Development of the sleeve welding process with an incorporated heating element for the joining of large-diameter pipes made of polyethylene using universally applicable flexible wound sleeves

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Summary

With the research project entitled "Development of the sleeve welding process with an incorporated heating element for the joining of large-diameter pipes made of polyethylene using universally applicable flexible wound sleeves", the German Plastic Centre (SKZ) has, in close cooperation with Frank & Krah Wickelrohr GmbH, successfully developed a high-quality and economically viable joining process for large-diameter pipes. The process is based on the new manufacturing process for heater spiral sleeves in which, in contrast with previous processes (extrusion and injection moulding), nearly any sleeve geometries can be implemented in an economically viable way. In this respect, the newly developed joining process was validated using joints with diameters up to 1,000 mm. Theoretically, even substantially larger sleeve joints are possible with the welding parameters calculated in the project.

1. Introduction

The largest proportion of the German sewage network with a length of 515,000 kilometers still consists of flexural stiff pipe materials such as concrete and stoneware. These pipe materials result in relatively high costs for the maintenance of the pipe systems (rectification of pipe fractures and collapsing, damaged connections, corrosion etc.). The utilization of high-quality sewage pipe systems made of polyethylene (PE) whose damage rates per kilometer are considerably lower entails notable potential for lowering costs. The manufacture of large-diameter pipes made of PE-HD, also for the pressurized field, is possible with today’s technology. However, the percentage proportion of PE pipes cannot rise because there is no joining technology for pressure-loadable large-diameter pipes or this is not yet economically viable.

In this respect, two joining processes for plastic pipes made of high-density polyethylene (PE-HD) are authorized for pipeline construction according to DVGW1 330: sleeve welding with an incorporated heating element (HM) and heated tool butt welding (HS). In this case, the optimization potential in relation to the economic viability and the environmental effect is still far from having been exploited to the full for both processes.

For many areas of application, it is indispensable to utilize sleeve welding processes with an incorporated heating element (HM). Amongst others, these include installation operations in poorly accessible areas and repairs (e.g. using coupling sleeves) for which the pipes cannot be moved or only to a limited extent.

2. Procedure

Technological research was conducted into the sleeve geometries which are customary today, i.e. in the corresponding pressure stages (SDR11 and SDR17). By extrapolating the established data to larger diameters, it was possible to define the geometrical ranges necessary for the manufacture of the large-diameter sleeves.
For technical and economic reasons, the outside diameter of the pipes to be joined was stipulated at 1,000 mm for this project. The following geometrical data could be derived from the preceding market research. The overall length of the sleeve might be approx. 550 mm and the wall thickness approx. 120 mm. Moreover, a decrease in the weight of the sleeve body might be enabled by integrated reinforcing elements or by the profiling of the outside contour.

For reasons relating to welding technology, the designing of the pressurized sleeve for large-diameter pipes made provision for a bifilar design (with two welding zones separate from each other). A bifilar sleeve design permits the utilization of a thinner heating wire and thus results in somewhat more compact sleeve geometry. Furthermore, a bifilar sleeve structure permits the utilization of the welding devices which are available on the market and whose powers are currently limited by the stipulation of the maximum permissible voltages on the building site (48 V). This complex of subjects is becoming ever more important with an increasing sleeve diameter since the necessary welding energies are rising substantially.

For the investigations into the temperature propagation (between two heater spirals and from the heater spiral into the cold zone) during the welding operation, photographs were taken with an infrared thermal imaging camera (Flir Systems Inc.) over a longer time (up to 600 s) at various heater spiral distances. Longer welding tests (> 600 s) were not possible because of the one-sided energy dissipation and the extreme development of smoke during this operation. On the basis of the welding tests and the temperature propagation extrapolations to longer welding times (up to 3,000 s), an optimum heater spiral distance of approx. 10 mm was established for the utilized wire. After the stipulation of the slight profiling of the outside contour of the sleeve and taking account not only of the properties of a suitable heating wire but also of the performed mechanical tensile shear tests (for the verification of the welding zone length determined computationally beforehand), the geometry was defined for the whole sleeve (overall length: 580 mm, welding zone length: 150 mm, wall thickness: 115 mm).

3. Production technique

Within the framework of this cooperation project, more detailed investigations were conducted into the usability of various production techniques. In this respect, the winding technique exhibited enormous advantages over the conventional extrusion technique, particularly with regard to the fabrication of small quantities. One of the advantages of the winding technique is the possibility of incorporating an additional heating circuit into the pipe wall at any depth. This can be utilized for the production of an increase in volume (e.g. in order to close an annular gap) or as “preheating” before the actual welding operation.

The residual stresses and the homogeneity of the produced sleeves were determined in addition to the mechanical properties. Less frequent destruction of the melt strip was achieved by adjusting and optimizing the process parameters. This leads to an optimized stress distribution condition in the sleeve and improves the geometrical properties. A closer consideration of the welding parameters of smaller sleeves and of those strength properties of the welded joints which were established by means of mechanical tests revealed a connection which was confirmed by checking welded joints with larger diameters (DA 560 and DA 630). Moreover, it was possible to derive a correlation...
between the energy input into the sleeve, the welding volume and the mechanical properties.

4. Welding parameters

Suitable parameters had to be developed for the stipulated sleeve geometry. For this purpose, extremely simplified assumptions were made on the basis of many variable and associated dependences. During the calculation of the parameters, the time-dependent energy and temperature were also taken into consideration as core variables.

The welding time results from the time dependent power and the energy which the welding device releases into the sleeve during the welding. Due to the voltage available on the building site (approx. 40 V), the energy to be input can only be varied via the resistance of the sleeve. The maximum initial power of the welding device should be exploited in order to keep the welding time as short as possible. However, since the temperature of the heater spiral is directly linked with the power (via the rising resistance at an elevated temperature) and PE-HD begins to decompose at a temperature as from approx. 250°C in an oxygen environment, this initial power must not be chosen at an excessive value.

Because of the electrical properties, just a few metals are feasible for the selection of the heating wire. A good price/performance ratio is provided by copper. Purely theoretically, constantan could also be considered since this material exhibits the preferred property of a constant resistance over the temperature but the transferable powers (in the case of a given wire cross-section) are too low in this respect because of the very high resistivity. For the selection of the wire geometry, consideration was given to the initial power of the welding device, to the welding time and to the total resistance of the heating circuit. In the case of a copper wire (D = 1.6 mm), the given geometry of the sleeve results in a resistance of 0.41 Ohm (at an initial power of approx. 4.8 kW with a maximum welding device power of 5 kW). Taking account of the relatively high temperature coefficient of the electrical resistance of copper, it is necessary to extend the welding time. Therefore, the resulting total welding time is around 42 minutes.

Moreover, the temperature development of the heater spiral depends on the axial position in the sleeve. In the preliminary tests, it was thus possible to establish approx. 20°C higher temperatures in the centre of the welding zone than in the peripheral regions of the sleeve.

A mean time-dependent power can be calculated by considering the energy as the surface integration of the power over the time as a core variable. With the mean power, it was subsequently possible to calculate the "welding time" parameter.

A mean power of approx. 3,200 W thus results in a welding time of about 45 minutes for a 1,000 mm sleeve.

By installing customary plug-in connections and creating a bar code, it was possible to weld the sleeves with commercially available welding devices.

5. Mechanical testing

Several sleeves were welded with the newly developed welding parameters and the parameters were subsequently verified by means of mechanical tests. Fig. 6 shows the corresponding strengths and examples of fracture patterns of the welded joints.
So-called welding factors can be calculated by comparing the results of the tensile tests on welded specimens with those of the unwelded material. In this respect, the attained short-time tensile program welding factors were in the range between 0.90 and 0.94. The ductile fracture behavior of the individual test specimens suggested a high-quality joint. The subsequent measurements of the oxidation induction time (OIT) in the welding zone suggested a very low reduction in the stabilizers. This also supplies an indication of the optimally developed welding parameters.

Not only the welded joints on the 400 mm sleeves but also those on the 560 mm sleeve achieved nearly the same strength as that of the base material. This suggests that, during the welding operation, the material has not been damaged and both good and durable joints were produced with the aid of the new parameters.

The checking of the welding zone geometry in the case of 400 mm, 560 mm and 630 mm joints implied a correlation between the input energy and the mechanical properties (with gentle energy input). The evaluation of the data confirmed that the welding zone geometry and the mechanical properties of the joints in the given conditions such as the wire diameter, the distance between the heater spirals, the welding voltage, the input energy and the duration of the welding operation can be predicted successfully with the aid of a mathematical calculation.

6. Internal-pressure creep test

A 1,000 mm joint was manufactured for the internal-pressure creep test. The pipes were closed at the ends with a welding neck and with the aid of a loose/blind flange joint.

After the preconditioning lasting 24 hours, an internal-pressure creep test according to DIN EN 12201-3 was carried out with the following testing conditions:

- Time: 100 h
- Temperature: 20 °C
- Circumferential stress: 12.4 MPa
- Testing pressure: 24.8 bar

The internal-pressure creep test was carried out successfully and the requirements which DIN EN 12201-3 sets on a joint executed by means of sleeve welding with an incorporated heating element were satisfied.

The internal-pressure creep test confirmed the optimized welding parameters for a joint executed by means of sleeve welding with an incorporated heating element for pipes with an outside diameter of 1,000 mm. A development tool for the calculation of the welding parameters was programmed on the basis of the calculated and subsequently verified parameters. With this programmed development tool, it was possible to develop and, in part, check the welding parameters for pipe diameters in the range from 400 mm to 2,500 mm. However, it is beyond question that the devices for sleeve welding with an incorporated heating element which are available today do not have enough power in order to weld pipe joints in the range of 1,600 mm in a monofilar or bifilar execution. The required powers cannot be achieved in justifiable time windows in operation on the building site with the currently applicable restriction of 48 V.

7. Assessment of the results

Within the framework of this project, parameters for sleeve welding with an incorporated heating element were successfully developed and checked for pipe systems with large...
diameters. With the aid of a mathematical tool based on several extrapolations, the corresponding parameters can also be adjusted to the pipe diameters to be welded (up to an outside diameter of 2,500 mm).

However, the testing or verification of the quality of such joints (e.g. by means of internal-pressure creep tests) was only possible up to an outside diameter of 1,000 mm for technical reasons.

In particular, this research paper dealt with the energy utilization (main influencing factor when the parameters were developed) during the welding operation. In the course of the project, the ovalities of the pipes and of the sleeves have, in any case, turned out to be disturbing factors (to an increasing extent with a rising diameter) with regard to the welds. However, problems relating to the processing of large-diameter pipes could primarily be attributed to shape deviations (ovality and flattening phenomena). Storage and transport influences may cause these deviations from the ideal round shape of the pipe, above all with regard to the dead weight or linear loads as support reactions. Thus, the out-of-roundness of the pipes cannot be avoided in principle and the sleeves must therefore exhibit a corresponding design against shape deviation. For example, a preheating technique might be used in order to improve the fit-up condition in the case of sleeve components and the gap bridging during the welding operation. Alternatively, it is also possible to utilize various clamping elements for the reduction of the arising gaps.

Individual variable factors become more significant in the case of the preheating technique. For example, the interval between the preheating and the beginning of the welding also plays a significant role in this respect. The wire temperature reached during the preheating drops exponentially so that the period (X in figure 12) between the preheating and the welding must be complied with very precisely for reproducible results. It is conceivable that this interval must already be incorporated into the welding operation (integrated into the bar code) as a fixed parameter so that any possible defects on the building site can be avoided.

A closer consideration of the electrical power which must be input by the welding device made it possible to establish that, in the case of the 1,000 mm sleeve, the power limit of the customary welding devices with 230 V AC / 16 A and 3,600 W is exceeded. A special heavy current version of the welding device with 400 V AC / 16 A can, with a duty cycle of 75 % of the full load, provide the 4,800 W demanded per welding circuit in the case of a 1,000 mm sleeve. That is the upper limit of the commercially available welding devices at present.

A reduction in the power required by the sleeve for the adjustment to standard devices entails an undesirable longer welding time (energy = power x time) and a lower temperature in the weld. The latter may lead to a drop in the welding quality in the joining zone. A certain temperature in the welding zone was defined from the investigations in order to obtain a reproducible and optimum welding quality. If this temperature is not reached or the time-related temperature course alters because of the change in the power, this will necessitate additional investigations into the consequences of these changes.

The flow processes in the joining plane during the welding may lead to displacements of individual wires right up to contact with a "neighboring wire" which may lead to the premature termination of the welding operation. In order to tackle this problem, it is appropriate to utilize a coated wire with a temperature stable non-conductive coating.
At the moment, the mechanical quality of joints executed by means of sleeve welding with an incorporated heating element can be tested with the aid of the DVS 2203-4 technical code, Supplement 1 (tensile creep test), the DVS 2203-6 technical code (shear and peeling tests) and the DIN EN ISO 1167 standard (pipes, fittings and component combinations made of thermoplastics for the transport of liquids - determination of the resistance to internal overpressure). In any case, the tensile creep test (DVS 2203-1, Supplement 2) is, for technical reasons, suitable for large-diameter pipes to a limited extent only. Relatively small areas of the weld are considered during this test procedure. Furthermore, shrinkage cavities and air inclusions in the weld are unavoidable with larger dimensions. Therefore, even a statistical scope of six test specimens does not always reflect the real mechanical properties of the overall joint.

The costs incurred during the execution of the internal-pressure creep test play a very great role since all the other tests must be postponed due to the occupation of a complete testing basin (e.g. with 1.5 x 1.5 m) by one weld and the closing caps for pipes with an outside diameter of 1,000 mm are associated with a scope of investment of approx. €40,000.

Expression of thanks

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Fig. 1: Integration of an adapter in the sleeve welding process with an incorporated heating element.

Fig. 2: Extrapolation of the geometrical data of the sleeves.

Fig. 3: Temperature profile for a heater spiral distance of approx. 9 mm, up to 300 s.
Fig. 4: Wrapping of the preheating circuit

Fig. 5: Connection between the power, the total resistance and the welding time of a 1,000 mm sleeve depending on the wire diameter
Fig. 6: Temperature course in the weld (T1 and T4: heater spiral in an axial position on the outside, T2 and T3: heater spiral in an axial position in the centre) during and after the welding.

Fig. 7: Course of the power over the welding time during one welding operation.
Fig. 8: Bifilar execution of a sleeve

Fig. 9: Tensile strengths on the welded test specimens and the corresponding fracture patterns
Fig. 10: Welding of a 1,000 mm sleeve

Fig. 11: Clamping element
Fig. 12: Principle of the temperature course between preheating and cooling for a joint executed by means of sleeve welding with an incorporated heating element.