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Process model assisted quality control for hot hedge welding of landfill HDPE geomembranes

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ABSTRACT: A process model has been developed with the aim of improving quality control for hot wedge weld seams using a data-assisted system (Lüders 2000). Based on a functional relationship between a quality criterion and suitable process parameters a numerical quality standard is identified. Whether it is satisfied can be checked relying solely on parameters provided by the welding machine on the construction site. This paper will explain the way the model can be used for direct selection of the correct weld parameters and for providing assurance of seam quality on construction sites. The results of an extensive testing project, sponsored by geomembrane manufacturers and installation companies through their joint Ground Water Protection Working Group (Arbeitskreis Grundwasserschutz -AK GWS), will demonstrate the practical advantages for the welder, for maintenance requirements and for quality management.

1 INTRODUCTION

Welding of HDPE geomembranes is performed manually on construction sites. The welder has to possess practical skills to be able to meet the requirements demanded by weld seam quality management. These are described in Guidelines (DVS 1996) which are part of the Guidelines for the Certification of HDPE Geomembranes (BAM 1999). In Germany, in-house and third-party monitoring prove whether the requirements for seam specifications and welding conditions are satisfied. Hot wedge weld seams are evaluated using the results of short-time peel tests, tests for imperviousness under pressure, plus measurements of reduction in thickness (i.e. difference between the sum of the thicknesses of the two welded geomembranes and the weld seam thickness). However, procedures nominally meeting the requirements but based on more typical experience and manual craftsmanship in welding, and less stringent testing methods for quality control, are open to interpretation and may not be adequate to the technically demanding hot wedge weld process.

Based on a functional relationship between a quality criterion and suitable process parameters a numerical quality standard is identified. To comply with this quality standard, the welder is provided with a set of parameters, described in graphs or tables, which he can easily adapt to a particular construction site conditions.

2 PROCESS MODELL IN ITS GENERAL FORM

2.1 *Quality criterion and quality standard*

Long-term performance of the weld seam serves as a quality criterion for the model. The failure time used has been obtained as a statistically secured mean of long-term peel tests under a constant line load of 4–6 N/mm in a stress-crack-inducing aqueous solution at 80 °C (Lüders 1998). If, when bent at the seam edge, the geomembrane material copes with these heavy-duty test conditions, every seam peels off, even those meeting the requirements. Failure time then allows differentiated statements to be made on seam quality and enables a quality standard to be identified. However, a standard defined by failure time cannot be applied for practical tests of integrity on construction sites. Since only those welding specifications indicated by the machine are readily available, the only feasible quality standard is one defined by such parameters. Therefore, knowledge of the general relationship between seam quality and the welding process parameters is required.

All hot wedge welding machines first partially melt the overlapped geomembranes in a thermal process and then, under force and melt flow conditions, immediately weld them together in a rheological process. The following three criteria are crucial for the seam quality:
- the amount of molten material produced during this process,
- its fraction extruded from the seam area, as measured by the reduction in thickness and
- the roller force required.

The relevant data was taken from the weld seam and the operational conditions of the machine, some of it being calculated (Lüders 1998).

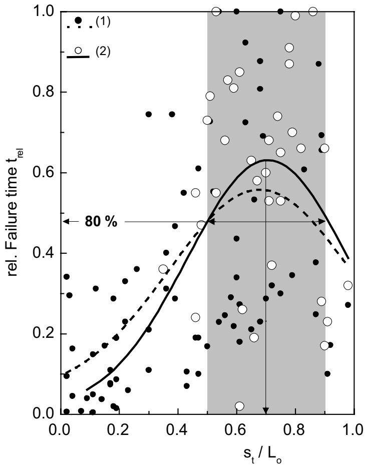

Figure 1. Relative failure time t_{rel} in the long-term peel test as a function of reduction in thickness ratio s_t/L_o.

2.2 *Reduction in thickness ratio s_t/L_o and melt layer thickness L_o as quality-determining process specifications*

The correlation of failure time, as a quality criterion of the weld seam, with s_t/L_o and L_o indicates, as shown in Figures 1 and 2, that these two process parameters determine the seam quality. L_o is the melt layer thickness, i.e. the depth to which the geomembrane material is melted under the actual welding conditions. s_t/L_o, the so-called reduction in thickness ratio, expresses the ratio of the extruded molten material, measured as reduction in thickness s_t at the seam, to the total amount of the free-flowing molten material.

In Figure 1 the relative failure time t_{rel} is plotted against s_t/L_o. The relative failure time is the ratio of the mean value of the seam's absolute failure times to the maximum value ever found in a seam in the same geomembrane material. Seams of the four geomembranes considered differ by one order of magnitude in their absolute failure times due to different stress crack resistance, although they have the same quality. Therefore by this normalization the t_{rel}-curve in the diagram solely reflects the seam quality as a combined result of the chosen key welding parameters, given by s_t/L_o. Influences due to different material properties are counted out.

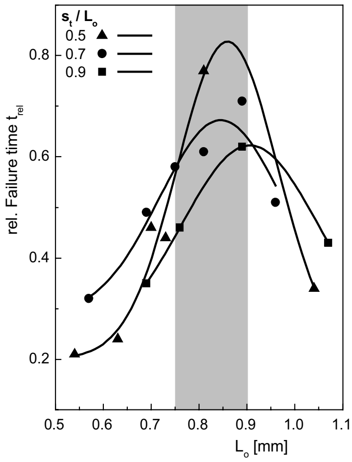

Figure 2. Relative failure time t_{rel} as a function of melt depth L_o with s_t/L_o as a curve parameter (each the mean of up to 60 seams).

Figure 1 indicates that it does not matter whether the welding conditions have been selected randomly (data point type 1) or by an experienced welder (type 2), within the limits set by Guidelines, including seven machine types. In all welding conditions, those leaving a reduction in thickness ratio of $s_t/L_o = 0.7$ on the seam always produce the maximum failure time. Since it is not technically feasible to comply exactly with this value, 80 % of the maximum failure time has been specified as a quality standard. The points of intersection then lay within the quality limits $0.5 < s_t/L_o < 0.9$. This means that seam quality has been coupled with an important, but obviously not sufficient process condition. A number of seams lay well below the t_{rel} level of 80 %, although they are within the s_t/L_o quality limits. The reason for this is their melt layer thickness L_o (melt depth).

Figure 2 displays the relative failure time as a function of L_o. The average of the three curves yields a clear failure time maximum at $L_o = 0.85$ mm, i.e. melt depth L_o is the second quality-determining process quantity. Consequently, L_o must also be limited by the welding conditions. The range $0.75 < L_o < 0.9$ mm as set in Figure 2 does not cover the maximum position centrally. Selecting a somewhat lower limit covers more than 80 % of medium failure time found in the maximum on the one hand, but takes account of practical requirements for the machine's advance on the other.

Melt depth is of central importance in modelling the welding process. L_o as a process specification describes not only the result of the thermal process, in which the extent of melting is reflected (Potente 1977; Lüders 1998), but is at the same time an important geometrical reference quantity for melt flow in the rheological performance. Since both processes in hot wedge welding always occur with the same velocity (i.e. that with which the machine is advancing), it is L_o alone that determines the roller force F required in the machine to achieve the reduction in thickness s_t on the seam.

2.3 *The model in graphical form*

Figure 3 illustrates the roller force ratio F/L_o for various melt depths, as a function of reduction in thickness ratio s_t/L_o. The straight lines can be determined using the general equation $F/L_o = ax + b$, with $x = s_t/L_o$. Slope a and constant b are characteristic for the melt depth, and the higher their values, the lower melt depth L_o. The high roller force increase indicates a liquid limit for $L_o \leq 0.5$ mm, i.e. the molten material looses its flowability at this thickness under hot wedge welding conditions (Lüders 2000). The straight lines F/L_o intersect the target range only at $L_o \geq 0.6$ mm, within the s_t/L_o limits of 0.5 and 0.9 (see Figure 1). The points of intersection of the straight lines for $L_o = 0.75$ and 0.9 mm (see Figure 2) provide the working field (welding window), which can guarantee compliance with the quality standard. As the position of this field is determined by L_o, F/L_o and s_t/L_o, so the position of each weld seam is determined by its particular data. If this data hits the welding window, e.g. at the ideal point or in positions 1 or even 2 (Figure 3), the seam has the quality as defined in the beginning; however it fails to exhibit this quality in the positions 3 to 5 (see further explanation in 4.1, Figure 6).

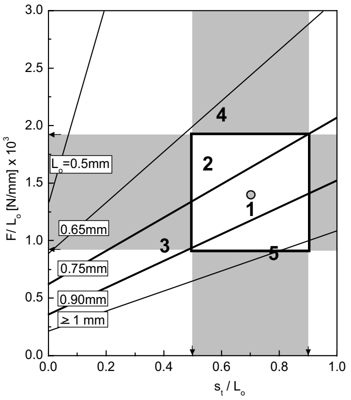

Figure 3. Process field (welding window) derived from the points of intersection F/L_o for $L_o = 0.75$ and 0.9 mm with $s_t/L_o = 0.5$ and 0.9 (See points 1 to 5 in the explanation of Section 4.1 and Figure 6).

The model is generally valid for all hot wedge welding machines and for seams in HDPE geomembranes with a thickness ≥ 2.5 mm. For a geomembrane thickness << 2.5 mm the s_t/L_o position of the failure time maximum should be verified.

3 FUNCTION-RELATED AND DESIGN-SPECIFIC INFLUENCES

Hot wedge welding machines are not of identical design; rather they differ in their design-specific characteristics and in their functional behaviour. If a quality standard is to be valid for all weld seams, these influences must be considered in determining the working field. Investigations were therefore made of how differences in seam width, effective hot wedge length, and the put up force used to achieve geomembrane contact at the hot wedge, can be reflected in the F/L_o curves.

3.1 *Seam width*

Roller widths of 2 × 16 mm are generally used to guarantee compliance with the requirement of a minimum seam width of 2×15 mm. To achieve the same reduction in thickness ratio s_t/L_o greater force has to be applied with increasing seam width, as a greater contact surface requires more molten material to be extruded. For example, for roller widths of 2 × 19 mm the F/L_o position of the straight lines which correspond to the particular L_o values has been increased by Δb in Figure 4a. Since flow resistance of the molten material becomes smaller with increasing L_o, Δb becomes smaller too.

3.2 *Effective hot wedge length*

Only a part of the hot wedge's total length has direct contact with the geomembrane. Through the pre-heat period the so-called effective hot wedge length eff.l_{HW} determines L_o and the viscosity gradient of the molten layer directed towards the interior of the geomembrane. Consequently, the force requirement $\Delta F/\Delta s_t$ needed to achieve a reduction in thickness depends not only on the amount but also on the viscosity gradient of the molten material affected by extrusion. If velocity and temperature are constant, $L_{o(v,T=const.)} = f(\text{eff.}l_{HW})$ holds, which must be expressed in the slope a of the F/L_o straight lines.

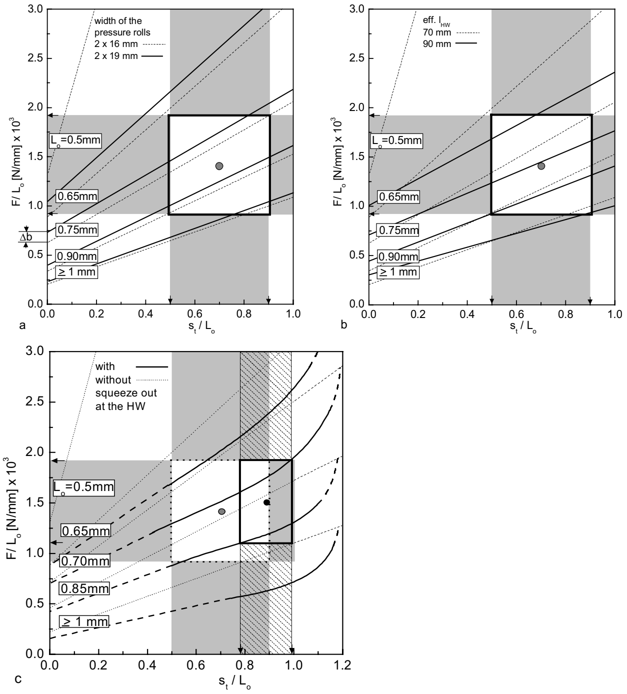

Figure 4. Influence of function-related machine parameters on roller force ratio F/L_o versus reduction in thickness ratio s_t/L_o. 4a Roller width; 4b effective hot wedge length; 4c geomembrane – hot wedge contact.

Figure 4b shows the influence of an effectively 20 mm longer hot wedge on the slope a and the constant b of the F/L_o lines. For each L_o, value b is noticeably greater and a noticeably smaller. Machines with an greater effective hot wedge length thus provide, as expected, more stable molten material with smaller viscosity gradients. With these advantages they hit the welding window in a considerably smaller force range and are less sensitive towards a premature melt extrusion in contact with the hot wedge.

3.3 *Geomembrane contact with the hot wedge*

A fraction of the molten material is squeezed out immediately after the geomembrane comes into contact with the hot wedge. This fraction seriously influences the whole process behaviour if the put up force is too large or the viscosity of the molten material is too low. The melt layer thickness L_o delivered to the rollers is then smaller than that calculated from thermal data by the depth of the extruded molten material. Since the hot wedge continually delivers melt heat, in this case $L_o <$ melt depth holds. In Figure 4c, the F/L_o slope is therefore smaller for every L_o, thus $s_t/L_o = 0.7$ can be reached e.g. with as low force as 700-900 N. Having this force, the grip needed for the machine to advance is not guaranteed, and the machine may come uphill to a halt and burn in!

Above $s_t/L_o = 0.7$ the F/L_o increases disproportionally, because molten material must be extruded in deeper layers with reduced flowability and increased viscosity gradient. The extrapolated curves in Figure 4c then intersect the relevant straight lines at $s_t/L_o \cong 1.2$, i.e. more material has been theoretically extruded, in terms of reduction in thickness, than is in reality available as flowable molten material.

This discrepancy requires another welding window. The failure time of relevant seams results approximately in the same quality standard being achieved between $0.7 < L_o < 0.85$ mm and within the limits $0.8 < s_t/L_o < 1$ (see also Figures 1 and 2). Having the points of intersection of the non-linear sections F/L_o as given in Figure 4c, the welding window is smaller and is shifted towards higher s_t/L_o values (hatched area). For the target in the middle of the field $L_o \cong 0.8$ mm is obtained at $s_t/L_o \cong 0.9$. $\Delta s_t/L_o \cong 0.2$ multiplied by 0.8 mm yields $\Delta s_t \cong 0.16$ mm. Hence reduction in thickness would be reduced by this amount, if $s_t/L_o = 0.7$ held and no molten material were extruded at the hot wedge. Conversely, according to the model, around 20% of the flowable molten material may be extruded during hot wedge contact if operating error or design conditions allow.

4 APPLICATION IN WELDING PRACTICE AND QUALTY CONTROL

The model in its form of the diagram in Figure 3 provides no help for welding practice. In order to hit the welding window, the force must be known for each particular machine design which can ensure compliance with the quality limits for s_t/L_o within the quality limits for L_o. For this purpose the machine parameters hot wedge temperature T_{HW}, velocity v, force F and reduction in thickness s_t have been derived from the process parameters for L_o, s_t/L_o and F/L_o and their quality limits, and a performance description has been compiled. This data enables the quality management , the maintenance service and the welder to decide without any calculation whether the machine is in proper working order and the seam meets the quality standard.

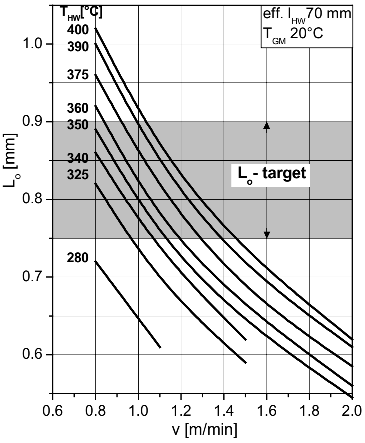

Figure 5. Melt depth L_o as a function of welding velocity v for various hot wedge temperatures.

4.1 *Performance description for a hot wedge welding machine*

Figure 5 shows L_o in dependence on welding velocity v at a geomembrane temperature $T_{GM} = 20°C$ and at eff. $l_{HW} = 70$mm. The position of the curves and the L_o target range determines the permissible v range, in which the quality standard can be met.

If eff.l_{HW} deviates from the manufacturer's specification, the machine is not fully operative. If eff.l_{HW} and/or T_{GM} are higher or lower, the ordinate of L_o must be updated by adding or subtracting 0.06 mm per 10 mm eff.l_{HW} and/or 0.025 mm per 10°C T_{GM}. The point of intersection with the same T_{HW} curve then yields higher or lower permissible welding velocities on the abscissa.

L_o reduces with increasing velocity, in principle in the same manner for all machines which transfer heat through the hot wedge inductively into the geomembrane material. However, the position of the curves with respect to the velocity axis is design-relevant. It is representative of the melting power of a particular machine and is determined by the effective hot wedge length. Consequently, higher velocities are permissible for machines with hot wedges of larger effective length.

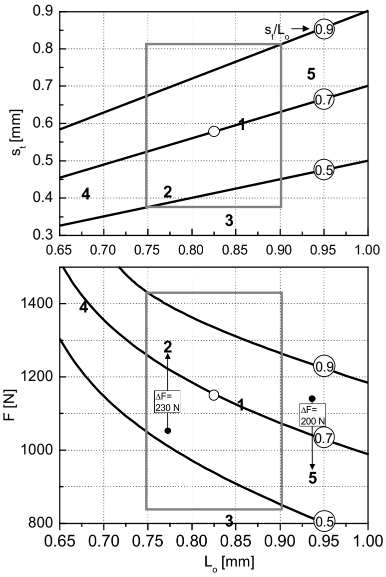

Figure 6. Roller force F on the rollers, required for a reduction in thickness s_t, as a function of L_o. Indicated: welding window for $0.5 < s_t/L_o < 0.9$.

Figure 6 illustrates the second part of the performance description. Force F, required in the machine to produce the reduction in thickness s_t in the seam, is illustrated here in two diagrams with the same L_o axis.

If L_o is known (Figure 5), starting from the relevant abscissa upwards, one can read the required ordinates from the points of intersection with the F and s_t curves. The relationship between s_t and F is valid of course for any other set of curves (e.g. with parameters s_t/L_o= 0.6 or 0.85) which can be imagined between the illustrated sets of curves, which are thus suitable for estimations. It must be born in mind in any case that the pair of values s_t and F has together approximately the same s_t/L_o parameter. For minor adjustments, the rule of thumb can be used that $\Delta s_t/L_o$= 0.1 corresponds to a force ΔF ≅ 100 N and reduction in thickness Δs_t = 0.08 mm.

Although current knowledge is based on the process performance of a number of machine types proved in practice, it cannot be expected that the set of parameters as predicted in the performance description is always satisfied in everyday welding practice. For maintenance purposes it is therefore of advantage, when using a data-assisted error analysis, that disturbance variables can be quickly recognised, limited and excluded. If test welding yields, for instance, the data characterised by points 1-5 in the Figures 3 and 6, the following can be concluded:

(1) Operation per performance description
(2) The s_t/L_o position for F ≠ s_t , because F is indicated at 230 N too high: calibration of F reading of the machine necessary.
(3) Operation per performance description: F has been selected too low.
(4) L_o is too small: v has been selected too high or eff.l_{HW} < 70 mm: welding window is missed.
(5) L_o is too high: v has been selected too low or eff.l_{HW} >70 mm: the s_t/L_o position for F ≠ s_t , because F reading is 200 N too low: welding window is missed.

4.2 *Hot wedge welding on the construction site*

The performance description, presented as diagrams or data tables, includes a complexity of possible parameters with all their interactions. This flood of data is confusing for the welder on the construction site. He has been used to selecting the hot wedge temperature T_{HW} and deciding, on the basis of test welding, what velocity v and/or force F provide a regulation-conforming reduction in thickness s_t . If he is to comply with the quality standard, quality management should provide him with a set of parameters, from the performance description of the machine, which he only has to adapt to particular construction site conditions.

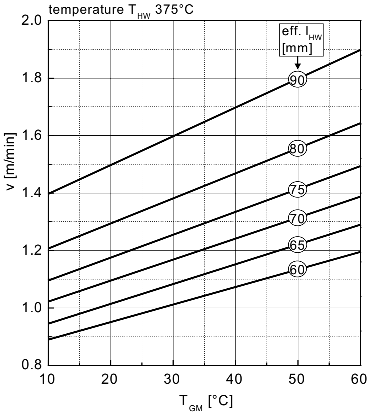

Figure 7. Welding velocity v as a function of geomembrane temperature T_{GM} for various effective hot wedge lengths.

By way of example, based on Figures 5 and 6, e.g. the following set of parameters is given for a machine with eff.l_{HW} = 70 mm: T_{HW} = 375°C ; v = 1.1 m/min and F = 1150 N. At T_{GM} = 20°C , s_t = 0.57 mm should be measured on the seam (L_o= 0.82 mm; s_t/L_o= 0.7).

However, if when the test welding is performed, an effective hot wedge length eff.l_{HW} (unequal to 70 mm) and a geomembrane temperature T_{GM} (differing from 20°C) are found, the set of parameters must be adapted for these two variables. This purpose is served by Figure 7, from which a welding velocity v can be taken. Using this the given set of parameters is valid for the actual effective hot wedge length and actual geomembrane temperature. For minor adjustments the rule of thumb can then be used that Δv = 0.1 m/min corresponds to ΔT_{GM} ≅ 13°C, Δeff.l_{HW} ≅ 5 mm and ΔF ≅ 40 N.

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