PECULIARITIES OF THE PROCESS OF ORBITAL LASER-ARC WELDING OF THICK-WALLED LARGE-DIAMETER PIPES

S. GOOK, A. GUMENYUK, M. LAMMERS and **M. RETHMEIER**
Federal Institute for Materials Research and Testing (BAM), Berlin, Germany

The results of development and testing of hybrid laser-arc welding of large-diameter pipes are given. The main results of the research, in particular, on the peculiarities of weld formation in different regions of circumferential joints, mechanical properties of the welded joints, and potentialities of the available equipment for construction of main pipelines are generalized.

Keywords: *hybrid laser-arc welding, orbital welding, high-pressure pipelines, fibre-optic lasers*

One of the key components of the world energy system is a network of main pipelines. Construction of these pipelines demonstrated advantages of manual and mechanised methods of arc welding, such as manual covered-electrode arc welding, mechanised gas-shielded welding using solid or flux-cored wire, and mechanised twin-arc tandem welding. Worthy of note among the non-arc processes is flash butt welding, which has not yet found wide application for construction of modern oil and gas pipelines despite the simplicity of its principle of operation [1]. Position butt welding of pipelines is a labour-consuming process, which determines to a considerable degree the rate of laying a line as a whole. The arc welding methods employed are characterised by a relatively low speed. This limitation may be quite appreciable, for example, in construction of pipeline with a diameter of 1229 mm and wall thickness of 35 mm or more. Furthermore, the oil and gas industry is in a state of search for solutions concerning application of modern high-strength structural materials, as this would allow reducing wall thickness of pipelines in order to cut their metal intensity or increase a working pressure in the pipeline to provide a more efficient transportation of product. Instead of standard pipeline steel grades of strength classes X60 and X70 with a yield point of up to 500 MPa, according to classification of the American Petroleum Institute, steels of a higher strength class, such as X80 or X100, are introduced into practice, as a result of which the working pressure in new pipelines that are designed now can be raised from 7–10 to 15–20 MPa. Despite the fact that increase of strength characteristics of steel in terms of welding metallurgy leads to deterioration of its weldability, traditional arc welding is capable of providing the required quality of welded joints, and the use of fully automated welding processes solves the problem of its reproducibility. It is likely that the choice of these welding processes or the other for construction of advanced pipelines from high-strength steel will be based primarily on the technical-economical factors, allowing for the volumes of construction and assurance of the quality of building and assembly operations. This strategy is inseparably connected with application of the latest achievements in the field of welding technologies, among which the most attractive ones today are highly efficient combined (hybrid) welding processes based on the synergic, complex effect of the laser beam and electric arc on the weld.

The idea of using beam welding to make circumferential welds on pipelines is not new. For instance, the possibilities of using electron beam [2], gas CO_2-laser [3] and solid-state Nd:YAG-laser [4] to implement the orbital welding process have been considered in a number of publications approximately since 2000. The feasibility of applying electron beam welding for making single-pass circumferential welds was demonstrated on the 762 mm diameter pipes with a wall thickness of 19 mm. However, the use of the said welding method under field conditions is hampered by technical difficulties associated mainly with the need of creating vacuum within the welding zone and ensuring protection from X-radiation generated when electrons hit a workpiece. In the case of the laser beam, the maximal wall thickness of a pipe is limited to 10 mm, which is caused by the maximal output power of laser units employed at that time (12 kW for the CO_2-laser, and 4.4 kW for the Nd:YAG-laser).

With emergence of the high-power solid-state lasers, such as fibre-optic and disk ones, the welding industry began using up to 20 kW continuous-wave laser units featuring an excellent quality of emission and compact design. Utilisation of the said advantages of modern lasers combined with the hybrid laser-arc welding process made it possible, for the first time ever, to perform single-pass butt welding of materials with a wall thickness of up to 20 mm [5].

Potentialities of the up-to-date fibre-optic lasers for welding pipelines have been intensively studied at a number of research centres of Germany and other countries. Studies of the highest current importance in this field, the results of which have been published in special literature in the last two years, include those performed by the German Welding Research and Education Centre (Schweisstechnische Lehr- und Versuchsanstalt Halle GmbH — SLV Halle) [6]. The 10 kW fibre-optic laser was used as part of the hybrid process for joining segments of pipes with a wall thickness of 10 mm. Hybrid welding with V-groove and 8 mm high root face was performed by using the 6.5 kW laser at a maximal welding speed of 0.61 m/min. The covering layer of the weld was made by automatic gas-shielded welding. At the Structural Materials Research Centre (CSM, Rome, Italy) the circumferential welds on 36 mm diameter pipes with a wall thickness of 16 mm were made by using the process of laser and hybrid laser-arc welding in two passes [7]. In this case, the point is a roll butt welded joint, which was made in flat position by rotating a pipe. The Yb:SiO_2-laser with an output power of 10 kW (IPG Company) was used as a laser radiation source. The arc power supply was the ESAB welding inverter Aristo MIG 500 operating at a maximal current of 500 A. The first pass with the V-groove and 5 mm root face was made only by laser welding using the 10 kW laser unit. This provided filling of the groove only to half of the pipe wall thickness. Remaining 8 mm were filled with the second pass made by hybrid laser-arc welding. The welding speed in making both passes was 1 m/min. Study [8] reports the field test results on hybrid welding of 610 mm diameter pipes. The 4.4 kW solid-state Nd:YAG-laser combined with the process of automatic metal-arc welding was used to make the root pass of a multilayer orbital U-groove weld. At a root face 4 mm high, the semi-orbital welding process can be implemented, starting from the flat position to the overhead one at a speed of 1.8 m/min.

Within the frames of this study, the authors planned to try out the fibre-optic Yb-laser with an output power of 10 KW, which is used to make the root passes of circumferential joints. However, by the time of the publication only a number of experiments on flat samples with the U-groove and 4–7 mm root face had been performed to investigate the penetration shape and select the welding parameters. Study [9] discusses a variant of using the 10 kW disk laser for hybrid welding of pipes with a diameter of 30 mm or more. The results presented concern flat position welding of the 10.4 mm thick flat samples of pipe steel X80. The V-groove with a 6 mm root face and 60° opening angle was filled up in two passes: the first pass was made by hybrid laser-arc welding using the 9 kW laser at a speed of 2 m/min, and the second one — by automatic metal-arc welding at a speed of 1 m/min. The authors of the said study also mention optimisation of the hybrid process on the circumferential welds.

The above literature data give a general idea of the state-of-the-art in development of hybrid laser-arc welding for large-diameter thick-walled pipelines. It can be concluded on their basis that no scientifically grounded results required for practical application of the hybrid laser-arc welding processes, which could provide high reliability and quality of the circumferential joints on pipes, are available so far. The results discussed apply to the pipes about 10 mm thick, which are usually joined by the multilayer welding technology. Potential of the modern lasers, which can provide deeper penetration of a material, is underutilised so far. Partly, this can be explained by the fact that power of the lasers employed is limited to 10 kW, and single-pass welding of the pipes with a wall thickness of 16 mm or more, which could be interesting in terms of cost effectiveness, is unfeasible. Moreover, no quantitative results of investigation into reliability of the welded joints on pipes made by hybrid laser-arc welding are available, the causes of hot cracking have not been studied to a sufficient degree, and no recommendations for prevention of hot cracking have been worked out.

In collaboration with a number of companies representing the industry, and with a support provided by the German Federal Ministry of Education and Research, BAM is active in studies of the orbital hybrid welding process by using the 20 kW fibre-optic laser. Utilisation of laser systems with a power of 15 kW or more is attractive for construction of large-diameter thick-walled pipelines, as lasers of the said power can provide such a penetration depth that allows achievement of a substantial economic benefit due to application of this equipment. This is associated, first of all, with modification of the groove for welding, so that the quantity of passes and, hence, consumption of filler material can be substantially reduced. As shown by comparison, consumption of welding wire for joining the 1020 mm diameter pipes with a wall thickness of 20 mm can be cut down by a factor of 4 owing to the use of the hybrid laser-arc welding process, compared to twin-arc tandem gas-shielded welding, which by now has been regarded as one of the most efficient methods for welding pipelines, and more than by a factor of 10, compared to manual arc welding. The higher speed of the hybrid laser-arc welding process, compared to the traditional methods, allows reducing the time needed to make one pass, thus leading to a higher rate of laying a line. Despite a comparatively low efficiency of the fibre-optic lasers (approximately 30 %), the power consumed with the hybrid welding method is commensurable with that consumed for the tandem arc welding process, and is an order of magnitude lower than for manual arc welding. Some parameters of the welding methods under consideration are given in Table 1.

As follows from the data presented, hybrid laser-arc welding is a promising resource-saving technology.

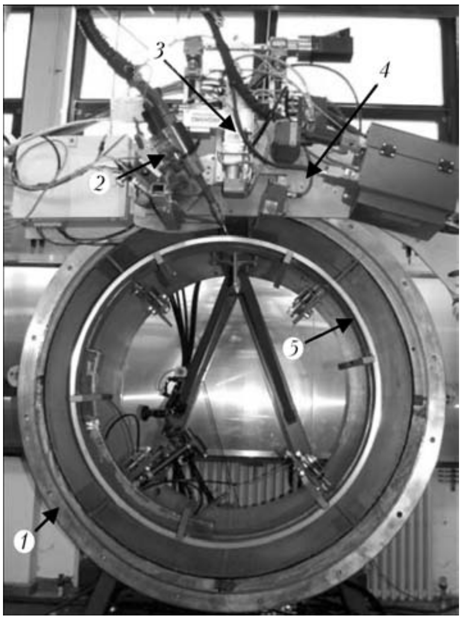

Figure 1. Device for orbital laser-arc welding

However, the necessary condition for successful commercial application of this technology is its correspondence to requirements of the quality standards with regard to permissible defects in the welds, as well as ensuring the required mechanical-technological properties of the welded joints specified in corresponding regulatory documents. One of the goals of the research conducted at BAM is to answer the question whether the welded joints on pipelines made by hybrid laser-arc welding meet the appropriate requirements.

The focus of this study is on two aspects of orbital welding of large-diameter thick-walled pipes. Considered is the feasibility of utilisation of the 20 kW fibre-optic laser to address the above problems, as well as peculiarities of the above methods for welding in different spatial positions. The mechanical-technological properties of the produced welded joints have been analysed, and methods for affecting their values have been suggested in this study.

Equipment and materials. The IPG 20 kW fibre laser YLR-20000 was used as a laser radiation source, and the Cloos automatic pulsed arc welding device of the GLC 603 Quinto type, providing the maximal welding current of 600 A, was used as the arc power supply. The device for orbital laser-arc welding of pipelines (Figure 1), which makes it possible to weld circumferential joints with a diameter of 914 to 1070 mm, was designed and supplied for welding tests by Vietz GmbH, a partner of BAM in the given project.

Table 1. Comparison of pipeline welding methods by an example of making one joint on 40 mm diameter pipes with 20 mm wall thickness

Welding method	Wire consumption, kg/h	Welding time, min	Power consumption, kW
Manual metal-arc welding	6.40	190	30.0
Gas-shielded twin-arc tandem welding	1.90	12	2.7
Hybrid laser-arc welding	0.33–0.44	1.5	2.2

Main components of the device are guide ring *1* and orbital carriage *4*, which is moved on the circumference of the ring by using a gearwheel. Position of the laser beam with regard to the joint during welding is adjusted by means of three extra electrically driven axles. The device as a whole is controlled by the Siemens SINUMERIK programmed numerical control system, which provides the ±0.1 mm positioning accuracy. The hybrid welding head consisting of the HighYag optical head *3* with a focal distance of 300 mm and gas-shielded welding head *2* was fixed on the orbital carriage. To conduct welding experiments under laboratory conditions, design of the device was adapted to welding of pipe rings *5* fixed at the guide ring centre. Laser radiation was transported from the laser to optics via an optical fibre with a core diameter of 200 μm. Diameter of the laser beam in the focal plane was 0.5 mm. Some experiments were carried out by using scanning optics. In this case, diameter of the focal spot was 0.42 mm. 120 mm wide rings cut from the 914 mm diameter pipes with a wall thickness of 15 and 16 mm were used as samples for welding.

The pipes were made from steels X56 and X65, according to the API 5L classification. Approximate analogues of these steels are Russian steels K52 and K56, which correspond to steels L360MB and L450MB (EN 10208–2). The materials investigated are characterised by a low content of carbon (about 0.09 % C). The contents of sulphur and phosphorus also were within the permissible ranges for the laser welding process [10]. Chemical compositions of the materials investigated are given in Table 2.

High values of yield stress of steels X56 and X65, combined with good impact toughness, are achieved due to controlled rolling of plates (strips). Mechanical properties of the steels under investigation are given in Table 3.

Table 2. Chemical compositions (wt.%) of investigated materials

Strength class of steel	C	Si	Mn	P	S	Cr	Ni	Nb	Cu	Al	Mo	V	Ti	Fe
X56	0.07	0.03	1.33	0.008	0.001	0.03	0.04	0.05	0.02	0.04	0.02	<0.01	0.02	Base
X65	0.09	0.36	1.57	0.011	0.001	0.03	0.05	0.04	0.02	0.04	0.01	<0.01	0.02	Same

The filler was 1.2 mm diameter welding wire G3Si1, according to DIN EN 440. Gas mixture ARCAL 21, consisting of 92 % Ar and 8 % carbon dioxide (M21 according to DIN EN 439) was used as a shielding gas. Argon (Ar 4.6) was utilised to shield the weld root. The hybrid welding process was implemented with the leading arc, deepening of beam focus Δz to 4 mm, and angle of inclination of the torch to the laser beam axis equal to 25°. Distance between the points of incidence of the welding wire and laser beam on the workpiece surface was 3 to 4 mm. Prior to welding, two rings were tack welded from inside by using six clips uniformly spaced on the perimeter. Welding was performed by the butt method without groove preparation. The maximal welding gap in some regions of the butt joint was 0.2 mm, and the maximal edge displacement ranged from 0.5 to 1.0 mm.

Semi-orbital welding of circumferential joints. The rings were downhill welded (from the flat position to the overhead one) to make the circumferential weld in two stages with two fading out regions. In our opinion, at this point it is reasonable to introduce a notion of the semi-orbital process and, to designate separate spatial welding positions, use a change in the tangent inclination angle to the circumference relative to the initial flat position. Therefore, position with the 0° angle (flat position) corresponded to the beginning of welding, and position with the 180° angle (overhead position) corresponded to the end of the process. When welding the second semi-ring, coordinates of the process start and stop points were shifted along the weld to provide its closing. Five sets of welding parameters P were used to make one semi-orbital weld. All operations associated with smooth variation and monitoring of these parameters were carried out by using the Siemens SINUMERIK digital control system. Figure 2 explains the procedure used to weld a semi-ring. Also, it shows strength symbols of process parameters P for different welding positions.

Welding was performed at laser power P_L = = 19 kW, which was constant for all welding positions, and at average welding speed v_s = 2 m/min. The speed was slightly adjusted within ±0.2 m/min relative to its average value depending on the welding position. The volume of the weld pool formed by fusion of the welding wire had a higher effect on formation of the external surface of the weld. The required penetration shape was provided by corresponding adaptation of welding wire feed speed v_d in transition from one welding position to the other. For example, the flat position is characterised by a high value of welding wire feed speed v_d (about 14 m/min). And it gradually decreases to 9 m/min with distance to the vertical position of 90°. Quality weld formation in the overhead position can be provided at such a volume of the molten metal that does not cause its flowing out from the weld pool. The maximal welding wire feed speed for the overhead position was limited (6 m/min).

Table 3. Mechanical properties of steels X56 and X65 (according to API 5L classification)*

Strength class of steel	Yield stress, MPa	Tensile strength, MPa	Elongation, %	Impact energy at 68 J/cm^2 (T = 20 °C)
X56	386	489	25.5	68
X65	450	530	23.5	68

*Minimal values of parameters are given.

When changing the welding position, arc length L_{LB} was adjusted from +5 to −12 % with respect to its nominal value at the preset welding parameters, in addition to adaptation of the wire feed speed. For example, welding in the overhead position was performed with the short arc at a correction factor of −12 %. In this case, forces of the gas- and electrodynamic impact of the arc on the weld pool metal had a positive effect, thus resulting in formation of the quality weld bead. Figure 3 shows macrosections and appearances of some characteristic regions of the semi-orbital welds.

It can be concluded from the character of occurrence of the process that at the correct settings of the main welding parameters (see Figure 2) the weld formation in the positions starting from the flat one (0°) to vertical (90°) is sufficiently stable. Welding was performed at an increased speed of 2.2 m/min, at which no sag of the weld root takes place, and its complete penetration is provided. The welds have a favourable shape of their cross sections with a smooth transition to the base metal, and feature a stable formation of the root with low spattering. However, visual assessment of the weld formation quality showed that the joint region from 50 to 80° is characterised by some sag of the weld front face. Despite

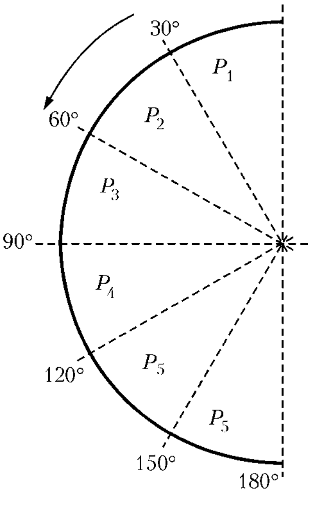

Figure 2. Schematic of semi-orbital laser-arc welding of circumferential weld with 914 mm diameter and 16 mm wall thickness: constant parameters P_L = 19 kW and Δz = −4 mm; variable parameters: P_1 (v_d = 14 m/min, L_{LB} = +5 %, v_s = 2.2 m/min); P_2 (v_d = = 12 m/min, L_{LB} = 0 %, v_s = 2.2 m/min); P_3 (v_d = 9 m/min, L_{LB} = −5 %, v_s = 2.2 m/min); P_4 (v_d = 7 m/min, L_{LB} = −10 %, v_s = 1.9 m/min); P_5 (v_d = 6 m/min, L_{LB} = −12 %, v_s = 1.7 m/min)

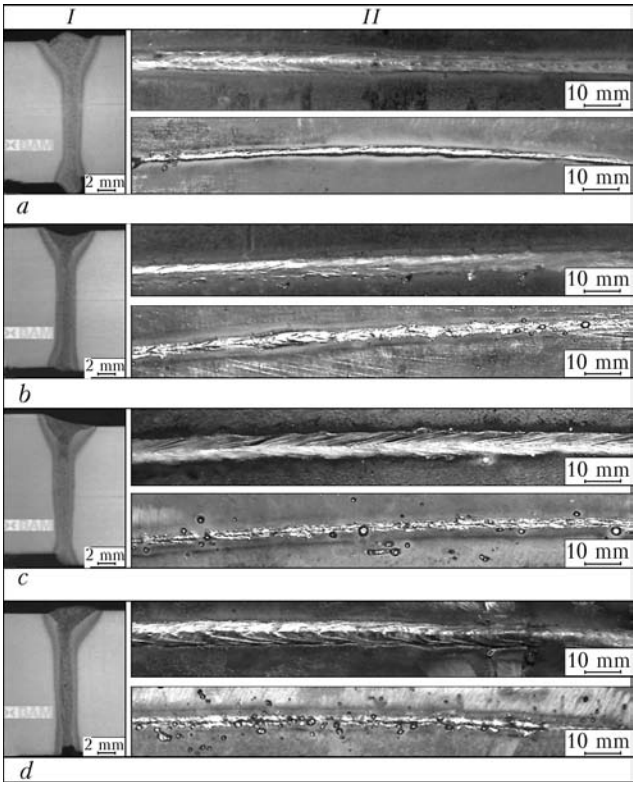

Figure 3. Macrosections (*I*) and appearance of the hybrid laser-arc weld (*II*) made on X65 steel pipe with 914 mm external diameter and 16 mm wall thickness: *a* — 0° angle (v_d = 14 m/min, v_s = = 2.2 m/min, L_{LB} = +5 %, I_a = 364 A, U_a = 35.5 V); *b* — 60° (v_d = 10 m/min, v_s = 2.2 m/min, L_{LB} = −5 %, I_a = 245 A, U_a = = 28.9 V); *c* — 120° (v_d = 7 m/min, v_s = 1.9 m/min, L_{LB} = −10 %, I_a = 180 A, U_a = 22 V); *d* — 180° (v_d = 6 m/min, v_s = 1.8 m/min, L_{LB} = −12 %, I_a = 174 A, U_a = 21.5 V)

the fact that the sag is insignificant, deposition of a covering layer will probably be required to form the weld reinforcement in the given region.

High sensitivity of the process to the weld pool volume was noted in transition to the 90° position. Even an insignificant excess of some critical value of the wire feed speed (9 m/min at an angle of 90°) led to spreading of metal over both sides of the weld. The process in this case occurred with increased spattering, and the reverse side of the weld might have metal rolls and partial penetration.

While approaching the 120° position, the heat input of the hybrid process decreased together with decrease in the welding wire feed speed to 7 m/min, thus leading to growth of the probability of lack of penetration of the weld root. Complete penetration with satisfactory formation of the weld root was achieved in this position at a simultaneous decrease of the welding speed to 1.9 m/min.

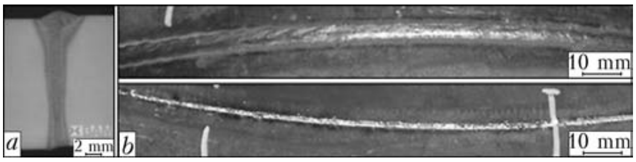

Figure 4. Macrosection (*a*) and appearance (*b*) of the overhead hybrid laser-arc weld made by using scanning optics and forming gas: P_L = 19 kW, v_d = 6 m/min, v_s = 1.8 m/min, L_{LB} = −12 %, I_a = 174 A, U_a = 21.5 V

In welding in the overhead position, the sound bead with a small reinforcement was formed at a process speed of 1.7 m/min starting approximately from 120° and to 180°. In this region of the weld, it was very difficult to provide acceptable formation of the weld root. In this position, the critical problem was the absence of fusion on the reverse, upward-looking side of the weld. On the one hand, this defect was caused by shortage of molten metal in the root zone of the weld because of its sagging under the effect of gravity and spattering. On the other hand, high sensitivity of the process to the accuracy of positioning of the welding head relative to the joint also involved a problem. For example, shifting the laser beam even to 0.3 mm led to one-sided melting of the edges and, as a result, to the absence of fusion in the root zone of the hybrid weld. Variation of the main welding parameters had almost no effect on this defect (constant parameters P_L = 19 kW and Δz = −4 mm).

Encouraging results were obtained with the scanning optics of Company «HighYag», which provides the possibility of linearly oscillating the laser beam in a direction normal to the welding direction at maximal amplitude of 13 mm and frequency of up to 1 kHz. The scanning optics was applied to stabilise the process in oscillation of the laser beam and increase cross section of the weld in order to ensure better coverage of the edges and their fusion. Reproducible results on satisfactory formation of the weld root in the overhead position were obtained at scanning with the 0.7 mm amplitude and 200 Hz frequency. These settings of the scanner provided complete penetration with no need to adapt other welding parameters. The pure argon gas was used to improve the quality of formation of the weld root. The gas was fed from the reverse side of the weld by using a specially made pool deposited on the joint and copying the internal contour of the parts welded. Macrosection and appearance of the overhead weld made by using the scanning optics and forming gas are shown in Figure 4.

We investigated the capabilities of the scanning optics, including for determination of the maximal

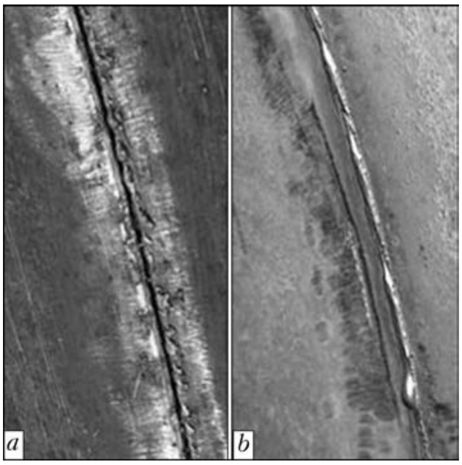

Figure 5. Defects in the weld root (*a*), and repair weld (*b*)

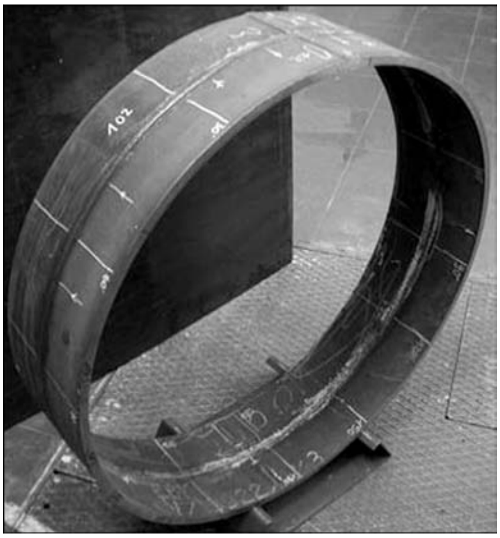

Figure 6. Sample made by semi-orbital hybrid welding

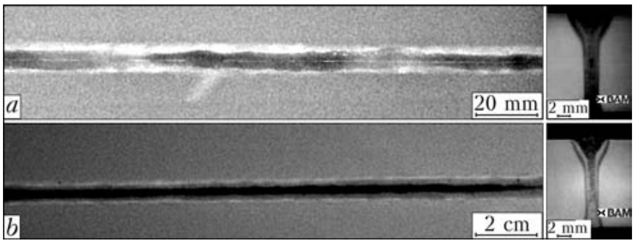

Figure 7. X-ray photos and macrosections of the hybrid welds on steels X65 (*a*) and X56 (*b*)

gap in the joint, which could provide reliable fusion of the edges [11]. As proved by a series of experiments conducted on 16 mm thick flat samples of steel X65, the stable process without fusion defects can be achieved at a maximal gap of 0.7 mm, with the conventional optics this gap being approximately 0.3 mm. The maximum permissible edge displacement is about 2 mm. The above tolerances apply only to the flat welding position, and it will be necessary to conduct a number of experiments to determine values of tolerances for other welding positions.

Some repair welds were tested to estimate the possibility of repairing defects in the hybrid weld. The tests were carried out both in flat position and in vertical position in a region from 60 to 70°. Regions of the circumferential welded joint with defects of the type of lack of fusion in the weld root were welded by the hybrid method over the existing defective weld by using the forming gas. All the repair welds thus made were characterised by formation of the satisfactory quality of the weld root. One of the examples of such a weld made in the vertical position is shown in Figure 5. The tests proved the feasibility of repairing defective regions of the welds by making the second pass. No systematic studies in this area, including in the overhead position, had been conducted by the time of preparation of this article.

The knowledge and experience accumulated as a result of research allowed us to make a series of samples (Figure 6), which were demonstrated at the «Schweiβen & Schneiden 2010» Fair in Essen, Germany.

Internal defects and mechanical properties of welded joints. Non-destructive and destructive testing methods were used to assess the quality and mechanical properties of the welds made. Metallographic and X-ray examinations of the welded joints on steel X65 revealed the presence of extended solidification cracks along the central line of the weld in parallel to the weld edges, the cracks locating deep, approximately in the middle of the pipe wall thickness (Figure 7, *a*). No such defects were detected in the welded joints on steel X56 (Figure 7, *b*).

The steels under investigation are characterised by complex chemical compositions (see Table 2). Hybrid welding of rings of both steel grades was carried out under identical conditions. One of the probable reasons of increased sensitivity of steel X65 to solidification (hot) cracking is the effect of zonal segregation, as well as the properties of structure of the pipe metal caused by thermomechanical rolling parameters. The structure of steel X65, in contrast to steel X56, is characterised by the presence of pearlitic streakiness (Figure 8), causing high anisotropy of mechanical properties of the rolled stock. At present, we are investigating the issue of the effect of its structure on hot cracking in laser and laser-arc welding.

Microhardness of the weld and HAZ zones was measured according to DIN EN 1043–2 on circumferential test samples of steel X65 with carbon content

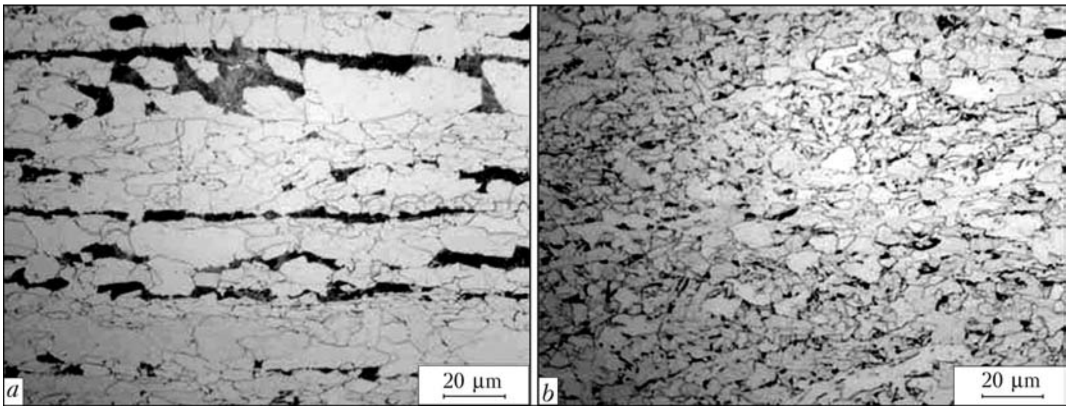

Figure 8. Microstructures of base metal: *a* — steel X65; *b* — X56

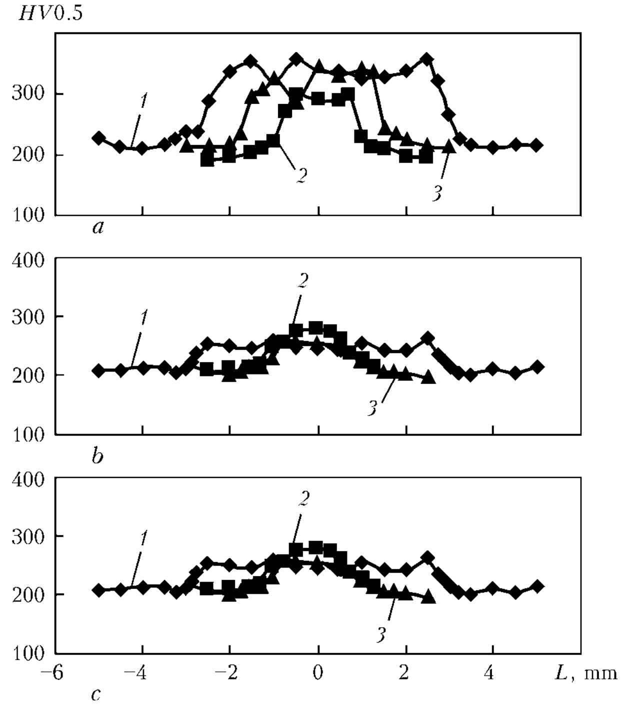

Figure 9. Distribution of microhardness across the welded joints made without preheating (*a*) and with preheating to 200 (*b*) and 300 (*c*) °C: *1–3* — upper, central and lower (root) weld zones; *L* — distance from the weld centre

of 0.09 wt.%. It was found that the maximal values of microhardness did not meet requirements of the above standard. Therefore, it was decided to use preheating to provide the required values of microhardness. The welding tests with preheating were carried out on segments of rings in the flat position. The parts were heated before welding by using resistance heaters to a temperature of 150 to 350 °C with a step of 50 °C. Thermocouples of the K type (nickel-chromium–nickel), mounted on the reverse side of a sample at a distance of 0.7 mm from the joint, were used to monitor the preheating temperature, as well as to measure the welding thermal cycle. The results of measuring microhardness of the weld metal and HAZ in welding with and without preheating are shown in Figure 9.

It was found that increase in the preheating temperature allows implementing the welding process with a lower laser beam power than that required for welding the «cold» samples. The laser power at a preheating temperature of 350 °C can be reduced to 17 kW. Cooling time $t_{8/5}$ measured in the HAZ (in a temperature range of 800 to 500 °C) is about 1 s in welding without preheating, while in welding with preheating it increases to 16 s. Maximal microhardness of the weld metal in this case is at a level of that of the base metal (*HV* 220). The values of microhardness achieved with preheating correspond to requirements of the active standards on production of pipes from materials that are not designed for operation in acid environment, e.g. DNV-OS-F101.

When using resistance heaters to preheat the entire circumference of a joint, it is necessary to take into account that this is a time-consuming operation, which may have a negative effect on the pipeline laying rate. As an alternative, we consider local preheating of the joint edges, e.g. by using an inductor moved together with the welding head. Depending on the configuration and location of the inductor, it is possible to provide extra heat input into the material both immediately prior to welding and after welding. In this case, power of the inductor should provide heating of the workpiece material through its entire thickness at a preset welding speed.

The possibility of welding the circumferential joint with two semi-orbital downhill passes at an average speed of 2 m/min and laser power of 19 kW was successfully demonstrated by an example of the 914 mm diameter pipes with a wall thickness of 16 mm. The overhead welding position (region from 150 to 180°) is most difficult in terms of ensuring the quality formation of the weld root.

Adaptation of the wire feed and welding speeds, and utilisation of the forming gas provide a marked improvement of the root quality in the overhead welding position. The scanning optics proved to be an efficient means for widening tolerances on the gaps in joints, allowing compensation for insignificant errors in positioning of the welding head relative to the joint. The gap established for the 16 mm thick metal, at which the stable welding process without fusion defects is still possible, is 0.7 mm, whereas in conventional welding it is 0.3 mm. Increase in cooling time $t_{8/5}$ from 1 to 16 s was achieved by using preheating, which led to a substantial decrease of microhardness in the heat-affected zone.

These studies are conducted under project MNPQ FK19/07 with the financial support provided by the Federal Ministry of Education and Research of Germany. The authors express gratitude to industrial partners, companies «Vietz GmbH» and «HighYag», for their fruitful cooperation and providing equipment to conduct experiments.

1. Widgery, D.J. (2005) Mechanised welding of pipelines. *Svetsaren — the ESAB welding and cutting journal*, **1**, 23–26.
2. Koga, S. et al. (2001) Study on all position electron beam welding of large diameter pipeline joints. Rep. 1, 2. *Welding Int.*, **5**, 28–33, 92–99.
3. Gainand, Y. et al. (2000) Laser orbital welding applied to offshore pipe line construction. *Pipeline Techn. Elsevier Sci.*, **2**, 327–343.
4. Fujinaga, S. et al. (2005) Development of an all-position YAG laser butt welding process with addition of filler wire. *Welding J.*, **19**, 441–446.
5. Rethmeier, M. et al. (2009) Laser-hybrid welding of thick plates up to 32 mm using a 20 kW fibre laser. *Transact. of JWRI*, 27(**2**), 74–79.
6. Neubert, J. et al. (2009) Influence of tolerances to weld formation and quality of laser-GMA-hybrid girth welded pipe joints: IV-1003–09.
7. Fersini, M. et al. (2009) Circumferential welding of gas pipeline pipes using hybrid technology with fibre-delivered laser beam. *Welding Int.*, 23(**6**), 450–459.
8. Harris Ian, D. et al. (2008) Hybrid laser/gas metal arc welding of high strength steel gas transmission pipelines. In: *Proc. of 7th Int. Pipeline Conf.* (Sept. 29–Oct. 3, 2008, Calgary, Alberta, Canada).
9. Begg, D. et al. (2008) Development of a hybrid laser arc welding system for pipeline construction. *Ibid.*
10. (1996) *Guidelines for approval of CO_2-laser welding in ship hull construction classification societies unified*.
11. Gumenyuk, A. et al. (2009) High power fibre laser welding for pipeline applications. In: *Proc. of 5th Congress on Laser Advanced Materials Processing* (July 2009, Kobe, Japan).