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Root formation and mechanical properties in laser keyhole welding of 15 mm thick HSLA steel

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Abstract. Deep penetration laser welding is promising in joining thick (> 10 mm) steel sections. Focused laser beam by drilling vapour cavity, the keyhole, generates deep and narrow welds. Full penetration single-pass joining has a persistent problem with root quality where humping is one of the most frequent imperfection. This strongly hampers the use of high-power laser for thick plate welding. A 16 kW disk laser was used for single-pass welding of 15 mm thick plates in a butt joint configuration. Root humping occurred within a wide range of welding parameters. This provides narrow processing window. By adding an arc source to the laser beam process, the tendency of root humping increases. To achieve humping-free welds and consistent root quality over length, a delicate balance of process parameters is required. High heat input (> 0.50 kJ/mm) was positive to achieve a combination of low hardness (< 325 HV) and good Charpy toughness at −50 °C (> 50 J).

1. Introduction

Thick steel plates (> 10 mm) are frequently used for structural application in assembling bridges, ships, structural beams etc. Arc welding is the most widely used process for fusion joining of such components due to reliability and lower cost investments. Laser beam welding (LBW) and laser-arc hybrid welding (LAHW) can become a viable alternative [1]. Their ability in joining plates with thicknesses beyond 10 mm may be restricted due to several factors such as sensitivity to various imperfections and high hardness. When short-wavelength Yb:fibre/disk lasers (1030-1070 nm wavelength) are used, a very few investigations have been made for thick plates using single-pass welding technique. Single-pass welding is of high relevance due to simplicity and readiness for production without the need to turn the sections and where access is limited, e.g. very large plates or orbital pipeline welding. However, full penetration single-pass welding often causes imperfections such as root humping or sagging. Haug et al. [2] showed that 1070 nm wavelength disk laser had very narrow process window in case of 12 mm thick steel joining. By contrast, a 10 600 nm long wavelength (CO_2) laser provided much wider power process window. Short-wavelength lasers have higher absorption coefficient and subsequent melt overheat with unfavourable melt dynamics at the keyhole exit. Frostevarg [3] reported that LAHW often provides humping due to unfavourable melt dynamics in the weld pool and wider root width compared to LBW. There are still many unknown factors in why and how to avoid root imperfection in welding thick plates. Application of electromagnetic backing can be a solution [4-9]. However, its viability on a full industrial scale (for welds longer than 5-10 m) is not proven. Therefore, further investigations are required on root formation.

Another challenge in LAHW/LBW is narrow and deep welds which tend to have excessive hardness due to the rapid cooling rates associated with lower heat input. In LBW of 20-25 mm carbon steel with 0.10 wt.% C, hardness up to 500 HV was reported [10]. With the use of lower carbon steels (< 0.08 wt.% C), the hardness can be up to 380 HV in partial penetration welds [11]. Such high hardness can be reduced by optimizing process parameters; an increase of laser beam power is effective to slow down the cooling rate [11], or alternatively preheating can be applied [12]. Up today, numerical simulations of root humping formation physics are not widely published. The main reason may be related to the complexity of the process since root formation requires an explicit model of the keyhole with considerable calculation time. Moreover, the precise mixture of filler wire and base metal must be identified in the molten state and during solidification, in addition to temperature dependent thermophysical properties such as surface tension, viscosity, density etc.

The present work is based on experimental observations using a wide range of parameter variations having heat input difference up to two times (0.48-0.82 kJ/mm). A 16 kW disk laser was used to weld 15 mm thick plates with a single-pass welding technique with the objective to obtain acceptable quality welds, level B according to ISO 12932 [13], and high toughness (min. 27 J at −50 °C).

2. Methodology

2.1. Materials

The steel plates were 15 mm in thickness and cut to dimensions of 500 mm in length and 150 mm in width. The base metal (BM) is thermomechanically rolled steel (TMCP) with a microstructure consisting of banded ferrite-pearlite providing min. 40 J impact toughness at −60 °C. A commercial 1.2 mm solid wire was selected. The steel and filler wire chemical compositions are shown in table 1. The BM has a carbon equivalent value of CE_{IIW} = 0.38 and P_{cm} = 0.25 representing good weldability. The base metal has 420 MPa min. yield strength ($R_{p0.2}$) and 520-680 MPa ultimate tensile strength (R_m). The solid filler wire provides yield and tensile strength of 420-460 MPa and 500-680 MPa, respectively.

Table 1. Chemical composition (wt.%) of base metal S420ML (mill certificate values, with small amounts of Nb, V and Ti < 0.05 wt.%) and wire (nominal values in manufacturer's datasheet).

Material	C	Si	Mn	P	S	Fe
Base metal	0.14	0.50	1.60	0.020	0.015	balance
Wire	0.10	1.00	1.70	0.025	0.025	balance

The Y-bevelling geometry is shown in figure 1a. Here, LBW or LAHW were used for the root with filling by the chosen arc welding method (GMAW). A standard (non-pulsed, spray) droplet transfer mode was chosen. Machined edges were used with fine surface quality (R_a = 0.8 µm). Run-in and run-out plates were tack welded to the plates.

2.2. Equipment and setup

A continuous wave multi-mode 16 kW disk laser (TruDisk16002 TRUMPF) was used in the experiments with 200 µm fiber core diameter, 8 mm·mrad beam parameter product, and 1030 nm wavelength. The laser beam had 600 mm focal length focused to a spot size of 300 µm in diameter.

The LAHW setup is shown in figure 1b. The laser beam had inclination angle was 7° from normal to eliminate high back reflections. A gas metal arc welding (GMAW) torch was tilted by 75° to the welding surface. The welds were deposited with an articulated robot. The filler wire stick-out was 20±2 mm, and the shielding gas composition was 80% Ar mixed with 20% CO_2 for LAHW and pure Ar for LBW with flow rate of 25 l/min.

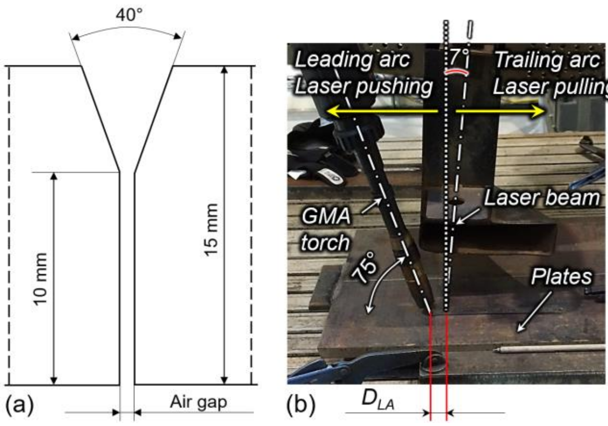

Figure 1. (a) Y-bevelling geometry and (b) welding setup.

2.3. Process variables

The process variables for LAHW and LBW are listed in table 2 and table 3, respectively. The main parameters are air gap, laser beam power (P_L, kW), welding speed (v_s, m/min), laser-arc distance (D_{LA}), wire feed rate (*WFR*, m/min), focal point position (*FPP*) and arc position (*AP*). Calculation formula of heat inputs which is measured in kJ/mm (Q_L for the laser, Q_A for the arc, Q_H for the LAHW) can be found in [14].

Table 2. LAHW parameters. *LA* – is leading arc, *TA* – is trailing arc. *a* – air gap (mm). The filling pass was made with arc using *WFR* of 9 m/min, travel speed of 0.5 m/min and heat input of 0.78 kJ/mm.

Weld	*AP*	*a*	P_L	v_s	*WFR*	D_{LA}	*FPP*	Filling pass	Q_L	Q_A	Q_H
1H	*LA*	0.5	10	1.0	4	15	0	−	0.42	0.14	0.56
2H	*LA*	0.5	10	1.0	2	5	0	−	0.42	0.06	0.48
3HA[a]	*LA*	0.5	10	1.0	2	15	0	+	0.42	0.06	0.48
3HB[a]	*LA*	0.5	10	1.0	2	15	0	+	0.42	0.06	0.48
4H	*LA*	0.5	12	1.0	2	5	0	−	0.50	0.06	0.56
5H	*LA*	0.5	12	1.0	4	15	0	−	0.50	0.14	0.64
6H	*LA*	0.5	12	1.0	2	15	+25	−	0.50	0.06	0.56
7H	*TA*	0.0	16	0.9	2	15	+25	−	0.75	0.07	0.82
8H	*TA*	0.0	16	1.2	2	15	+25	−	0.56	0.05	0.61
9H	*TA*	0.0	16	1.3	2	15	+25	−	0.52	0.05	0.57

[a] These two experiments had identical parameters and A/B is used to distinguish runs.

Table 3. LBW parameters. *LP* – is laser position. *PS* – is laser pushing, *PL* – is laser pulling. *a* – air gap (mm). Filling pass made with arc with *WFR* of 6-10 m/min, travel speed of 0.5 m/min and heat input of 0.41-0.95 kJ/mm.

Weld	*LP*	*a*	P_L	v_s	*FPP*	Filling pass	Q_L
1L	*PS*	0.0	9	1.0	0	+	0.38
2L	*PS*	0.0	10	1.0	0	+	0.42
3L	*PS*	0.5	9	1.0	0	+	0.38
4L	*PS*	0.5	10	1.0	0	+	0.42
5L	*PS*	0.5	11	1.0	0	−	0.46
6L	*PL*	0.0	16	1.2	+25	+	0.56
7L	*PS*	0.0	16	1.2	+25	+	0.56

2.4. Testing and characterization
The Charpy V-notch (CVN) impact toughness test was performed according to ISO 9016 [15] with standard specimen dimensions of 55×10×10 mm^3 and V-notch type geometry. Three test series were included; (*i*) the notch located at the weld metal (WM) centre in the arc zone, (*ii*) WM centre in the laser zone, and (*iii*) the fusion line (FL) of the laser zone (where the fusion line is straight and nearly perpendicular to the plate thickness direction). The samples were cut transverse to the welding direction (WD) with parallel fracture path during Charpy test. All tests were performed at −50 °C, using three specimens for each notch position.

Metallographic studies were performed according to the ISO 17639 [16] standard. Etching was carried out in a 2% nital solution for 5 s. Macrographs were examined with optical microscope for microstructure characterization. Measurements of Vickers microhardness ($HV_{0.5}$) were conducted with a 500 gf load according to the ISO 22826 [17] standard.

3. Results and discussion
3.1. Laser-arc hybrid welding
Initial experimental runs were conducted to achieve full penetration by using 0 mm *FPP* and leading arc position with low *WFR* (2-4 m/min). Welds No. 1H and 2H had incomplete penetration by using 10 kW laser power and 1.0 m/min weld speed at different D_{LA}. A reduction of *WFR* to 2 m/min with 15 mm D_{LA}, full penetration was achieved Weld No. 3HA, see figure 2. Thus, lower amount of added filler wire does not affect the effective thickness of the plates. However, full penetration was unexpected. The process shows very high sensitivity to D_{LA} and small changes in *WFR*. Moreover, both humping or dropout and melt ejection (melt expulsion or cutting) were present within the same weld. Such behaviour is very unusual in welding, and this implies that there is process instability issues or lack of melt flow control in the root. This observation may be related to the fact that higher laser power is required to achieve full penetration in welding of thick plates (> 12 mm). Hence, a larger weld pool volume and higher pressure inside the keyhole is reached due to high temperatures with excessive evaporation. When the keyhole penetrated the whole plate, turbulent melt flows were achieved with unstable behaviour. The experiment was repeated (Weld No. 3HB), and similar results were achieved with few large underfills. By increasing the laser power to 12 kW, the strong melt ejection mode (similarly to laser cutting) is achieved at different D_{LA}.

Different parameter set was applied including defocused laser at +25 mm *FPP* with increase of laser power, zero air gap, and trailing arc setup. The humping was generated more frequently (Welds No. 6H–8H, see figure 2) at any welding speed with inconsistent top weld quality. By increasing welding speed to 1.3 m/min (Weld No. 9H), the humping was significantly reduced but still variation of underfill and humping was present. This point may indicate that *FPP* of 0 mm with narrower keyhole at the bottom is more beneficial for the root quality. In addition, a small air gap (0.5 mm) provided better results since less BM was melted and the laser beam went partially through the plates. Thus, a lower pressure inside the keyhole was formed. It is challenging to achieve high quality of the root with the LAHW process due to the extra heat from the arc and unstable behaviour of the keyhole by adding filler material.

3.2. Laser beam welding
Autogenous LBW was tested with 0 mm *FPP*. Promising results can be achieved at zero air gap and 10 kW laser power (Weld No. 2L, figure 3). However, the weld root had inconsistent quality with humping and slight underfill at the same time. The root can be qualified to level B according to ISO 12932 [13]. However, the geometrical inconsistency can provide low fatigue properties and may not be suitable for application with dynamical loads. Such inconsistent quality of the root formation might be related to transversal laser beam oscillations which can be natural or forced (e.g. by equipment and/or optics, thermal lensing effect) with unequal amount melting of base metal, weld plume oscillations causing irregular laser power supply, and unequal laser power distribution due to multi-mode technology.

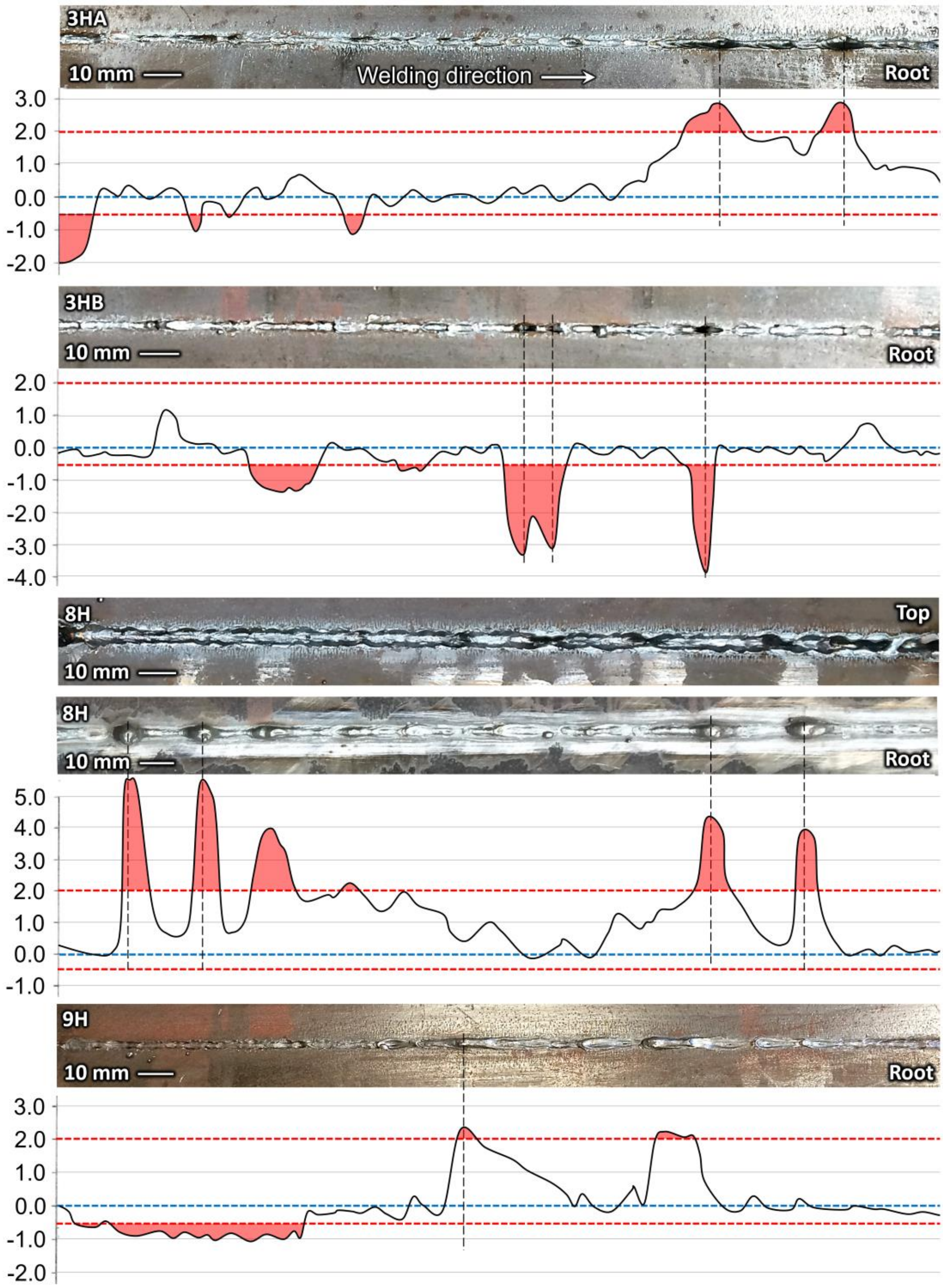

Figure 2. Weld seam appearance from root side of LAHW. Red dashed lines represent tolerance limits for imperfections, level B according to ISO 12932 [13]. *y*-axis shows deviation (in mm) of humping (upwards from 0.0) and underfill (downwards from 0.0).

By increasing the air gap to 0.5 mm, the quality was insufficient (Weld No. 3L). Further increase in laser power (by 10-20%), generated even more underfill. This implies that the process switched to a melt ejection mode. An increase in beam power only by 1 kW (< 10%) caused more underfilling through the whole weld length (Weld No. 4L). A further increase of laser power by 1 kW, generated

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more underfill (Weld No. 5L). This is another indication of the process sensitivity to a slight change in certain parameters (e.g. laser power).

By changing the *FPP* to +25 mm, combined with higher laser energy of 16 kW, zero air gap and welding speed of 1.2 m/min, the underfilling from the root was diminished (see Weld No. 6L). However, still some humping was present within the limits of the level B quality. A flatter and more consistent weld root quality was achieved (Weld No. 7L) by using laser pushing setup. In this case, the process is in melt ejection mode and showed good process repeatability (more than 3 m long welds were made in total). As a result, more stable process can be established with zero air gap using higher laser power, in melt ejection mode. In this case, the hanging humps were dropped out (cut out) from the root of the weld pool by generating higher pressure at the keyhole exit.

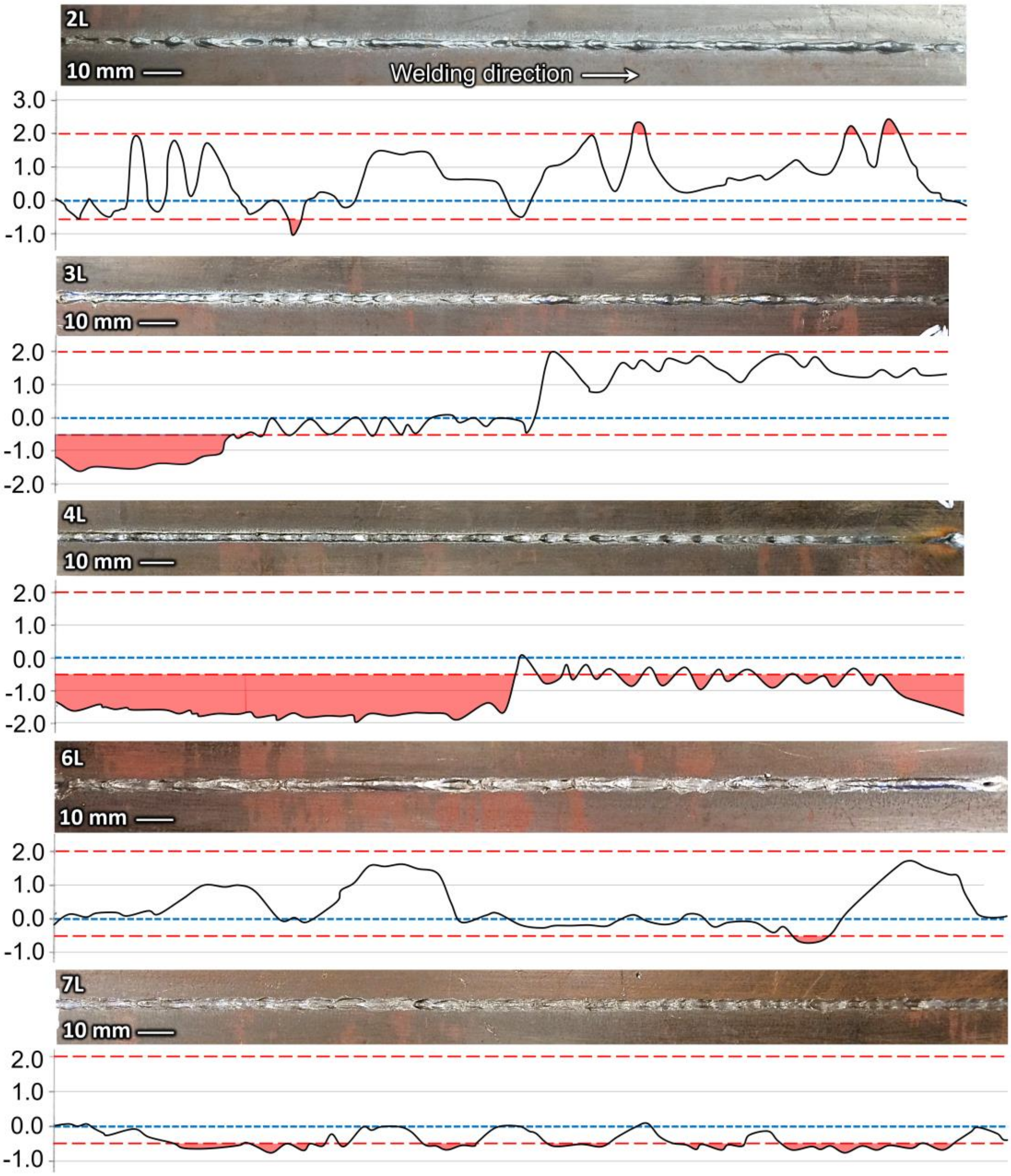

Figure 3. Weld seam appearance from the root side of LBW. Red dashed lines represent tolerance limits for imperfections for level B according to ISO 12932 **[13]**. *Y*-axis shows deviation (in mm) of humping (upwards from 0.0) and underfill (downwards from 0.0).

In figure 4, a comparison of the present study with published results is shown. The present case with carbon steel and 15 mm thickness, has a very narrow process window compared to thinner plates since higher heat inputs were used. Higher power density is required to achieve full penetration and leads to higher temperatures in keyhole, larger melt pool with faster melt flows at keyhole front (> 15 m/s [18]). As soon as keyhole penetrated the bottom surface, there is low control over melt dynamics, thus humping is produced. Here, the balance of forces is interrupted since surface tension is too low to sustain dropout and large weld pool with high melt forces are increased by gravity [3]. As a result, the balance is interrupted leading to high susceptibility to humping. A further increase in the laser beam power provides smooth root appearance with a slight reinforcement. Subsequent increase in laser power, generates melt ejection mode generating underfill/undercuts in the root area. More advanced studies are required in such case to understand the real reason of humping and to develop preventive methods. One of the possibilities to prevent humping is to use much smaller spot size at the same time lower laser power is needed. However, it will lead to high hardness increase. Chemical composition of the base metal and shielding gas may be important to reduce humping as shown by other researchers. The effect of filler wire also should be considered since it can influence on the physical properties of the molten metal during solidification with surface tension probably being the most influential during root formation [3, 19].

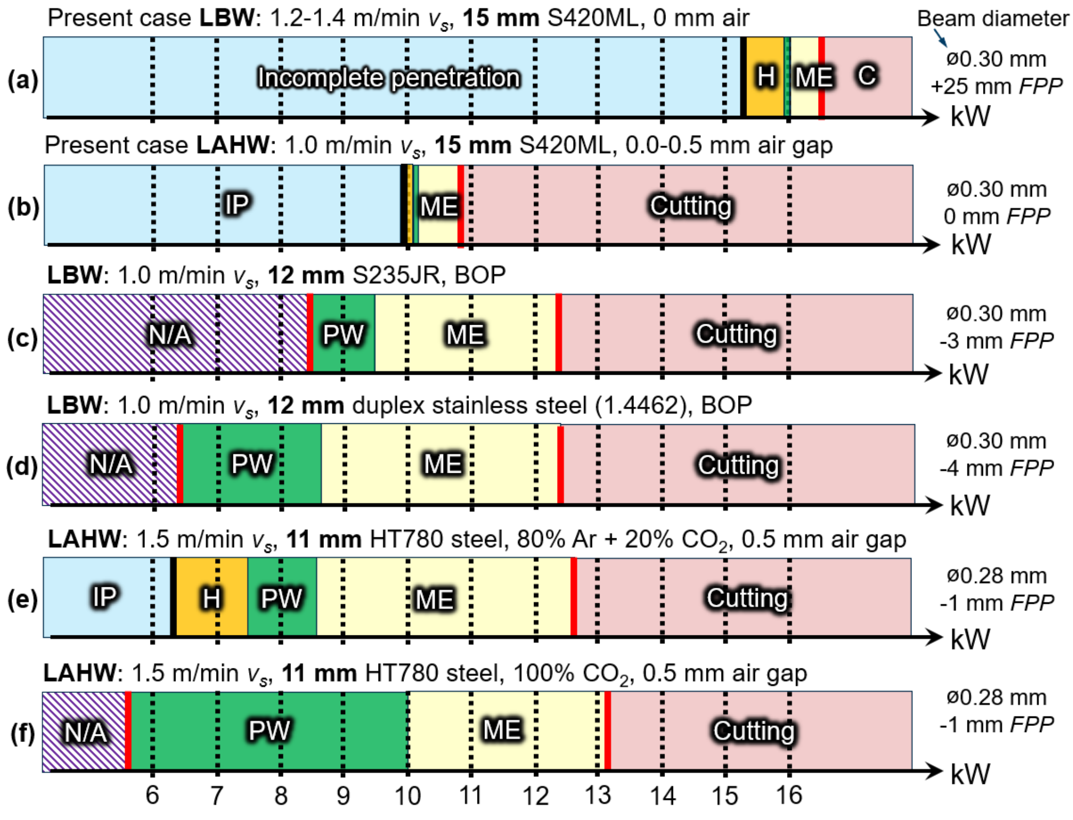

Figure 4. Comparison of (a, b) present case results with published results from (c, d) TRUMPF [2, 20] and (e, f) Osaka University [21]. *IP* is incomplete penetration, *ME* is melt ejection, *PW* is process window, *H* is humping, *C* is cutting, *N/A* is not reported. BOP is bead-on-plate experiments.

3.3. Microstructure and mechanical properties

In the upper part of the welds, a fine-grained acicular ferrite was developed (nearly the same heat input was used in almost all experiments, see table 2) and shown in figure 5. Therefore, high impact toughness is expected. In the laser part in WM, regardless of heat input, a mixture of upper bainite with some lath martensite (possibly with small fraction of retained austenite) was observed (figure 6).

As a result, lower impact toughness is expected. A mixture of martensite and bainite was found in the CGHAZ in all welds, see figure 7.

Hardness results are shown in figure 8a,b for low and high heat input. Hardness in the arc part in WM was low, 250 HV, similarly to the HAZ of the arc part, 300 HV. Higher hardness was found in the laser part. Low laser heat input (0.38 kJ/mm) provided 381 and 351 HV in the HAZ and WM, respectively. Higher heat input (0.56 kJ/mm) provided hardness of 346 HV and 333 HV, which satisfies the acceptance criterion (< 350 HV).

The Charpy test results are shown in figure 8c. As expected, the lowest toughness occurred for specimens extracted from the laser zone with the notch located at the weld centreline. The average impact toughness was 54 J. Such toughness is still much higher than the minimum acceptable value of 27 J at −50 °C. Slightly higher toughness was found for the arc zone with an average of 84 J. This observation agrees with the higher acicular ferrite volume fraction. The fusion line toughness results showed very high values with the average of 223 J. By inspection of the specimens after testing, there is a clear indication that the fracture deviated towards the fine-grained heat affected zone and the BM. Whereas in case of WM, the fracture was propagating within the weld metal. It is possible that the toughness at the fusion line may provide lower values if the crack did not propagate into other softer zones due to strength mismatch in the heterogeneous weld. Another reason of deviation may be due to narrow width (50-150 µm) of HAZ.

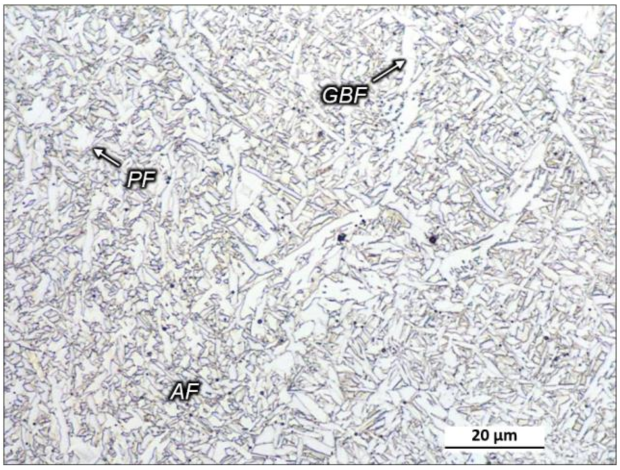

Figure 5. Weld metal microstructure in arc part (Weld No. 7L) representing large fraction of small grained acicular ferrite (AF) with some polygonal ferrite (PF) and grain boundary ferrite (GBF).

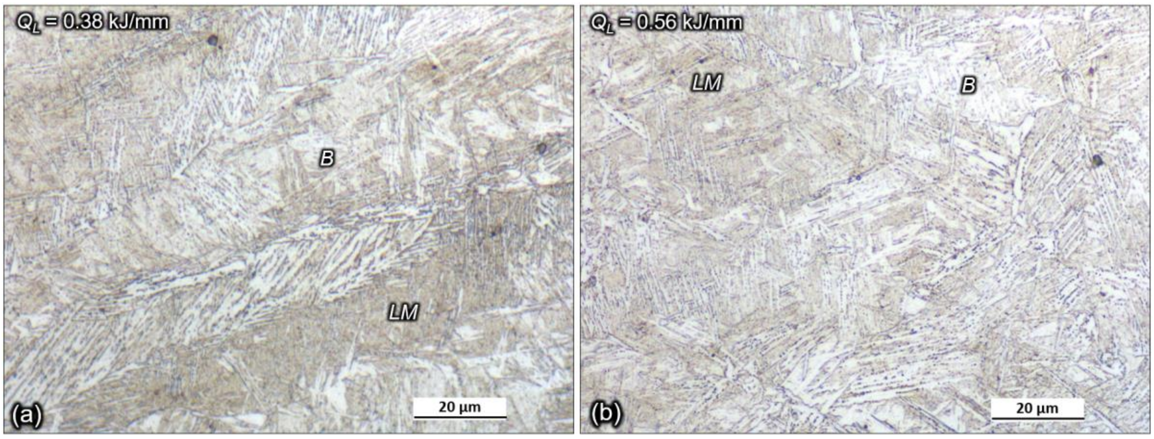

Figure 6. Weld metal microstructure in laser part in root for (a) low (Weld No. 3L) and (b) high heat input (Weld No. 7L) showing mixture of bainite (B) and lath martensite (LM).

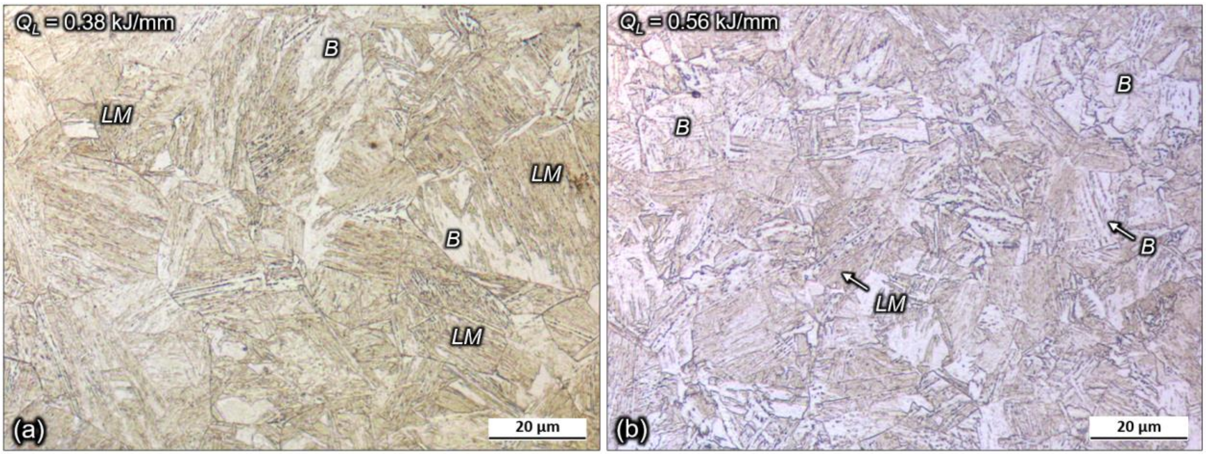

Figure 7. Microstructure in CGHAZ for (a) low heat input weld (Weld No. 3L) and (b) high heat input (Weld No. 7L) showing mixture of bainite (B) and lath martensite (LM).

Weld No. 7L did not qualify due to root underfill. However, based on X-ray radiographic testing, no cracks were detected, and only few pores were observed. Solving the issue of root humping is of primary concern since this has been found to represent the most frequent imperfection in single-pass welding according to this work and noted by other several researchers [2, 3, 22]. LBW/LAHW may gain increased acceptance in industry, even though some hardness spikes may occur. These spikes are easily prevented by using more modern TMCP steels with finer grain size and decreased carbon content (< 0.07% C).

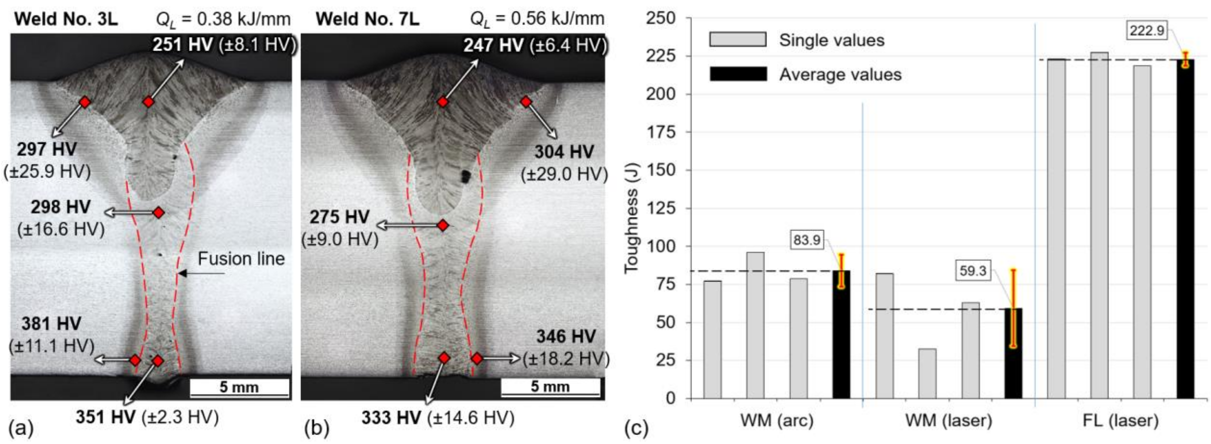

Figure 8. Hardness results of (a) low heat input weld and (b) high heat input weld. (c) Charpy V-notch toughness results of Weld No. 7L at −50 °C.

4. Conclusions

Laser beam and laser-arc hybrid welding has been conducted for a 15 mm thick 420 MPa structural steel. Based on the experimental results, the following conclusions can be drawn:

- LBW and LAHW very sensitive processes for the root formation using high powers (> 9 kW) and large thickness of plates causing high temperatures, pressure in the keyhole with unstable melt conditions.
- LBW showed better root control compared to LAHW due to absence of the secondary heat source. The added arc has an adverse effect on the root formation affecting melt flows. Therefore, LBW showed higher robustness due to repeatability compared to LAHW.

- The process is more robust within the melt-ejection mode due to narrow process window providing acceptable root quality. However, it may generate a slight root underfill and in some cases undercut.
- Appropriate hardness can be achieved (< 350 HV) by applying more than 0.50 kJ/mm heat input.
- LBW provided microstructure consisting of mixture of lath martensite and bainite. However, good toughness (> 27 J at 50 °C) was achieved showing promising results for industrial use.

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