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ИЗЫСКАНИЕ, ПРОЕКТИРОВАНИЕ, СТРОИТЕЛЬСТВО И МОНТАЖ ТЕХНОЛОГИЧЕСКОГО ОБОРУДОВАНИЯ ОБЪЕКТОВ АТОМНОЙ ОТРАСЛИ

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ГИБРИДНАЯ ЛАЗЕРНО-ДУГОВАЯ СВАРКА ВЫСОКОПРОЧНЫХ ТРУБНЫХ СТАЛЕЙ КЛАССОВ ПРОЧНОСТИ API X80 И X120[1]

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Целью настоящей работы являлось изучение возможностей гибридной лазерно-дуговой сварки в части выполнения продольных швов труб большого диаметра классов прочности API 5L X80 и X120. Экспериментальные исследования были сфокусированы на изучении методов повышения ударной вязкости гибридных сварных швов для условий низких температур эксплуатации трубопроводов. Улучшенные показатели ударной вязкости были достигнуты за счет применения металлопорошковых проволок, обеспечивающих формирование предпочтительной мелкозернистой микроструктуры металла шва. Современные технологии дуговой сварки, такие как сварка модифицированной импульсной струйной дугой, были использованы в составе гибридного лазерно-дугового процесса для обеспечения более глубокого проникновения присадочного материала в узкую зону проплавления гибридного лазерно-дугового шва. Форма разделки кромок с высотой притупления не более 14 мм принята в качестве оптимальной. Анализ химического состава металла шва обнаружил лишь частичное присутствие присадочного материала на глубине проплавления 14 мм. Сверх указанной глубины металлургические воздействия на металл сварного шва с помощью сварочной проволоки не могут быть гарантированы.

Требуемые механико-технологические свойства изготовленных гибридных швов подтверждены результатами соответствующих испытаний. Полученные средние значения ударной вязкости составляют величину около 150J при температуре испытаний -60°C для стали X80. Для стали X120 была достигнута средняя величина ударной вязкости 53J при при температуре испытаний -40°C. При этом, требуемое значение ударной вязкости металла сварного шва в соответствии со стандартами API 5L и DIN EN 10208-2 составляет лишь 40J при температуре испытаний 0°C.

Ключевые слова: высокопрочные трубные стали, гибридная лазерно-дуговая сварка, сварка модифицированной короткой дугой, сварка продольного шва, магистральные трубопроводы, перемешивание, предел прочности, ударная вязкость.

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LIST OF SYMBOLS AND ABBREVIATIONS

A_5 – elongation after fracture
A_v – absorbed impact energy
CE_{PCM} – carbon equivalent
$I_{L□}$ – arc current
L_{LB} – correction of the arc length

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P_L – laser power
$R_{p0.2}$ – 0.2% proof stress
R_m – tensile strength
t – thickness
t_s – height of the weld root face
U_{LB} – arc voltage
v_d – wire feeding speed
v_s – welding speed
EMPA – electron microprobe analysis
GMAW – metal active gas welding
HAZ – heat affected zone
SAW – submerged arc welding

INTRODUCTION

To a large extend, longitudinally welded large-diameter pipes are used for modern oil- and gas-pipelines. Most applied base materials are API-steels X65 and X70 [1]. Constantly increasing natural gas and oil delivery rates demand advancements of the assigned materials. Wall thickness minimization or operating pressure increase are achieved by material substitution, e.g. employment of a high strength steel grade API-X80, API-X100 or API-X120 [2-4]. Material substitution already allows material savings of more than 10 % or wall thickness minimization to about 14 % compared to steel grade X70 [5]. Such pipes are usually produced by first forming a large plate to an open ring. Subsequently, the ring is continuously tacked along its longitudinal gap by means of a metal active gas GMA welding process. In the further process, the remaining double-sided joint gaps are filled with layers using cost-intensive multiple-wire submerged arc welding SAW processes. The GMA-tack weld is completely remelted in the process. The maximal root face depth depends on the welding process and is currently 8 mm. The innovative laser hybrid welding technology offers a significant increase in fully penetrated root face depth and welding speed compared to conventional welding technologies. This means for pipe production that the amount of SAW filler layers will be reduced and, in parallel, the increased welding speed will lead to a shortening of the production cycle for longitudinally welded pipes. Fig. 1 shows schematically the significant potential savings through an increased root face depth of 12 mm by application of laser-hybrid welding.

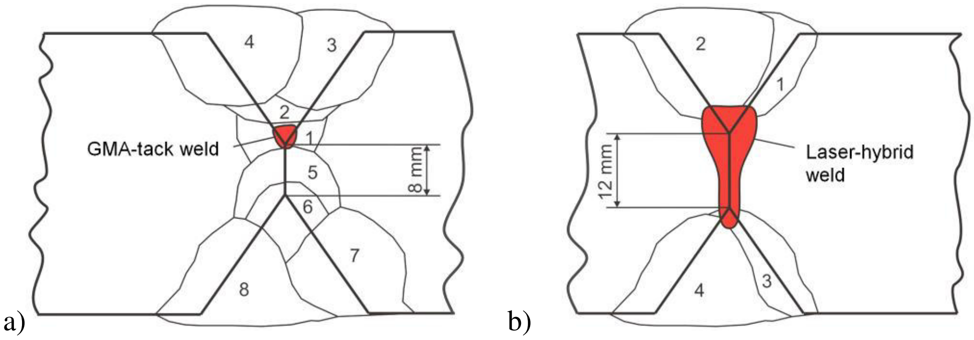


Fig. 1: Comparison between two welding technologies: longitudinal weld consisting of a GMA-tack weld and SAW filler layers (a); longitudinal weld consisting of a laser-hybrid weld and SAW filler layers (b)

In addition to the mentioned economic efficiency the strength and impact toughness required for laser hybrid welded joints have to be ensured. The achievable mechanical and technological properties of laser hybrid welds are currently being investigated intensively by international research groups. Thus, sufficiently high notch impact toughness of the laser hybrid welds on steel grades up to X70 with maximal wall thickness of 16 mm could already be demonstrated [6-9]. Laser hybrid welding trials on X80 grade steel have also demonstrated acceptable notch impact toughness of welds with a maximum root face depth of 9 mm [10]. Some promising results regarding weldability aspects of X100 grade steel in the high power fibre laser welding process have already been achieved [11]. Here regular sound laser welded root passes with a maximum depth of 6 mm, generally free from defects and porosity, could be produced. The toughness measured in the fused zone of the laser welded root passes shows some scatter, but is in general above 60 J at -60 °C, which is acceptable according to the specification for linepipe API 5L. Microstructure and properties of laser hybrid welds made from a range of commercially available, mainly pipeline steels are discussed in detail in [12]. A series of crack free laser hybrid welds could be produced with a root face of 7.5 mm used for all tested steels. It is demonstrated by the authors of this study that laser/GMA hybrid welding enables the microstructure and mechanical properties of pipeline steels welds to be improved significantly. In this context, the greatest influence on the weld microstructure is exerted by a filler wire that affects the weld metallurgy and promotes the formation of a desirable microstructure containing acicular ferrite, for example, which improves hybrid weld toughness. It also appears that filler material transport deep into the narrow laser welding gap and its homogeneous distribution play an important role. Elements added by filler wires concentrate in the upper weld metal region rather than in the root region. This is to say that homogenous element distribution is difficult to obtain in narrow and deep penetration hybrid welds. The influence of welding conditions on filler wire element distribution was investigated in CO_2 laser and pulsed GMA hybrid welding of 11 mm thick high strength structural steel JIS SM490A [13] using filler wire containing 72% Ni. It was found that the regions with homogenously distributed Ni from the filler wire reached depths down to 8 mm for welding with leading arc and down to about 10 mm with leading laser (square butt joint without gap). However, all the experiments of this study were carried out with quite constant welding parameters (except a slight change in wire feed rate) and any effects of energy parameters on the alloying element distribution were not observed. The effect of higher arc current with greater arc force on the laser hybrid weld shape is discussed in [14]. The results of this study demonstrate that the filler material penetration depth from pool top to root can be increased by approx. 3 mm to 6 mm for 6 mm thick plate when choosing an appropriate energy ratio (laser/arc) in laser MIG hybrid welding . These results suggest that innovative arc welding technologies, such as modified pulsed GMAW, can be decisive for increased fusion penetration. Such technology uses microprocessor-based metal transfer control permitting a very stable short arc with high plasma pressure on the weld pool and deeper filler material transport in the welding gap [15 - 19]. This is the reason why implementation of modified pulsed GMAW in the laser hybrid process is of practical interest in view of further hybrid weld quality improvement. However, any quantitative investigations dealing with this issue are still lacking.

Another factor to be considered is that the superior toughness of fine grained or ultrafine grained X100 or X120 microstructure obtained through a thermomechanical controlled process may be irreversibly altered when the steel is welded with high heat input (GMAW, SAW processes). Coarsening of fine ferrite grains, caused by recrystallisation or abnormal phase transformation from austenite, results in remarkable HAZ softening and thus in remarkable reduction in HAZ toughness [20]. As reported in [21], a fast cooling process can effectively improve the HAZ toughness of high strength pipeline steel X120. Therefore, high power fibre laser hybrid welding, as a very low heat input process, offers a good opportunity of minimizing HAZ softening effects.

Overall it can be stated that reliable laser hybrid field welding results for modern high strength pipeline steels and commercially interesting process parameters, e.g. root face depths of 12 mm and above, are not available yet. Although some promising results regarding X80 and X100 laser and laser hybrid weldability could already be achieved, any results concerning X120 laser hybrid weldability are still completely lacking.

The present study demonstrates the laser arc hybrid weldability of high strength pipe steels X80 and X120 with 14 mm root face for producing longitudinal welds. Filler material distribution and penetration depth in laser hybrid welds produced by different arc modes such as GMA normal, GMA pulse and GMA modified spray arc are shown. The produced welds were tested and achievable mechanical and technological characteristics are discussed.

MATERIALS, JOINT PREPARATION AND EXPERIMENTAL SETUP

As base materials the pipe steels X80 and X120 with the chemical composition shown in Table 1 were used. According to the requirements of API 5L and ISO 3183 for the chemical composition and mechanical properties (Table 2) of high-strength pipe steels, the investigated materials belong to the group of low-alloy Si-Mn steels additionally micro alloyed with strong carbide-forming elements. In order to achieve the necessary high strength in X120 boron is added. Boron addition not only increases the strength of the base metal, but also transforms the weld heat affected zone HAZ into lower bainite and is effective in increasing the toughness of the HAZ [22]. In order to ensure a good weldability, the carbon content is kept below 0.1% and the low cold cracking susceptibility of these steels is guaranteed by a low carbon equivalent CE_{PCM}.

Table 1: Chemical composition of X80 and X120 steels and carbon equivalent

Steel grade	Element in wt. %															CE_{PCM} in %
	C	Si	Mn	P	S	Cr	Ni	Al	Mo	Cu	V	Nb	Ti	B	Fe	
X80	0.052	0.33	1.8	0.008	0.0008	0.17	0.01	0.04	0.14	0.02	0.004	0.04	0.012	-	rest	0.17
X120	0.054	0.31	1.6	0.009	0.0006	0.41	0.04	0.03	0.21	0.03	0.038	0.04	0.012	0.001	rest	0.19

In combination with the higher cooling rate in thermomechanically controlled rolling, this results in high strength characteristics and brittle fracture resistance.

Table 2: Mechanical properties of X80 and X120 steels

Steel grade	Thickness in mm	$Rp_{0.2}$ in MPa	R_m in MPa	A_5 in %	R_p/R_m in %	A_v in J
X80	23.4	548	648	21.9	85	330 (-60°C)
X120	20.0	816	1020	14.7	80	270 (-40°C)

As filler materials, solid wires and metal cored electrodes made by two producers, i.e. Böhler Schweißtechnik und Drahtzug Stein, were used. The filler wires were developed for high strength steel welding of X80 and above according to EN 12534 and EN 18276. Chemical compositions and mechanical properties of the filler wires are listed in Table 3 and Table 4, respectively. The used wire diameter was 1.2 mm.

Table 3: Chemical composition of the filler wires

Filler wire	Element in wt. %								
	C	Mn	Si	P	S	Cr	Ni	Mo	Fe
Solid wire Böhler NiMo 1-IG	0.08	1.8	0.6	<0.015	<0.015	-	0.9	0.3	balance
Solid wire Böhler X 90-IG	0.1	1.8	0.8	<0.015	<0.015	0.35	2.3	0.6	balance
Metal cored electrode Böhler alform 700–MC	0.07	1.6	0.7	<0.015	<0.015	0.35	2.0	0.3	balance
Metal cored electrode Megafill MF 940 M	0.05	1.4	0.6	<0.015	<0.015	-	2.0	-	balance

Measurements of diffusible hydrogen content in the deposited metal were performed according to DIN EN ISO 3690. The requirements for the hydrogen content in high strength filler materials were met. All measured values do not exceed 5 ml/100 g. The used wires belong to the "extra low hydrogen" filler materials according to AWS A5.1 pointing out their good resistant against hydrogen related cracking.

Table 4: Mechanical properties of the filler wires

Filler wire	$R_{p0.2}$ in MPa	R_m in MPa	A_5 in %	A_v in J (-60 °C)
Böhler NiMo 1-IG	620	700	23	> 47
Böhler X 90-IG	890	950	15	> 47
Böhler alform 700–MC	770	830	18	> 63
Megafill MF 940 M	550	640	22	> 47

Welding experiments were performed on flat specimens in PA-position. The thickness of the metal plates was 20.0 mm for X120 and 23.4 mm for X80. The examined edge preparation with a 14 mm root face and a 45° bevelling angle is shown in Fig. 2a.

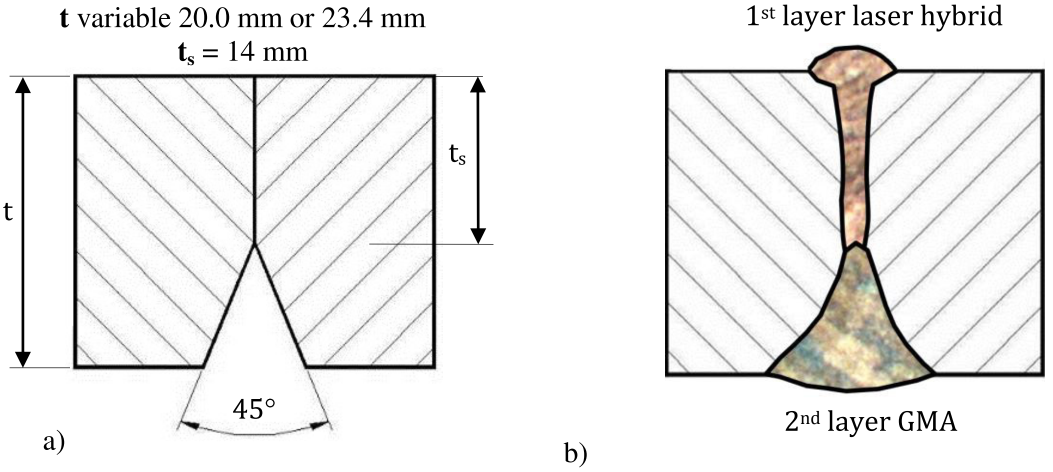


Fig. 2: Edge preparation (a) and welding sequence (b)

The welds were performed in two layers as shown in Fig. 2b. At first a laser hybrid layer was welded in a butt joint. After that, the specimens were turned 180° and then the remaining volume with the 45° beveling angle was filled with one layer using a conventional GMA process.

A 20 kW Yb fibre laser (IPG) (wave length 1064 nm, beam parameter product 11.2 mm x mrad) was used as laser power source. The optics used for the experiments had a focal length of 350 mm. The laser beam was transmitted by an optical fibre with a core diameter of 200 µm and focussed to the diameter of 0.56 mm. A micro-processor controlled welding machine Qineo Pulse 600 (Cloos) with a maximal welding current of 600 A was used as an arc welding power source. Laser head and GMA torch were mounted on the robot arm. Welding was carried out with leading arc, backhand with a fixed angle between laser beam and GMA torch of 25°. The gas mixture M21 (18% CO_2 in Ar) was used as shielding gas in accordance with EN 439. The experimental setup and used process parameters for the welding experiments can be seen in Fig. 3.

a)

- leading arc, backhand
- stick out 16 mm
- distance from laser beam to wire 3.5 mm
- focus position -4 mm

b)

Welding processes	1st layer laser hybrid	2nd layer GMA normal
P_L in kW	16…17	-
v_s in m/min	2.2…2.6	0.5
v_d in m/min	16	10
U_{LB} (max) in V	42	29
I_{LB} (max) in A	513	300
shielding gas flow rate in l/min	20	
L_{LB} in %	1…45	30

Fig. 3: Experimental setup (a) and welding parameters (b)

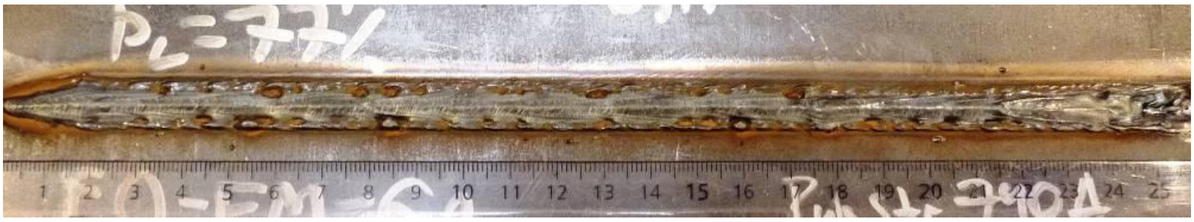
It should be mentioned that the welding machine Qineo Pulse 600 supports the new arc processes such as modified spray arc. A modified spray arc is a very short arc with extremely high directional stability that results from a highly dynamic voltage regulation [15-19]. It results in improved welding process conditions such as stronger focused arc plasma with increased plasma pressure on the weld pool and higher energy density, which leads to a higher penetration level and deeper filler material transportation into the welding gap.

RESULTS AND DISCUSSION

Series of welding experiments were performed with the following combinations of the base materials and filler materials: X80 with Böhler NiMo 1-IG; X80 with Megafill MF 940 M; X120 with Böhler X 90-IG; X120 with Böhler X 90-IG. Analytical electron microprobe analysis EMPA was conducted to establish the weld metal composition and to obtain some representative information about the filler material penetration depth in the narrow laser welding gap. Hardness measurements, Charpy impact tests and tensile tests were carried out to examine the achievable mechanical properties of the laser hybrid welds and to verify their accordance with the standards API 5L and ISO 3183. X-ray examinations were made on most welds. All welded joints were found to be free from crack-like defects and the volume fraction of porosity was about 1.7% compared to the maximum permitted amount of 2.0% ("C" level as defined in EN ISO 13919-1). The largest pore diameters were below 1 mm.

Welding with modified spray arc

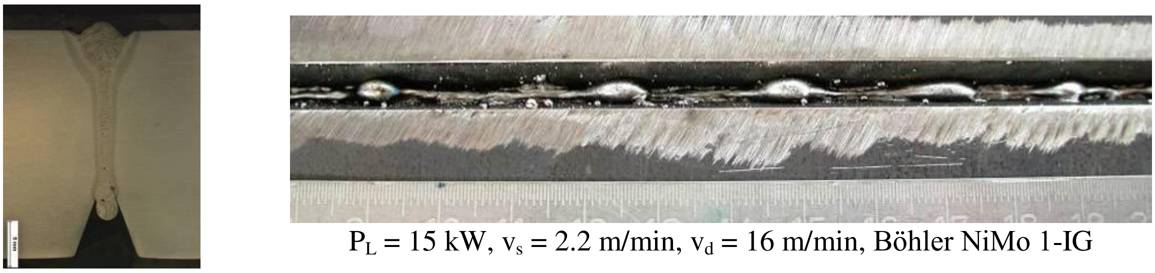
The authors' own experience in laser hybrid welding and knowledge about the process suggest that welding of a 14 mm root face using conventional GMA process (normal or pulse) should not pose any problems. First welding results with modified spray arc indicated that the process needs to be optimised. It was noticed that the modified spray arc can provoke significant undercuts on the top side of the laser hybrid weld, Fig. 4.



v_s = 2.4 m/min, P_L = 16 kW, v_d = 16 m/min, I_{LB} = 513 A, U_{LB} = 42 V, Böhler NiMo 1-IG

Fig. 4: Laser hybrid welding with modified spray arc, undercuts

Excessive penetration appears at the lower welding speed of 2.2 m/min, Fig. 5. One reason must surely be the high plasma pressure on the weld pool, which would not happen in the case of conventional GMA pulse welding using standard welding parameters.

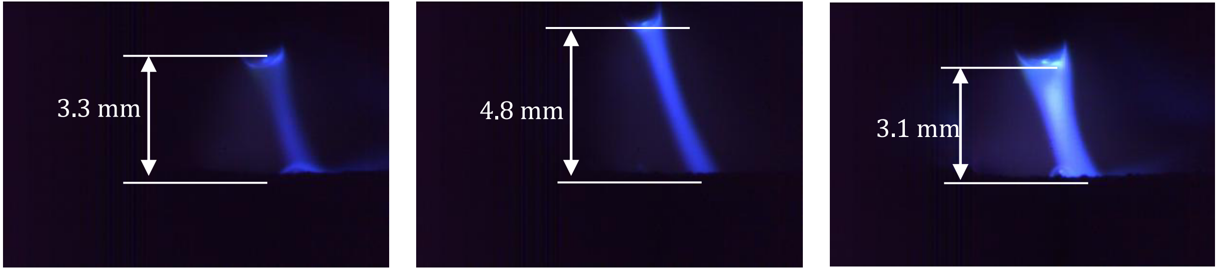


P_L = 15 kW, v_s = 2.2 m/min, v_d = 16 m/min, Böhler NiMo 1-IG

Fig. 5: Laser hybrid welding with modified spray arc, excessive penetration

Arc diagnostics using a PHOTRON Fastcam high speed camera were done in order to understand the relationships between arc parameters and weld quality. GMA welding trials were carried out for comparison using solid wire Böhler NiMo 1-IG in different operating modes of the welding machine. Visual evaluation of the arc length can be done using the high speed pictures shown in Fig. 6.

v_s = 1 m/min, v_d = 10 m/min, Böhler NiMo 1-IG



a) b) c)

Fig. 6: Arc diagnostics, high speed pictures of comparative GMA welding: GMA Pulse (a), modified pulse spray arc with L_{LB} 5% (b), modified pulse spray arc with L_{LB} 45% (c)

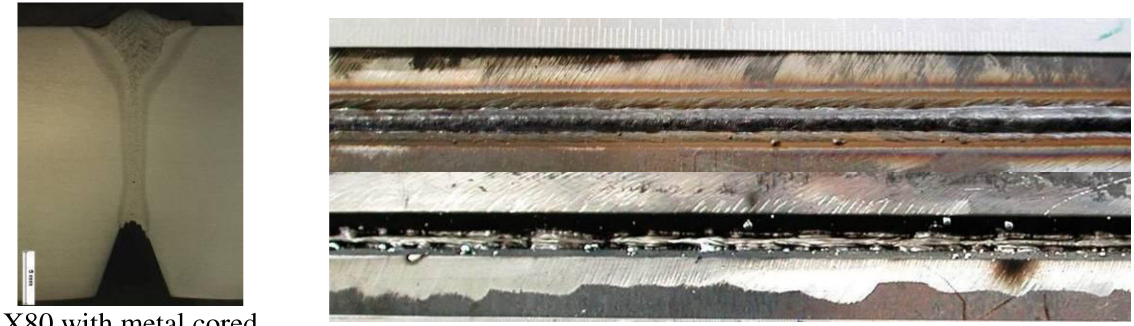
The corresponding voltage and current characteristics were recorded and summarised in Table 5. The evaluation of measured signals shows that with the change of the arc type from conventional GMA pulse to modified pulse spray arc the arc parameters, primarily pulse current and base current, are also modified. The result is an arc with higher power on the one hand and increased arc length on the other hand. With an arc about 5 mm in length (Fig 6b), the energy introduced into the weld pool is no longer concentrated, i.e. the arc energy gets lost at the flanks and defects of the kind shown in Fig. 4 occur. The best way to get the arc energy more concentrated is to reduce the arc length. Arc length correction L_{LB}, which can be done through arc voltage reduction, helped to reduce the arc length from 4.8 mm to 3.1 mm and to get it more directionally stable (Fig 6c). All further laser hybrid welds produced within the scope of this work were made using modified pulsed spray arc with arc length correction L_{LB} 45% from a nominal value.

Table 5: Arc diagnostics, voltage and current characteristics for the comparative GMA welding trials, v_s = 1 m/min, v_d = 10 m/min, solid wire Böhler NiMo 1-IG

Parameter	GMA Pulse	GMA – modified pulse spray arc	
arc current I_{LB} in A	237.4	238.0	247.9
arc voltage U_{LB} in V	30.9	31.7	30.6
welding power in kW	8.4	9.1	9.4
base current in A	87.3	63.7	65.4
pulse current in A	494.0	573.9	608.2
pulse width in ms	2.1	2.3	2.3
pulse frequency in Hz	183.5	168.4	168.4
arc length correction L_{LB} in %	5	5	45
arc length in mm	3.3	4.8	3.1

An increase in welding speed from 2.2 m/min to 2.6 m/min and in laser power from 16 kW to 17 kW was very effective for avoiding excessive penetration during welding with modified spray arc. Subsequently it was possible to produce a series of welds with an appropriate quality. An example for the material combination X80 with metal cored electrode MF 940 M is shown in Fig. 7.

P_L = 17 kW, v_s = 2.6 m/min, v_d = 16 m/min, I_{LB} = 396 A, U_{LB} = 35.6 V



X80 with metal cored electrode MF 940 M

arc length correction L_{LB} = 45 %

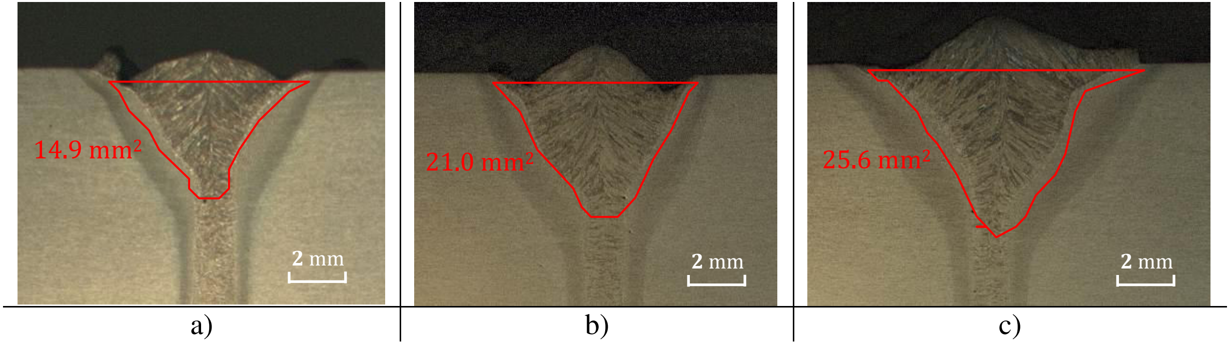
Fig. 7: Welding with modified spray arc and optimised arc length

The metal cored electrodes could be used with modified pulse spray arc and with the same parameters as for solid wires. A very stable low-spatter process with slight undercuts could be observed for both types of wires.

Penetration depth and dilution of the filler material

The toughness of laser hybrid welds should be mainly controlled by the solidification behavior which is dependent on the filler material. Any other technological procedure for improving the weld metal toughness, such as preheating, would reduce the production efficiency and lower the throughput rate in high volume production of pipelines. Laser hybrid welding produces quite narrow welds with a high height-to-width ratio and filler material transportation into such narrow and deep welding gaps represents a difficult technical challenge. Welding trials with different arc variants, including modified pulse spray arc, were conducted to study the possible filler material penetration depth and the character of dilution. The trials demonstrated that the modified pulse spray arc, thanks to its more powerful dynamic effect on the weld pool, really provides the deepest penetration in the GMA part of the laser hybrid weld, which is around 5.0 mm deep. Macrographs illustrating the difference between the used arc variants are presented in Fig. 8.

v_s = 2.6 m/min, P_L = 17 kW, v_d = 16 m/min, Böhler NiMo 1-IG



a) b) c)

Fig. 8: GMA molten area: GMA Pulse (a), GMA Normal (b), GMA modified spray arc (c)

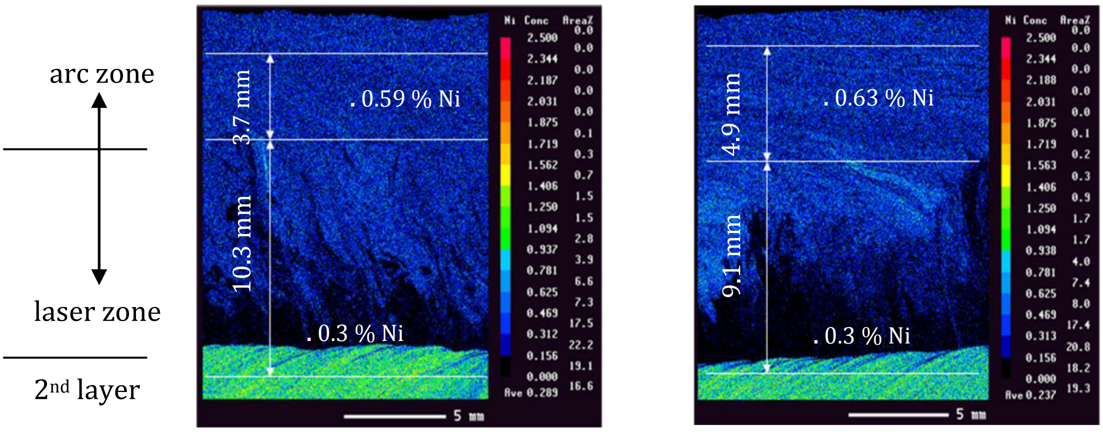
Planimetrically determined dimensions of the GMA zone for a solid wire and a metal cored elctrode are summarised in Table 6. By differences with the GMA molten area and GMA penetration depth, three measurements were used to calculate the average value of these variables. The GMA heat input per unit length in Table 6 was calculated by using an efficiency factor of 0.8 [12].

Table 6: GMA molten area and penetration depth, v_s = 2.6 m/min, P_L = 17 kW, v_d = 16 m/min

GMA process	avg. GMA molten area in mm^2	avg. GMA penetration depth in mm	GMA heat input in J/mm
Solid wire Böhler NiMo 1-IG			
GMA Pulse	14.9 ± 0.2	3.7 ± 0.2	271.2
GMA Normal	21.0 ± 0.2	4.4 ± 0.2	297.0
GMA modified spray arc	25.6 ± 0.2	5.1 ± 0.2	388.6
Metal cored electrode MF 940 M			
GMA Pulse	13.8 ± 0.2	3.9 ± 0.2	240.1
GMA modified spray arc	18.8 ± 0.2	4.5 ± 0.2	260.2

The comparison shows that the GMA molten area and the GMA penetration depth depend on the arc technology. The deepest penetration can be obtained with modified spray arc using solid wire. When using the metal cored electrode, the GMA penetration depth and molten area are slightly smaller, because the arc is softer.

An element map showing the 2D distribution of Nickel was prepared on longitudinal sections of laser hybrid welds produced with conventional pulse arc (Fig. 9a) and modified spray arc (Fig. 9b). Both welds were performed with metal powder wire MF 940 M containing 2% Nickel chosen as a contrast element for the element mapping.



a) b)

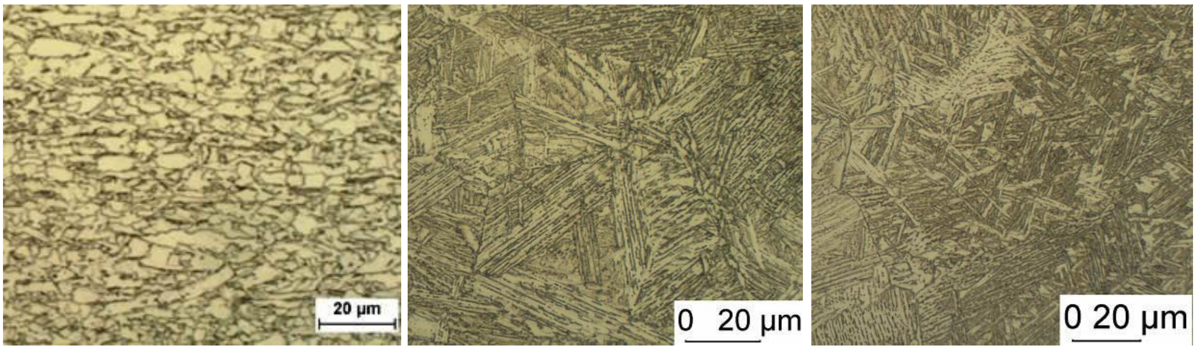
P_L = 16 kW, v_s = 2.6 m/min, v_d = 16 m/min, MF 940 M

Figure 9: Distribution of Nickel in longitudinal laser hybrid weld sections, GMA Pulse (a), GMA modified spray arc (b)

The analyses show that the areas with homogeneous distribution of Nickel are located in the top part of the laser hybrid welds, which is dominated by the arc process. The areas with homogeneous distribution of Nickel (0.59% – 0.63%) extend up to 3.7 mm for the conventional normal and pulse arc and up to 4.9 mm for the modified spray arc. The arc type does not have any influence on the character of Ni-distribution in the laser part of the hybrid weld. It was found that the maximum filler material penetration is not deeper than 13 mm – 14 mm at all.

Microstructure

The optical micrograph in Fig. 10a shows, that base metal X80 has a ferrite-bainite microstructure, which is quite uniform and fine with a mean grain size only a few micrometers. Randomly-oriented ferrite particles can be observed in the weld microstructure of X80 (Fig. 10b and 10c). This weld microstructure is highly desirable as it reduces the effective grain size, exhibit crack propagation and improves toughness in welds. The microstructure of base metal X120 is fully bainitic with a very fine grain size (Fig. 11a). The resulted weld microstructure of X120 steel is also bainite with thin bainitic ferrite lath, which should exhibit good toughness of the HAZ (Fig. 11b and 11c). In order to correlate the microstructure results to mechanical properties, Charpy impact testing and tensile testing were performed for both steels.



a) b) c)

Figure 10: Microstructure of the base metal and weld metal in the laser hybrid welds: X80 base metal (a); weld metal X80/940 M (b); weld metal X80/ Böhler NiMo 1-IG (c)

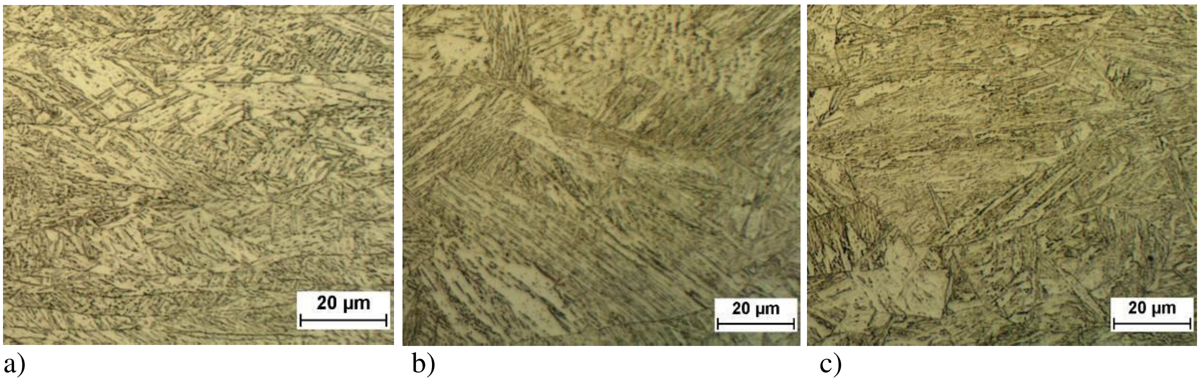


Figure 11: Microstructure of the base metal and weld metal in the laser hybrid welds: X120 base metal (a); weld metal X120/700 MC (b); weld metal X120/Böhler X90 (c)

Hardness measurements and Charpy impact test

Vickers hardness measurements were made using a 10 kg load. The Vickers hardness testing machines had been calibrated according to DIN EN ISO 6507-3. The maximum deviation of the hardness measurements HV10 was ± 3 %. The Charpy-V-notch specimens (10 mm x 10 mm) were notched in the middle of the laser-hybrid weld. Testing was executed in accordance with EN 10045. Details to the taking plan for Charpy specimens as well as location of the HV10 paths are shown in Fig. 12a and 12b respectively.

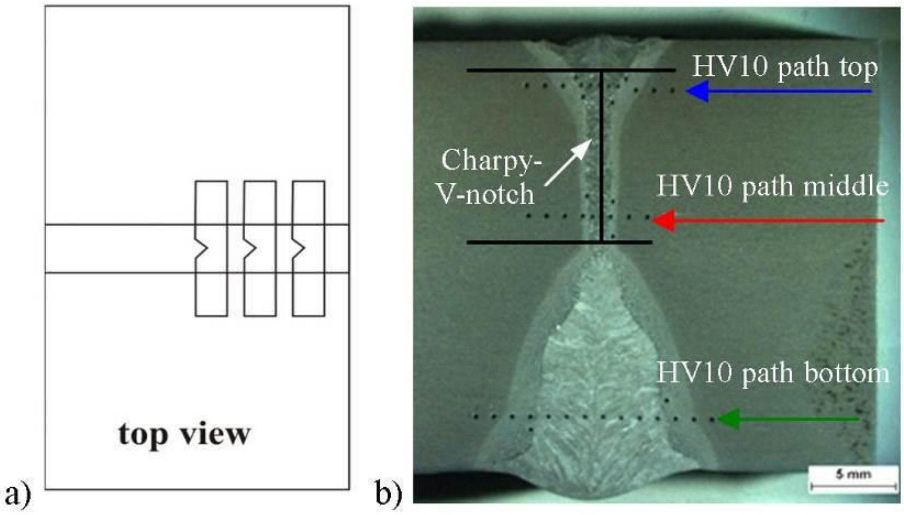
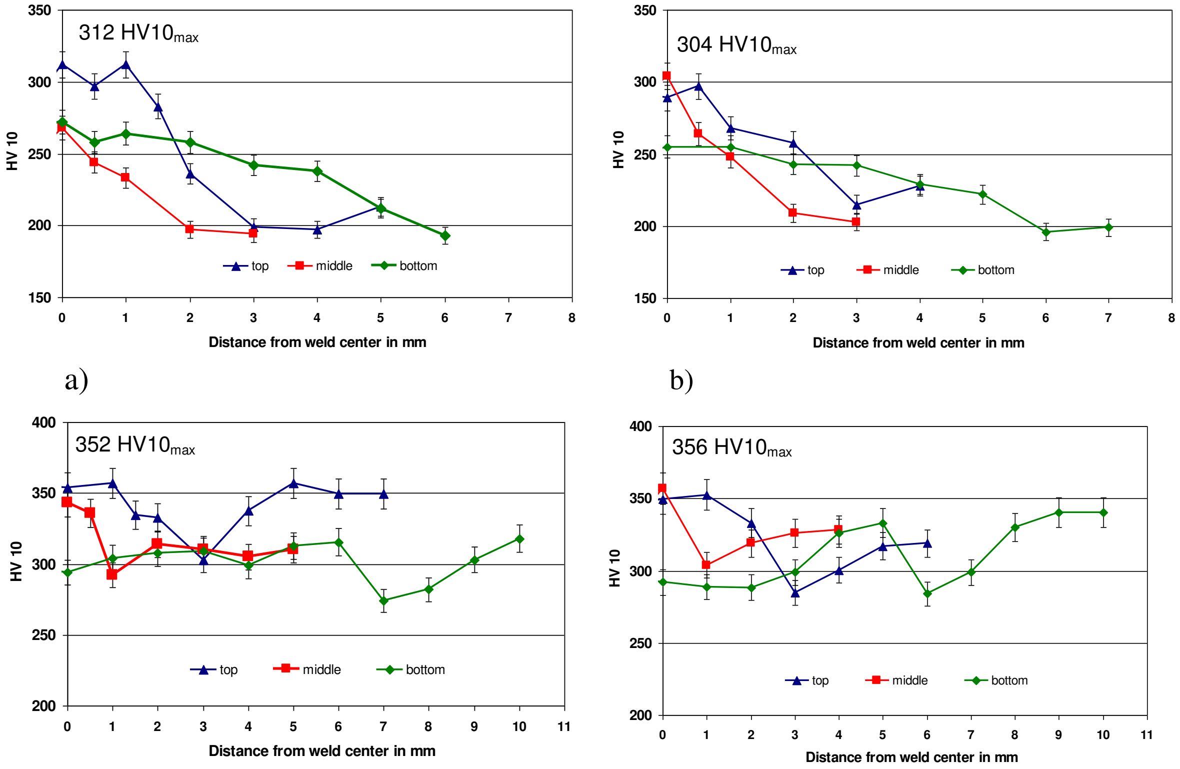


Figure 12: Taking plan for Charpy test specimens (a) and location of Charpy-V-notch as well as HV10 paths in details (b), root face 14 mm

The measuring results for the Vickers hardness are illustrated in Fig. 13.

The comparison shows that the peak hardness for X80 measured in the top of the laser hybrid weld was 312 HV10$_{max}$. This hardness level is well below the maximum hardness limit specified for line pipe in API 5L or ISO 3183, which is 325 HV10$_{max}$ for steel grades X80 and above. The peak hardness for X120 was around 356 HV10$_{max}$ which is too high to fulfill the requirement of the API specification, but compared to the base material hardness of 320 HV10 it can be considered as tolerable. A slight decrease in hardness of about 50 HV10, particularly in the HAZ of the 2nd filler layer ("bottom" hardness line), could be observed at the welds X120. The measured peak hardness values are summarised in Table 7.



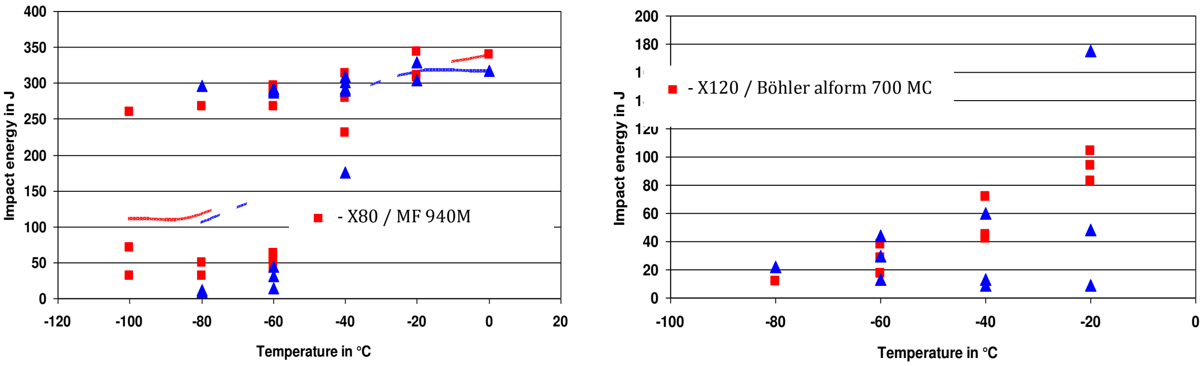
a) b) c) d)

Fig. 13: Macrohardness HV10 for different material combinations:
X80 with Böhler NiMo 1-IG (a); X80 with MF 940M (b); X120 with Böhler X 90-IG (c);
X120 with alform 700 MC (d)

Table 7: Hardness results for different material combinations

Welded materials	HV10$_{max}$			
	base material	top	middle	bottom
X80 with Böhler NiMo 1-IG	220	312	286	285
X80 with MF 940M		298	304	267
X120 with Böhler X90-IG	320	344	352	346
X120 with alform 700 MC		356	347	320

The results of Charpy tests are given in Fig. 14 by plotting measured impact energy versus temperature.



a) b)

Fig. 14: Charpy impact energy results for laser hybrid welds: X80 (a); X120 (b)

The results show that the welds of X80 produced with the metal cored electrode MF 940 M have rather high Charpy values at -60°C (190J average) and meet the requirements of API 5L and ISO 3183. The laser hybrid welds of X120 produced with metal cored electrode Böhler alform 700-MC demonstrate also acceptable Charpy values (53J average) at the temperature -40°C. The used solid wires show rather scattered results at the lower test temperatures.

Tensile tests

Tensile tests were carried out using round specimens with 14 mm diameter at room temperature. Three specimens were tested for each material combination. The characteristic values determined for the different material combinations are shown in Table 8.

Table 8: Tensile tests results

Materials	R_m (average) in MPa	Fracture location
X80 with Böhler NiMo 1-IG	640 ± 2.4	base metal
X80 with MF 940 M	651 ± 2.4	base metal
X120 with Böhler alform 700-MC	942 ± 5.0	HAZ
X120 with Böhler X90-IG	940 ± 5.0	HAZ

The strength of the weld metal of all X80 welds was always much higher than that of the base metal. The fracture location for all tested X80 welds was in the base metal. The fracture location for all tested X120 welds was in the HAZ.

The minimum failure stress requested for X120 according to API 5L is 915 MPa. The requirements of API 5L are definitely fulfilled with the obtained failure stress of 940 MPa for ultrahigh strength steel X120 (Table 8).

CONCLUSIONS

Potentials of the hybrid laser arc welding processes were investigated regarding reliable production of longitudinal welds of high strength pipe steels X80 and X120. The achievable mechanical properties of the laser hybrid welds were evaluated. The findings of the study can be summarised as follows:

(1) The modified spray arc, thanks to its more powerful dynamic effect on the molten pool, shows an increased penetration depth in the GMA part of the laser hybrid weld, which is around 5.0 mm deep. The areas with homogeneous filler material distribution extend up to 3.7 mm for the conventional pulse arc and up to 4.9 mm for the modified spray arc. The arc type the does not have any influence on the character of dilution in the laser part of the hybrid weld. Edge preparation with a root face of 14 mm is proposed as optimum, because no filler material penetration could be detected beyond this depth limit and any metallurgical influence on the weld metal properties through the welding wire is not possible.

(2) The peak hardness for X80 was 312 $HV10_{max}$ which is well below the maximum hardness limit specified for line pipe in API 5L or ISO 3183, which is 325 $HV10_{max}$ for steel grades X80 and above. The peak hardness for X120 was around 356 $HV10_{max}$ which is too high to fulfill the requirements of the API specification, but compared with the base material hardness of 320 HV10 it can be considered as tolerable.

(3) The Charpy test results have shown that the welds of X80 produced with the metal

cored electrode MF 940 M exhibit rather high Charpy values at -60°C (190J average) and meet the requirements of API 5L and ISO 3183. The laser hybrid welds of X120 produced with metal cored electrode Böhler alform 700-MC also exhibit acceptable Charpy values (53J average) at the temperature of -40°C. The used solid wires show rather scattered results at the lower test temperatures.

(4) The strength of the weld metal of all welds X80 was much higher than that of the base metal. The fracture location for all tested welds X80 was in the base metal. The fracture location for all tested welds X120 was in the HAZ. The requirements of API 5L are definitely fulfilled with the obtained failure stress of 940 MPa for X120 (the minimum failure stress requested for ultrahigh strength steel X120 according to API 5L is 915 MPa).

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HYBRID LASER ARC WELDING OF HIGH GRADE X80 AND X120 PIPELINE STEELS

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Abstract – The aim of the present work was to investigate the possibilities of hybrid laser arc welding regarding reliable production of longitudinal welds of high strength pipe steels X80 and X120 and to evaluate achievable mechanical properties of laser hybrid welds. The study focused on weld toughness examination in low temperature range up to -60 °C. Suitable filler materials were identified in the context of this task. It could be shown that metal cored electrodes guaranteed sufficient Charpy impact toughness at low temperature for both investigated materials. Modern arc welding technologies such as modified pulsed spray arc were used to promote deeper penetration of the filler material into the narrow laser welding gap. Edge preparation with a 14 mm deep root face was considered as optimum, because no penetration of the filler material could be detected beyond this depth limit and therefore any metallurgical influences on the weld metal properties through the welding wire could be excluded.

Keywords: high strength steel, hybrid laser arc welding, modified spray arc, longitudinal weld, pipeline.