Quality Assurance in Hot Wedge Welding of HDPE Geomembranes

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ABSTRACT: In Germany HDPE geomembrane welding in landfill must satisfy the requirements of the DVS 2225/4 Guideline. These requirements are based on the extensive experiential know-how used by welders on site who are able to ensure that quality standards are satisfied by their choice of appropriate welding parameters. This paper presents a process model aimed at the application of a data based quality standard for hot wedge weld seams and optimisation of the welding process. The criterion of quality used will be the failure time in long-term peel tests. This will be correlated with the hot wedge welding process parameters and the reduction in seam thickness. The use of experimental test results from hot wedge welds produced by machines used on site on BAM-certified geomembranes will ensure that the quality standard applied is truly empirically sound. This standard is based on the long-term behaviour of hot wedge weld seams. The use of selected process parameters will make it possible to check that this quality standard has been adhered to on site and to develop quality-controlled hot wedge welding machines.

1 INTRODUCTION

In Germany the use of geomembranes to protect ground water from contamination from landfills is regulated by extensive quality assurance guidelines that must ensure that every step in the construction of large-area liners is fully compliant with the standards (TA Abfall 1991; TA Siedlungsabfall 1993; DVS 2225/4 1996; BAM 1999). In addition to the organisational structure, efficient quality management systems must incorporate all methods and processes used (EN ISO 8402 1997). Only the manufacturer’s quality management system is certified, not the product itself (ISO 9001 1998). The formulation of such quality criteria and their utilisation as targets to determine quality within process management therefore depends to a very large extent on those involved in leading edge technology and further development encoding the existing and new process information into them.

Hot wedge welding has already gained acceptance for the fusion of long HDPE geomembranes to form large-area liners. It is controlled by in-house and third-party on-site monitoring and forms part of the quality assurance system for which the Working Group Groundwater Protection (Arbeitskreis Grundwasserschutz - AK GWS) has been awarding a quality seal of approval to installation companies in Germany for the past 2 years (AK GWS 1997). Quality standards include the regulations laid out in the DVS 2225 Part 4 guideline which regulate weld seam production for landfill liners. These requirements are based on the extensive experience which has influenced machine design and the parameter limits when choosing welding conditions. Although it has been proved that the practical skill of welding operatives ensures that the weld seams produced are standards compliant, experientially based custom and practice, even though conforming to the appropriate guidelines, is open to interpretation and is not a sufficient basis for the technically demanding process of hot wedge welding. Quality verification still lacks a functional relationship between a distinguishing quality criterion and generally applicable quality-relevant process parameters.

The paper present a process model developed based on the results of long-term weld seam tests. It is currently being tested on seams produced by 13 installation firms within the framework of a quality control exercise by AK GWS on 7 machine types with BAM certified geomembranes.

Details of the analysis of the thermal-rheological processes in hot wedge welding, calculation of the melt depth, the relationship between seam quality and failure time and experimental procedures can be found in earlier papers (Lüders 1997; 1998; 1999).

2 PROCESS MODEL FOR SEAM QUALITY ASSESSMENT

There were two main aims in developing this model :
(1) To establish a quality criterion which would allow the inherent quality of acceptable weld seams to be expressed differentially and to identify it in terms of generally valid limits.

The aim of welding is a conclusive material bond. Its properties will however always differ from those of the bodies being welded by virtue of its structure and geometry. The question of bond quality is determined by on which prerequisite the quality is based. Naturally, the weld seam in a liner must be impervious. However, in order that a seam meets all the requirements, the one property that the seam can be shown not to possess a priori but only under certain conditions must be chosen. This will not be imperviousness, which even a cold welded hot wedge seam in which both contact faces are ideally aligned can exhibit. It is not unusual for such seams to withstand short-term peel tests and to yield near seam edges in the same way as seams produced according to requirements. Short term peel tests therefore fail to differentiate with respect to seam quality. This is, however, precisely what is required if compliance with welding conditions that ensure quality in the weld properties is to be expressed.
(2) To find a functional relationship between machine adjustable parameters and those process parameters that indicate an appropriate seam quality under site conditions. One general characteristic of all types of hot wedge welding machine is that first they partially melt the geomembrane material in a thermal process and then they weld the material under force and melt flow in a consecutive rheological process. In order to describe this process for every suitable practical operational condition, three questions must be answered:

- To what extent will the geomembrane be melted?
- How much melt will be extruded from the weld area?
- What roller pressure ratio (see section 2.5) is required for this?

In order to answer the first two questions, it is possible, at least in part, to fall back on some results that were used in the 70's and 80's for process modelling in butt welding (Potente 1977; Michel 1988). Unlike in this method, however, hot wedge welding allows no variable time adjustment; both processes are bound in with the speed at which the machine is actually moving. In addition, the period during which both processes occur in hot wedge welding is only a fraction of the time available in butt welding.

2.1 *Quality characteristic*

The model uses seam strength, measured as failure time in long-term peel test, as its quality characteristic. Unlike short-term peel test, in this test every seam, even those complying with the requirements, peels off as long as the geomembrane material at the seam edges held in the clamps can withstand the harsh test conditions, i.e. a constant line load of 4 or 6 N/mm at a temperature of 80°C and an aqueous medium to initiate stress cracking. This test method is not portable and is neither suitable for construction sites, nor as an element of the quality assurance process for hot wedge welding within the time limits of a build. This is because expensive instrumentation and extensive statistical analysis are required for each measurement (a minimum of 6 test samples) and test times are long.

The level of the absolute failure time of hot wedge weld seams is generally determined by the geomembrane material and its stress crack resistance. Values of several hundreds of hours for seams in materials that are particularly stress-crack resistant can be compared with some tens of hours for those that are less stress-crack resistant. However, since seams ought to be assessed as a function of welding conditions, the comparison must be free of materials influences. For this reason the arithmetic average of a seam's failure time will be related to the maximum failure time found in the same material, i.e. relative failure times will be used.

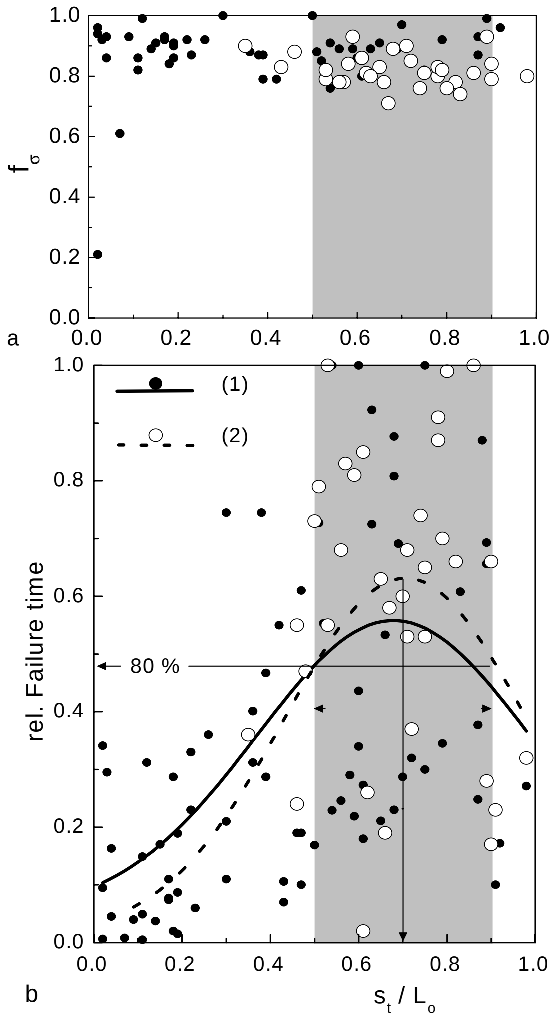

Figure 1. Yield stress ratio f_σ in short-term peel test (a) and relative failure time t_{rel} in long-term peel test (b) as a function of the thickness reduction ratio s_t/L_o. Marked: Range between quality limits of s_t/L_o.

2.2 *On the relationship between failure time and seam thickness reduction*

Seam thickness reduction s_t of a hot wedge weld seam is a geometric characteristic of melt flow and, as the change in thickness Δd_N within the limits of 0.2 to 0.8 mm, is an important part of the DVS Guidelines in force. The welder uses it as a point of reference when selecting balanced parameters for trial welds. The relationship between the seam failure time and this seam thickness reduction, measured as the difference between the double geomembrane thickness and the thickness of the seam, is, however, uncertain - i.e. both long and short failure times are found for the same value. Instead the ratio of the seam thickness reduction to the melt depth L_0, the so-called seam thickness reduction ratio s_t/L_0, has proved to be a significant reflection of the relationship between seam quality, measured as failure time, and the process conditions. It is the thickness ratio of extruded to available melt in the welding phase and is an important process parameter.

2.3 *Quality limits for the seam thickness reduction ratio s_t/L_0*

Figure 1a shows the yield stress ratio f_σ, defined as the ratio of the maximum stress in short-term peel tests to the yield stress of the geomembrane material itself. Figure 1b displays the relative failure time t_{rel} as a function of the seam thickness reduction ratio s_t/L_0.

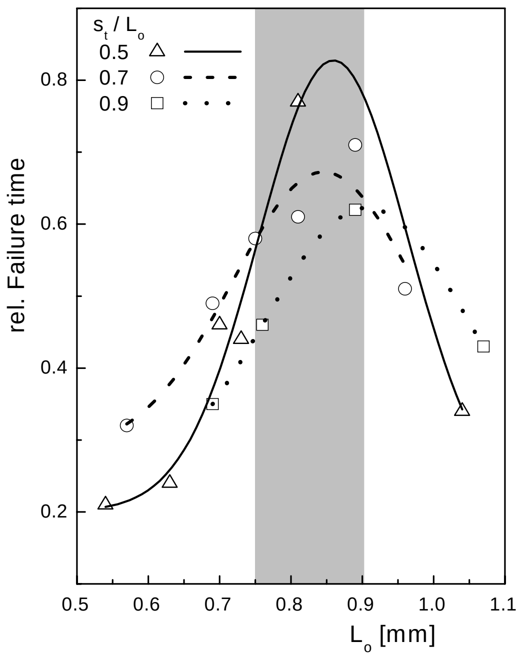

Figure 2. Relative failure time t_{rel} as a function of the melt depth L_o with s_t/L_o as a curve parameter. Marked: Range between quality limits of L_o. Each data point represents measured failure times from 30-60 samples.

The seams in question were produced from 4 different geomembrane materials under welding conditions that were adjusted by arbitrary parameter selection within the permitted limits in the DVS 2225 Part 4 Guideline. f_σ from the short-term peel tests was found to be independent of the seam thickness reduction ratio s_t/L_0 throughout almost the entire seam thickness reduction range, i.e. it is a pass/fail test in quality assessment for seams produced under welding conditions that fall on or beyond permitted parameter limits (Fig. 1a), t_{rel}, on the other hand, increased six fold on average at $s_t/L_0 \cong 0{,}7$ across all the seams tested (Fig. 1b). In other words: out of all possible welding conditions, those which yield a seam thickness reduction ratio of 0.7 the seams produce the longest failure times, independent of the geomembrane material. Therefore s_f/L_0 is a process parameter that contributes considerably to determining failure time and as a quality characteristic must be fixed within the appropriate limits. About 80 % of maximum failure time is always achieved within the limits $0.5 < s_t/L_0 < 0.9$, as obtained from the points of intersection with the curve maximum. Setting narrower limits results in a higher quality standard and conversely. The s_t/L_0 location of the failure time maximum can now be seen to be generally valid not only for the HDPE geomembrane material but also for every type of hot wedge machine. In Figure 1b the test seams (open circles) produced on site by experienced welders from quality controlled installation companies with 7 types of machine show an almost identical maximum.

The large number of measurement points which fall within the s_t/L_0 limits but deviate considerably from the curve of the middle failure time is not only statistically founded. It proves that other process parameters besides s_t/L_0 have a determining influence on seam quality. One such parameter is the melt depth L_0.

2.4 *Quality limits for melt depth L_0*

In order to be able to calculate the seam thickness reduction ratio, it is necessary to know the melt depth L_0, i.e. the depth to which the geomembrane material was melted under specific welding conditions (velocity *v*, hot wedge temperature T_{HW}). It can be calculated from the crystalline melting point of the HDPE, the geomembrane temperature and the effective thermal diffusivity of the molten material using Fourier's equation for non-steady-state heat transfer (Potente 1977; Michel 1988). Other requisite information on the pre-heat period, the contact period and the plasticising temperature is type specific and must be determined individually from a series of welding tests using the relevant machine type.

The relationship between failure time and melt depth L_0 for seams with $s_t/L_0 = 0.5$; 0.7; 0.9, displayed in Figure 2, shows the maximum failure time occurring in the range $L_0 = 0.75 – 0.9$ mm.

L_0 as an arithmetical process parameter can therefore be considered as another seam quality assurance condition. As L_0 is a result of the heat input over unit time, compliance with this condition also represents a practical deployment limit for the welding machine. Thus the welding velocities of a machine for which the L_0 condition is satisfied within set parameter limits for the hot wedge temperature are characteristic of its thermal efficiency.

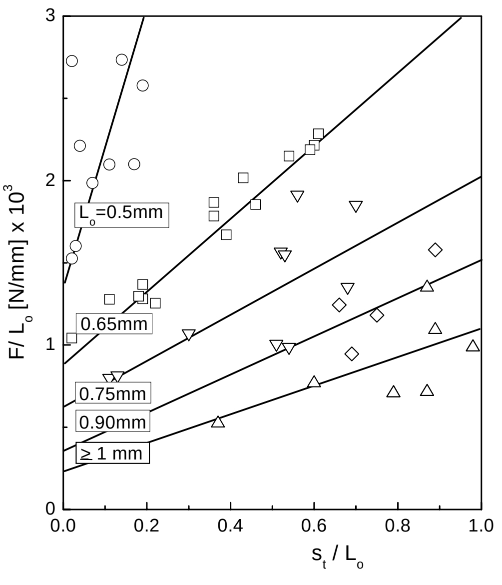

Figure 3. Roller pressure ratio F/L_o as a function of the thickness reduction ratio s_t/L_o with L_o as a curve parameter. Data Points are the the mean of measured values for groups of 18 to 24 seams.

2.5 *Quality limits for roller pressure ratio F/L_0*

Welding causes pronounced melt flow. The bead is produced from the part of the melt depth L_0 corresponding to the seam thickness reduction s_t. Roller pressure F is in non-linear relationship to both the seam thickness reduction s_t and the seam thickness reduction ratio s_t/L_0.

The roller pressure increases exponentially with increasing seam thickness reduction ratio due to melt flow occurring within fractions of a second, increasing bead production in the welding phase and, in particular, due to a temperature gradient directed inwards within the melt layer. However, the ratio of roller pressure to L_0 – the so-called roller pressure ratio F/L_0 – increases linearly with increasing seam thickness reduction ratio as illustrated in Figure 3.

The straight lines determined by the general equation $F/L_0 = a\,x + b$, with $x = s_t/L_0$. The slope a and the constant b are functions of the particular melt depth L_0 (Table 1).

Table 1. Values of *a* und *b* of the s_t/L_o – F/L_o - lines

L_o [mm]	(*a*) [N/mm]	(*b*) [N/mm]	$F_o=b/L_0$ [N]
0,50	8800	1335	668
0,65	2200	880	572
0,75*	1400*	625*	470
0,90*	1150*	360*	325
≥ 1,00	≤ 870	≤ 225	≤ 240

* L_o – Quality limits according Figure 2

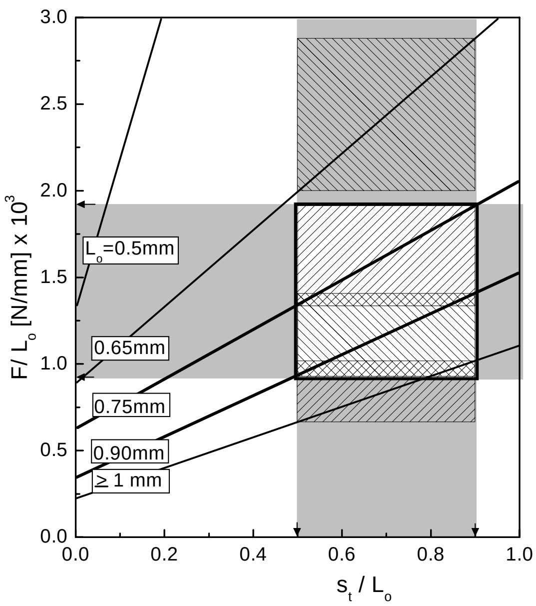

Figure 4. Process fields yielded by intersection of the lines of L_o with the quality limits of s_t/L_o. marked: Work field (Welding window) with datas of corner points corresponding Table 2.

In this case, the lower the melt depth L_0, the higher the value of a which expresses the roller pressure required for each mm of seam thickness reduction: $\Delta F/\Delta s_t$. The value b characterises the minimum roller pressure ratio F_0/L_0 required to compensate for the rheological start effects and geometric influences without which melt flow cannot occur. Straight lines with a = 1400 - 1150 N/mm and b = 625 - 360 N/mm are obtained for melt depths L_o within the quality limits 0.75 and 0.9 mm, corresponding to a minimum roller pressure of F_0 = 470 - 325 N.

2.6 *Work field (welding window)*

The intersection points of the straight lines in Figure 3 with the established quality limits for s_t/L_0 yield several process fields as shown in Figure 4.

The position of these fields is determined by the three process parameters L_0, s_t/L_0 and F/L_0. In the same way, the work field can be obtained if the quality limits for L_0 are brought in. In order to verify the required quality of a seam, all its process parameters must fall within this field. The corner points of this field are indicated in Table 2.

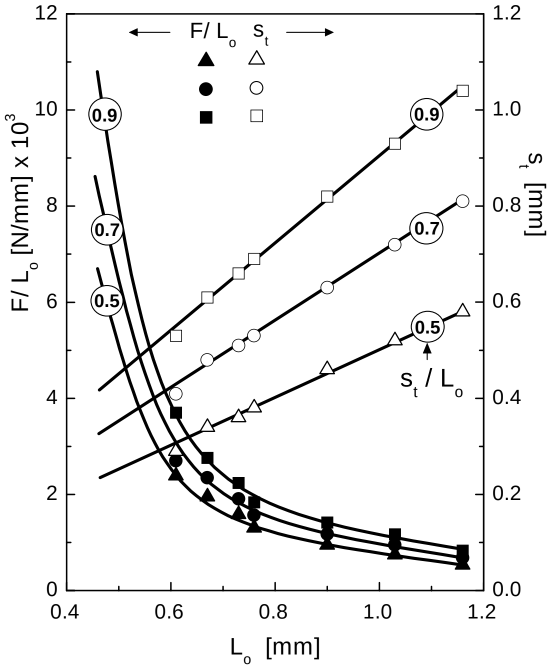

Figure 5. Roller pressure ratio F/L_o and thickness reduction s_t as a function of melt depth L_o with s_t/L_o as a curve parameter.Groups of seams with a certain s_t/L_0 value (white symbols) were used to show this function (black symbols).

Table 2. Datas of the process fields at the quality limits s_t/L_o = 0,5 und 0,9

L_o	F/L_o [N/mm]		F [N]	
[mm]	s_t/L_o=0,5	s_t/L_o=0,9	s_t/L_o=0,5	s_t/L_o=0,9
0,50	5736	9255	2868	4628
0,65	1995	2890	1297	1879
0,75*	1330	1900*	998	1425*
0,90*	935*	1400	842*	1260
≥ 1,00	≤ 660	≤ 1010	≤ 660	≤ 1010

* Corner point datas of the work field (welding window) in Figure 4

If L_0 and the corresponding welding parameters wedge temperature and velocity are known, the roller pressure *F* required at any one time to achieve the seam thickness reduction s_t on the weld seam can be determined so as to fall within the work field. The quality of such seams then corresponds to a minimum of 80% of the maximum of failure time in the long-term peel test. In other words, it is only possible to assess seam quality when the seam parameters which are obtained from the 3 process parameters L_0, s_t/L_0 and F/L_0 are known. In this respect these parameters are generally valid for HDPE and are suitable for process control and quality assurance.

3 SUMMING-UP DISCUSSION AND PRACTICAL CONCLUSIONS

The model presented here was developed from experimental results on weld seams produced with site welding machines. It describes in principle the interaction of the process parameters obtained numerically from adjustable welding parameters, the influence of machine type and the weld seam thickness reduction. They are suitable for determining a process field (welding window) within which the process parameters of weld seams will lie if they satisfy the quality characteristics demanded in the requirements that are laid down. This quality standard was based on a percentage minimum with which the maximum failure time of seams in long-term peel tests will be reached. 80% of the maximum failure time is represented e.g. by a work field within the quality limits $0.75 < L_0 < 0.9$ mm; $0.5 < s_t/L_0 < 0.9$ and $900 < F/L_0 < 1900$ N/mm. A broader field reduces and a narrower field increases the quality standard.

To sum up, it is possible to establish an data aided quality standard based on long-term hot wedge weld seam performance using selected on site process data. (Weather-dependent geomembrane temperatures can be taken into account by means of a correction factor.)

The model applies to all hot wedge welding machines that transfer heat into the geomembrane through gliding contact at the hot wedge with no convective component. Its proper functioning depends crucially on whether the melt depth L_0 and the pre-heat period and melt temperature needed to calculate it are known precisely. To achieve a high seam quality, L_0 must satisfy certain conditions and the speed of a hot wedge welding machine is definitive in assessing the (thermal) performance at which these conditions are satisfied.

Slope *a* of the straight lines in Figures 3 and 4 approximately expresses those rheological requirements that will cause the melt to flow within a fraction of a second. Shallow melt depths, e.g. $L_0 = 0.5$ mm place too high a demand on the performance of hot wedge welding machines, requiring a roller pressure $\Delta F/\Delta s_t$ of almost 9000 N/mm for a seam thickness reduction s_t of 1mm (see Table 2). As illustrated in Figure 5, if L_0 is below 0.45 mm, practically no melt flow can be expected.

Incidentally, this qualifies the meaning of ‚melt‘ in the sense of free-flowing. Therefore only the portion of L_0 greater than about 0.45 mm is free-flowing under hot wedge welding conditions. Since every molten layer produced by surface contact exhibits a distinct temperature gradient, it can be assumed that thicker molten layers reach their liquid limit at a considerably lesser thickness than that calculated solely ‚thermally‘ based on the crystalline melting point. Since the effective flow cross-section is then uncertain, although L_0 under hot wedge welding conditions is a real quantity in the thermal sense, rheologically it is only fictive. Therefore both s_t/L_0 and F/L_0 are to be considered purely as process parameters in order to make welding functional relationships visible and the data measurable. The existence of an immobile part of L_0 on too cold or too quickly welded seams was proved experimentally years ago (Lüders 1998).

L_0 values considerably above 0.9 mm, on the other hand, are very demanding of the accuracy of the control of roller pressure and machine advance due to the greater flowability of the molten material and the relatively high seam thickness reduction. *a* values of well under 1000 N per mm seam thickness reduction in Table 2 indicate that relatively small differences in *F* are enough to cause the corresponding narrow process field to be missed (Fig. 4).

These examples should emphasise that the rheology of the extremely short weld time is both a mechanical and a control engineering problem that is closely related to welding practice and can scarcely be solved by numerical modelling. Those machine-relevant factors not considered here include the diameter of the pressure rollers and the distance between the geomembrane emerging at the hot wedge tip and the contact line of the pressure rollers where the molten material could already have cooled.

Just as the position of the work field is determined in the co-ordinate system, the location of each weld seam is determined by its process parameters s_t/L_0 and F/L_0. With the quality limits for L_0 = 0.75 - 0.9 mm, the straight lines are fixed by the limits of their slope *a* (Table 2). Since a straight line with its characteristic slope can be expected for every other melt depth, it cannot be ruled out that, e.g. at L_0 = 0.7 mm the process parameters of this weld seam may also hit the work field. The quality limit for L_0 is not therefore synonymous with a sudden change in seam quality, as the failure time measurement data also indicates in Figure 2.

The process model is currently being tested at installation companies in practical trials. In the course of these, test seams have been produced

(1) in 4 geomembrane materials using 7 types of machine under welding conditions that are permissible by arbitrary parameter selection within the limits of the DVS 2225 Part 4 Guideline.

(2) under welding conditions chosen by experienced welders.

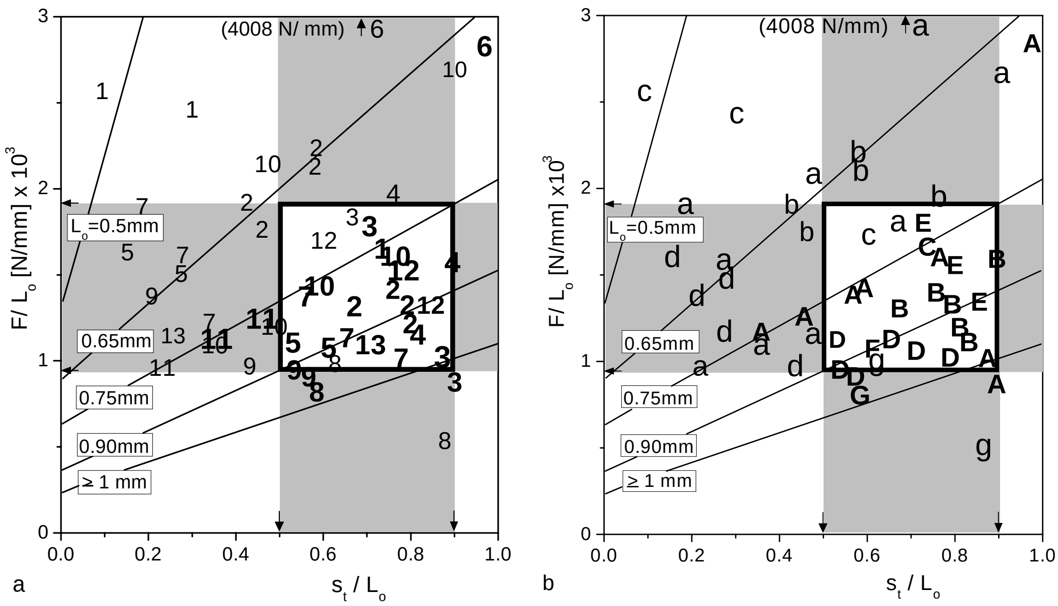

Figure 6. Practical test of the process model:
Location of the data of process s_t/L_o and F/L_o of seams made by
-arbitrary choice of welding parameter (small and standard numbers/letters) (1)
-experienced welder (big and bold numbers/letters) (2)
(a) in 13 installer companies marked by numbers 1 – 13
(b) using hot wedge welding machines of 7 construction types marked by letters A(a) – G(g).

Process parameters were calculated from data sets, and it should be noted here that the melt depth L_0 was not precisely known in all cases and certain deviations had therefore to be tolerated.

The results are illustrated in Figures 6a and 6b. Here the $s_t/L_0 - F/L_0$ position of each test seam is indicated by a number for a company (Fig. 6a) and by a letter for a machine (Fig. 6b). Test seams according to (1) are denoted by small numbers and letters; test seams according to (2) by large numbers and letters in bold.

Conformity between the model predictions on the one hand and the process-determined position of the test seams on the other is sufficiently well shown. The accumulation of seams produced according to (2) in the work field establishes that the quality standard used as identified in Figure 1 is met. Here too the relatively high failure times of these seams are concentrated within the quality limits. In those cases where the work field was missed or only just hit, the machine was subject to functional or display errors that were not observed by the welder.

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