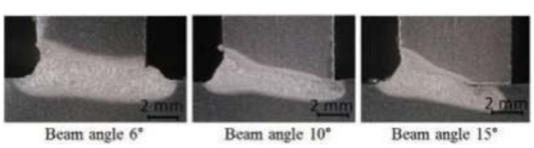


FIG. 8. The effect of the beam incline angle on the weld propagation. $P_L = 6$ kW, fpp = −2 mm, and $v_w = 1.25$ m/min.

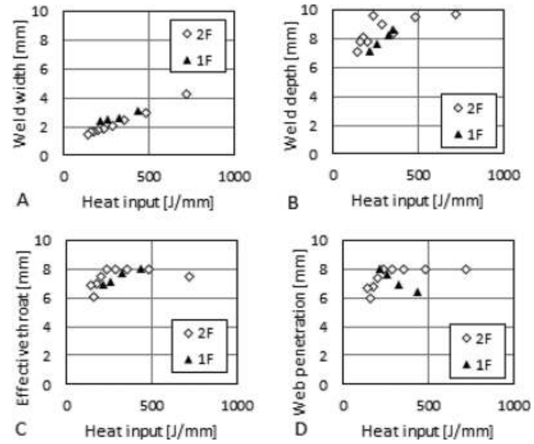


FIG. 9. The weld dimensions under same heat input in 1F and 2F welding positions. fpp = −2 mm and beam angle of 6°.

Figure 9(a) shows that the width of the weld bead (w_w) is increasing as heat input increases. The welds made in 1F at high welding speeds were slightly wider than welds made in 2F with corresponding heat input. This difference was diminished when heat input is greater than 350 J/mm.

The depth of the weld (d_w), measured from top of the bead to end of the fusion zone regardless whether the weld is hitting the seam or not, was similar in range of 300–500 J/mm [Fig. 9(b)]. When heat input was less, the welds made in 2F position were deeper. The difference is explained by different top bead profile, which was rather straight or slightly concave in 2F, but always concave in all of the welds produced in 1F position. This becomes clearer from Fig. 9(c) that the dimensions of effective throat of welds produced in 2F were longer than those made in 1F. The gravity, pulling the melt during welding and solidification, forms concave top bead in 1F position, sometimes causing undercut and sagging of the weld, especially at higher heat inputs when the melt pool is larger. In 2F position, the movement of melt was more restricted as gravity acts from different direction. The melt movement is slower; heat is dissipated into base material, resulting in wider HAZ and higher top bead.

Figure 9(d) shows how much of the web plate was melted, e.g., the reach of penetration along the web–flange interface. Again, it must be noted that not in all of the cases the weld was aligned along the seam, sometimes crossing it and hitting only the flange. Full penetration or 8 mm penetration is reachable with heat input above 260 J/mm in both welding positions. However, the range for acceptable quality is differing, as 1F position results in undercut when heat input exceeds 350 J/mm. Figure 10 displays two welds made in different welding positions with same heat input, 360 J/mm, using 6 kW laser power and 1 m/min welding speed.

The energy distribution is different in the welds shown in Fig. 10. The HAZ of the weld produced in 1F position is narrow and the fusion at the root of the weld is thorough, the melt has flown through the seam and solidified on the back of the joint. Weld produced in 2F position, pictured

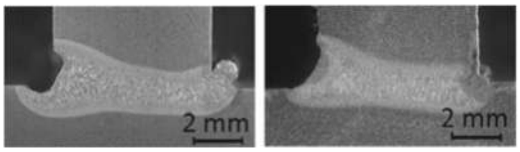


FIG. 10. The weld geometry in 1F (left) and 2F (right) welding positions at heat input 360 J/mm. fpp = −2 mm and beam angle of 6°.

on the right, has received same amount of energy, yet the geometry of the fusion zone and dimensions of surrounding HAZ are larger. HAZ is wider throughout the joint, and the fusion at the root is not as complete as it was in 1F position.

The shape of the top bead of the 1F weld can be characterized as concave; the top of the weld bead has sunk. For improving the quality of the fillet under existing setup, heat input has to be decreased, either by increasing the welding speed or by decreasing the laser power. The bead of the 2F weld is also concave; bead has smooth junction to base metal and corresponds to demands in standards. However, judging from the geometry of the root, this weld requires more heat input to be completely sound throughout the whole length of the seam. This phenomenon becomes less noticeable as the heat input decreases (see Table III welds made with welding speed of 1.75 and 2.25 m/min). Apparently, the parameter window for heat input seems to be narrower in case of 1F than in case of 2F, horizontal position also requires higher heat input for producing full penetration.

2. HLAW

Figure 11 shows the effect of heat input on the geometry of the hybrid welds, only 1F welding position was used.

The areas of melt and HAZ increased linearly with increasing heat input [Figs. 11(c) and 11(d)], same can be said of the width of the weld bead. However, there is no straightforward correlation to dimensions of effective throat [Fig. 11(b)]. The depth of the penetration is primarily dependent on the laser power and full penetration welds with narrow melt area were produced at low heat inputs as

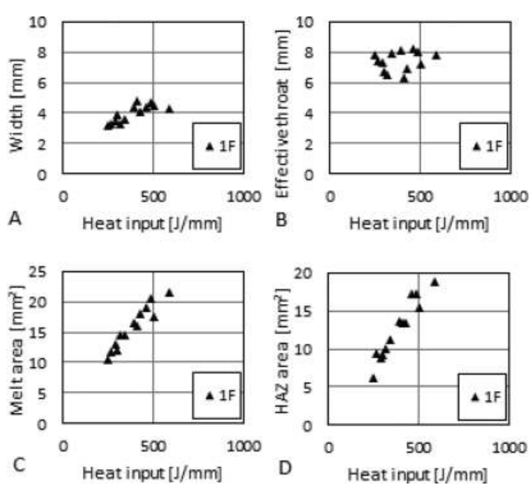


FIG. 11. The effect of the heat input on the weld dimensions in hybrid welding. fpp = −2 mm and beam angle of 6°.

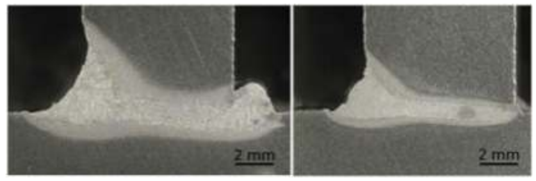


FIG. 12. The change in weld geometry in respect to heat input. $P_L = 6$ kW, fpp = −2 mm, $v_w = 1$ m/min (left) and 2.5 m/min (right).

well, as long as there was sufficient laser power available. Figure 12 shows how the geometry of the bead is changing depending on the heat input.

Figure 12 displays the welds preformed with the same laser power at heat inputs of 494 J/mm and 255 J/mm. The area of the fusion zone is correlated to heat input, as welding speed is increased, the weld narrows, but maintains the needlelike profile. While maintaining complete penetration, the weld shown on the right in Fig. 12 has a solidification cracking defect close to the root, which is common for high welding speeds.

E. The effect of the welding speed on hardness

Hardness is one of the most important critical factors indicating the quality of the weld and its performance in service. The hardness of the shipbuilding steel AH36 was measured to be HV 170. Maximum allowable peak hardness according to the classification societies related to ship production applications is 380 HV and hardness should be kept under 350 HV. In this study, the hardness was measured along the fusion lines of the laser and HLAW welds produced at corresponding welding speeds. All of the welds displayed in Fig. 13 were made with 6 kW laser power and fpp of −2 mm.

At 2.25 m/min welding speed, the HLAW weld has full penetration, while laser weld has lack of fusion in the root side. When comparing the welds produced with 1 m/min welding speed, interesting phenomena occurred—hardness is lower in laser weld than in hybrid weld throughout the joint. Corresponding heat inputs are 300 J/mm for laser weld and 430 J/mm for hybrid weld. As welding speed is increased (heat input becomes smaller), situation is changed, thus, higher welding speed (insufficient heat input) is the cause of increased hardness and smaller penetration. Addition of the filler wire and larger heat input in HLAW slows cooling of the weld, resulting in smaller peak hardness.

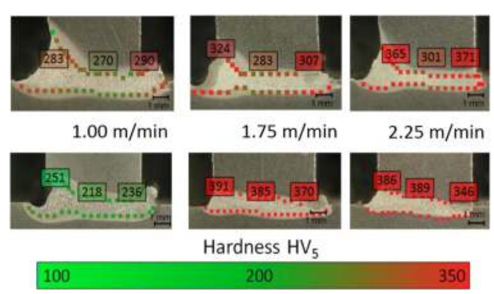


FIG. 13. The macro-indentation hardness profiles of the T-joints made with corresponding speeds using HLAW (up) and laser welding (down).

IV. CONCLUSIONS

In this study, the effects of focal point position, beam inclination angle, welding position, and heat input on the geometry of the fillet welds produced with laser and HLAW were examined.

In both welding processes, the focal point position below the workpiece surface results in deeper penetration. However, in the case of laser welding process, this results in under-filled top bead, while in HLAW process, the preferred concave top bead is achieved due to the filler wire added.

The welds produced in 1F position were deeper than those welded in 2F position, having narrower fusion and HAZ. The gravity likely increases the melt flow inside of the melt pool in direction of the seam resulting in deeper penetration in 1F welding position.

Beam inclination angle is a major factor influencing the penetration, as the weld is narrow and propagating along the beam path. For obtaining full penetration, the beam should be positioned in a way that it passes the root of the weld or the melt pool reaches the root side. This can be achieved by increasing the distance of the beam from the flange while simultaneously increasing the inclination angle.

Increasing the heat input increases the size of the melt area, HAZ, and width of the weld, while there was no straightforward correlation to penetration depth, which is strongly dependent on laser power.

The hardness, measured from the fusion lines of the weld, was rather uniform throughout the sample thickness. The hardness of the welds produced at higher welding speeds was below 400 HV, remaining in acceptable range for AH36 material at welding speeds up to 2 m/min.

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