Welding of crosslinked polyethylene pipes

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SUMMARY
The butt-welding of pipes made of crosslinked polyethylene, the most efficient joining method for the material PE-X, which up to now has been regarded an 'non-weldable', will enable it to be used for industrial and underground pipes and hence will make a major contribution to state-of-the-art and future-orientated pipeline applications.

In the future, it should also be possible to weld PE-X pipes with diameters of less than 90 mm and work is also being performed to develop welded joints with the same temperature resistance as the pipes. This will permit the use of welded PE-X pipes for hot-water systems and heating technology.

1. INTRODUCTION
Since the 60s, HDPE pipes have occupied a dominant position in Germany's gas and water supply industries. Polyethylene pipes (HDPE pipes) are characterised by their excellent properties. They are flexible, elastic, corrosion-proof, electrically insulating and easy to weld. However, due to their susceptibility to notching and abrasion, they have to be laid in stone-free soils and sometimes sand-filling is necessary. Frequently, it is not economically viable to lay the pipes without trenches or to perform relining by inserting the pipes into existing worn-out pipelines. These requirements determine the costs of pipeline construction. Crosslinked polyethylene pipes (PE-X pipes) have superior properties to PE pipes; they are resistant to abrasive solids and media, they have good long-term resistance, a low coefficient of friction and are not susceptible to stress crack formation or to rapid crack propagation. Their higher wear resistance means PE-X pipes may be used effectively in the public sector for gas, water and sewage pipes and cable ducts. Their notch resistance means there is no need for laborious and expensive sand bedding courses and also permits trenchless pipe laying with deep ploughing. They may also be used advantageously for the relining of drinking water and sewage pipes made of steel or concrete by inserting a flexible and scratchproof PE-X pipe. This leads to significant savings as a result of the simplification of the laying technology and the possible reduction of the pipe wall thickness due to the higher strength of the PE-X. PE-X would be the ideal pipe material if its very poor weldability did not impose restrictions on its use due to the limited joining technology. Traditional pipe welding methods fail due to the material's thermoelastic properties.

There are several methods for the crosslinking of polyethylene, with peroxide crosslinking and radiation crosslinking predominating. Crosslinked PE pipes have been produced for about 25 years and the problem of how to join them has been with us ever since then. The first successes with the use of PE-X pipes were achieved in the fields of underfloor heating and underpitch heating in football stadiums. However, over the decades PE-X pipes have become established in building installation practice for sanitary pipes and radiator connections. With the development of larger dimensions it was hoped to open up further areas such as district heating and other industrial applications and also underground pipeline construction, but these attempts always failed when it came to the joining of the pipes, as the connecting elements, the mechanical connectors and electro-welding sleeves represent a significant cost factor.

The current position is that welded joints between PE-X and PE-X are not possible. The Plastics Centre in Leipzig has therefore set itself the task of developing welded joints to permit the use of PE-X pipes in pipeline construction.
2. STATUS AND COMPARISON OF THE JOINING TECHNOLOGY USED FOR NORMAL AND CROSSLINKED PE PIPES

2.1 Welding method for HDPE pipes

Heating element butt welding joins pipes and pipeline fittings without additional components or foreign material and produces friction-locked connections. The pipes and pipe components are secured in guide and clamping devices, planed with parallel faces, heated by a heating element and welded after the joining of the pipe ends (Fig. 1). The machines currently used for the butt welding of heating elements have to conform to directive DVS 2208 Part 1. This directive specifies deviations and temperature tolerances. In some modern machines, the welding process is virtually automatically controlled (CNC) and fully documented so that manual work is kept to a minimum and the possibility of errors reduced. In pipe trenches, this procedure is only practicable from a pipe diameter of 90 mm.

In the case of electro-sleeve welding, pipes and pipe fittings are connected not directly, but by a welded sleeve with an integrated heater coil made of a resistance wire. A control device supplies the heater coil with a specific current pulse, determined by the diameter and type of sleeve, which welds the sleeve with the pipe (Fig. 2).

The contact pressure required for the welding is achieved by using the principle of the volume increase of the PE melt due to a temperature increase. At the same time, the pipe exterior and the sleeve interior to be welded together are melted. The application starts with the smallest diameter of 20 mm and finishes (at present) with a dimension of 630 mm. The connection cable permits the flexible use of the heater coil welding system in pipes trenches and in fixed positions.

2.2 Joining process for PE-X pipes

At present, PE-X pipes are joined by means of mechanical squeezing or sliding sleeve fittings made of brass. These joints with fittings are costly in terms of material and labour and they also represent material-induced faults in the properties of the crosslinked polyethylene. They are primarily used for compressed air systems, heating water pipes and industrial installations. As the gas and water industries have a general interest in the use of PE-X pipes, the DVGW (German Association for Gas and Water Fitters) has established a project to examine possible joining methods and assess their reliability, which will build on the results of previous studies.

Originally, it was assumed that PE-X could not be welded. Then, literature searches and investigations performed by a Dutch Institute, the DVGW and a German pipe manufacturer revealed that it was possible to weld crosslinked polyethylene to non-crosslinked polyethylene. They produced a theory for the binding mechanism which was primarily based on the possibility of the crystallisation of chains on both sides of the welded seam (co-crystallisation) in the molecular plane. The preconditions for this are an adequate pressure build-up and an adequate melt flow index. It was established that PE-X cannot be welded to PE-X, although it may be welded to HDPE. Heating element welds achieve a welding factor of \( a = 0.41 \).

However, these PE-X/HDPE pipe joints are of no economic significance. The fact that there is a welded joint between PE-X and HDPE is demonstrated by the successful use of electro-welding sleeves to join PE-X pipes. During the welding process, the HDPE is melted, while the PE-X only becomes rubbery. Strength studies have found this joint to be suitable for the gas and water supply industry. There are some PE-X gas lines in operation.

Fig. 1  Principle of heating element butting welding

Fig. 2  Principle of electro-sleeve welding
3. NEW WELDING TECHNIQUE FOR PE-X PIPES

3.1 High-temperature heating element welding

One innovative solution for the welding for PE-X pipes is a variant of heating element welding known as high-temperature welding. This has been used for about 15 to 20 years in automated series welding, for example for car parts, and is completely unknown in the field of manual welding. The procedure is similar to that used for traditional heating element welding, but the contact areas are plasticised at heating element temperatures of >350°C and with much shorter heating times by contact with the bright metallic heating element. Only thermoplastic materials whose thermal decomposition products are liquid or gaseous at higher temperature (e.g. polyolefins, polyamides, etc.) may be welded. For example, normal PE produces a very low-viscosity melt, whose sometimes thermally damaged components are pressed out of the seam during the joining process. This process was used as the basic variant for the welding of PE-X. In the case of crosslinked polyethylene, after the thermal decomposition of the material, a plasticising zone with a very complex layer structure from a steam phase to a integral thermal melt layer forms at the high temperature heating element. Within this zone decomposition of the crosslinking occurs right up to the degradation of molecule. Reactive thermoplastic melt components also form within this local area and under pressure, these form a welded joint.

3.2 Increasing the contact area and mixing effects due to profile heating elements

With heating element welding, surface-dependent bonding forces occur. Increasing the contact area also increases the number of bonding forces. Profile heating elements, which significantly increase the weld's contact area, cause a cyclic shear of the melt in the weld area. This causes a mechanical mixing effect. The heating element's profile teeth melt into the pipe faces so that when the pipes are fused the teeth and spaces mesh together (Figs. 3 and 4).

With heating element butt welding with flat heating elements, depending upon their viscosity, the melts flow in a velocity profile running vertically from the contact area into the material (Fig. 5). Even in the macroscopic range, the sharp parting line in the joining plane does not indicate any turbulence in the zone of the highest flow rates. This phenomenon occurs if elastic deformation oscillations of the particles occur in elastic-viscous liquids. If these oscillations are so great that they cannot be attenuated during the course of the flow, the laminar flow changes to an 'elastic-turbulent' flow. A 'sliding-adherent' phenomenon occurs which is determined by the degree of the shear stress $\tau$ and which encourages the thorough mixing of the material in the weld zone.

These findings were used for PE-X and further developed to enable selective higher shear to be used to achieve thorough mixing of the material and hence high strength in the profiled joining zone. In the profiled joining zone, the melt is forced to flow in the resulting flow directions and force

Fig. 3 Principle of contact surface enlargement by profile heating elements

Fig. 4 Principle of contact surface enlargement and the mechanical mixing effect

Fig. 5 Flow processes with heating element butt welding with flat heating element (principle)
directions along the molten profile flanks. This produces a higher relative speed and shear of the counterflowing melts (Fig. 5). At the moment of contact, the melt interfaces first remain adhering to each other and then, under the action of opposing weld component movements and the weld pressure, shearing occurs in the large melt areas. A mixed zone with no visible joining area forms.

3.3 High-temperate welding of PE-X pipes

The process of the melting of the pipe faces into the profiled heating element surface also changes the flow diagram for standard heating-element butt welding (Fig. 6). As with traditional heating element butt welding, the pipe faces are peeled so that they fit each other snugly in a plane parallel configuration. This is followed by the melting of the pipe faces. When the crosslinked polyethylene is heated at the high-temperature heating element, thermal decomposition into gaseous or steam material phases takes place at the interface, followed directly by a narrow integral melt layer going from low-viscosity to high viscosity. Behind this, a wide zone forms in the viscoelastic area. A welded joint is only formed with the material in the integral melt layer in which the crosslinking was thermally broken up. When welding with a profiled heating element, this means that in the melting and heating phases of the profiled heating element, a viscoelastic tooth profile coated with a thin melt layer forms at the pipe face. During the welding process, the profile is slightly deformed, but the enlarged joining surface is stabilised. Due to the relative movement, the flow movements of the melt and its shear take place in a very narrow layer only. This means that an enlargement of the bonding surface is guaranteed and the actual joining zone is spatially distributed. This means that a profile weld seam is always a guarantee of the welded seam quality.

The welded seam region is not crosslinked polyethylene, but thermoplastic. This means that standard welding factors according to the DVS 2203 Parts 2 and 4 cannot be determined, as the basic material and weld material are different materials which cannot be compared with each other. Therefore, criteria to evaluate the long-term properties need to be developed by a higher-ranking, central body, the DVS (German Welding Association). Therefore, the test parameters for crosslinked pipes defined in DIN 16 892 should not and cannot be used as a basis for long-term failure tests under internal hydrostatic pressure.

For this reason, the test for normal HDPE pipes was used for the intended application as underground gas and water pipes.

4. PRACTICAL IMPLEMENTATION OF THE PROCEDURE AND OUTLOOK

The research performed by the Plastics Centre in Leipzig into the welding of PE-X pipes has not yet been completed. For small pipe diameters of up to 90 mm, a high-temperature heating-tool sleeve welding procedure and an alternative procedure were developed which are more efficient than welding with electro-sleeves. In addition, the Plastics Centre is also working on the development of a welding technique which guarantees the full temperature resistance of the PE-X pipes for the weld as well.

The first practical application of heating element butt welding took place in September 1999 in the Leipzig public utilities and involved the laying of an underground test line (low-pressure gas line, 100 x 10 mm) in Leipzig with approximately 1000 welded joints applied using the first series welding machine for heated-tool butt welding, the WIDOS 4600 NC/PE-X. The low-pressure gas line laid by Leipzig public utilities was put into operation after a pressure test. A full inspection is performed each month with gas testing equipment. According to a joint decision, the pipeline was laid outside a residential area under a minor road with no through traffic and no heavy traffic.

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