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Hybrid laser-arc welding of steel S700MC butt joints under different sheet thickness

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Abstract

In this paper is discussed Hybrid Laser-Arc Welding (HLAW) of high strength steel S700MC. High strength steel is commonly used at the heavy industry for the steel frames, beams and sandwich panels welding. Assurance of high process productivity and repeatability it requires state of the art technologies. This investigation was focused for the different thickness 6 mm and 8 mm butt joints with 2 mm misalignment. Aim of the paper was to obtain understanding of non-standard seams weldability, microstructure and mechanical properties behavior based on the continuous wave fiber laser IPG YLS-30000 and metal active gas (MAG) welding combination. Specimens were produced under various laser-arc parameters and material setups, e.g. welding speed, laser power, wire feed rate speed, joint preparation. Evaluation of process involved hardness, tensile strength and macroscopic cross-section analysis. The results will be reported in this paper.

Keywords: Hybrid Laser-Arc Welding; high strength steel S700MC; fiber laser; mechanical properties; misalignment;

1. Introduction

Hybrid Laser-Arc welding (HLAW) is process which utilizes the energy of a Laser Beam Welding (LBW) and the energy produced by electric arc source e. g. Gas Metal Arc Welding (GMAW). The necessity of discovering of hybrid welding technology arose in the late seventies but due to laser beam welding limitations and problems, acceptance of application for the industrial sector shown in the 1990s Bagger and Flemming, 2005. High energy density laser beam and conventional electric arc are different welding sources

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that make it possible to combine into hybrid welding. Since the hybrid welding utilizes two different sources it can produce synergy effect and compensate the drawbacks in the both processes.

HLAW synergy effect provides multiple benefits such as reduction of undercut formation at the higher feed rates, deeper keyhole penetration, lower material distortions and better gap bridgeability Baskutis et al., 2014, Turichin et al., 2015. Further, HLAW deeper penetration occurs due to keyhole effect. Application of conventional arc method for deep penetration welding requires multi-layer process. At that time, it reduces welding speed and dramatically increases production time Lahdo et al., 2014. Undercut formation is welding defect which occurs due to fast solidification and melting flows at the high speed. As well as, insufficient welding material in the fusion zone causes undercuts. As a result, HLAW combination provides more material in the fusion zone. Undercuts occurrence and impact was studied by Norman et al., 2011, Frostevarg and Kaplan, 2014.

There is still a lack of information about potential usability of fiber laser and GMAW source combination. Adaptations of HLAW cause problems due to the huge amount of laser-arc parameters and material setups. It can be grouped into design parameters (material thickness and gap geometry), combined processes (welding speed, process distance and others) and material types Kah et al. 2011. HLAW process influence of weldability in accordance with edge preparation, material composition, joint type, roughness and gap tolerance has been studied by Rethmeier et al., 2009, Hayashi, 2003 and Haferkamp, 2006. Impact of sheets misalignment has been discussed by Mazar Atabaki et al., 2014, Rethmeier et al., 2009.

Application of high strength steel such as S700MC allows to decrease material consumption and increase loading due to higher yield strength and superior toughness. As follows, these advantages concerning to mechanical properties in the combination of good weldability makes this steel economically attractive for steel frames, mobile cranes, utility vehicles, shipbuilding and offshore constructions Lahdo et al., 2014, Unt et al., 2014.

This paper investigated weldability influence of non-standard welds made from the high strength steel S700MC. Investigation was performed on the 6 mm and 8 mm of thickness sheets of the scope to gather knowledge about misalignment overfilling possibilities, undercuts formation and ability to withstand the loads. Process development was carried out by the flat position (PA) for the butt joints welding and the horizontal vertical position (PB) applied for the fillet seams welding. As a purpose of evaluation of weldments quality, destructive and non-destructive testing methods has been done and shown in this paper.

2. Experimental procedures

2.1. Testing and welding material

In this study, 2 mm misalignment butt joints with thickness 6 mm and 8 mm were welded from high strength steel S700MC. The Böhler EMK 8 D welding wire of 1.2 mm diameter was applied for this process. Retrieval of repetitive and stable process sheets of dimension 1000 mm length and 260 mm width were used. Prior to HLAW specimen plates were cut by fiber laser. Chemical compositions and mechanical properties of the S700MC and welding wire are shown in the Table 1 and Table 2, correspondingly.

Table 1. Chemical composition (wt. %) of S700MC and Böhler EMK 8 D wire.

Material	C	Si	Mn	P	S	Al	Nb	V	Ti	Mo	B	Ceq
S700MC	0.12	0.60	2.10	0.025	0.015	0.015	0.09	0.20	0.22	0.50	0.005	0.40
Böhler EMK 8 D	0.1	1.0	1.7	-	-	-	-	-	-	-	-	-

Table 2. Mechanical properties of welding material and wire.

Material	ReH 0.2 (MPa)	Rm (MPa)	Ae (%)	$KV^{+20}J$	$KV^{-20}J$	$KV^{-20}J$
S700MC	700	750-950	12	-	40	27
Böhler EMK 8 D	480	620	26	150	-	80

2.2. Equipment description

The research of HLAW was performed using IPG YLS continuous wave fiber laser with a maximum laser beam power of 30 kW and a welding source CLOOS GLC 403 Quinto. The process fiber diameter was 300 µm and the laser was operated at 6 up to 6.8 kW power as follows in the Table 5. The laser beam was focused on the steel plates using Precitec YW52 head of 150 mm collimating length and 300 mm focusing length lens. In the experiment setup focal point diameter was approximately 700 µm. Table 3 is described comprehensive characteristics of the YLS-30000 laser and its equipment. In the Table 4 is displayed technical characteristic of the arc source GLC 403 Quinto.

Table 3. Technical characteristic of the fiber laser IPG YLS-30000 and its equipment.

Laser characteristic	Value
Laser type	Fiber laser IPG YLS-30000 (Ytterbium Laser System)
Operation mode	Continuous wave (CW)
Maximal output power (kW)	30
Emission wave length (nm)	1070 +/-10
Beam parameter product (mm/mrad)	12
Working fiber core diameter (µm)	300
Laser head type	Precitec YW52
Collimating lens focal length (mm)	150
Focusing lens focal length (mm)	300
Focal point diameter (µm)	700

Table 4. Technical characteristic of the arc source GLC 403 Quinto.

Welding source parameter	Value
Welding source type	GLC 403 Quinto
Arc current (A)	40…400
Idle Voltage (V)	71
Current and Voltage at continuous loading 60 %	400 A / 34 V
Supply voltage	400 V / 50 Hz / 3 phases
Operating modes	2-cycle, 4-cycle, super 4-cycle, spot welding/interval

This analysis had two positions. Investigation of Hybrid Laser-Arc Welding was carried out at PA and PB positions to obtain good overfilling of 2 mm misalignment, full penetration and prevention of undercut formation in the cross-section. Fig. 1(a, c) indicates HLAW at the flat position (PA) for the butt joints. In the Fig. 1(b, d) is shown horizontal vertical position (PB) applied for fillet welds. Both positions were corresponding to DIN EN ISO 6947 standard.

Further, compressed air was applied to blow particle cloud as known plasma plume above the process zone. It can scatter the beam, despite the wavelength of radiation and the laser power density on the material surface. As a consequence, airflow above the process zone can be able to protect the shielding glass from spatters, obtain narrower and deeper penetration. In this study, welding equipment was implemented second cross-jet nozzle. The first cross-jet was built in the laser head as shown number 6 in the Fig. 1(b). Secondary cross-jet system was constructed over torch nozzle approximately 100 mm above the workpiece surface. Installed cross-jet was raised over due to interference of compressed air for welding process. Compilation of secondary cross-jet is marked number 7.

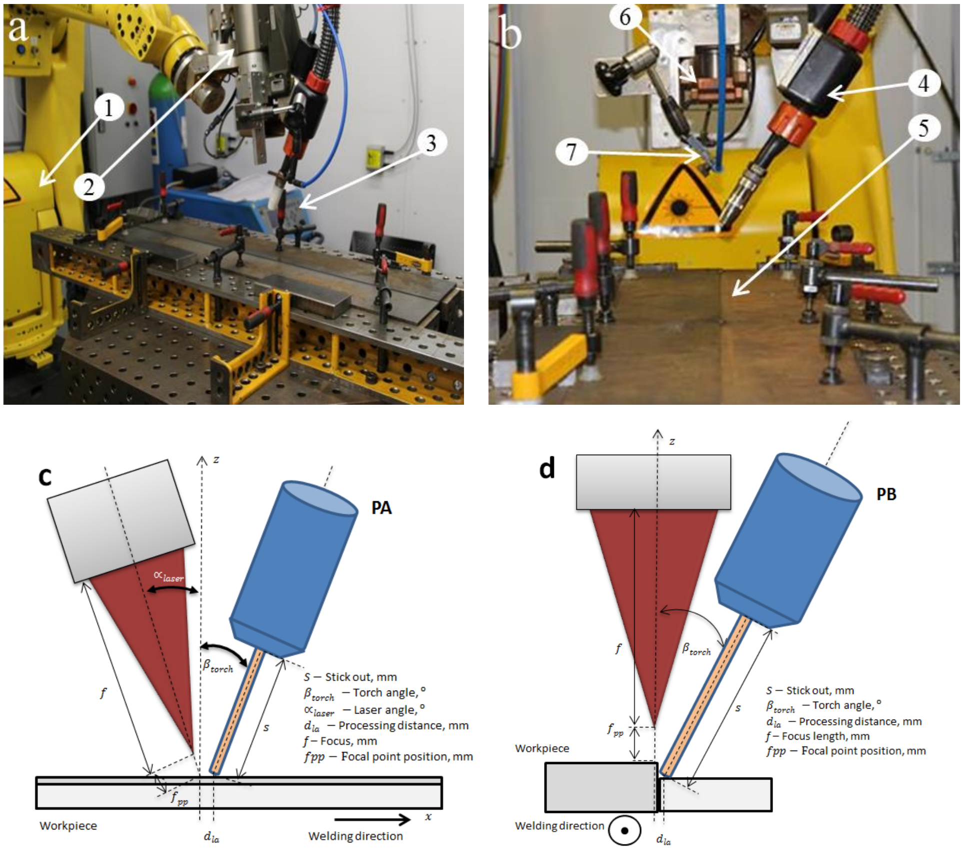

Fig. 1. (a, c) HLAW at the PA position; (b, d) HLAW at the PB position. Experimental equipment elements used for welding: 1 – industrial robot Fanuc; 2 – Precitec laser head; 3 – CLOOS GLC 403 Quinto arc source; 4 – MAG torch; 5 – workpiece; 6 – first cross-jet; 7 – second cross-jet.

2.3. Welding parameters

The butt joints welding of S700MC has been conducted by the combination of fiber laser and conventional arc source. Before welding three tack welds were made due to prevention of thermal distortions along the seam. As a consequence, welding gap condition has been constant and equal to 0 mm gap.

Table 5. The main HLAW welding parameters.

Welding characteristic	H14	H15	H46	H1	H3	H5	H33	H45
Welding speed (m/min)	2.5	2.5	2.5	3	3	3	3	3
Laser power (kW)	6.3	6.8	6.8	6	6.3	6.8	6.8	6.8
Wire feed rate (m/min)	12	14	13	13	12	15	13	13
Ground current (A)	85	85	85	90	85	80	85	85
Arc pulse frequency (Hz)	220	220	230	220	220	230	230	230
Torch angle at PA (β, °), PB (β, °) position	28	28	35	28	28	28	28	35

In the Table 5 is shown the main HLAW parameters applied for the research. HLAW was tested by the speed rate of 2.5 m/min and 3 m/min as possibility to create good quality welds with fully filled bead and complete penetration. The laser power range was from 6 kW up to 6.8 kW. Furthermore, specimens were optimized by the wire feed rate, frequency and ground current.

Detailed view of HLAW arrangement is shown in the Fig. 1(c) and Fig. 1(d). The combination has been done by arc process leading 3 mm in the front for PA and PB positions. Laser head was tilted in the both positions 7° creating α angle of laser and z axis. Hereby, a small angle of beam lurch can reduce the risk of back reflection. In the flat position (PA) arc torch had backhand welding which was forming β angle of 28°. PB position was carried out sideways at 35° angle between z axis and arc torch. In the both welding methods stick-out and focal point position was maintained constant at the 15 mm and the 0 mm values, respectively.

GLC 403 Quinto was operated in the pulse mode. The shielding gas mixture ARCAL 21 (92 % Ar and 8 % CO_2) was delivered through MAG torch at the flow rate 20 l/min. Arc pulse duration 1.9 ms and voltage 37 V was constant and applied for entire process . As well as, all samples were produced under air flow when first and second cross-jet pressure was 10 bar and 4 bar, correspondingly. Other essential welding parameters are shown in the Table 5.

2.4. Testing equipment

Non-destructive testing analysis of hybrid welded seams has been done by the cross-section macrographs. Process involved three steps: cutting, mechanical polishing and etching. Specimens have been cut perpendicular to the weld axis to expose weld profile of the test piece. Evaluation of macroscopic cross-section appearance was taken by DIN EN ISO 12932 standard which provides guidelines for HLAW visual inspection. However, it discusses various imperfection defects such as cracks, porosities, undercuts and many more. It is designated to three quality levels: B – stringent, C – intermediate, D – moderate corresponding to highest requirements.

The estimation of mechanical properties of welded joints has been performed by destructive testing method such as transverse tensile test and Vickers hardness measurement. Vickers hardness (HV1) was measured into two lines. Top line was 1 mm below the surface of 6 mm plate and the bottom line was 1 mm above the backside, indicated in Fig. 4 Hardness survey was done by 0.2 mm displacement in accordance with DIN EN ISO 9015-2 standard which encompassed parent material, fusion and HAZ zone examination.

Specimens for the tensile strength analysis were cut by fiber laser machine. Before tensile strength testing 2 mm plate was welded as a support of misalignment compensation. Transverse tensile strength test has been done by testing specification DIN EN ISO 4136 standard without mechanically milled edges. According to DIN EN ISO 4136 standard for the butt joints it was taken 25 mm width of testing area. The cross-section area has been calculated by thinner sheet thickness.

3. Results and discussion

3.1. Macroscopic analysis

The aim of study was to estimate overfilling capability, undercut formation and stringent quality assurance. Geometry of cross-section provided essential information about hybrid process quality, penetration depth and defects formation. Experiments were performed by the feed rate of 2.5 m/min and 3 m/min in the composition of PA, PB position. Visual seams inspection was carried out according to DIN EN ISO 12932 standard for HLAW. The following laser-arc source parameters are mentioned before and displayed in the Table 5.

Cross-section appearance in the Fig. 2 revealed that 6 kW laser power was sufficient to cause full penetration. Comparison of samples pointed out narrower root area in the H1 and H3 at the 3 m/min feed rate welded by 6 kW and 6.3 kW power. Therefore, laser power was increased up to 6.8 kW.

Moreover, examination of results disclosed weldability and bead formation at the different positions. Horizontal vertical position (PB) of HLAW has shown result of an inferior weldability with higher speed. Sample H45 indicated poorer visual appearance at the range of 3 m/min welding speed. As an assumption, imperfection occurred due to higher feed rate and sideways position which was interfering melting properties of the bead. In the same time, specimen H46 pointed out better quality with lower feed rate. In the comparison of PA position welded samples this feature was not indicated.

As shown in the Fig. 2 samples H14, H15, H33, H45 and 46 are relatively fine, fully penetrated and completely filled groove without defects such as cracks and undercuts. Samples H33 and H46 showed extraordinary good quality and were taken for the measurements of destructive testing. On other hand, specimens H1, H3 and H5 indicated incomplete filled groove. In accordance with DIN EN ISO 12932 standard was not able to evaluate by the stringent (B) quality.

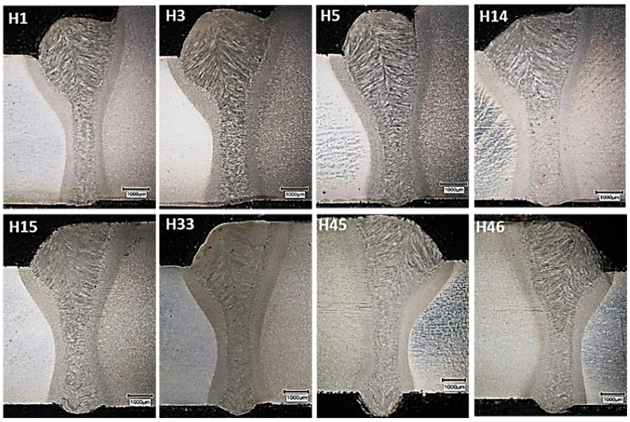

Fig. 2. joints cross-section appearance according to welding parameters in the Table 5.

Moreover, investigation of macrographs disclosed that cross-sections had changes in the welding area. Measurements in the Fig. 3 indicated HAZ and fusion zone displacement. Research revealed deviations occurrence due to welding speed and torch positioning. It can be seen the effect of energy and positioning in the specific zone of 8 mm thickness plate. Sample H45 welded at 3 m/min speed was affected by the highest deviation of 381 µm in the HAZ and fusion zone. In the comparison to sample H15 calculation values were more than 10 times higher. As well as, specimen H46 indicated same feature performed by 2.5 m/min welding speed. Examination of sample H15 and H33 indicated contrary results in the HAZ and fusion zone where impact was almost without curves. Measurements are presented in Fig. 3.

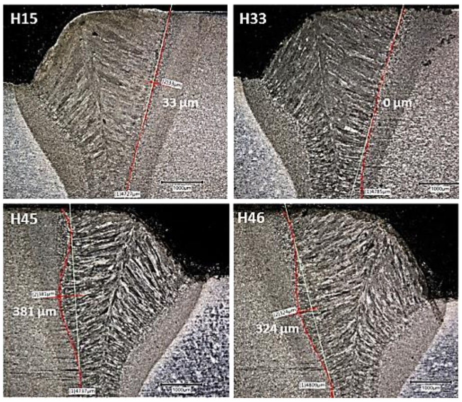

Fig. 3. deviation calculation in the HAZ and fusion zone according to PA, PB position.

3.2. Hardness measurements

Hardness measurement indicates material structure changes in the parent material, heat affected zone (HAZ) and fusion zone. Welding speed is correlated to amount of energy and cooling rates which cause structural changes. Thus, an increasement of welding speed decreases energy input, meanwhile cooling rate increases and microstructure of the weldment has more martensite phase as well as high value of the hardness. Therefore, 2.5 m/min and 3 m/min speed welded joints were examined to the determination of composition change. In the Fig. 4 is shown result and hardness distribution graphics. Distance value of 0 mm indicates center line in the middle of fusion zone. Measurement results revealed that HLAW welded joints was affected by HLAW at the specific zones.

Investigation of hardness displayed higher top line values than bottom line measurements in the fusion zone. Likewise, bottom line values researched the same or even higher results in HAZ. Sample H33 had the peak value of 305 HV1 at the same time the highest value of specimen H46 was 297 HV1. The lowest point of 255 HV1 had sample H33 and 242 HV1 specimen H46. Both samples microstructure changes have been founded in the HAZ. The base material average value was 285 HV1 for 6 mm thickness plate meanwhile 279 HV1 for 8 mm thickness sheet. To conclude, peak values exceeded measurements approximately 12 up to 26 HV1 and drop values fell 24 up to 43 HV1 in the comparison to base material.

Analysis of hardness revealed impact of welding speed. As follows, laser hybrid process had a result of the high cooling rate. As a consequence, lower welding speed had a longer cooling time in addition to higher heat input energy. Sample H46 was welded under 2.5 m/min speed indicated lower values in comparison to specimen H33 joined by 3 m/min rate. To sum up, hardness peak and drop values had no influence for welding quality. All break points happened in the 6 mm thickness base material, approximately 25 mm away from the middle of fusion zone.

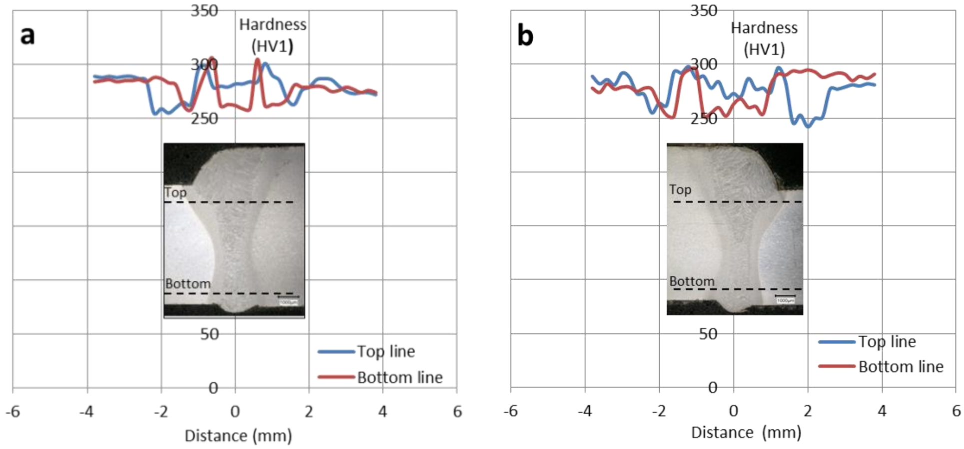

Fig. 4. (a) hardness distribution at the top and root of sample H33; (b) hardness distribution at the top and bottom of weld H46.

3.3. Tensile strength evaluation

Tensile test examination was used to characterize weld deformation and failure modes as well as to evaluate the strength and ductility of HLAW. The curves show variations of yield stress, failure strength and ultimate tensile strength. Generally, it was done by 5 tests from H33 and H46 samples compare to base material S700MC 6 mm and 8 mm thickness. The purpose was designed to test loading fluctuation in the same material and obtain more precise information about stresses behavior. Furthermore, it was taken by different feed rates. In the Fig. 5(a) and Fig. 6(a) are shown typical tensile stress-strain curves for specimen welds.

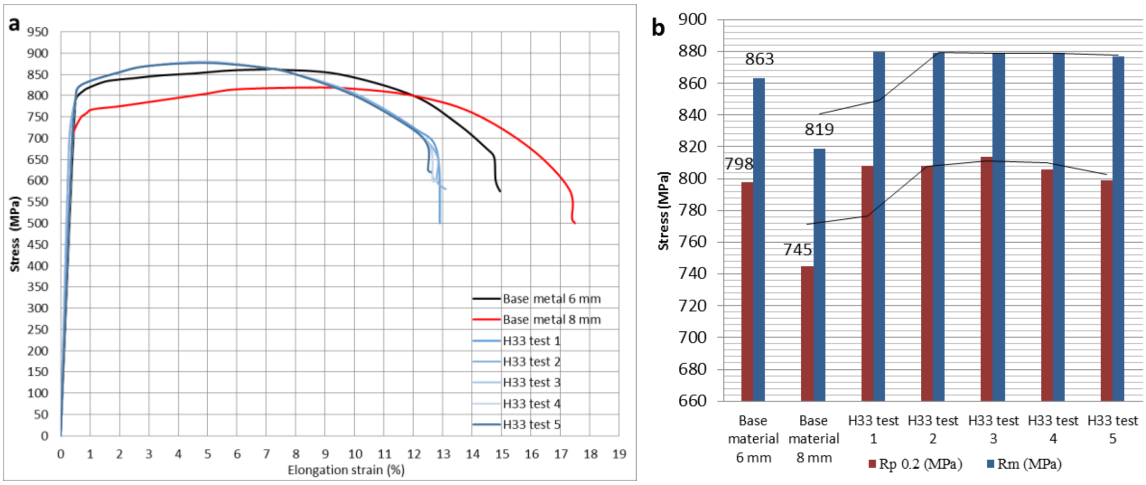

Fig. 5. (a) transverse tensile test graphics for the S700MC material and sample H33; (b) results comparison of base material and specimen H33 yield point Rp 0.2 and ultimate tensile strength Rm.

As we can see, the welded specimens had clear yield and breaking point. Base material 6 mm thickness indicated higher yield and ultimate strength than 8 mm parent material. In the Fig. 5 and 6 a higher yield stress and ultimate joint strength were found in the sample H33 to compare with sample H46. The cooling rate was taken into account as one of factor caused lower strength in the weldment H46. As consequence, longer cooling rate decreased alloying composites thermal changes and hardness in weldment area. Likewise, samples H33 and H46 had different position which was able to increase energy distribution in the joint H46. On other hand, sample H46 tests indicated longer elongation compare to specimen H33. To sum up, the break point for all samples occurred in the 6 mm plate and both weldments had shorter elongation strains in comparison to parent material S700MC.

In the Fig. 5(b) and Fig. 6(b) are shown measurement of yield stress Rp 0.2 and ultimate tensile strength Rm. Diagrams revealed base material and specimen's comparison of stress measurements. Sample H33 values were fluctuating in the range 799-814 MPa of yield stress and 877-880 MPa of ultimate strength. Meanwhile, specimen H46 indicated measurement values among 733-760 MPa of yield strength and 838-853 MPa of ultimate stress. In the same way, base material S700MC of 6 mm and 8 mm thickness had values of 798 MPa and 745 MPa yield stress as well as 863 MPa and 819 MPa of ultimate strength, respectively. Comparison of HLAW sample strengths revealed value distribution among base material and welded samples or even higher measurements as in sample H33.

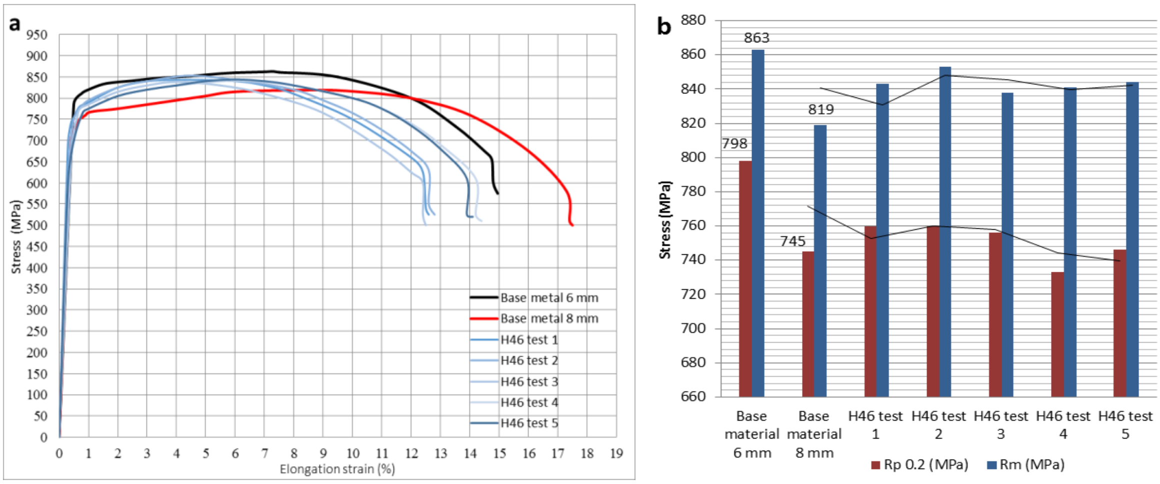

Fig. 6. (a) transverse tensile test graphics for the S700MC material and sample H46; (b) results comparison between base material and specimen H46 yield points Rp 0.2 and ultimate tensile strengths Rm.

4. Conclusion

This study investigated Hybrid Laser-Arc Welding (HLAW) weldability of high strength steel S700MC under 2 mm misalignment with various laser-arc parameters. Examination of cross-section macroscopic pictures, tensile strength graphics and hardness tests provided results which may be summarized as follows:

- Investigation has been done for specimens H14, H15 and H46 welded by 2.5 m/min speed as well as samples H1, H3, H5, H33 and H45 jointed by 3 m/min feed rate. Full penetration occurred at the 6 kW laser power but acceptable results were welded by 6.8 kW. The majority of weldments indicated relatively fine quality, completely filled groove and full penetration. Sample H33 and H46 satisfied stringent (B) quality results. Moreover, experimental procedure revealed weldability and bead formation at the different positions. Horizontal vertical position (PB) of HLAW has shown an inferior weldability with higher speed. Visual inspection of sample H45 and H46 indicated specific deviations in the HAZ and fusion zones. Deviation calculation in the sample H45 and H46 were 381 µm and 324 µm, respectively. Meanwhile, sample H15 and H33 had 33 µm and 0 µm, correspondingly.
- HLAW influenced hardness test results due to welding speed and cooling time. Specimen H33 had the highest value of 305 HV1 and measurements were not significantly higher at the top and bottom line than sample H46. Sample H46 had the lowest measurement of 242 HV1. Analysis of base material hardness average indicated values of 285 HV1 and 279 HV1 in the 6 mm and 8 mm, respectively. Hardness distribution in the HAZ had no impact for weldment quality.
- Comparison of yield and tensile strength graphics has displayed that joints welded by 2.5 m/min and 3 m/min speed had a shorter elongation strains as a base material S700MC. Moreover, measurements revealed that samples H33 and H46 had stresses distributed among parent material and welded specimens. Sample H33 graphics indicated higher measurement of stresses than the base material S700MC and sample H46. All break points occurred in the 6 mm plate approximately 25 mm away from fusion zone.

After comprehensive study, it was gained understanding of non-standard joints weldability, microstructure and mechanical properties behavior based on laser-arc source. To sum up, non-standard seam welding showed high potential results.

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