Automated Laser Beam Welding and Testing of Pipe Joints

The welding of pipes with an orbital process has proved its worth in the pipeline construction sector for many years, particularly when it comes to large pipes. Laser beam welding today provides a technology which allows for comparable results to be achieved but with substantially less expenditure of time and material. And in the interim this process has become an interesting alternative to manual welding with electrodes in smaller construction undertakings as well. In addition to this, the very low heat transfer incurred by the process in the area of the weld seam allows a check of the welding very soon after it has been carried out, which means that in a combined process a not inconsiderable logistics advantage in the site development can be achieved. As part of a joint research project, a prototype for this type of operation has now been created.

1 INTRODUCTION

The welding of steel pipes in pipeline construction has a long tradition, but it remains heavily dependent on the skill of the welder in handling the electrodes, and is therefore still predominantly manual labour. At the start of a construction project a set of welding procedures is frequently drawn up, matched to the particular project, and if necessary arrangements for checking the process and instructions in the event of difficult welding tasks. If a particular project is going to continue for months, the time taken for this is scarcely worth considering. But while with pipeline construction a regulated sequence for the work is assured, from the trace out of pipes, preparing the pipe ends, the welding until the field joint coating, when it comes to smaller construction projects in the gas and water supply sector, such procedures involve substantial effort and costs in time and logistics. And while in pipeline construction a pipe string is in most cases initially prepared beside the trench, with smaller projects provision has to be made not only for a single pipe laying, but also for trench dimensions, which has to be walkable and needs also man holes in the area in which the welder is working.

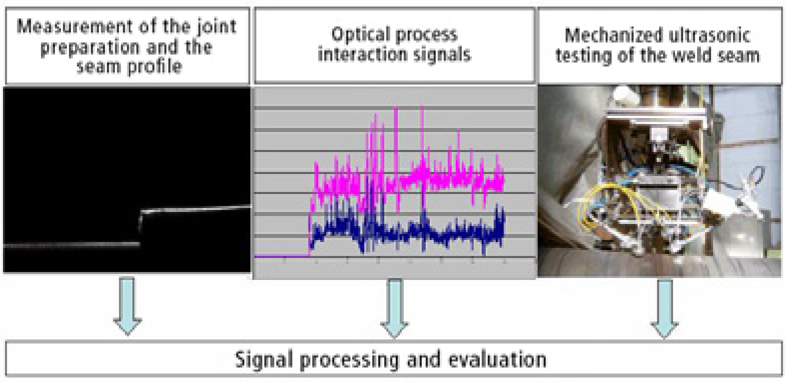


***Figure 1**: Monitoring and testing strategy*

This effort and expenditure is also an impediment when it comes to new laying techniques such as the relining with steel pipes. It is precisely in cases such as these that the time savings which could be achieved are in many cases brought down because of a complex welding procedure. As part of a joint project, the possibility has been explored of reducing this effort and expenditure with the technical solutions available today, such as laser welding and new testing techniques.

2 STATE OF THE ART, MOTIVATION, AND OUTLINING THE TASK

As part of a sponsored research project, the intention was that a prototype for laser beam welding should be developed, which will allow a combined solution for the welding and testing of steel pipes with the aid of an orbital process. The development effort in this situation consists of the combining different test techniques, in order finally to achieve a degree of reliability of results appropriate to the area of application. Right from the start, the prototype was to be based on a design which was as easy to handle as possible, and as space-saving as could be achieved. With an eye to the areas of application which have already been described, as a first step a rated wall thickness range of the steel pipes from 3 to 5 mm was covered, which finally corresponds to the application range of pipe external diameters from diameter DN 100 to about DN 400 [1, 2]. The permissible tolerances for the welding gap and the error values acquired by the test technology are to be determined.

The construction equipped with testing and welding technology for the pipe welding is to be kept distinct from the equipment required for the generation of the welding energy required and for processing the measurement signals. The connection is to be produced by an appropriately arranged service line. In this way, even considerable distances can be covered between the equipment technology and the actual workplace. This means that, depending on the area of application, the equipment can be installed on a site vehicle.

3 EXPERIMENTAL SET UP AND PROCEDURE

To resolve the basic task successfully, it was first of all necessary to design a device for carrying out the circumferential welding movement of the laser optics. As well as this, the device had to provide sufficient space for the sensor system for the process monitoring (LWM) and the non-destructive testing. In this context, the focus of the investigations was set on the creation of a unitary monitoring and testing strategy, which would provide an analysis of the seam quality achieved directly after the concluding of the welding. The information required for this can be acquired before, during, and after the welding process, in the form of different signals. ***Figure 1*** illustrates this strategy and the signal processing required.

The analysis of irregularities in laser-beam welded joints shows that the majority of these are attributable to interference in the process sequence. The cause of these, in turn, is the quality of the joint preparation with regard to geometry (presence of gap or poor edge alignment) and the standard of cleanliness.

3.1 Experimental set up for orbital laser-beam welding, with integrated process monitoring

As the first step, the design and layout of a suitable construction was developed, for transforming the circumferential movement of the laser optics on the pipe, including the clamping technique required for the joining and fixing the pipe joints for the laser-beam welding of pipes in the rated diameter range from DN 80 to DN 150 with wall thicknesses from 2 to 5 mm. This is described as follows, together with its basic components.

The construction consists of four ring-shaped plates, open downwards in order for the pipes which are to be joined to be laid on them. The two outer plates are each connected to one of the pipes by means of a clamping device. The two inner rings are guided along them, so that a circular movement around the pipes can be carried out. The two inner rings are rigidly connected to one another. Arranged between these rings are all the components which carry out the jointing and testing procedures.

In the first step, a miniaturized welding optics unit was integrated into this construction, which resulted in a set up shown below being provided for the further development of the prototype (***figure 2***).

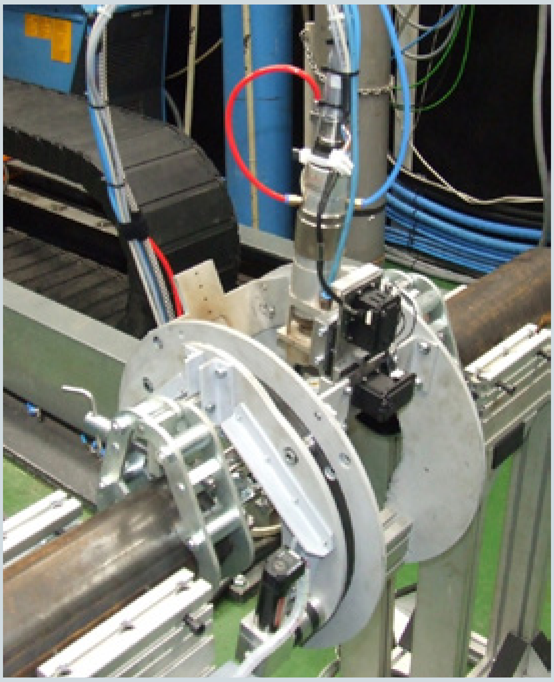


Figure 2: *Construction with welding optics in place*

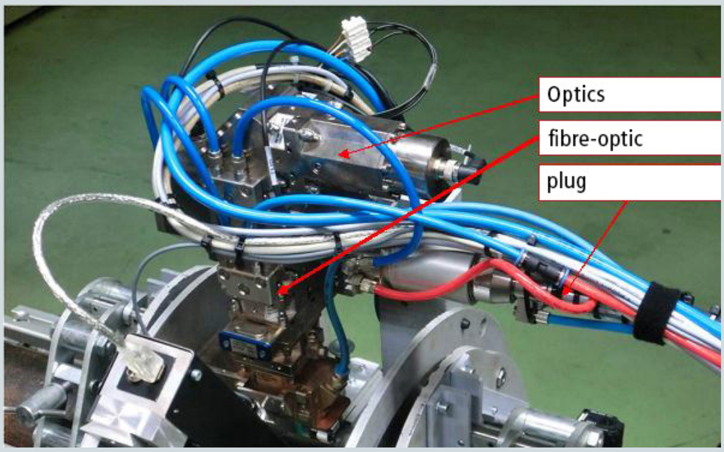


Figure 3: *Laser optics with LWM sensor and fibre-optic plug*

The core of the experimental arrangement is a transmitting processing optical unit, type YW30 from Precitec, with sensor array integrated coaxially to the path of the beam, for the photo-optical acquisition of relevant emissions from the laser-beam welding process. This processing optical array was adapted to the construction for the purpose of the experiment. The whole arrangement for performing the test is shown in ***figure 3***.

The recording of the radiation emitted by the process was carried out with an industrial PC. In this situation, first the optical radiation is measured in different wavelength ranges by means of photodiodes, and converted into analog voltage signals. After amplification of the signals, the processing of the measured values takes place as time-dependent signal sequences over different measuring channels of the industrial PC.

3.2 Camera system for determining joint and seam geometry

For the assessment of the weld seam, in particular with regard to edge alignment and gap, the bead produced by a line laser, transverse to the joint, is recorded by a camera. The camera and the line laser are located close to the laser optic centrally between the two inner plates of the carrier system, and are guided around the pipe with the circumferential movement. Following the welding process, the same

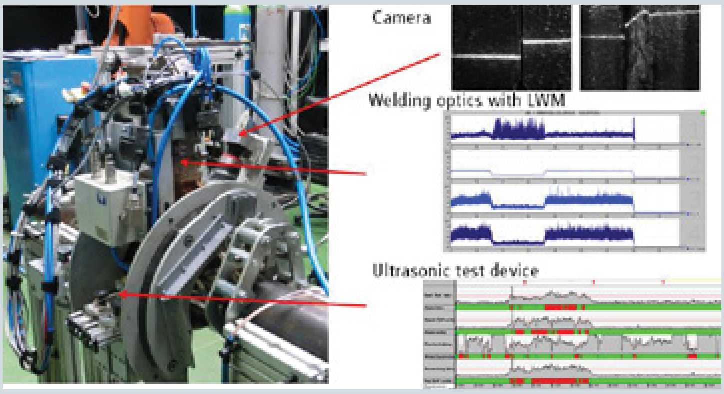


Figure 4: *Prototype with camera, laser optic and ultrasonic test device*

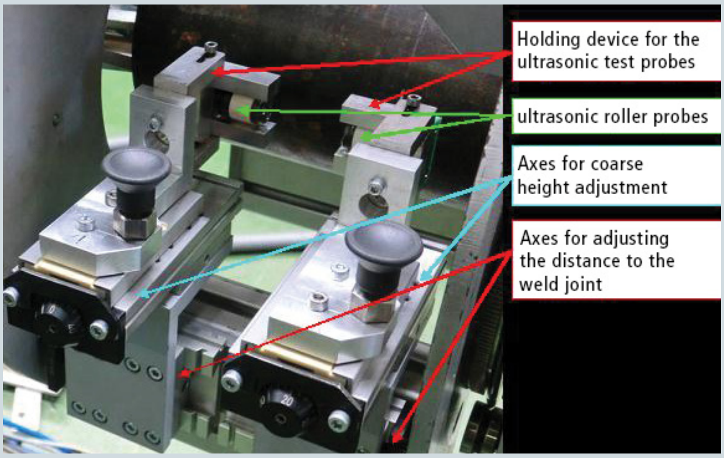


Figure 5: *Ultrasonic test device*

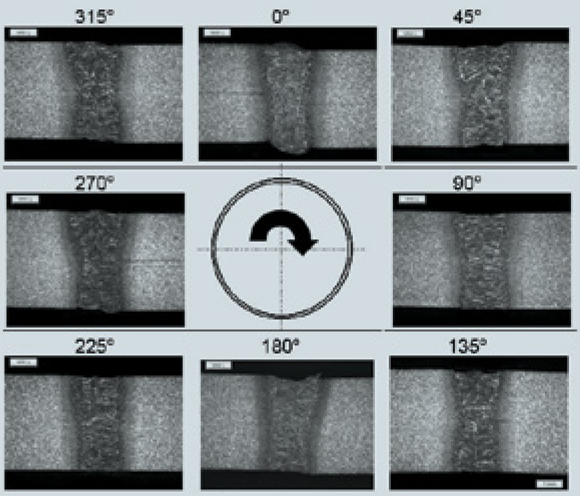


Figure 6: *metallographic specimens of the seam, relative to the pipe angle*

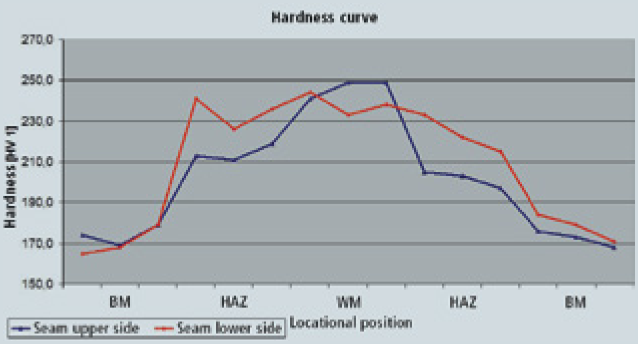


Figure 7: *Hardness curve over the weld seam in the area of the pipe angle 180° (t = 5 mm)*

camera is used to record the topography of the weld seam. In this situation, particular attention is paid to the gap and the edge alignment in the preparation of the seam, to seam irregularities (depressions or elevations), and to welding defects open to the outside. Examples of situations which were examined are shown in ***Table 1***. The changes in the laser line registered during the circumferential movement can also be used for position calculation and for height and side adjustment of the welding optics.

3.3 Experimental set-up for qualifying the ultrasonic technique

The ultrasonic inspection equipment used in the investigations is made up of the actual ultrasonic testing instrument itself, the USIP 40, and the roller angle beam probes. The USIP 40 is a multi-channel ultrasonic system with five channels, separated from one another with the aid of a multiplexer. In addition to the transducers, it is possible for external devices to be connected to the USIP 40. These may be, for example, encoders for position determination, or devices for test data approval. These can be connected via two I/O interfaces and synchronized by way of a SYNC interface.

In addition to the USIP 40, special roller angle beam probes are used for oblique application of the ultrasonics, with an angle of 55 ° and a frequency of 6 MHz. These probes are characterized in that the effective coupling is carried out not with the aid of couplants but by way of a silicone tyre. The probe is moved on this tyre above the component, whereby only a movement parallel to the weld seam can be carried out.

4 INTEGRATION OF THE ULTRASONIC TECHNIQUE

In the final project phase, the individual systems which had been developed, consisting of the welding optics, the camera for recording the joint topography and process monitoring as well as the arrangement for the ultrasonic roller probes were all brought together to form a complete prototype solution (***figure 4***).

For the direct evaluation of internal weld irregularities, the two ultrasonic roller probes are guided around the pipe at a defined interval from one another, left and right of the weld seam. ***Figure 5*** shows the arrangement of the ultrasonic test device.

Contact between the ultrasonic roller probes and the pipe is maintained by means of spring tension. Height adjustment is possible for different pipe diameters.

5 RESULTS OF THE MATERIAL TESTING

In the first step, in order to create a reference for the process monitoring (LWM) and in order to determine the mechanical-technological characteristic values of the laser-beam welded pipe joint, a series of experiments were carried out under ideal conditions for pipe end preparation and without any provoked defect settings. After the production of this reference sample, metallographic specimens were taken in increments of 45 °, divided over the circumference. These are shown in ***figure 6***, related to the pipe angle in each case.

As can clearly be seen, for the parameters selected no influence derives from the orbital constantly changing welding position, which supports the constant signal level of the process monitoring system. This analysis relates both to the seam geometry in respect of the upper and lower side of the weld seam, as well as to the occurrence of internal weld irregularities. As a result, it can be estimated that, under the conditions chosen, an evaluation group B according to DIN EN ISO 13919-1 is fulfilled. In ***figure 7*** below, the hardness is shown for the weld position 180 °.

The investigations for determining the static seam strength and toughness values, making reference to the DVGW Worksheet GW 350 [3], likewise did not reveal any anomalies. The values determined accordingly in the tensile test and the notch impact test (undersize samples) for the material L360MB (t = 5 mm) are shown in ***Table 2***, ***Table 3*** and ***Table 4***.

5.1 Defect simulation for testing the interaction of testing and monitoring systems

In the following section, the redundant interaction of the testing and monitoring systems is demonstrated. To do this, during the test, parameter deviations are programmed at defined points, and irregularities introduced into the pipe end preparation. The joints are then welded making use of the process monitoring system (LWM), and then tested by the integrated ultrasonic technique. By a comparative consideration of the signals from both systems, and with the aid of the images from the CCD camera, the identifiable irregularities can be classified. To back up the results, the areas concerned were then examined by means of radiographic inspection.

All the irregularities proved by the radiographic inspection are also detected by the process monitoring and ultrasonic testing. By the evaluation of the supportive joint and seam inspection, a local classification of the irregularities can be achieved, and, in part, also the causes of these irregularities.

5.2 Irregularities provable by the testing and monitoring system

As a result of the work presented for the development of an In-Situ testing and monitoring strategy for laser-based pipe welding, the function and suitability have been

Table 1: *Images of joint and seam profiles in different tolerance situations*

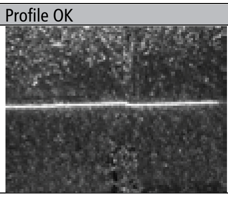
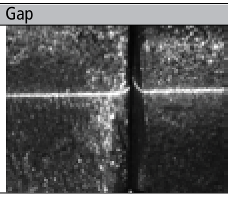
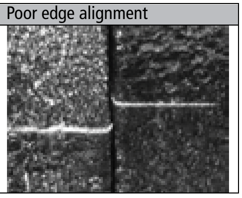
	Profile OK	Gap	Poor edge alignment
Joint (not welded)			

Table 2: *Results of the notch impact test in the middle of the seam at 0°C - 2 sample sets*

Specimen location	Test temperature [°C]	Specimen width a [mm]	Specimen height b [mm]	Charpy notched impact test notch impact energy Av: Induvidual values [J]	Mean value [J]	Requirement GW 350 [J]
Middle of seam (weld material)	0	3.4	8.0	59	62	27 min. 20
		3.4	8.0	75		
		3.4	8.0	53		
		3.4	8.0	79	71	
		3.4	8.0	66		
		3.4	8.0	68		

Table 3: *Results of the notched bar impact test in the heat affected zone at 0°C - 2 sample sets*

Specimen location	Test temperature [°C]	Specimen width a [mm]	Specimen height b [mm]	Charpy notched impact test notch impact energy Av: Induvidual values [J]	Mean value [J]	Requirement GW 350 [J]
Heat influence zone	0	3,4	8,0	63	55	27 mind. 20
		3,4	8,0	56		
		3,4	8,0	45		
		3,4	8,0	40	41	
		3,4	8,0	42		
		3,4	8,0	41		

Table 4: *Results of the transverse tensile test*

Specimen	Yield strength $R_{p0,5}$ [MPa]	Tensile strength R_m [MPa]	Elongation of fracture A [%]	Contaction of fracture Z [%]	Location of fracture -
1	448	487	20.1	70	GW
2	418	467	24.5	70	GW
3	416	466	21.6	67	GW
4	413	463	25.8	62	GW

Note: With the location of the fraction in the basic material (BM), the requirements of DVGW (A) GW 350 are fullfilled

Table 5: *Measurement data generated when welding and testing according to the InSitu testing monitoring strategy, with the example of a lack of penetration and a partial beam offset transverse to the welded joint.*

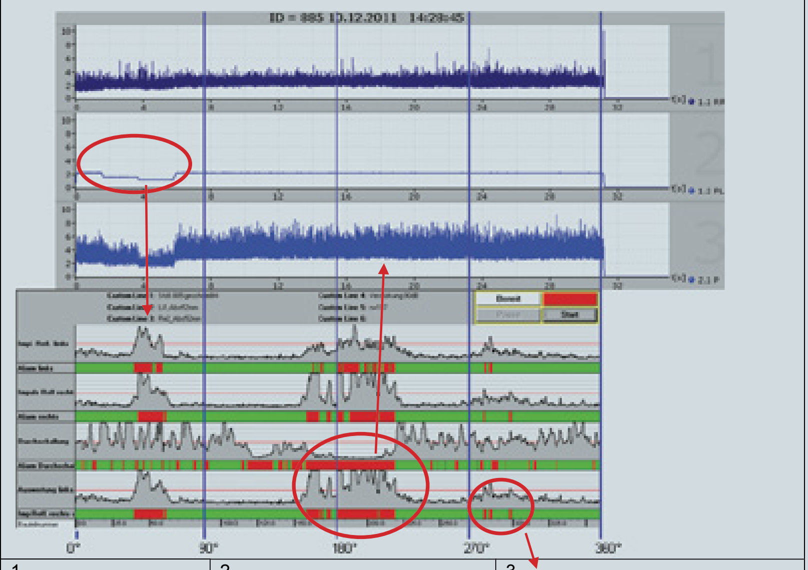
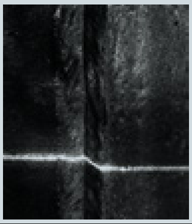
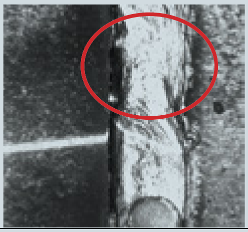
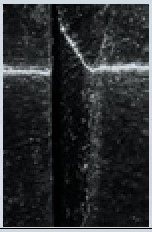
LWM UT				
Display No.	1	2	3	
Interpretation	Linear indication; reduced laser power	Linear indication, Cause not unambiguously identifiable from the LWM signal	Short UT display, no LWM indication	
CCD Camera				
Evaluation	**Seam width too small, poor edge alignment; NOK.**	**Non-welded edge identifiable, erroneous positioning: NOK**	**Seam depression due to defect in the seam preparation: NOK**	

Table 6: *Minimum sizes determined for irregularities detectable by Ultrasonic testing for the wall thickness range examined*

Irregularity	**Minimum detectable size according to the current state of development**	
	t = 3 mm	**t = 5 mm**
Pores (200) Pore lines (2015)	5 mm x 0.5 mm	5 mm x 0.5 mm
Lack of penetration (402) (Irregularity impermissible for evaluation group B und C)	0.4 mm	0.6 mm
Cracks (100) (Irregularity impermissible for all evaluation groups)	0.4 mm	0.4 mm
Poor edge alignment (507)	0.8 mm	0.8 mm
Lack of fusion (401) (Irregularity impermissible for evaluation group B und C)	0.4 mm	0.4 mm

proved at the laboratory level. In specific terms, this means that the ability to test laser-beam welded connections by means of ultrasonic technology can also be achieved in the range of wall thicknesses from 3 to 5 mm for critical irregularities, such as lack of fusion, root defects (lack of penetration), pore lines, and serious seam depressions, in the present phase of development, up to the sizes of the irregularities shown in ***Table 6***. Restrictions must be imposed with regard to the detectability of individual pores, which, because of their geometry, exhibit very poor reflection behaviour in relation to the ultrasonic waves.

In the final arrangement of the equipment, it was shown that the interaction of the individual systems of the camera, photo-optical process monitoring, and ultrasonic testing is indeed achieved. This was proved in the error simulations. Further optimization of the assessable sizes of irregularities in the weld seam is foreseeable in the further course of the work.

6 SUMMARY AND OUTLOOK

Within the framework of this research project a prototype was created for the combined welding and testing of a pipe joint in the orbital process. The joints produced by orbital laser-beam welding fulfil the requirements of the DVGW worksheet GW 350 in respect of their mechanical and technological characteristic values. At the present time, the regulations and rulings of relevance to pipeline construction do not encompass either the welding process or the testing process presented here. The requirements on ultrasonic testing have been described for a wall thickness range from about 6 to 10 mm [3].

The optimization of the prototype, its use under construction site conditions and the clarification of acceptance of the welding and testing techniques for application in gas and water distribution as well as in district heating supply systems, will be the next steps in the further development of the technical solution presented here.

7 THANKS ARE DUE

The work presented here has been supported by the BMWi (Federal Ministry of Economy and Technology) as part of the

project "Development of redundant In-Situ monitoring and testing strategies for laser-based pipe joint welding" (FKZ MF090208). Thanks are particularly expressed for this.
Thanks are also due to the industrial partners who participated in the project, Salzgitter Mannesmann Line Pipe GmbH; Gelsenwasser AG, and Stadtwerke München Services GmbH, for their support in carrying out the investigations.

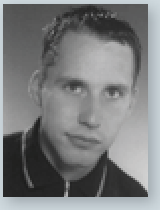
LITERATURE

[1] DIN 2460: Steel water pipes and fittings; June 2006 version
[2] DIN 2470-1: Steel gas pipelines for permissible working pressures up to 16 bar, December 1987 version
[3] DVGW Worksheet GW 350: Welded connections on pipelines made of steel for gas and water supply; October 2006 version

AUTHORS

Dipl.-Ing. (FH) **JAN NEUBERT**
Schweißtechnische Lehr- und Versuchsanstalt Halle GmbH, Halle (Saale)/Germany
Tel. +49 345 5246-428
E-Mail: neubert@slv-halle.de

Dr. rer. nat. **HANS-JÜRGEN KOCKS**
Salzgitter Mannesmann Line Pipe GmbH, Siegen/Germany
Tel. +49 271 691-170
E-Mail: hans-juergen.kocks@smlp.eu



Dipl.-Ing. (FH) **TONY KRÄKER**
Schweißtechnische Lehr- und Versuchsanstalt Halle GmbH, Halle (Saale)/Germany
Tel. +49 345 5246-422
E-Mail: kraeker@slv-halle.de