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Solutions for joining pipe steels using laser-GMA-hybrid welding processes

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Abstract

This paper focuses on high power fiber laser welding of steel material for the field of pipe production. X65 and X70 steel plate material in thicknesses of 9.5 mm and 14 mm was welded with laser-GMA-hybrid welding processes with a maximum laser power of 8 kW. Two different filler wires and joint preparations were tested for their weldability. Relating to these welding procedures and thicknesses, characterisation of welded samples such as hardness, tensile testing and Charpy V-notch testing were carried out and the results will be reported in this paper.

Keywords: Laser welding; laser-GMA-hybrid-welding; pipe steels; X65; X70

1. Introduction

During the last few years, the application of laser beam welding technologies for joining thick section steels has found its way into several different industrial fields such as shipbuilding [1], pipe production [2;3], or pipelaying [4;5]. Considering shipbuilding, it was shown [1] that the application of CO_2-laser beam welding in panel production allows an improvement of economic competitiveness whilst improving quality e.g. by reducing distortion and obtaining strength overmatched weld zone while satisfying required weld properties. However, earlier CO_2-laser systems are characterised by low energetic efficiency and high efforts needed to deliver the beam to the workpiece. Besides the CO_2-laser, high-power fibre lasers have been successfully applied for shipbuilding showing their specific advantages such as fiber delivery, high powers up to 20 kW and more in cw mode and its excellent beam quality also at higher powers [6].

Pipelaying, meaning girth welding of pipelines, was hardly accessible to laser welding up to now. Especially for onshore pipelaying under field conditions, the laser systems previously available were missing such qualities as

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robustness, mobility and the high degree of freedom needed for welding around the pipe. Howse et al. have successfully applied fibre delivered lasers for welding to show their potential for the application of pipeline welding [7].

In pipe production e.g. longitudinal welding or spiral welding, conventional laser welding techniques such as CO_2-laser-GMA-hybrid welding have been investigated for the production of a variety of steel grades [2], [3]. Fiber lasers have not yet been widely applied in this field, yet with the advantages over CO_2-lasers as described above, it would be a viable alternative. In this paper the main focus is set on presenting research work done for process development and weld characterization of pipe steels. Process development was carried out firstly in the field of single pass welding of X65 pipe steel to demonstrate the feasibility of laser welding/laser hybrid welding to reduce bottle-neck situations in production. Secondly, welding 14 mm X70 using a hybrid process for the root pass and a GMAW process for the fill or cap pass with as little passes as possible, is presented.

2. Materials, Experimental Set-up and Test Methods used

2.1. Material

Two different grades of base material were used for laser-hybrid welding processes. The X65 steel in 9.5 mm thickness and X70 steel in 14 mm thickness were used in the form of flat plates with dimensions of 450-500 mm long and 150-200 mm wide. The chemical compositions of these two steels are given in Table 1. For the hybrid welding experiments, two different welding wires of 1.2 mm diameter were used: a solid one, Nertalic 70S (T46 4 M M 1 H5 according to EN 758) and a metal cored wire, SAF DUAL 200 (G2 Si according to EN440), Table 2.

Shielding gases for the laser-GMA-hybrid welding process have been chosen in accordance with European standard DIN EN 439, M21. Gas mixtures with 82 % Ar and 18 % CO_2 as well as 90 % Ar and 10 % CO_2 have been used. Several different joint preparations were applied for welding the plate material. For the X65 material, an I-butt joint configuration was used. In order to weld the 14 mm X70 with 8 kW of laser power, a specific joint preparation was necessary. Thus, a single V-butt joint with root faces of 6 mm and 8 mm and an included angle of 45° was used for this welding task.

Table 1. Chemical compositions of the X65 and X70 steels

Chemical analysis (wt %)													
C	Si	Mn	P	S	Al	Cr	Cu	Mo	N	Nb	Ni	Ti	V
X65, t = 9.5 mm													
0.05	0.18	1.07	0.012	0.0015	0.03	0.03	0.01	-	0.006	0.057	0.02	0.002	0.035
X70, t = 14 mm													
0.083	0.228	1.73	0.013	0.0028	0.049	0.031	0.047	0.002	0.0054	0.051	0.055	0.005	0.082

Table 2. Chemical composition of welding consumables used

Chemical analysis (wt %)				
C	Mn	Si	S	P
Nertalic 70S Solid wire – on deposited metal with gas M21				
0.06	0.9	0.45	0.015	0.015
SAF DUAL 200 Metal cored wire – on deposited metal with gas M21				
0.04	1.7	0.5	0.014	0.01

2.2. Experimental set-up

For the experiments carried out, an YLR-8000 S fibre laser set-up with 8 kW output power was used for laser-GMA-hybrid welding. A DalexVario MIG 600 l(w)-B power source and an Abicor Binzel APD wire feed unit were employed for the hybrid welding process. A hydraulically operated clamping device was used to ensure correct fixation of the work piece during welding. A special feature of the YLR-8000S fibre laser is the 100 µm feeding fibre coming from the beam combiner and not being interrupted by an optical coupler or a beam switch, thus acting as the processing fibre at the same time. This configuration of the fibre laser allows a very high brightness of the laser beam and consequently a very high beam quality of 4.2 mm*mrad. The fibre was connected to a 160 mm Optoskand collimator mounted on a Trumpf BEO D70 laser welding head with a 280 mm focusing lens producing a focal spot of 0.22 mm in diameter. For the hybrid welding process, the laser welding head was mounted together with a specially developed GMAW torch to a gantry robot work station, Fig. 1. By using the fine adjustments, the position of the torch relative to the laser beam could be changed. The welding experiments were carried out with the torch in leading position. Concerning the X70 material with the single V-butt joint preparation, the weld was made in two separate steps. First, the root pass was welded with the hybrid process and second the fill pass was made using the same torch, but without the laser beam.

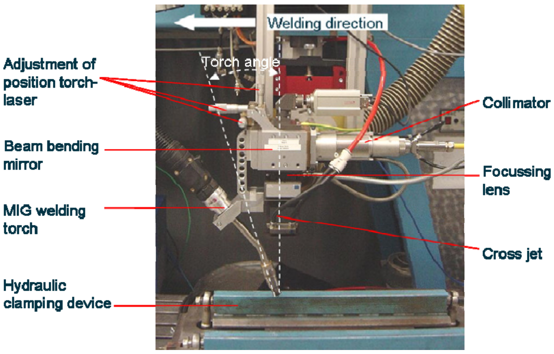


Fig. 1. Experimental set-up for laser-GMA-hybrid welding with 8 kW

2.3. Test methods

The following methods were used to characterize the welded specimen and determine the properties of the weld seams. Non-destructive testing as a visual inspection was carried out to check on the visual appearance of root and fill pass as well as X-raying of the welded samples. Several destructive testing methods were carried out. First, macrographs of polished and etched cross-sections were prepared to allow an evaluation of possible imperfections and determination of the microstructure as well as conducting hardness measurements. Mechanical testing was carried out by conducting tensile testing, micro tensile testing and Charpy V-notch testing. All three methods comprised testing of base materials and welded seams.

3. Results

3.1. Welding X65 material with I-butt joint

In the first set of experiments, X65 material with a thickness of 9.5 mm was welded as butt joint in a single welding pass using a hybrid laser welding process. Experiments were carried out with welding speeds between 1 m/min and 2 m/min with solid wire and metal cored wire, specified above. For all welding speeds and both wire electrodes used, acceptable up to good weld seams according to visual inspection and requirements of DIN 13919 for laser welded joints were achieved. Fig. 2 shows cross-sections of the weld joints welded with solid wire and Fig. 3 those welded with metal cored wire.

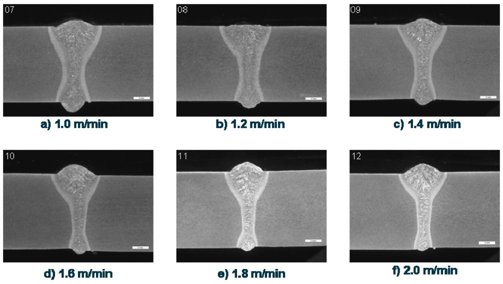


Fig. 2. Welding of 9.5 mm thick X65 plate material with solid wire

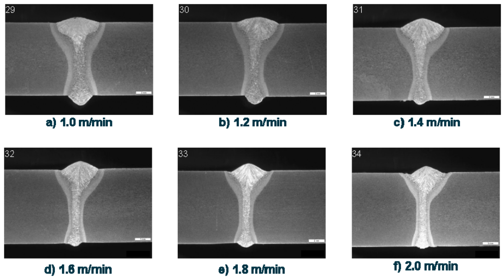


Fig. 3. Welding of 9.5 mm thick X65 plate material with metal cored wire

Regarding the experiments made with the solid wire, increasing the weld speeds lead to a narrower shape of the weld seams, excess weld metal protruding through the root decreased with increasing welding speed. As for the welds made with the metal cored wire, the weld beads had a relatively uniform width at all welding speeds, the cap part was wider than compared to the weld beads with the solid wire. On the root side of the seams welded with both wires, excessive penetration is visible with a tendency to form drops at a welding speed of 1 m/min. Weld seam characterization was carried out for the laser-GMA-hybrid welded X65 plates according to API 5L. The mechanical analysis comprised hardness measurement, tensile testing and Charpy V-notch testing. Samples for testing purposes were welded at 1.8 m/min welding speed with the solid wire exclusively, for parameters see Table 3. X-ray analysis of the samples showed some incomplete fusion at the beginning of two weld beads. All other tested samples passed this test without defects. Hardness testing results for the base material ranged from 187 to 220 HV10, the HAZ and weld metal had hardnesses between 207 to 245 and 215 to 256 HV10 respectively. The yield strength achieved lay between 518 to 543 MPa, the tensile strength between 610 to 623 MPa. For Charpy V-notch testing, out of 10 test series tested with the notch location in the weld, only two produced values in the range of 25 to 40 J at temperatures of 0 °C and -20 °C which did not meet the requirements of the API 5L standard. Yet values achieved with the notch location in the HAZ for the same samples were around 180 J to 220 J. Full testing range and average values of the results of all tested specimen are presented in Table 3 and 4.

Table 3. Welding parameters for welded X65 material for testing purposes

Laser power [kW]	Welding speed [m/min]	Wire feed speed [m/min]	Current (range) [A]	Voltage(range) [V]	Gap [mm]	Focal position [mm]
8	1.8	7.5	313-312	23.6-23.8	0	-2

Table 4. Hardness testing of welded samples

Hardness testing [HV10]					
Base metal		HAZ		Weld metal	
range	average	range	average	range	average
187-220	198.9	207-245	215.8	215-256	234

Table 5. Tensile and Charpy V-notch testing of welded samples

Tensile testing		Charpy V-notch testing			
R_m [MPa]		Notch location	Temp. [°C]	range [J]	average [J]
range	average	Weld	0	25-342	171
610-623	617	Weld	-20	25-307	175
		HAZ	0	174-323	210

3.2. Welding X70 material with 6 mm root face

Fig. 4 shows the cross-sections of a root pass and fully welded seam. The joint preparation was 6 mm root face and 45° included angle welded with 0 mm gap. Both weld passes welded with solid wire have no indications of visible defects. The root has a straight, uniform shape with little excess penetration. Due to the zero gap used, the width of the weld seam is narrow in the middle and bottom part. The cap height of the fill pass is acceptable, the weld bead itself free of undercuts. Parameters for the welded sample are listed in Table 6.

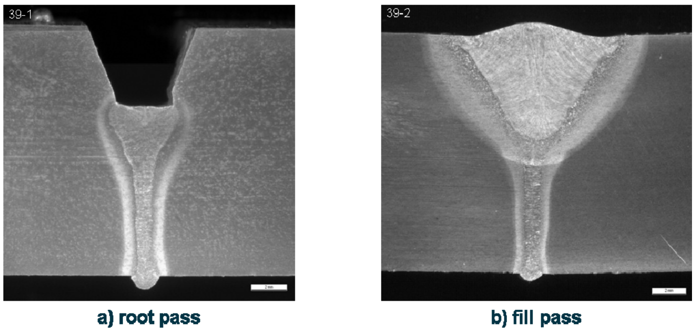


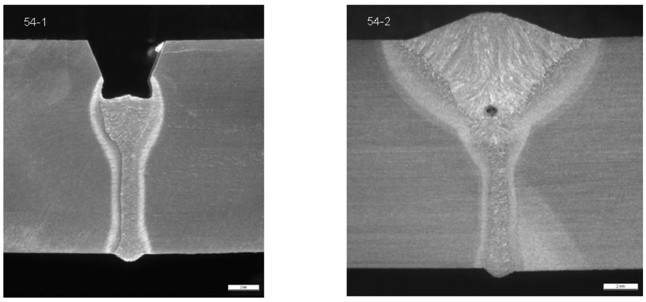
Fig. 4. Cross-sections of 14 mm thick X70 material, single V-butt joint preparation, 6 mm root face and 45° included angle

Table 6. Parameters for welded samples shown in, Figures 4, 5 and 6

Layer	Root face [mm]	Included angle [deg.]	Laser power [kW]	Welding speed [m/min]	Wire feed speed [m/min]	Current (mean) [A]	Voltage (mean) [V]	Gap [mm]	Focal position [mm]
Figure 4, single V-butt joint preparation, 6 mm root face and 45° included angle									
root pass	6	45	8	1.6	6.5	257	24.2	0	-2
fill pass	-	45	-	0.4	9	294	28.4	-	-
Figure 5, single V-butt joint preparation, 8 mm root face and 45° included angle welded with solid wire									
root pass	8	45	8	1.6	7.6	296	24	0.5	-2
fill pass	-	45	-	0.4	7.1	259	24	-	-
Figure 6, single V-butt joint preparation, 8 mm root face and 45° included angle welded with metal cored wire									
root pass	8	45	8	1.6	7.5	297	25.9	0.5	-2
fill pass	-	45	-	0.4	8	246	26.4	-	-

3.3. Welding X70 material with 8 mm root face

Prepared joints with 45° included angle and 8 mm root face were welded the same way as described above, but a 0.5 mm gap was additionally introduced. Two different wire electrodes were used for the welding experiments, a solid wire and a metal cored one. Depicted in Fig. 5 and Fig. 6 are cross-sections of the root pass and the fill pass of a sample welded with the solid wire and metal cored wire respectively. The sample welded with the solid wire has a root pass of regular shape with a nicely formed root side, Fig. 5. The fill pass shows a pore on the bottom side and the cap part is slightly excessive compared to the sample welded with metal cored wire. This sample, Fig. 6, shows excessive penetration on the bottom side. The upper side of the root pass shows an inclination of the weld seam towards the right groove face. The fill pass melted both sides of the groove face uniformly and the asymmetry of the upper part of the root pass has disappeared. Slight undercut can be seen on the top right side. Parameters for both welded samples are given in Table 6. Concerning the use of a 0.5 mm gap, both samples showed a broad, nicely developed root bead and a root seam in the cross-sections which was wider than compared to the root with 0 mm gap shown in Fig. 4. Samples with this joint preparation as welded with parameters given in Table 6 were extensively tested.



a) root pass b) fill pass

Fig. 5. Cross-sections of 14 mm thick X70 material, single V-butt joint preparation, 8 mm root face and 45° included angle welded with solid wire

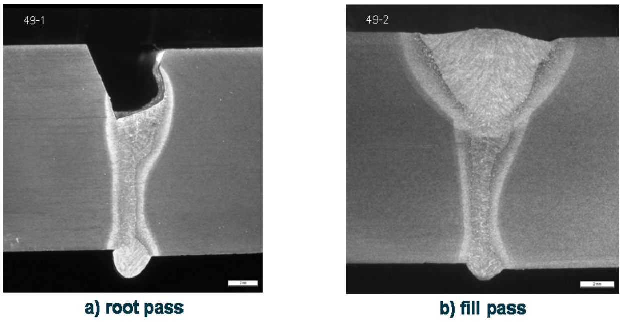


Fig. 6. Cross-sections of 14 mm thick X70 material, single V-butt joint preparation, 8 mm root face and 45° included angle welded with metal cored wire

3.3.1. Hardness testing

The hardness of the welded joints, in accordance with EN 1043-1, was measured across the weld beads in two lines. The first line was situated 2 mm below the upper surface and the second line 2 mm above the lower surface. Shown below are exemplary hardness measurements for samples welded with solid wire, and metal cored wire, Fig. 7. Both samples had identical joint preparationsm, a single V-butt joint with 8 mm root face. The highest hardness was measured on both samples for the HAZ and the weld metal of the root pass. For the fill pass or cap, the hardness dropped down to around 250 HV5 while it kept the level of the root pass in the HAZ.

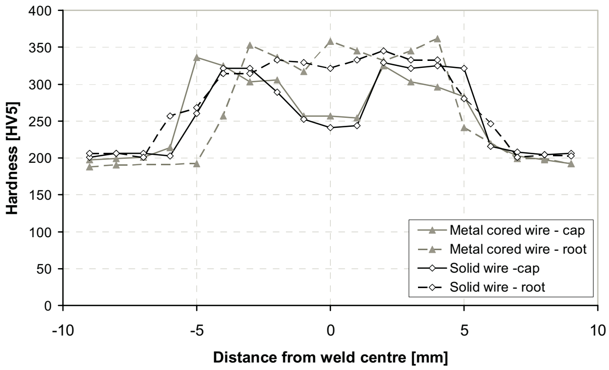


Fig. 7. Hardness measurements of a sample from 14 mm thick X70 material welded with solid and metal cored wire

3.3.2. Charpy V-notch impact testing

Altogether, three series of Charpy V-notch tests were carried out from specimen welded with solid wire and metal cored wire according to EN 10045-1 and EN 875 at temperatures of -20 C. Notches were prepared in the base metal, weld metal and the HAZ 50/50. The values obtained from testing are shown in Table 7. Those obtained from testing the base material were expectedly the highest ones. Test results of the weld metal and HAZ showed that values obtained from specimens welded with solid wire, were - on average - above the ones welded with metal cored wire. However, all specimens tested exhibited ductile fracture.

3.3.3. Tensile testing

The tensile properties of the tested specimen are presented in Table 7. Testing was carried out at 20 °C according to EN 10002-1 and EN 895. Along with the base metal, specimens welded with solid wire and metal cored wire were tensile tested. In the case of the welded specimens tested, the position of fracture was located in the base material. The test results obtained for the welded specimens showed only little deviation from those made of the base material. Values for tensile strength were about in the same range for all tested specimen; results for solid wire and metal cored wire did not show any significant differences.

Table 7. Results of mechanical testing

Tensile Testing at 20°C					
Base Metal		Solid wire		Metal cored wire	
$R_{p0,2}$ [MPa]	R_m [MPa]	R_m [MPa]		R_m [MPa]	
521	633	625		623	
529	635	618		620	
543	639				
Charpy V-Notch testing at -20°C					
Base Metal		Solid wire		Metal cored wire	
[J]		Weld Metal [J]	HAZ 50/50 [J]	Weld Metal [J]	HAZ 50/50 [J]
280		152	246	105	206
250		124	189	126	214
297		130	215	92	146

3.3.4. Micro Tensile Testing

A special micro tensile testing technique [8] was used to determine the local tensile properties of the welds. The specimens 2 mm wide and 0.5 mm thick were cut out longitudinally from the weld at two positions, root pass and fill pass using spark erosion. Test results were obtained for the base material, the HAZ and the weld metal. Samples welded with solid wire and metal cored wire were tested accordingly. Fig. 8 shows the obtained results from altogether 24 tested specimens, 15 from the fill pass and 9 from the root pass. For the fill pass, the values for yield strength and ultimate tensile strength correspond to each other quite well, the values of the test results from the solid wire were on average 20 MPa lower for the yield strength and 46 MPa for the ultimate tensile strength. Clearly visible is the influence of the HAZ (specimen no. 4 and 13) on the tensile strength of the fill pass which produced the highest values. Within the weld metal (specimen no. 5 to 12) the values are close to the yield strength and ultimate tensile strength of the base material. This trend is not clearly reproduced by the elongation values of the solid wire specimens, the values are in the range of the elongation of the base material, merely the value from specimen 14 responds to the higher tensile strength. The values of the elongation obtained from samples welded with metal cored wire perform according to the pattern of yield strength and ultimate tensile strength. At the peak values of the tensile strength in the HAZ the elongation is lowest, approximating the elongation value of the base material in the weld metal except specimen no. 8 and 9 which are significantly lower.

On the root pass tested, the weld metal of the samples welded with solid wire can be easily distinguished by the prominent peak (specimen no. 19). Adjacent to it are two samples (no. 18 and 20) representing the HAZ, in Fig. 8 b. Less distinctive is the difference between HAZ and weld metal for the specimen taken from the sample welded with metal cored wire. The transition from HAZ to weld metal is rather smooth, the tensile strength for the weld metal can be expected at specimens no. 20 and 21 and the transition to the HAZ for specimen no. 19 on the left and no. 22 on the right side. Regarding the elongation measured for the solid wire, the values show as can be expected, a contrary behaviour to the tensile strength, having the lowest value at around 10 % and approaching the elongation of the base material on specimens no. 16 and 17 and from specimen no. 21 onwards. The elongation of the metal cored wire shows a similar trend, however, with a larger scatter band over the whole test series.

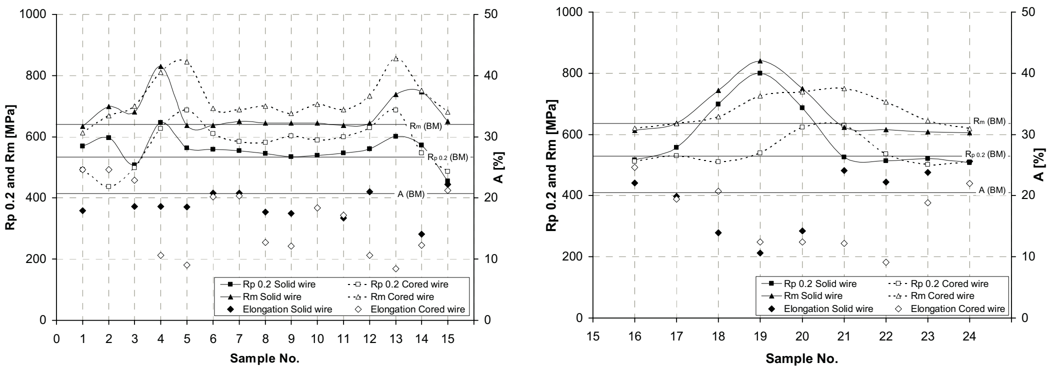


Fig. 8. Micro tensile testing of X70 specimens welded with solid wire and metal cored wire, a) fill pass and b) root pass

4. Discussion

By using a laser-GMA-hybrid welding process with a maximum of 8 kW laser power, it was possible to join 9.5 mm thick plates for the task of welding a pipe in a single weld pass. Furthermore, it was shown that this process was feasible within a wide process window applying welding speeds ranging from 1.0 m/min up to 2.0 m/min without an significant loss of weld quality. The two different filler wires used, a solid one and a metal cored one, did not affect on the quality of the weld, merely the MAG dominated top part of the weld seam varies a little bit in shape comparing the two wires. Concerning the results from mechanical testing, especially the hardness achieved for the X65 samples tested and presented in this paper having a range of 215-256 HV10 would comply with recognised standards like the DNV, for example, where for this material with the respective value for yield strength a maximum hardness of 270 HV10 is permitted according to DNV-OS-F101 (table 6-3) for linepipe. The values presented for tensile testing were in a range that can match those achieved with conventional welding. Even though two values obtained from two different Charpy V-notch test series at 0°C and -20 °C were below the admissible minimum, the average of all tested samples was in a range comparable to values achieved with arc welding processes.

Altogether, this hybrid process has two apparent advantages over conventional methods used for longitudinal welding in pipe production. First, a specific joint preparation for tack welding and the subsequent e.g. submerged arc welding is not needed, an I-butt joint is sufficient. Second, with the employed hybrid welding process this thickness of 9.5 mm can be welded in one pass from one side, whereas using conventional methods two passes are usually required. The application of a single pass hybrid welding process for pipe production would save production time, considerable amounts of filler wire and the preparation of a more or less complex and costly joint in a production environment that uses sequential multi pass welding today.

Welding 14 mm thick X70 material with a hybrid process in one pass was not possible with a maximum of 8 kW laser power available. At least two weld passes and a suitable joint preparation were needed to weld this thickness successfully. The material was prepared with a single V-butt joint with an included angle of 45° and root faces of 6 mm and 8 mm. Previously published results have shown that a laser-GMA-hybrid welding process was not suitable for welding fill passes so far since pores and occasional hot cracking appeared in the welds [9]. Hence, the fill passes for the welds presented in this section are done with a conventional arc welding process. A root face of 6 mm could be welded successfully with the given laser power. Up to a root face of 8 mm full penetration was achieved. Higher root faces, however, led to incomplete penetration and were thus not used as joint preparation. The positive effect of a higher root face is that less wire is needed for the fill pass. The amount of wire used to fill the groove left for the second pass was 9 m/min for the sample with 6 mm root face and 7.1 m/min for the sample with 8 mm root face which is a saving of about 20 % of wire electrodes. Concerning the use of a gap for welding the

14 mm thick material with a zero gap, the hybrid welded root of the weld seam was very thin and the surface of the visible part of the root on the welded plate was slightly irregular in shape and height. With a gap (in this case 0.5 mm was chosen), the root pass became thicker and opened up a little towards the bottom of the root side. The visible part of the root was wider and more regular in shape. A difference between the two wires also used for the X70 material during the process concerning hybrid welding was not observed. For the fill passes carried out with arc welding about 10-12 % more metal cored wire was needed to fill the groove.

Comparing the test results obtained from mechanical testing in general, the results for Charpy V-notch testing and tensile testing achieved with this welding process and material were comparable to those achieved with other welding processes and the same or slightly higher grade material presented in [10], for example. As expected, the highest hardness with values well over 300 HV5 were measured in the weld metal of the laser-GMA-hybrid welded root pass as well as in the HAZ region of both weld passes. These characteristics are also reflected by the local tensile properties measured by micro tensile test specimen. In the region with the highest hardness, the yield strength and tensile strength are the highest while the measured elongation is low. Furthermore, the micro tensile tests results revealed that there is no excessive overmatching or undermatching which can be seen especially in the weld metal of the fill pass where the achieved tensile strengths are close to the ones of the base material. This behaviour would have not been observed with ordinary tensile testing alone. Regarding the two different wires used, a significant difference of the mechanical properties from the mechanical testing results could not be found. Concerning the application of pipe welding, the hardness particularly in the laser-GMA-hybrid welded root pass, is higher than those normally expected and exceed the maximum acceptable requirement by standards. However, in order to reduce the hardness, additional measures such as pre-heating prior to welding, can be considered [11].

5. Conclusion

Welding experiments with X65 and X70 pipe steels carried out as part of the FIBLAS project have shown that laser-GMA-hybrid welding can be regarded as potential welding processes to be employed among conventional welding processes for the field of pipe production. In order to join 9.5 mm X65 material, it was demonstrated that a laser-GMA-hybrid welding process with max. 8 kW of laser power was able to weld the given sheet thickness in a single pass. The mechanical properties such as hardness and tensile strength as well as impact toughness obtained from the hybrid welded samples were comparable to those achieved with conventional arc welding. Welding 14 mm thick X70 grade material also with a maximum of 8 kW laser power and a hybrid process showed that:

- two weld passes and a proper joint preparation was needed to join this thickness.
- the use of a 0.5 mm gap brought better quality of the root than a zero gap.
- test results achieved for tensile testing and Charpy V-notch testing were comparable to those of other arc welding processes.
- hardness values of the tested samples were above the average values accepted in standards, thus further measures need to be undertaken to reduce it.

For the first time local tensile properties were investigated for samples welded with the combination of hybrid process and GMAW process by micro tensile testing. The achieved results show a good correspondence to those of the standard mechanical testing methods and point out trends of the hardness testing on the investigated welds.

The advantages of the two approaches presented are saving of filler material as well as a reduced number of welding passes. These advantages contribute to a higher productivity and lower production costs.

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