

10 Welding of HDPE Geomembranes

10.1 Welding Machines, Devices and Weld Seams

HDPE geomembranes are manufactured from a nonpolar thermoplastic polymer which is chemically very stable but forms a melt above 140 °C, and so can be extruded at approximately 200 °C. Therefore in practice, HDPE geomembranes cannot be glued by chemical processes and welding by a thermal process is the jointing technology of choice.

The *Plastics Handbook* (Saechtling et al. 1998) defines welding of thermoplastic polymers as “connecting ... with the use of heat and pressure and with or without the use of aid materials. The surface is heated to a temperature above melting point and joined under pressure in such a way that a connection as uniform as possible develops”. The welding process therefore consists of a thermal process (melting of the material, the technical literature often speaks of plasticising the material) and a rheological process (melt flow and mixing of the melted material areas). It is beyond the scope of this book to deal with the “mixing” of polymeric materials, i.e. the behaviour of polymer-polymer interfaces and their dissolution by molecular interdiffusion in detail (Potente 1977; Wool et al. 1989). However, for the following it is important only that the thermal process is triggered and controlled by a heat supply and the rheological process of the melt flow by the application of an external force. The two processes can occur simultaneously or proceed consecutively depending on the way the welding process is performed in terms of process engineering.

In principle, different welding methods (extrusion fillet welding, extrusion flat welding, hot wedge welding and hot air welding) and corresponding types of seams (extrusion fillet seams, extrusion flat seams, hot wedge seams and hot air seams) are possible. Welding of large-area HDPE geomembranes is, however, predominantly carried out using hot wedge welding or extrusion fillet welding. Hot wedge welding usually produces two parallel seams with a channel between them, while extrusion fillet welding provides single extrusion fillet seams. In the following, these two procedures and the two relevant seam types will be dealt with in more detail.

The relevant guidelines of the German Society for Welding Technology and Associated Methods (Deutscher Verband für Schweißen und verwandte Verfahren e. V. (DVS), www.dvs-ev.de), which describes the state of the art of welding geomembranes in geotechnics in Germany, will be considered in detail. The operating conditions for welding machines and devices and the weld seams are described in the guidelines DVS 2225-3:1997 *Joining of Lining Membranes Made of Polymer Materials (Geomembranes) in Geotechnical and Hydraulic Applications – Requirements for Welding Machines and Welding Devices*, and DVS 2225-1:1991 *Joining of Lining Membranes Made of Polymer Materials (Geomembranes) in Geotechnical and Hydraulic Applications – Welding, Adhesive Bonding and Vulcanisation*. There is a special guideline available for the use of HDPE geomembranes for lining landfills and contaminated land: DVS 2225-4:1992 *Welding of Geomembranes from Polyethylene (PE) for Lining Landfills and contaminated Land*.

The EPA/600/2-88/052:1991-05 *Technical Guidance Document: Inspection Techniques for the Fabrication of Geomembrane Field Seams* of the US Environmental Protection Agency (US-EPA) describes in detail welding methods, machines and devices as well as weld seams for HDPE geomembranes (Landreth 1991). However, US American and German guidelines are not completely similar in all details. Comparable to the German DVS, in the United Kingdom, The Welting Institute (TWI, www.twi.co.uk), offers information and advice on welding of plastic geomembranes.

Hot wedge welding is carried out by a hot wedge (Fig. 10.1), which is heated to a temperature of 300–400 °C and is pulled between the overlapping lower and upper geomembranes. A system of guide rollers provides a complete surface contact between geomembrane and the two separate tracks of the dual hot wedge. The surface layers of the geomembranes are melted and the two melt layers are pressed together by a squeeze roller system immediately behind the wedge. Figure 10.2 gives a schematic representation of the procedure. In the hot wedge welding machine¹ the three substantial functional elements are integrated into one basic unit: the heating system, i.e. the heatable wedge with its guide rollers, the pressure system, i.e. the squeeze roller and the pressure device, and the driver system, i.e. the drive rollers and the drive motor. The driver system ensures that the welding machine proceeds at a constant speed along the overlap joint and the two geomembranes are continuously welded. Usually the squeeze roll-

¹ The equipment is called welding machine if it is self-propelled and the pressure is produced by the machine. It is called a welding device or apparatus, if it is moved by hand and the pressure results from the welder's muscular force.

ers have a knurled surface and serve as drive rollers as well. Figure 10.3 shows a commercial hot wedge welding machine.

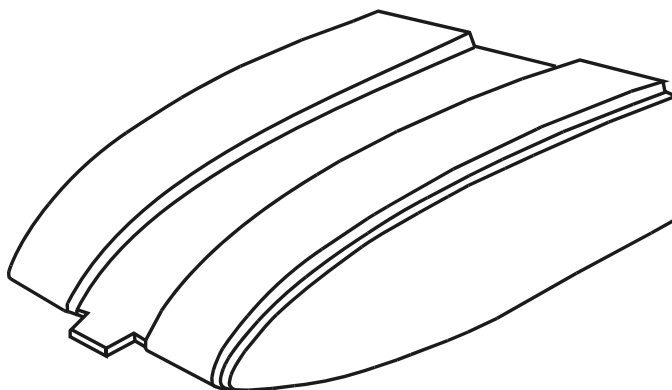


Fig. 10.1. Sketch of a hot wedge. The two tracks, which glide along the geomembrane surface and heat up a stripe of material, can be recognised. The geomembrane surfaces are united by the wedge-shaped arrangement and pressed together by the squeeze rollers immediately behind the wedge nose. The groove between the tracks results in a test channel between the seams. The nipple is to prevent the welding bead or squeeze-out, i.e. melt, which is squeezed out when the melted areas are pressed together, from clogging the test channel. Hot wedges are manufactured in different forms and lengths as well as with grooved or smooth tracks

The key welding parameters that determine the hot wedge welding process are connected with these three functional elements: hot wedge temperature and hot wedge track length, which determine how the geomembrane surface is melted by the hot wedge, the roller pressure which squeezes the melt layers together (more exactly: the force which is applied over the contact surface of the squeeze rollers) and finally the welding speed or seam velocity, which is adjusted with the driver system so determining the contact time of the geomembranes on the hot wedge and under pressure. When the squeeze roller system simultaneously serves as driver system, it is assumed that the permissible pressure necessary for the welding is always larger than the pressure necessary for advance and transport. This is usually, but not necessarily always, the case. One has to consider the case of a heavy machine, which has to weld up a steep slope.

Hot wedge temperature, roller force and welding speed, as process engineering welding parameters, must allow the independent regulation and adjustment to the nominal value. The hot wedge track length is a given machine constant. The actual roller pressure induced by a certain force is machine dependent, too. The hot wedge welding process itself and the

choice of the welding parameters necessary for a high seam quality will be dealt with in detail in Sect. 10.3.

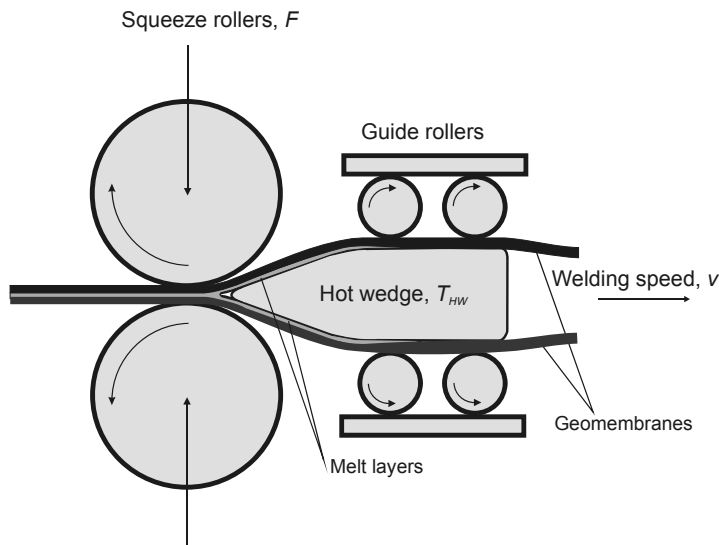


Fig. 10.2. Schematic diagram of a hot wedge welding machine with the three substantial functional elements: hot wedge (hot wedge temperature T_{HW}) with guide rollers and squeeze rollers (roller force F), which serve here simultaneously as driving rollers (Gehde 1999) (see also Fig. 4 in DVS 2225-1). The welding machine travels at a welding speed v (in the picture to the right) on its travel rollers pushed by the squeeze rollers. If the subgrade of the geomembrane is too soft, the travel roller may “bulldoze” into the ground. In this case a base has to be provided, e.g. a “drag strip” (from a piece of geomembrane), which is pulled along step by step

In dual hot wedge welding the wedge (Fig. 10.1) and the squeeze roller system are built in such a way that in the overlap, two seams, called front and rear seam or first and second seam, are produced separated by a small gap, the so-called test channel, which is used for the non-destructive testing of the tightness of the seam (Fig. 10.4). This weld seam is called dual hot wedge seam or hot wedge seam with air channel. The shape of the seam must meet certain geometrical requirements. Figure 10.4 shows the requirements in accordance with DVS 2225-4 for a hot wedge seam with air channel on 2.5 mm thick HDPE geomembranes, used in Germany for lining of landfills and contaminated land. Of special importance for the assessment of seam quality is the so-called thickness reduction due to joining s_r defined as:

$$s_r = (d_t + d_b) - d_s . \quad (10.1)$$

The symbols are explained in Fig. 10.4. The importance of this quantity will be dealt with in more detail in the section after next.

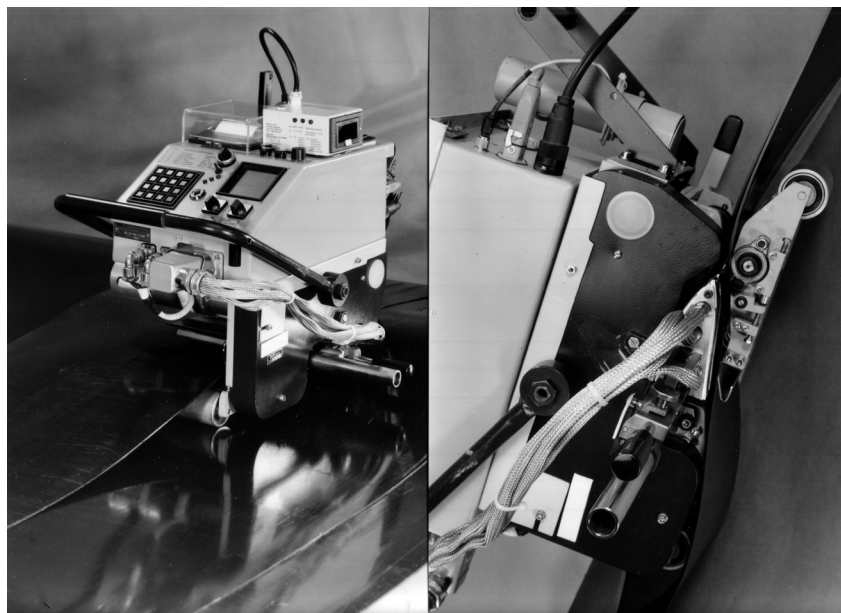


Fig. 10.3. Photographs of a hot wedge welding machine. Compact, electronically controlled machines with display, control desk and data logger are offered by several manufacturers. On the right, the travel rollers are seen underneath and on the lower geomembrane as well as the hot wedge over which the two geomembranes are guided

Today robust and easy-to-use hot wedge welding machines are available which fulfil the high technical requirements. Impairment by mechanical influences during operation and transport, and by dirt and moisture cannot be avoided on civil and hydraulic engineering construction sites. The machines must function faultlessly under these conditions. The conclusion is that the electrical and electronic components particularly must be protected against corrosion and contamination and that the functional elements, in particular the hot wedge, must be easily accessible, easy to clean and maintain under these conditions. The basic frame must be light and easy to handle. On the other hand, it must be so stable and torsion-resistant that the forces developed when applying the pressure can be absorbed with little deformation. The mechanics of the guide rollers, the pressure element and

the hot wedge must allow a limited mobility, so that the hot wedge has proper access to the surfaces of the geomembranes under operating conditions.

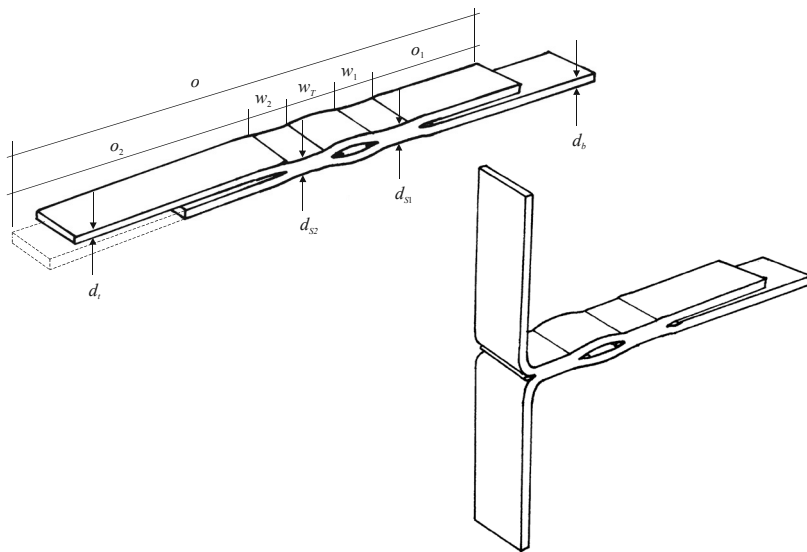


Fig. 10.4. Dual hot wedge seam with test channel: schematic view of the test specimen for the tensile test (top left), cut from a sample, which is taken from the weld seam. The upper geomembrane extends to the left, the lower to the right. The rear overlap shortened for the tensile shear test is indicated with dotted lines. The dimensions, characteristic for this seam shape, are indicated: d_t (thickness of the top geomembrane), d_b (thickness of the bottom geomembrane), d_{S1} , d_{S2} (thickness of the front and rear seam), w_{S1} , w_{S2} (width of the front and rear seam), w_T (width of the test channel), o_1 and o_2 (overlap in front and in the back). According to DVS 2225-4 the following requirements apply to dual hot wedge seams of HDPE geomembranes for landfill lining: d_t and $d_b \geq 2.5$ mm, $5 \text{ mm} \leq o_1 \leq 15$ mm, $o_2 \geq 40$ mm, w_{S1} and $w_{S2} \geq 15$ mm, as well as $w_T \geq 10$ mm. Further, requirements are made on the seam thickness (and thickness reduction), see text. DVS 2226-2 stipulates the following dimensions for the test specimen for tensile shear test: width ≥ 15 mm and at least 5 times geomembrane thickness, gauge length (clamp distance) = $100 \text{ mm} + \text{seam width}$. Overall length $\geq \text{gauge length} + 50$ mm. Bottom right: schematic view of the test specimen as inserted in the short-term or long-term peel test device. Its dimensions in accordance with DVS 2226-3: width ≥ 15 mm and at least 5 times geomembrane thickness, length of the two legs = at least 10 times geomembrane thickness in each case, gauge length = 40 times geomembrane thickness, overall length $\geq \text{clamping length} + 50$ mm. The squeeze-out, which forms at the seam edges, is indicated

Some of the current requirements of DVS 2225-4 on the operation and control of the functional elements are set out here. The hot wedge temperature must allow a continuous temperature adjustment up to 400 °C and regulated to between ± 5 °C. The temperature measured on the surface of the hot wedge point near the place where the geomembrane leaves the hot wedge can be used as a control parameter. The roller force must allow it to be regulated with a maximum tolerance of ± 100 N. With sudden changes in geomembrane thickness, such as at T-junctions, the roller pressure usually exceeds the permissible tolerance. The guideline requires that this excess does not exceed 30 % of the adjusted value. The pressure system must apply the roller pressure evenly on front and rear seams. Permissible difference in thickness reduction s_r of the two seams may not exceed 0.1 mm. Welding speed must allow adjustment and regulation with an accuracy of ± 5 cm/min.

Modern machines regulate the welding parameters (hot wedge temperature, roller force and welding speed) to the adjusted nominal values, indicate the actual values on a display, announce inadmissible deviations with an audio signal and print an error log. They are additionally equipped with data acquisition, which stores the welding parameter values electronically at regular intervals (e.g. every 2.5 cm seam length). The data can be read out after welding the seam, graphically represented on a laptop and analysed. Ranges of abrupt thickness changes are indicated where the roller force ran out of the permissible parameter window. Such places can be more thoroughly looked at, evaluated and examined if necessary. Apart from the welding parameters, surface temperature of the geomembrane and air humidity should be included in the data acquisition. Using such an automatic welding machine is often referred to as “smart welding”.

Using hot wedge welding, geomembranes can be welded by the machine continuously over large seam lengths. Seams can be produced which have been welded with welding parameters clearly specified in terms of process engineering and regulated to the required nominal value. The dual seam provides additional safety. The tightness can be evaluated non-destructively using the test channel over a large seam length. Therefore, as far as technically possible, the geomembrane should be welded using this welding method. There are however difficult-to-access weld areas, connections to buildings and penetration systems, repairs and rework, which cannot be machine-welded. In such cases extrusion fillet welding using an extruding fillet welding device should be selected as the joining technology (Struve 1990).

In extrusion fillet welding of geomembranes a melt strand (extrudate) of the same or very similar HDPE resin material as the geomembrane is ap-

plied along the edge of the overlap (Fig. 10.5). The extruded material strand has to be merged with both geomembranes. Therefore the geomembrane surface is heated by hot air directly before applying the strand. Heat transfer between the strand and the unprepared surface of the geomembrane is, however, poor. Therefore the range, which has to be over-welded, must be additionally prepared. Seam preparation requires special attention with the extrusion fillet welding. A thin layer of wax, which can form from low-molecular polyethylene molecules diffusing to the surface of the geomembrane and any oxidation layer must be ground off, the leading edge of the upper geomembrane must be tapered to a 45° bevel and the two geomembranes must be tacked using simple portable hot air welding devices so that an overlap develops with a rigid fixed contact. Small hand held electric rotary grinders and sufficiently fine sandpaper are used for surface preparation. When tapering the edge of the upper geomembrane, the welding zone of the lower geomembrane must not be damaged by deep scoring or grooving. The end result must be an even, finely grained surface, with the grinding marks running predominantly perpendicularly to the seam. All of the material ground off must be wiped or blown away from the welding zone. The worked welding zone must later be completely covered with the extrudate. Careful attention must be paid not only to the surface properties of the worked welding zone, but also its width. Seam preparation in extrusion fillet welding is thus laborious and lengthy and requires patience and manual skill. This is one of the reasons why hot wedge machine welding should be used as far as technically possible.

The extrudate used with extrusion fillet welding should consist of the same resin as that of the geomembrane to be welded, or at least of an HDPE material with very similar flow properties². A seam of sufficient quality to meet the required standards can only be reached under such conditions. In accordance with DVS 2207:1995-08 *Welding of Thermoplastics – Heated Tool Welding of Pipes, Pipeline Components and Sheets Made of PE-HD* the rule applies that HDPE resins with a melt mass-flow rate (MFR 190/5, see Sect. 3.2.4) within the range between 0.3 and 1.7 g/10min may be welded with each other. In the outdated standard DIN 16776-1:1984 *Polyethylene and Ethylene Copolymer Thermoplastics; Classification and Designation* the resins had been classified according to melt flow rate classes defined in Table 3.4. The above-mentioned range covers half of the melt mass-flow rate class T003 and, in addition, the melt mass-flow rate classes T006 and T012 and then a small part of the melt mass-flow rate class T022. This rule was slightly extended for HDPE geomembranes so that geomembranes themselves and geomembrane and ex-

² Of course, stress crack resistance and oxidation stability must be comparable too.

trudate can be welded if they are in the same melt flow rate class, or if the resins belong to the neighbouring classes T006 and T012 (Müller 2001).

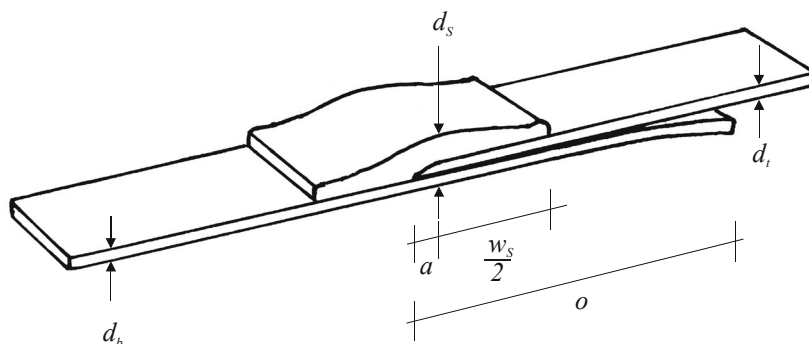


Fig. 10.5. Schematic view of a test specimen from an extrusion fillet seam. The top geomembrane extends to the right, the lower to the left. The dimensions characteristic for this weld shape are indicated: d_t (thickness of the top geomembrane), d_b (thickness of the bottom geomembrane), d_s (thickness of the seam), w_s (width of the seam), a (off-setting, disalignment), o (overlap). DVS 2225-4 stipulates the following requirements on extrusion fillet seams of HDPE geomembranes for landfill lining: d_t and $d_b \geq 2.5$ mm, $o \geq 40$ mm, $w_s \geq 30$ mm, $a \leq 5$ mm. Further requirements are made on the factor of seam thickness, see the text

The technical terms of delivery for extrudates are described in the DVS 2211:1979 *Filler Materials for Thermoplastics – Scope, Designation, Requirements and Tests*. If there is a deviation from the rule specified above, which is unnecessary with newly installed geomembranes but may especially occur when new geomembranes are joined to geomembranes already installed in a former construction section, then the guidelines demand that a suitability test is performed on a case-by-case basis. What a suitability test should consist of for an extrusion fillet seam or a dual hot wedge seam is so far, however, not clearly regulated. Most often, the results of short time tensile shear tests and short time peel tests are used to evaluate the seam. The assessment procedure described in Sect. 10.3, however, offers the possibility of performing a systematic quantitative evaluation of the seam quality for dual hot wedge seams and should therefore be used as suitability test.

The hand-held portable extrusion welding device or apparatus also consist of three functional elements: preheat system for the hot air, which is used to preheat the welding zone; the plasticising system with temperature control, a small extruder, in which the extrudate pellets or an extrudate rod are melted, homogenised and brought to a controlled mass temperature and from where the melt strand is discharged at a certain discharge speed

through the Teflon welding die which is the third functional element. Figure 10.6 shows a schematic of the device. The extrudate is smoothed, formed and transported to the weld area over the welding die. The die has two lateral support surfaces with which the device rests on the geomembrane.

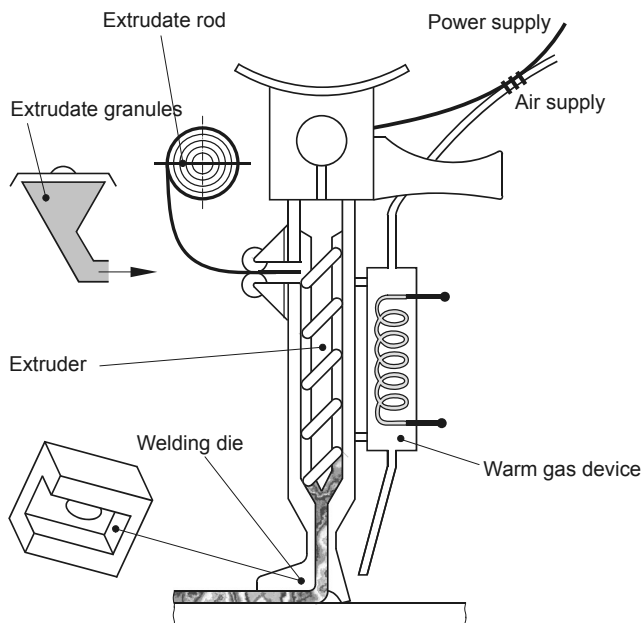


Fig. 10.6. Schematic view of extrusion welding equipment (the figure is based on Fig. 2 of DVS 2209-1). The resin of the extrudate is filled as granules or as a rod in a small extruder. The melt flows over a Teflon welding die. The Teflon welding die consists of a horseshoe-shaped skid (schematic diagram, view from below), which slides along the geomembrane. The extrudate is discharged between the legs and is advanced onto the geomembrane. Immediately before the front end of the Teflon welding die the geomembrane is warmed up by a hot air unit, which is connected to the mainframe

Extrusion welding produces a so-called extrusion fillet seam. Figure 10.5 shows the seam shape. Certain geometrical conditions are required of this seam shape as well. Figure 10.5 shows the dimensions of the extrusion fillet seam in accordance with DVS 2225-4 for minimum 2.5 mm thick HDPE geomembranes used in Germany for lining landfills and contaminated land. In addition to the actual dimensions, the so-called factor of seam thickness f_{SA} is used to assess seam quality:

$$f_{SA} = \frac{d_s}{d_t + d_b}. \quad (10.2)$$

The symbols are defined in Fig. 10.5. Subject to repeated discussion is the issue of whether or not beads may be squeezed out on the right and left under the support surfaces of the welding die. In this respect one should pay attention to two aspects: first, large squeeze-out are an indication that proper craftsmanship has not been applied, i.e. the lateral supports of the extrusion die were not directly seated on the geomembrane, the extrudate temperature was improper for adequate flow or the seaming velocity was too slow. Second, the squeeze-out may not under any circumstances have damaging consequences, such as obstructing vacuum testing or encouraging the whole seam to peel off when the squeeze-out is pulled up.

Not all welding parameters are defined exactly or regulated in terms of process engineering within extrusion welding procedure. In accordance with the guidelines the mass temperature of the extrudate must be regulated and controlled to $\pm 10^\circ\text{C}$ and the hot air temperature continuously adjusted to 350°C and regulated up to $\pm 20^\circ\text{C}$. However, the temperature of the hot air preheated geomembrane is not yet explicitly determined by adjusting these parameters. Welding pressure and welding speed depend on the capacity of the extruder, geometry of the Teflon welding die and the welder's skill. None of the process parameters are quantitatively recorded in current welding engineering practice. The quality of the extrusion fillet seam chiefly depends on the welder's experience, knowledge, manual skills and physical ability.

In those critical places of a geomembrane liner, such as penetration points and connections to structures in the deepest point of the liner system, extrusion fillet seams are often necessary. Therefore, the importance of a technically qualified and experienced installation contractor to produce seals of high quality with geomembranes can hardly be overestimated. On the other hand, thermoplastic geomembranes are the only sealing materials that enable the manufacture of a really watertight and homogenous seam without any bonding agent especially in such critical places.

10.2 Testing Seams

The dual hot wedge seams and extrusion fillet seams must be tested on the construction site. The construction-site tests are supplemented to a certain extent with tests under laboratory conditions. In the laboratory, long-term

tests on weld seams can be performed. Long-term tests are in principle aimed at investigating the influence of the welding process parameters on seam quality, long-term behaviour of the seams and welding properties of various resins.

Construction site tests are described in the guideline DVS 2225-2:1992 *Joining of Lining Membranes Made of Polymer Material in Geotechnical and Hydraulic Engineering, Site testing* and in the DVS 2225-4. The standard ASTM D4437-84 *Practice for Determining the Integrity of Field Seams Used in Joining Flexible Polymeric Sheet Geomembranes* also contains a brief overview. Pressurised-air testing and vacuum testing are also covered by ASTM standards: ASTM D5820-95 *Practice for Pressurized Air Channel Evaluation of Dual Seamed Geomembranes* and ASTM D5641-94 *Practice for Geomembrane Seam Evaluation by Vacuum Chamber*. The tests are to help adjust the process parameters by trial and error. (A systematic adjustment of the process parameters with regard to the optimum seam quality can be performed using the process model described below.) The tests mainly enable the determination of the quality of the seams with respect to specifications developed from field experience and non-destructive proof of its water tightness. The following seam properties are investigated: external appearance, the dimensions, strength and, of course, water tightness.

The external appearance is controlled by visual inspection. The naked eye of the examiner assesses whether the seam exhibits perfect craftsmanship. The assistance of a blunt instrument (e.g. a screwdriver) is needed, which is moved along the seam edge and some pressure applied. Even this simple, so called mechanical point stressing test may reveal individual defects or unbonded areas, in particular in the case of extrusion fillet seams. Usually, the instrument only leads the eye of the examiner. Only qualitative instructions can be given concerning the requirements of the visual inspection. The examiner must observe shape and appearance, central position and uniform boundary regions of the seam. He must evaluate the squeeze-out on the edge of dual hot wedge seams and extrusion fillet seams and the smooth and streak-free texture of the surface of the fillet seams and look for inadmissible notches and scoring from the preparation of the joining zones with extrusion fillet seams and of T-junctions and structured geomembranes with the hot wedge welding. Obviously, this test can only be performed by an experienced specialist with extensive training in welding technology, no matter if he acts for the in-house monitoring by the installation contractor or for third-party inspection by an independent body. When performing such an important, but only qualitatively described test, which is so crucial for extrusion fillet seams whose quality depends to a large extent on the welder's manual skills, all involved should

agree on the quality criteria for perfect welding zone preparation, for appearance and surface texture prior to the commencement of welding by inspecting a longer stripe of the test seams.

The dimensions of the seams are determined on specimens from test samples, which are usually taken at the beginning and end of the seam. The relevant dimensions are shown in Figs. 10.4 and 10.5. The width of the rear overlap should be at least 40 mm to allow easy handling in tensile tests, such as peel tests and tensile shear tests. For HDPE geomembranes used in landfills and for containment of contaminated land, there are minimum requirements on other dimensions in the DVS 2225-4 guideline. In addition to the actual dimensions, the previously mentioned reduction in thickness s_r (Eq. 10.1) for dual hot wedge seams and the factor of seam thickness f_{SA} (Eq. 10.2) for extrusion fillet seam are important parameters. There are defaults given in the guidelines. It holds for the thickness reduction:

$$0.2 \leq s_r \leq 0.8. \quad (10.3)$$

The factor of seam thickness for extrusion fillet seam must meet the following requirement:

$$1.25 \leq f_{SA} \leq 1.75. \quad (10.4)$$

In the case of extrusion fillet seams, off-setting of the centre of the seam from the edge of the upper geomembrane may not exceed 5 mm.

The dimensions and, to certain extent, homogeneity of the seam can be tested non-destructively using ultrasonic measurements. A small ultrasonic measuring head is placed on a clean, even part of the seam, impulses at an ultrasonic frequency of 4 to 6 MHz are sent through it and the delay time of the echoes from the back of the seam and the geomembrane, or a defect in the seam, is measured (pulse-echo testing). The thickness can be determined from the delay time of the geomembrane back echo. Coupling of the probe is made over water or special pastes. The test should not be started within one hour of welding the seam. On the construction site small hand devices are used which, after adjustment and calibration on planar reference plates, directly indicate the thickness. Such devices cannot only be used for random sampling but also for systematic measurement of the thickness reduction along the seam. Shorter echo delay times indicate defects in the seam. Enclosed dirt, pores and air gaps in the seam also generate ultrasonic echoes. Ultrasonic measurements can therefore indicate seam inhomogeneity. Welded areas, which are only superficially attached or not sufficiently melted, cannot be recognised.

The strength of the seam is tested in the peel test. The test is described in the guideline DVS 2226:1997-07 *Testing of Fusion on PE-Liner – Peel Testing* and in the Standard ASTM D6392-99 *Standard Test Method for Determining the Integrity of Nonreinforced Geomembrane Seams Produced Using Thermo-Fusion Methods*. It is now state of the art that peel tests can be carried out on the construction site with a tensile test device, which allows a peel test of the required constant test speed. Times are long forgotten when converted car jacks with a crank handle were used. However, the test has to be performed in the laboratory in strict accordance with the requirements of the guidelines or standards by the third party inspector as well. A minimum of 15 mm but usually a 20 mm broad strip is cut off transversely to the seam as a test specimen. Figure 10.4 shows the test specimen. The overlapping ends are unfolded and then clamped in such a way in a tensile test device that the joining plane or welded area, i.e. the imaginary plane in the centre of the seam, lies in the middle between the clamps. The specimen is pulled at a test speed of 50 mm/min and the deformation and failure behaviour is observed. The test result is the description of the deformation and failure behaviour, which is, however, only qualitatively assessed, and the quantitative evaluation of peel strength (maximum force at break) and peel separation (ratio of the area of separation to the original bonded area, both areas estimated by “visual approximation”).

Standards for peel testing are described in the above-mentioned guidelines DVS 2225-1 to 2225-4 and in the GRI Standard GM19 *Seam Strength and Related Properties of Thermally Bonded Polyolefin Geomembranes*. A weld seam between HDPE geomembranes has good seam strength, if it does not peel off and the basic material in the test strip strains and breaks outside the seam. With the dual hot wedge seam, straining and peel-off in the boundary region of the seam (i.e. peel separation) is still permissible by some regulations, if the residual width of the seam is larger than the minimum width required for the respective application, 15 mm according to DVS 2225-4 for instance, or if it is less than 10 % of the intended seam width. However, as was stated by I. Peggs: zero peel separation is regularly achieved by capable operators, therefore it should be recommended (Peggs 2005). When extrusion fillet seams are tested they can still be passed if the extrudate strains and tears in certain cases and the maximum tensile force reached is “within the order of magnitude” (DVS 2225-4) of the comparable maximum tensile force of the tensile shear test (see below) on the extrusion fillet seams. A seam (dual hot wedge seam or extrusion fillet seam) does not have undoubtedly sufficient strength when it either peels off or the test specimen breaks in the bound-

ary region or outside the seam in a brittle way without any clear elongation.

The peel test in accordance with DVS 2226-3 or other standards generally serves to test the jointing connections in polymeric material geomembranes. Seams of soft PVC geomembranes, ECB geomembranes and elastomer geomembranes, such as EPDM geomembranes³ are also tested using this test. Usually, these seams peel off. The medium force, which must be applied when peeling, related to the width of the test strip is called peel strength. The unit of this quantity is therefore N/mm. The seam strength exhibited when peeling seams is then assessed by the size of the peel strength. Although a perfect seam between HDPE geomembranes may not peel off, the DVS guideline defines the maximum tensile force related to the specimen width that can be measured, even when elongating and tearing of the test strip outside the seam, as peel strength. The DVS 2226-1:2000 *Testing of Fused Joints on Liners Made of Polymer Materials - Testing Procedure, Requirements* specifies a thickness-dependent minimum value for this “peel strength” for HDPE geomembranes: $15 \cdot d$ N/mm (d : value of thickness of the geomembrane measured in mm). For a 2.5 mm geomembrane one obtains 37.5 N/mm. Considerable lower values are specified in the GM19 standard for smooth and structured HDPE geomembranes, e.g. 26 N/mm for hot wedge seams of 2.5 mm geomembranes.

The use of the same term for two different fracture modes – namely peeling off a seam and elongating and tearing the test strip outside the seam – can easily lead to misunderstandings. The so-called “peel strength” for HDPE geomembranes should therefore be used very carefully. Since a clear elongation is required before the test strip tears, the maximum tensile force related to the initial cross section of the strip should be at least in the range of the yield stress, which formally corresponds to the required minimum value of the peel strength. On the other hand, it is doubtful whether one may compare the maximum tensile forces on specimens deformed by shear flow near or at the edge of the seam from different HDPE materials and with different seam geometry. The maximum tensile force in the tensile test with HDPE geomembranes is highly sensitive to the test specimen characteristics.

³ Soft PVC: polyvinyl chloride with low-molecular organic mixtures as softeners; ECB: ethylene copolymer bitumen; EPDM: terpolymer from polyethylene, polypropylene and dien-monomers. This terpolymer is a rubber, which can be interlaced with sulphur to an elastomer by the double bonds, brought in over the dien-monomers (vulcanisation).

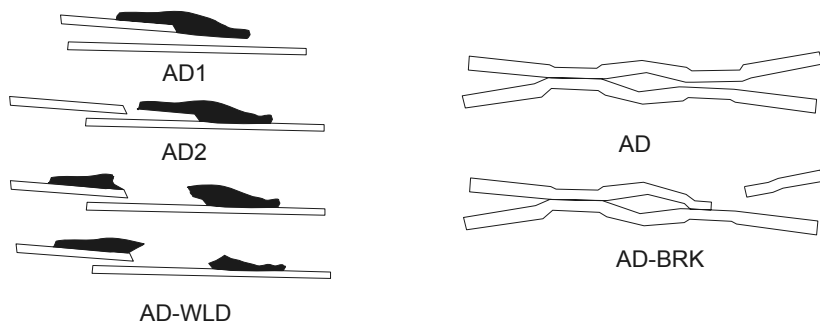


Fig. 10.7. Examples for the locus-of-break code of ASTM D6392 and GM19. AD is described as failure in adhesion, AD-BRK as break in a seam of either the top or bottom sheet after some adhesion failure, AD-WLD as a break in the fillet either in centre or off centre

A quantitative evaluation of the peel test, i.e. the determination of the peel strength or peel separation, is usually only possible in the laboratory. Here a tensile shear test, another short-time tensile test, can be carried out for the quantitative assessment of the seam, too. The test method is described in the DVS 2226-2:1997 *Testing of Fused Joints on Liners Made of Polymer Materials – Lap Shear Test* and in ASTM D6392. The tensile shear test is similar to the peel test with respect to the test parameters. However in this test, the specimen is clamped at the strip end of the lower geomembrane on one side of the seam and at the strip end of the upper geomembrane on the other side of the seam. Figure 10.4 shows the test specimen. The seam lies in the middle and across the tensile direction. If the test strip elongates and tears in this test outside the seam, then good seam strength is assigned to the seam. The ratio of the maximum tensile force in the tensile shear test on the test strip with a seam to the maximum tensile force determined on a test strip of the geomembrane without a seam, is called the short-time welding factor or short-time seam strength factor. Experience-supported typical values and minimum values can be derived for this welding factor. However, similar reservations apply, which were made in connection with the peel strength above. DVS 2226-1 requires a factor ≥ 0.9 . GM19 specifies thickness dependent values for the tensile strength measured in N/25mm. To make the important qualitative criteria of clear and unambiguous yielding of the specimen material outside of the seam more quantitative, the shear elongation is defined in ASTM D6392 as percent ratio of extension at test end (after breaking) to original gauge length. Usually a value of greater than 100 % is required. However, allowable shear elongation for structured geomembranes should be determined on a case-by-case basis. Since some manufacturing proc-

esses have strong influence on the elongation at break point of the structured geomembrane in the tensile test.

It was repeatedly mentioned that the qualitative assessment of the deformation behaviour and rupture mode of the specimens in the peel test as well as in the shear test are of paramount importance. It is getting tedious to say that these tests can only be performed and evaluated by trained and experienced specialists. To offer some help in communicating test result GM19 and ASTM D6392 offer a classification scheme for rupture modes or “a locus-of-break code” (Fig. 10.7). Using this code it may be said that adhesion failures (AD, AD1 and AD2) or break in the seam (AD-BRK) are clearly unacceptable, break through the fillet (AD-WLD) is acceptable only when certain minimum specification values for strength and elongation at break are met.

Finally, on the construction site, the tightness of the seams must be tested. Dual hot wedge seams with a test channel are tested using a pressurised air test, the extrusion fillet seams with a vacuum box or high voltage test. The pressurised air test is described in the guideline DVS 2225-4 and with slight differences in parameters and procedures in the standard ASTM D5820-95 *Standard Practice for Pressurized Air Channel Evaluation of Dual Seamed Geomembranes*. Dual hot wedge seams with a test channel can thus be non-destructively tested over the entire seam length, which can be as long as 300 metres. A compressed air test can begin about 1 hour after welding at the earliest. At one end of the seam an HDPE quick coupling hose connector nipple is welded to the test channel, to which a compressor with a pressure gauge and a pressure recorder is attached. The test channel is blown through and welded shut or clamped hermetically at the other end of the seam. Compressed air is then applied. First, pressure is adjusted above the actual test pressure for approx. 1 minute. The test channel must open and bulge out first. After this pre-loading the proper test pressure is adjusted. The selected test pressure is, to certain extent, based on the geomembrane temperature and test channel width. It is usually about 3–5 bar (300–500 kPa). After the test pressure has been adjusted, the actual test begins. The pressure is recorded over a test period of 10 minutes continuously with the pressure recorder. The pressure gauge must correspond to the test device class 1.0 in accordance with EN 837⁴. The meas-

⁴ EN 837-1:1996 *Pressure Gauges – Part 1: Bourdon Tube Pressure Gauges - Dimensions, Metrology, Requirements and Testing*

EN 837-1:1996 *Pressure Gauges – Part 2: Selection and Installation Recommendations for Pressure Gauges*

EN 837-1:1996 *Pressure Gauges – Part 3: Diaphragm and Capsule Pressure Gauges – Dimensions, Metrology, Requirements and Testing*

urement range of the pressure gauge and recorder should be no larger than double the test pressure and the scale not coarser than 0.1 bar (10 kPa). During the test time the pressure must not drop more than 10 % of the initial value. At the end of the test time the test channel is opened at the clamped or welded end. Air must suddenly escape and the pressure gauge reading drop rapidly. With this inspection results the tested seam section qualifies as tight. If the inspection result deviates from these requirements, then error tracing begins. Sometimes the seam section must be further tested piece by piece, until the error sources are identified.

Testing tightness of the extrusion fillet seams is more laborious. They must be tested piece by piece by applying a vacuum box or chamber using the vacuum box method. The vacuum box test is described in the guideline DVS 2225-4 and with slight differences in parameters and procedures in the standard ASTM D5641-94 *Standard Practice for Geomembrane Seam Evaluation by Vacuum Chamber*. The testing device consists typically of a 10 cm long and about 10–15 cm wide transparent test box, whose edge is provided with a flexible sealing ring, so that the box can be pressed hermetically on the weld seam section. A small pump and a pressure gauge are attached to the box. The measurement range of the pressure gauge and recorder should be no larger than double the test pressure and the scale not coarser than 0.1 bar (10 kPa). For transition zones between slope and base, edges and corners there are specially formed test boxes available.

This test should also start 1 hour after welding at the earliest. The seam section, which is to be tested, is covered or sprayed with a bubble-forming liquid. The vacuum box is placed on the geomembrane and then a vacuum applied. During the test a vacuum of at least 0.5 bar (50 kPa) must be kept constant for at least 10 seconds. In a leaky place the liquid will make bubbles. If the vacuum can be built up “rapidly”, the pressure maintained for the duration of the test and no bubbles are observed, then the tested section is considered as tight. The test box is ventilated. Places, in which bubbles had formed, are marked and repaired later. The test box is then placed on the next section brushed-in or sprayed with test liquid. The test sections must overlap by at least 10 cm.

Extrusion fillet seams can be non-destructively tested using another testing method, namely a high voltage electrical test. This procedure is used instead of the vacuum test above all on places, which are difficult to access with the vacuum box. The description of the procedure again follows the guideline DVS 2225-1. Further details may be obtained from the standard ASTM D6365-99 *Standard practice for the Nondestructive Testing of Geomembrane Seams using the Spark Test*. Use is made of the fact that a gas discharge occurs between two electrodes when high voltage is applied. The spark discharge is visible and audible: it sparks and cracks. The test

equipment consists of a high voltage source to which a brush electrode or a ball electrode is attached. At the back of the extrusion fillet seam, along the overlapping edge of the upper geomembrane, an electrode, such as a wire of good electrical conductivity, is placed and over-welded. The welded-in electrode is earthed. The testing voltage applied to the brush electrode must not exceed the breakdown voltage of the HDPE geomembrane. The height of the voltage on the other hand determines the possible length of the discharge distance. The permissible test voltage is 60 kV for HDPE geomembranes with a thickness of 2.5 mm. Thus a sparking distance of approx. 20 mm can be reached. A central electrode lying in the seam thus enables 30 to 40 mm wide extrusion fillet seams to be tested. The brush travels at a speed of approx. 10 m/min along the seam edge. However, only such defects can be detected where a sufficiently short discharge distance develops over a sufficiently large air duct running almost perpendicularly to the seam. Such defects trigger a spark discharge. The relevant places are marked and repaired. What “sufficiently” really means is not clear and this test fails to recognise closed but poorly attached seam zones anyway. The effectiveness and reliability of this test method is therefore disputed.

So far construction site tests have been discussed which are supplemented by tests in the laboratory (peel and tensile shear test), for example by an independent inspection body that carries out the third-party control. In addition, there are laboratory tests on weld seams where the aim is to clarify fundamental questions, i.e. the dependence of quality of the weld seam on the welding parameters and the long-term behaviour. These are the long-term tensile creep test (more exactly: the long-term tensile shear creep test), the long-term slow tensile test, the long-term relaxation test and the long-term peel creep test. The tests are characterised as “long-term” since they are performed at elevated temperature to accelerate processes that might lead to failure. In addition a water bath or a water-surfactant solution is used to accelerate brittle failure.

The long-term tensile creep test was discussed in great detail in Sect. 3.2.16, for testing stress crack resistance of structured geomembranes. The same test can be performed on weld seams. The guideline DVS 2226-4:2000 *Testing of Joints on Liners Made of Polymer Materials – Tensile Creep Test on PE* describes the test method. The specimens are prepared in accordance with the DVS 2226-2 guideline (see Fig. 10.4) for the short-term tensile shear test and clamped in the long-term tensile creep test apparatus. The long-term peel creep test has not been standardised yet but is carried out analogous to as the long-term tensile creep test. The test specimen is prepared according to the instructions of the peel test guideline DVS 2226-3 (see Fig. 10.4) and clamped in the long-term tensile creep test

apparatus. Usually, not the applied stress (unit: N/mm²) is used as a test parameter but a line test force defined as applied tensile force related to the width of the test specimen (unit: N/mm). The long-term peel creep test is dealt with in greater detail in the next section.

The question of the long-term behaviour of geomembrane seams was originally tackled by using concepts from the well-established field of polyethylene pipe seam testing and evaluation. The so called long-term welding factor or long-term seam strength factor was introduced by G. Diedrich and E. Gaube for the description of the long-term behaviour and quality of weld seams in polyethylene pipes and plates compared to the base material (Diedrich and Gaube 1970, 1973). A short discussion of the derivation of this factor might be helpful in understanding the approach to characterise the long-term behaviour of geomembrane seams.

For testing the long-term behaviour of pipes the pipe pressure test is used (Sects. 5.4 and 3.2.13). This test can also be performed on a pipe section welded together from two pipe parts. To evaluate the long-term behaviour, the brittle branch of the hoop stress versus time-to-failure curve is determined i.e. the range of the curve where the fracture mode can be clearly characterised as brittle failure due to stress crack formation. Results from G. Diedrich and E. Gaube as well as other working groups showed that the location of the branch and therefore the medium service lives did not differ in unwelded and correctly butt welded pipes in the brittle range at all test temperatures. Failure usually arose in the base material of the pipe. The result shows that the butt-welded seam is not a weak point, which would dramatically impair the maximum strength in the pipe.

From this, however, no conclusion can be made on the quality of the seam and on its long-term strength in comparison to the base material. In the pipe pressure test the longitudinal component of stress, i.e. the stress perpendicular to the plane of the seam of the butt-welded seam, is only half of the hoop stress. The weld seam is thus exposed to a much smaller tensile stress than the base material in planes outside the seam.

Therefore, G. Diedrich and E. Gaube cut out tensile test bars (parallel test bars or strip specimens and shoulder test bars) from the pipe walls, once without a weld seam and once with a central weld seam and tested them in long-term tensile tests. The plane of the seam is now essentially perpendicular to the tensile stress and the weld seam area and the base material is similarly loaded. By measuring the times-to-failure at different tensile stresses, a brittle branch of the tensile stress versus time-to-failure curve was found both for the base material and for the seam. Depending on the quality of the seam and type of welding method (e.g. hot element butt welding and extrusion welding) different positions in the hoop stress versus time-to-failure diagram were found for the seam's brittle branch in

comparison to the branch of the base material. These differences are described by the long-term seam strength factor. The long-term seam strength factor is defined as the ratio of the two stresses, one on the brittle branch of the tensile stress versus time-to-failure curve of the seam sample, the other one on the brittle branch of the base material, which leads to the same time-to-failure. Or expressed in a different way: the long-term seam strength factor indicates, how the tensile stress must be reduced so that the same medium time-to-failure can be reached for the pipe with a weld seam as for a pipe without seam. In an ideal case the long-term seam strength factor should be unity: weld seam and base material behave in the same way. However, the branches of base material and weld seam in the pipe pressure test diagram rarely run in such a way that the same long-term seam strength factor can be calculated for each stress. Usually the long-term seam strength factor depends rather strongly on the testing stress. The test method and the determination of the long-term seam strength factor were standardised in the guideline DVS 2203-4:1997 *Testing Welded Joints on Thermoplastic Plates and Pipes – Long-term Tensile Test*. A long-term seam strength factor can; however; also be defined as the ratio of the time-to-failure of a seam to that of the base material at a pre-set test stress. One then obtains a factor with which the service life of the pipes must be reduced to take account of pipe seams.

In the late eighties it was suggested that this procedure could be used for geomembrane seams as well. The long-term tensile creep test (or more exactly the long-term tensile shear creep test) and the determination of the long-term seam strength factor derived from it was used by J. Hessel and P. John for the characterisation of the long-term behaviour of weld seams (dual hot wedge seam and extrusion fillet seam) with geomembranes (Hessel and John 1987). The test and procedure for the determination of the “long-term seam strength factor” of geomembrane seams was described in the DVS 2226-4 specified above. However; there are three unresolved methodical problems in the application to geomembranes for this procedure.

1. The time-to-failure of a specimen from an unwelded geomembrane and thus the reference value for the time-to-failure of the weld seam depends highly on the type of specimen preparation. The specimens from the base material always fail by stress crack formation, which begins at machining defects located at the edge of the specimen. Punched tensile test bars fail rapidly; specimens sawed with a high-speed tungsten carbide saw or milled with high-speed milling endure longer. The time-to-failure increases if the edges are smoothed with fine sandpaper. Only if completely smooth cut edges are produced by

cutting by a microtome blade or very fine plane will a range of times-to-failure be reached where, in individual cases, stress cracks initiated from the geomembrane surface result in a failure. The time-to-failure obtained in this case is very long for HDPE geomembranes of acceptable stress crack resistance ($> 10,000$ h). It follows from this observation that the long-term seam strength factor is larger or smaller depending on the quality of the specimen preparation, i.e. it depends on the preparation technique. In accordance with the DVS 2226-4 guideline the tensile test bars must not be punched. Rather they may "... be manufactured by sawing, milling or cutting (e.g. using a water jet). In order to attain a notch-free cut section, these have to be repeated if necessary by smoothing in a longitudinal direction." But even such a detailed description of specimen preparation fails to provide a clear definition of a reference value for the base material.

To avoid this ambiguity in the DVS 2226-1 a minimum time-to-failure of the basic material for the determination of the long-term seam strength factor was required: for HDPE geomembranes a time-to failure of 500 h at a test stress of 4 N/mm^2 in an 80°C hot surfactant solution with Arkopal N100[®] surfactant. The seam strength factor for dual hot wedge seams (extrusion fillet seams) should then be at least 0.5 (0.4). This approach seems to be rather "long-winded". Obviously, one can directly specify a minimum value for the time-to-failure of the weld seam instead of defining the minimum time-to-failure for the basic material and requiring a minimum value for the seam strength factor. Under the test conditions mentioned that would simply be 250 or 200 hours respectively.

2. The two branches in the tensile stress versus time-to-failure curve, which describe the range of brittle failure of a weld seam and the base material, do not usually run parallel, but diverge. Therefore the long-term seam strength factor depends not only on specimen preparation but also on the selected test tensile stress. With decreasing test stress the seam strength factor would become lower and lower.
3. In the long-term tensile test on tensile test bars with dual hot wedge seams and extrusion fillet seams the plane of the seam is not perpendicular to the tensile direction, as in butt welded pipe seams, but parallel. The force flow in the loaded specimen is directed over the weld seam from one geomembrane into the other in an offset direction, therefore force flow lines get more dense in the boundary region of the weld seam and a stress concentration develops. In the boundary region there are also notch effects induced by the transition from the welded material area to the base material. A crack that develops there

grows perpendicularly to the force flow lines toward the strongest downward gradient in the line density and therefore leads into the base material. Indeed: the observed stress cracks actually start in the boundary region of the weld seam and then run perpendicular to the seam plane through the base material. The stress crack in dual hot wedge seams therefore practically never runs within the seam (Gehde 1992; Viertel 1997). Therefore the time-to-failure is essentially a function of the specific geometry of the weld seams in the geomembranes.

For these three reasons it is not possible to consider the time-to-failure in the long-term tensile creep shear test as a criterion for the quality of the weld seam and the welding method in geomembranes at all.

However, from the results of long-term tensile test on dual hot wedge and extrusion fillet seams in geomembranes one clearly sees that these types of seam in particular should not be put under long-term tensile stress in the field⁵: the time-to-failure is always substantially smaller than in the non-welded geomembrane itself when put under permanent tensile stress. Therefore the requirement for the HDPE geomembranes be installed in such a way that no long-term effective tensile stresses develop, applies above all to the weld areas. The DVS 2225-4 guideline describes appropriate precautionary measures to avoid permanent tensile stress in installed geomembranes (see Chap. 9). For example, on slopes, the seams must run parallel to the line of maximum slope to a large extent. Patching geomembrane panels using transverse joints on slopes is not permitted. The connecting seam between geomembranes on the slope and the base should be located in the base at a distance of at least 1.5 m from the slope toe, and so on.

The test condition for seams in the long-term relaxation test is closer to actual mechanical effects occurring under field condition of an installed geomembrane. The relaxation test was described in Sect. 3.2.10. This test can also be performed as a long-term test. The test apparatus is modified in such a way that the specimen can be kept in a test liquid at an elevated test temperature while a specified constant strain is applied and the consecutive stress relaxation is measured. There are still no standards or guidelines available, which describe the long-term relaxation test on seams. The specimens are prepared as for the long-term tensile creep test and the test

⁵ This frequently used formulation is somewhat lax. It is meant that the geomembranes may not be intended to be used to transfer and absorb permanent loads in a structure. Naturally, tensile stresses that are strictly zero can not be required. A tensile stress below 2 N/mm² is considered harmless even for seams (Heitz and Henkhaus 1992). See also Sect. 3.2.10.

procedure is analogous to the one in the long-term tensile creep test: instead of the rapid application of a constant tensile stress, a strain is swiftly applied and held constant. Not only is the relaxation curve of interest, but also the time-to-failure and the failure modes. The fracture modes resemble those seen in the long-term tensile test. The times-to-failure measured on seams in this test are very long even for a strain close to the yield strength (> 1000 h). Therefore measuring critical limiting strain of seams using this test would be very time-consuming. So far only a few test results have been published (Knipschild 1992).

E. Heitz and R. Henkhaus carried out slow tensile tests on dual hot wedge seams, also called constant strain rate tests by the authors (Heitz and Henkhaus 1992). In this test the tensile test specimen is subjected to a slow constant strain rate (0.2 % a day up to 2.5 % an hour) instead of a constant load in the tensile creep test or a constant strain in the relaxation test. From the measurement of times-to-failure at different strain rates and test temperatures, an attempt was made to determine a critical limiting strain for the seams (defined here as the permissible strain for a theoretical service life of 100 years at 20 °C) using the time-temperature superposition law (see Sect. 4.2). Extrapolation uncertainties are naturally very large. A conservative estimation was tried and limiting strains of 1.7 to 2.7 % were determined for HDPE resins. The tests were performed in a 2 % surfactant solution. The critical limiting strain in this medium is substantially smaller than in water or air (see Sect. 5.3.4). On the other hand the load was only uniaxial. For a planar state of stress the limiting strain should be lower compared to the limiting strain in the state of uniaxial applied force. All in all, the limiting strain of 3 % used for HDPE geomembranes (Sect. 5.3.4) seems to be comparable to the permissible limiting strain for properly manufactured seams as well.

In addition to these mostly “customary” laboratory and construction site tests, further tests have been and will be conceived on geomembrane seams - usually derived from test procedures on the geomembrane itself. However, all these tests only provide necessary, but insufficient conditions for a “perfect” seam. The burst test described in Sect. 3.2.9, used to test the multiaxial deformation behaviour, can be performed on a geomembrane disk with a centrally placed seam. For this purpose, sufficiently thick elastomer rings must be used in order to provide a watertight clamping. With properly manufactured seams the arch-height versus pressure diagram measured in the burst test does not show any difference to the diagram of the geomembrane without a seam (Hutten 1991). The seam does not therefore impair the multiaxial deformation behaviour. From a methodical point of view, long-term relaxation tests on seams, in which a constant planar strain is applied using a test device analogous to the burst

test apparatus would probably be the most informative test for the long-term behaviour of seams. These tests are, however, expansive, difficult to design and very lengthy. So far, to the author's knowledge, such tests have not been tackled.

Burst tests were performed on T-junction dual hot wedge seams and also destructive pressure tests with water in the test channel on dual hot wedge seams, analogous to the pressurised air test. Marked differences can be observed in the deformation behaviour of T-junctions. The arch elongation of a good seam T-junction is above 6 %, but it does not in principle reach the values of the geomembrane (at least 15 %) because of the reinforcing effect of the T-junction of dual seams and the change in thickness at the seam edge (Müller and Preuschmann 1992). Instead of using pressurised air, the test channel can be pressurised with water, in similar fashion to the hydrostatic burst test with water. The pressure is increased in steps of 2 bars, and the pressure is maintained at each step for 2 minutes. The increase in pressure is carried on until the seam breaks. Properly manufactured seams reach pressures of 20–40 bar (Müller and Preuschmann 1992). The different failure modes are noteworthy. There are seams where the test channel bulges, elongates and exhibits a ductile failure similar to the ductile failure of a pipe in the pipe pressure test. Other seams peel off in localised limited areas. There are, however, seams where the material shows sudden and sharp-edged brittle fracture in the boundary region of the test channel over a distance of a few centimetres. How these markedly different failure modes depend on material, seam characteristics and welding parameters, has so far not been examined.

Infrared thermography of seams is as yet a somewhat little used test method, which is only occasionally applied. The seam is photographed immediately after welding using an infrared camera. Cavities and zones of poor adhesion in the seam can be seen to some extent as anomalies in the infrared picture (Peggs 1995).

To finish this section a few remarks about the amount of destructive testing as part of construction quality control measures will be added. The tradition has long prevailed in the construction quality control of third party inspectors to use extensive destructive testing to document installation integrity. Coupons are regularly cut out of the dual hot wedge seams with high frequency. The holes are then repaired by patches, which are extrusion fillet welded. As mentioned above the extrusion fillet seam is a much less reliable welding method than a hot wedge machine welding. Therefore, extensive destructive testing and repair work will reduce the overall reliability and performance of the geomembrane liner system. Quality control measures can check the quality of the geomembrane installation, i.e. the extent to which the specifications are met. However, subse-

quently quality control measures and associated repair work can only “heal” to a very limit extent an already inferior quality of a finished installation work. Against this background the approach to achieve a high quality output from the very beginning was emphasized in this book: to commission only certified installers, to use smart welding, to use non-destructive test methods, like ultrasonic testing, to use geomembranes with taped edges, to choose welding parameters not by trial and error but by systematic application of a process model. A comparable approach was recently suggested by a white paper of the International Association of Geomembrane Installers (IAGI), which summarised the results of a panel discussion at the Geosynthetics 2003 conference in Atlanta. It is recommended that the installer, who has shown that he installs with low failure rates and who uses the various technical improvements in geomembrane installation, should be “rewarded” by systematically reducing the frequency of destructive sampling.

10.3 Process Model for Quality Assessment of Dual Hot Wedge Seams

When is a weld seam good? The guidelines, like those of DVS or GRI GM 19, specify criteria based on the experience of specialists over many years and various aspects: seam geometry and appearance must be correct, failure behaviour in the peel and tensile shear tests must correspond to the qualitative description in the guidelines, the seams must be tight in compressed air or vacuum tests, the thickness reduction and the factor of seam thickness must be within given tolerances (see Eqs. 10.3 and 10.4). How are welding parameters selected so that a good seam develops? The guidelines consolidate practical experience into a range of parameters. The exact parameter set of choice is then defined on the construction site by performing and testing a test seam. What is the long-term behaviour of a good seam? Long-term behaviour of weld seams has so far been primarily investigated under tensile shear stress. Service lifetimes achieved here are always substantially smaller than those of the geomembrane due to seam geometry, which produces a stress concentration in the area of the seam edge. The service lifetime achieved is then primarily determined by the stress crack resistance of the material and the quality of the seam itself is of rather secondary importance. From these investigations it follows that, regardless of their quality, seams must not be subjected to continuous tensile stress (see Footnote 5). However, a quality criterion for the welding



<http://www.springer.com/978-3-540-37286-8>

HDPE Geomembranes in Geotechnics

Müller, W.W.

2007, XVIII, 485 p., Hardcover

ISBN: 978-3-540-37286-8