Osnabrück University of Applied Sciences
High Voltage and EMC Laboratory

Influence of Material and Surface Finish on Onset of Partial Discharge at Interfaces with Transformer Oil

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1 Background and aim

A variety of insulating materials, such as laminated densified wood, pressboard and paper, are used in oil filled power transformers. These materials are subjected to high electric field strengths.

The aim of this investigation was to help arrive at a better understanding of the factors, particularly the type of material and surface finish, that influence the onset of partial discharge at the interface between solid insulating materials and insulating oil. The references [1] provide general information about partial discharge phenomena. More specialised tests with laminated densified wood (LDW) are described in [2].

Röchling Engineering Plastics kindly provided the test pieces.

2 Test pieces and setup

Figures 1 a, and b show the electrode configuration chosen for the tests. The minimum clearance s between the electrodes is 20 mm. The discharge path of interest in this situation is shown as a red line in the figures.

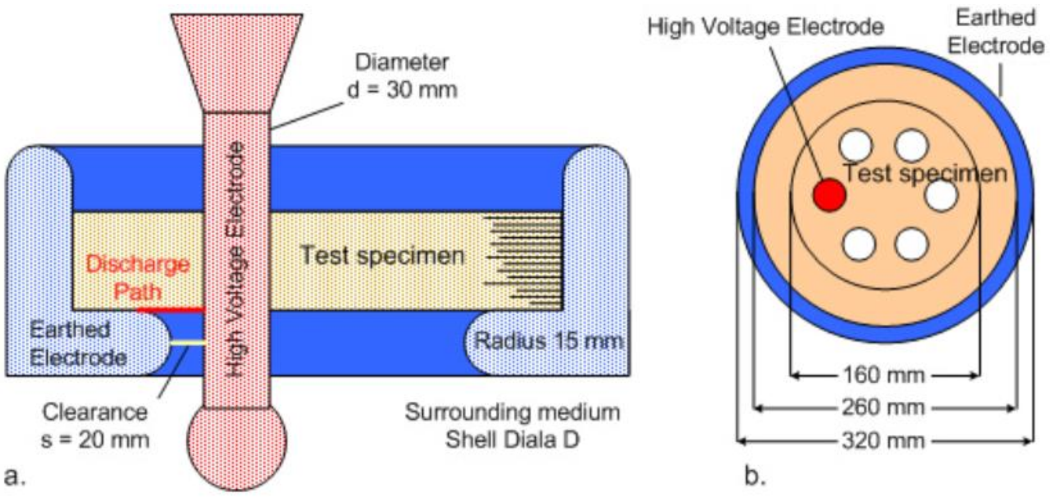


Figure 1 Electrode and test piece setup. a. Cross section b. Top view

Figure 2 shows four photographs to clarify the electrode configuration and the position of the test piece. During testing, the complete arrangement is positioned in a circular, oil-filled test tank with a diameter of 700mm and height of 700mm.

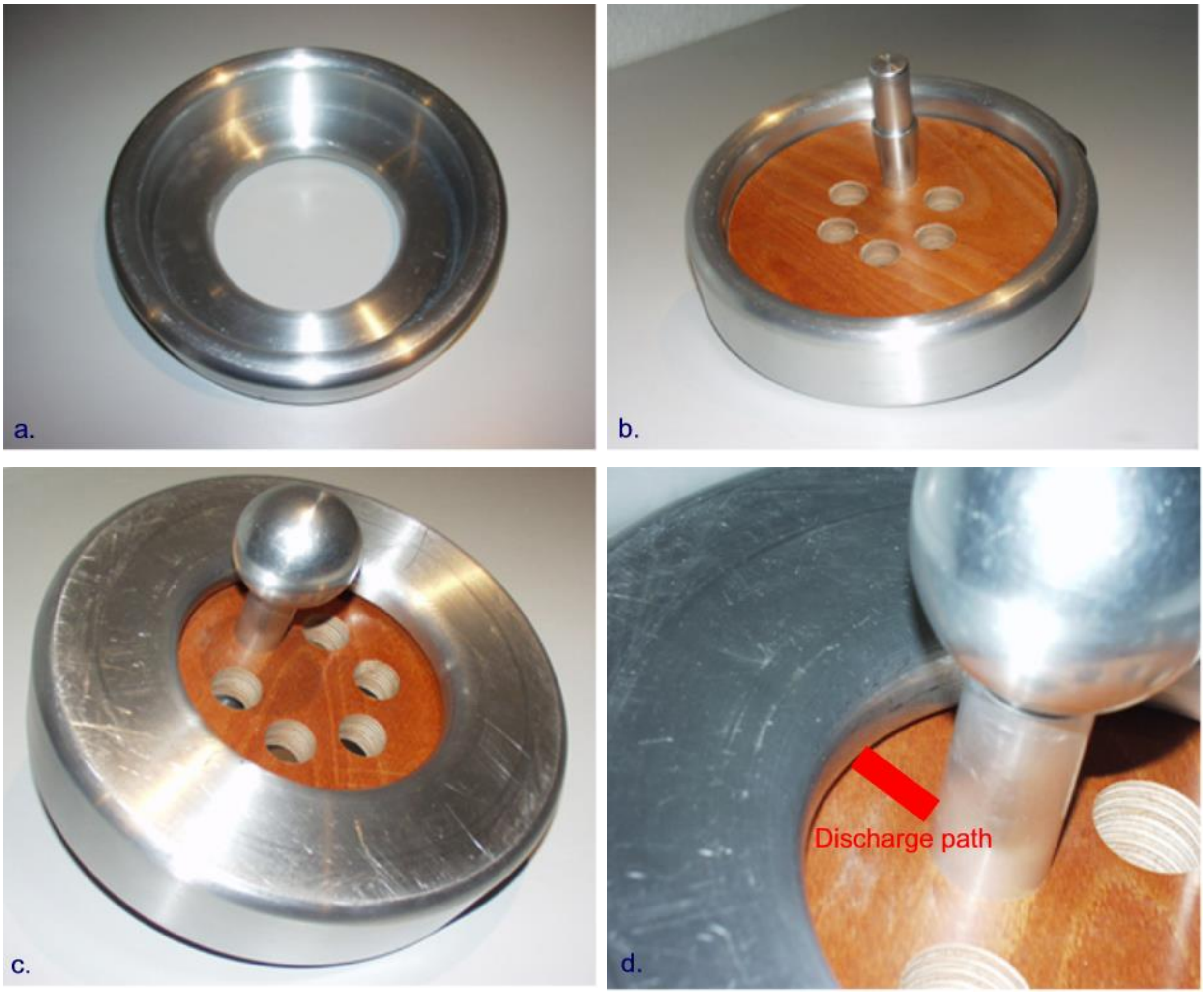


Figure 2 Electrodes and test piece. **a.** Earthed electrode. **b.** Top view of earthed electrode with inserted test piece and the high tension electrode in one of the holes in the test piece. **c.** Bottom view of the earthed electrode with inserted test piece and the high tension electrode in one of the holes in the test piece. **d.** Magnified view of Figure **c.** with discharge path marked.

The discs used as test pieces had six holes to allow each disc to be used for 6 tests. The types of test piece were chosen to provide a range of materials and surface roughnesses:

1. **LDW, sanded with 60 grade paper**: laminated densified wood manufactured by Röchling Engineering Plastics, grade L II/2 E3, surface sanded with 60 grade paper.
2. **LDW, platen finish**: laminated densified wood manufactured by Röchling Engineering Plastics, grade L II/2 E3, platen finish, ie the surface consists of a thin coat of phenolic resin.
3. **LDW/PB without surface treatment**: laminated densified wood manufactured by Röchling Engineering Plastics, grade L II/2 E3, surfaced with 1mm thick pressboard without surface treatment.
4. **LDW/PB with surface treatment:** laminated densified wood manufactured by Röchling Engineering Plastics, grade L II/2 E3, surfaced with 1mm thick pressboard. The surface of the pressboard consists of a thin coat of phenolic resin.
5. **Durostone**: Durostone UPM 203, a plastic manufactured by Röchling Engineering Plastics.

Figure 3 shows a photograph of the 5 types of material used.

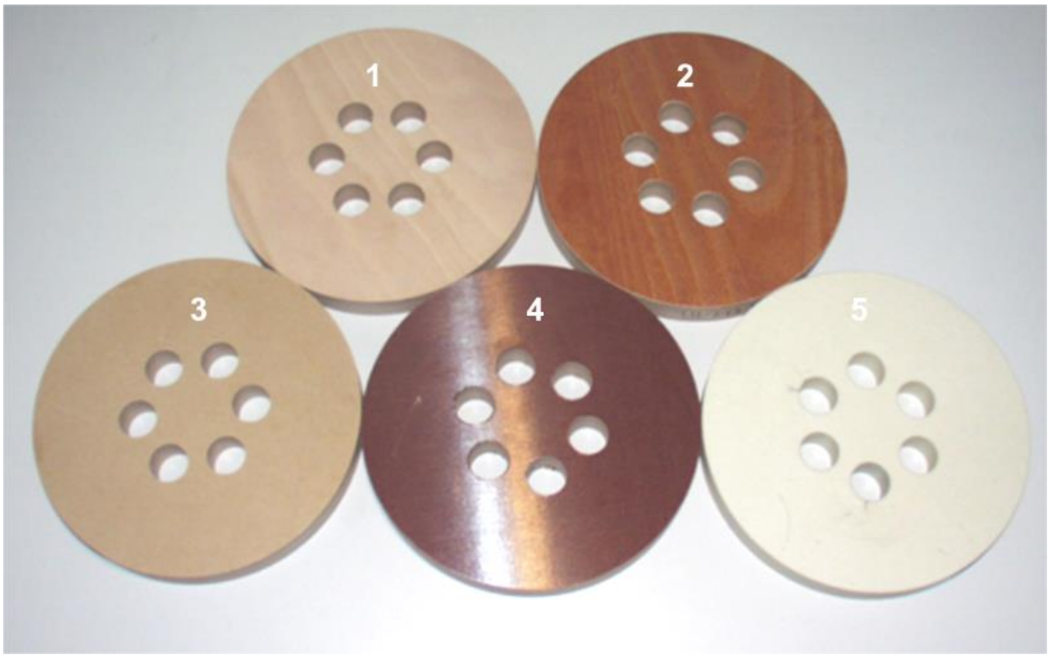


Figure 3 Tested types of material. **1.** LDW, sanded with grade 60 paper. **2.** LDW, platen finish. **3.** LDW/PB without surface treatment. **4.** LDW/PB with surface treatment. **5.** Durostone

After being filled with Shell Diala D mineral oil, the test tank was allowed to stand for 3 days before testing was started.

The test pieces were dried using a standard procedure and impregnated with Shell Diala D insulating oil. After being mounted in the test tank full of oil, each test piece was allowed to stand for at least half an hour.

The electric field in the vicinity of the discharge path was simulated with the FEMLAB 3.0 [3] field simulator. Since the electric field does not differ significantly for the five types of test piece, only the diagram for Lignostone laminated densified wood is shown. **Figur 4** shows the electric field strength and the equipotential lines.

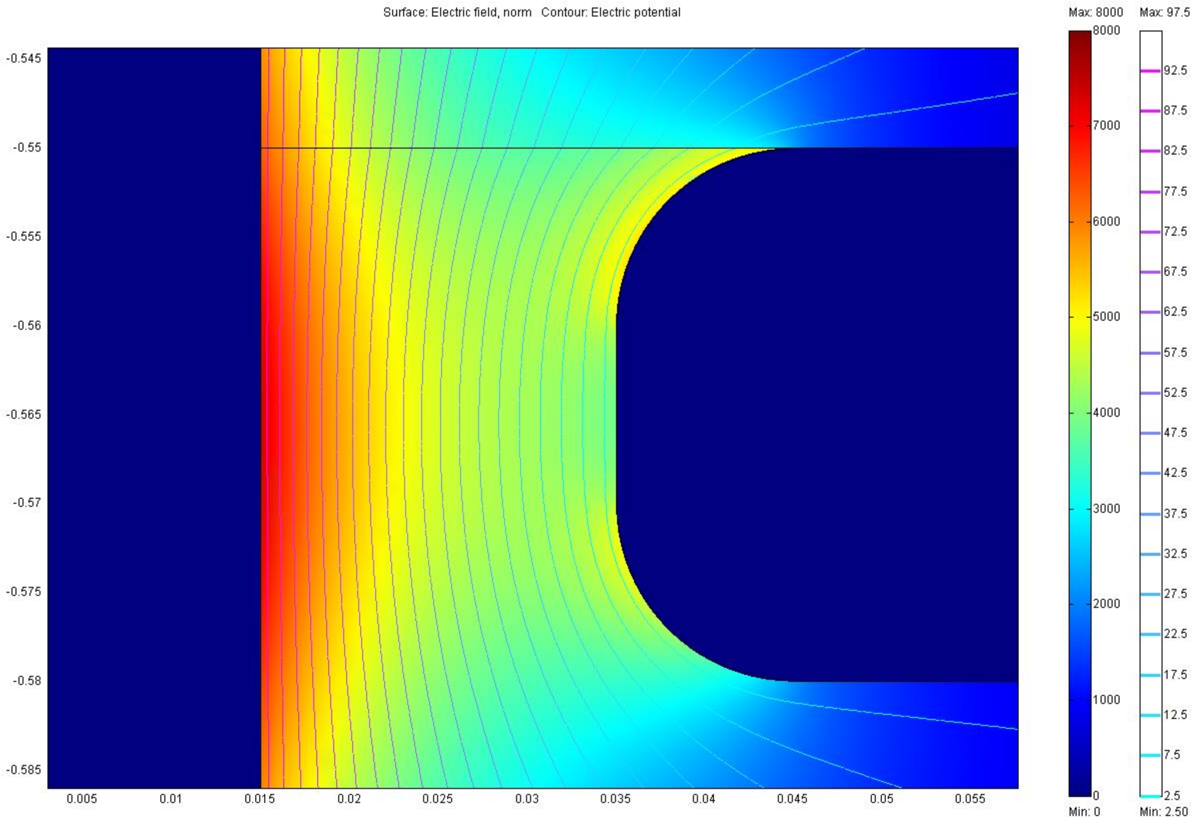


Figure 4 Electric field in the vicinity of the discharge path. Surface plot of the magnitude of the electric field strength and equipotential lines in 5% increments

The variation in electric field strength along the interface between the test piece and the mineral oil is shown in **Figure 5**.

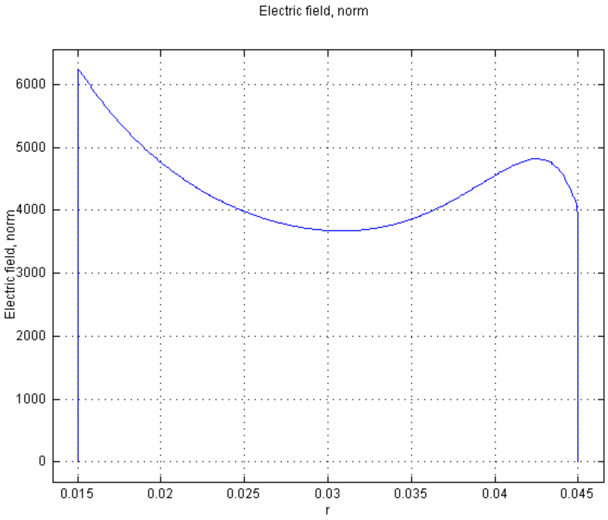
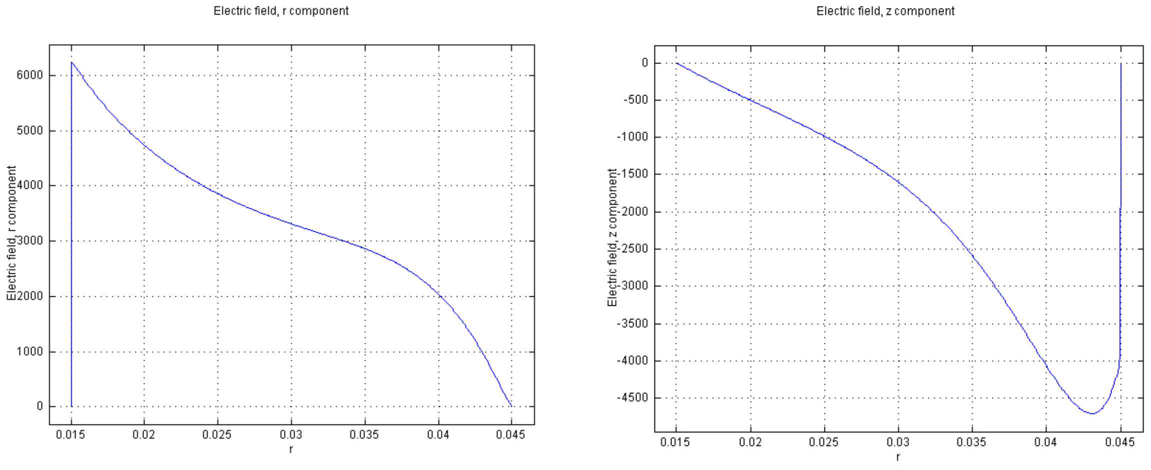


Figure 5 Magnitude of electric field along the interface between the test piece and the mineral oil. All field strengths are relative to an applied voltage of 100V.

This shows the field strength is a maximum in the vicinity of the round conductor. A second, slightly lower field strength maximum arises at the triple point between test piece, aluminium ring and oil.

Figure 6 shows the electric field strength resolved into a radial and an axial component.



a. **b.**

Figure 6 Electric field along the interface between the test piece and the mineral oil. All of the field strengths are relative to an applied voltage of 100V. **a.** Radial field strength component E_r along the discharge path. **b.** Axial field strength component E_z along the discharge path.

The maximum radial field strength component is at the round conductor, whereas the highest axial field strength component is in the vicinity of the triple point.

3 Tests conducted

The 50Hz AC voltage was increased linearly at the rate of about 100kV/min to 0.6 times the anticipated breakdown voltage, and from there in 5% increments of the initial value, each level being applied for 60 seconds.

At least 15 test pieces of each type of material were tested to breakdown.

4 Test results

Figure 7 shows photographs of typical traces of burning on the test pieces after a breakdown. In the case of individual test pieces showing no traces of burning on the surface, the breakdown must have arisen entirely in the oil. Some other test pieces show signs of a breakdown through the insulating material. In both cases the partial discharge breakdown is higher than the measured breakdown voltage.

Omitting the breakdowns that cannot be clearly identified as partial discharges from the evaluation would eliminate the test pieces with particularly high partial discharge voltages.

For this reason, the breakdowns that cannot be identified as cases of partial discharge are also evaluated. As a result, the real mean breakdown voltages and subsequent statistical results are greater than or equal to those determined here. The breakdowns that cannot be clearly identified were most frequent in the case of the test pieces surfaced with PB.

Figure 7 f shows that the breakdown channels in the LDW sanded with 60 grade paper tend to start parallel to the direction of the fibres rather than following the shortest path radially from the round conductor to the triple point. The same behaviour was observed in the case of laminated densified wood with a platen finish.

a. LDW, sanded with 60 grade paper

b. LDW, platen finish

c. LDW/PB without surface treatment

d. LDW/PB with surface treatment

e. Duroplastic (Durostone)

f. LDW, sanded with 60 grade paper

Figure 7 Typical traces of burning on the different test pieces.

Figures 8–12 show the breakdown probabilities for the five types of specimen. The 3-parameter Weibull distribution function was chosen. The 3 parameters $U_{D63\%}$, $U_{D0\%}$ and δ were determined with the Visual-XSEL 2000 Version 7.1 b software package, using the methods described in [4]. The frequency distribution was calculated from these parameters using the following equation:

$$H = 100\% \cdot \left[1 - e^{-\left(\frac{U_D - U_{D0\%}}{U_{D63\%} - U_{D0\%}} \right)^{\delta}} \right]$$

where H = frequency, D = breakdown, U = voltage. For the frequency distributions shown in **Figures 8-10 a** minimum breakdown voltage was determined, whereas this was not possible for LDW faced with pressboard (**Figures 11** and **12**). For these two cases a minimum discharge voltage $U_{D0\%}$ of zero was entered, ie the Weibull distribution is based on 2 parameters (ie only still depends on $U_{D63\%}$ and δ). A larger number of test pieces would allow a minimum breakdown voltage $U_{D0\%}$ to be determined in this case as well.

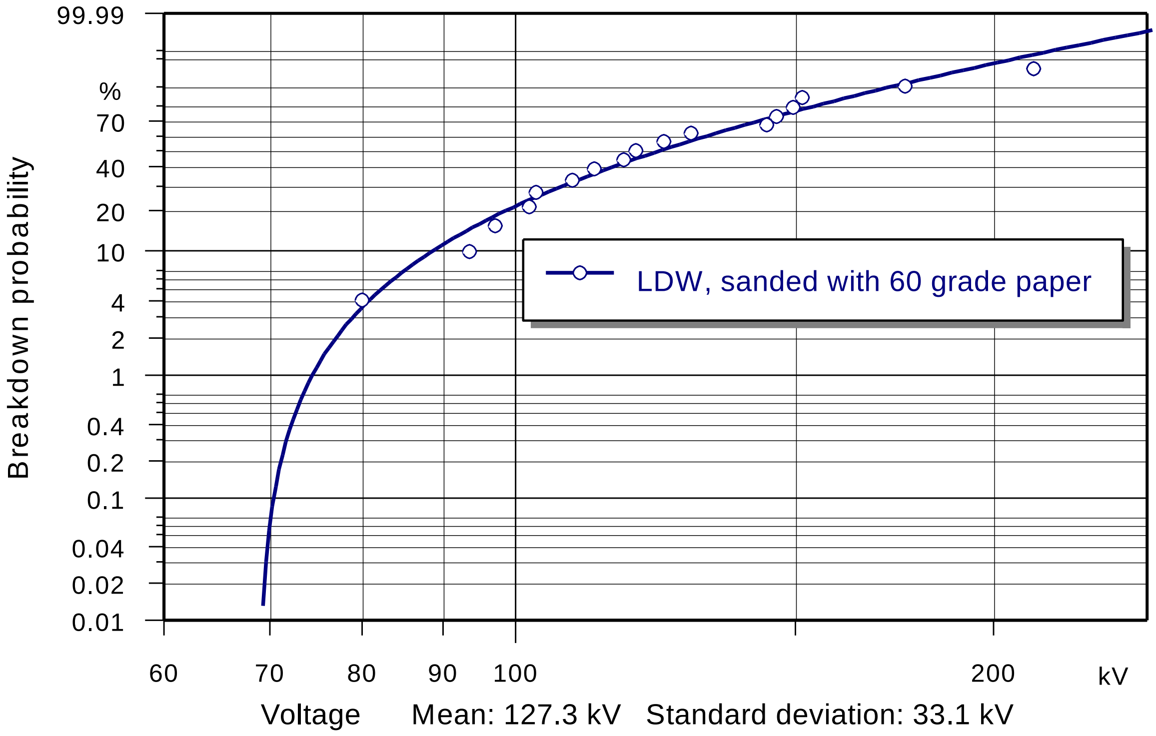


Figure 8 Three-parameter Weibull distribution of the measurements for the LDW sanded with 60 grade paper. The diagram also specifies the mean and standard deviation.

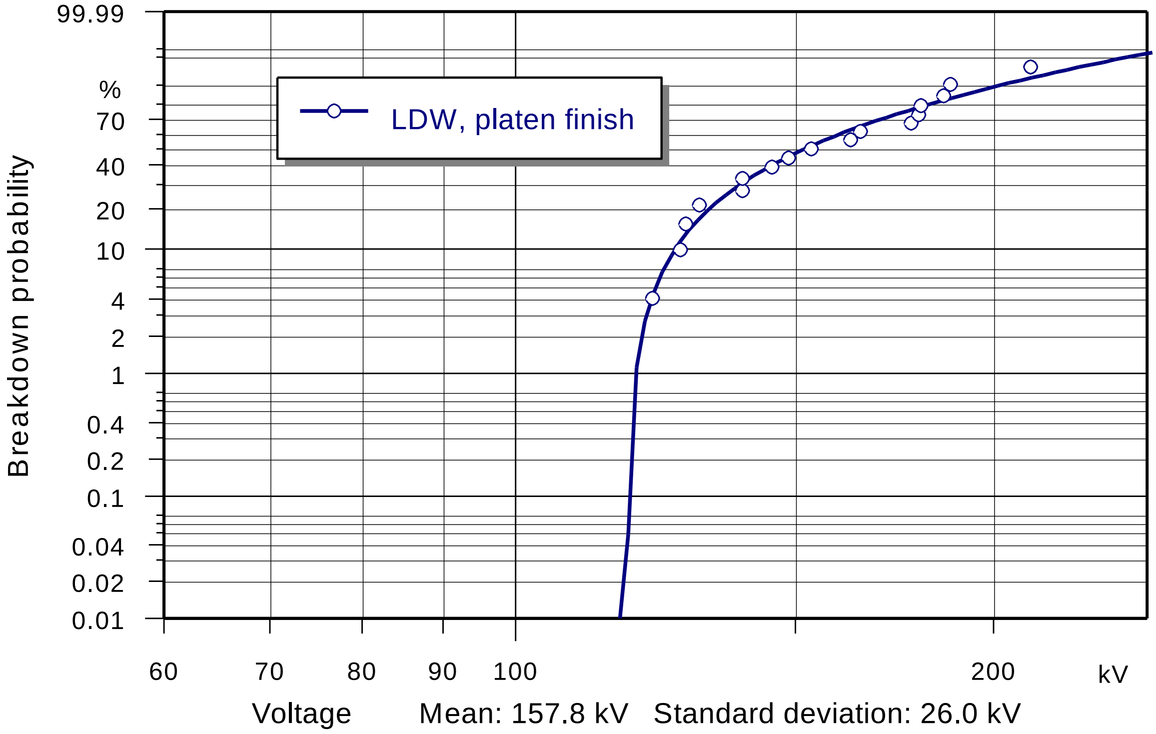


Figure 9 Three-parameter Weibull distribution of the measurements for the platen finish LDW. The diagram also specifies the mean and standard deviation.

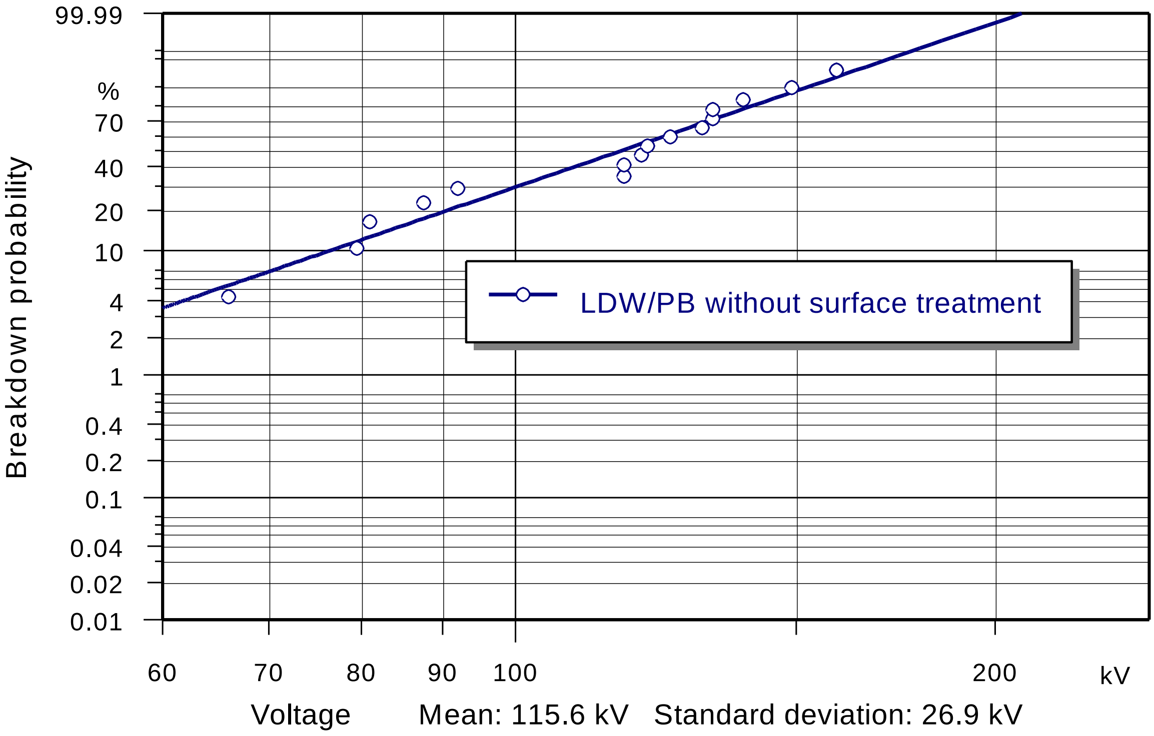


Figure 10 Three-parameter Weibull distribution ($U_{D0\%} = 0$) of the measurements for LDW/PB without surface treatment. The diagram also specifies the mean and standard deviation.

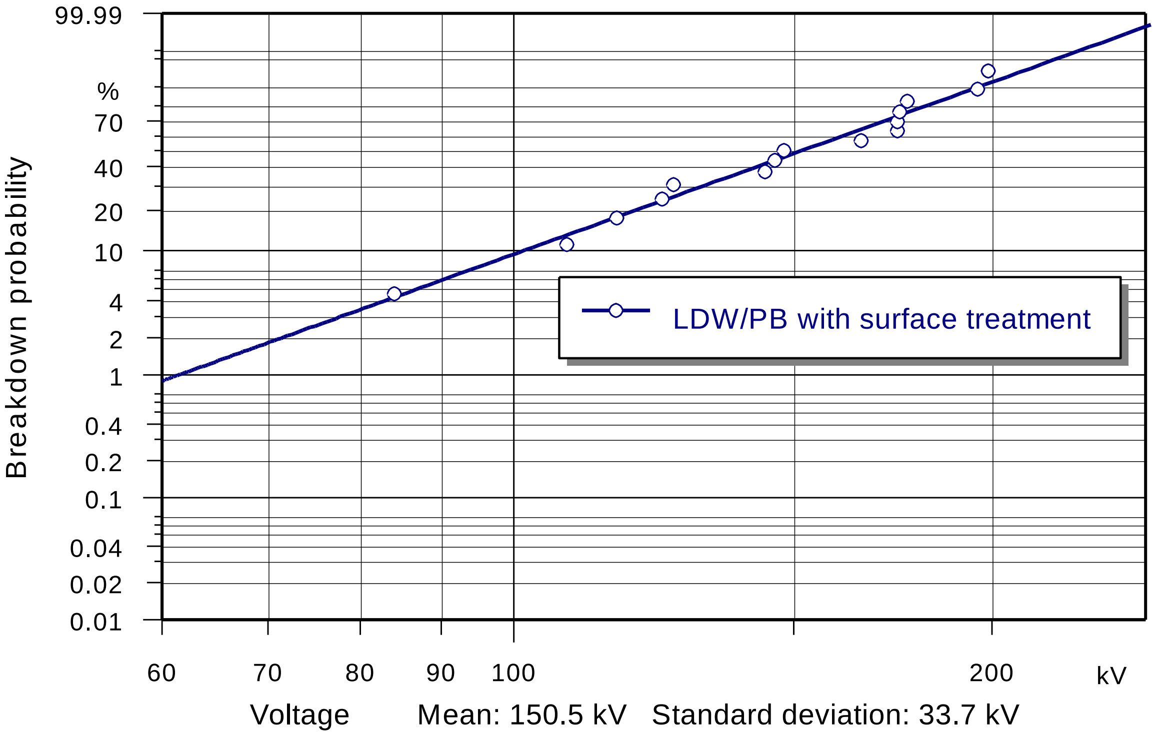


Figure 11 Three-parameter Weibull distribution ($U_{D0\%} = 0$) of the measurements for LDW/PB with surface treatment. The diagram also specifies the mean and standard deviation.

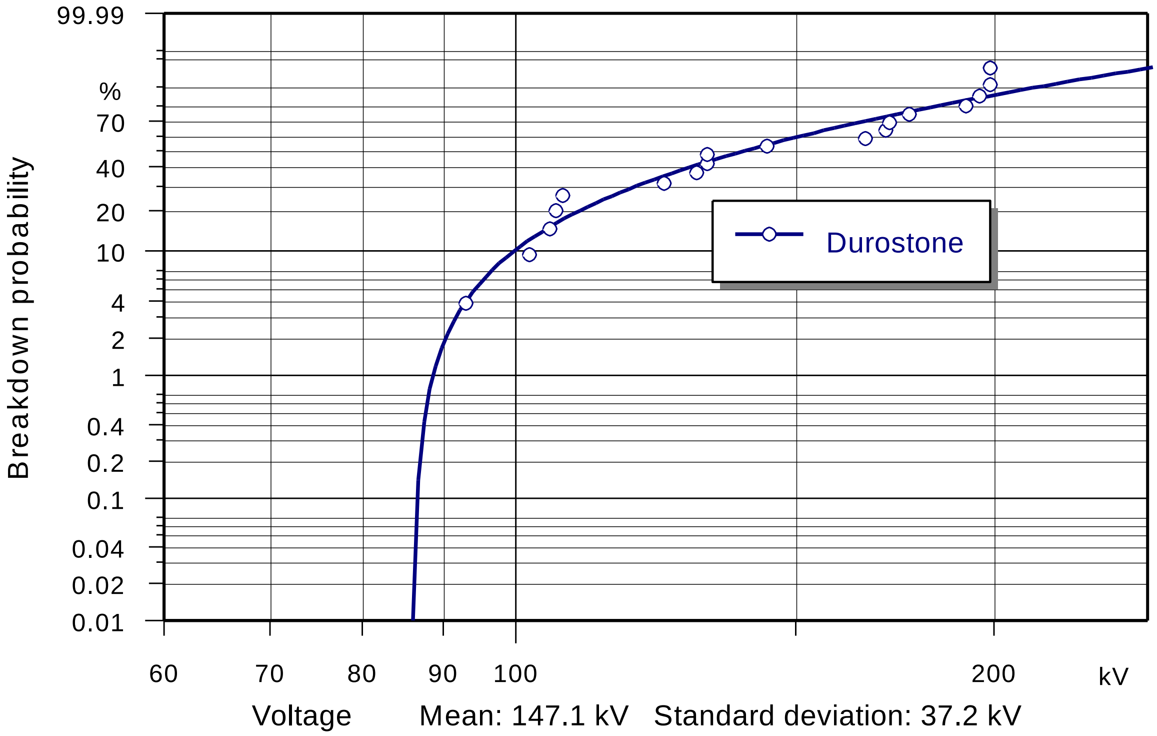


Figure 12 Three-parameter Weibull distribution of the measurements for Durostone. The diagram also specifies the mean and standard deviation.

Table 1 summarises the result from **Figures 8-12** with the means of the breakdown voltages, the standard deviation and the 3 Weibull parameters for the five different types of material.

Table 1 Results of breakdown tests on five different types of material

Statistical data on breakdown voltages					
Type of test piece	**LDW sanded with 60 grade**	**LDW platen finish**	**LDW/PB without surface treatment**	**LDW/PB with surface treatment**	**Durostone**
Mean [kV]	> 127.3	> 157.8	> 115.6	> 150.5	> 147.1
Standard deviation [kV]	33.1	26.0	26.9	33.7	37.2
$U_{D63\%}$ [kV]	135.4	163.2	126.8	164.5	155.9
$U_{D0\%}$ [kV]	68.7	117.6	0.0	0.0	86.2
δ	1.88	1.34	4.47	4.68	1.38

Allowing for the scatter, the materials with smooth surfaces, ie platen finish LDW, LDW/PB with surface treatment and the duroplastic Durostone, tended to have similar characteristics.

Even the materials with rough surfaces, ie LDW sanded with 60 grade paper and LDW/PB without surface treatment, behave similarly when scatter is taken into account.

However, the breakdown voltages of platen finish LDW differ by a factor of 1.24 from those of LDW sanded with 60 grade paper. The mean breakdown voltage of test pieces with pressboard with and without surface treatment also differ by the very considerable factor of 1.30.

The plastic test pieces also tested to provide a comparison with platen finish LDW and LDW/PB with surface treatment have very smooth surfaces and similarly high mean breakdown voltages. These tests show that it is probably the surface finish that is crucial, and the material itself does not play the key role.

5 Further work

The results reveal an interesting approach to influencing partial discharge characteristics through the surface finish. Further tests with a larger number of specimens and different, precisely defined smoothed surfaces must be conducted to enable detailed conclusions to be drawn about the relationship between roughness and surface finish on the one hand, and breakdown voltage on the other.

References, equipment and software manuals

[1]	Küchler, A	Hochspannungstechnik (High Voltage Engineering), VDI-Verlag, 1st edition 1996
[2]	Buckow, E Havekost, M	Investigation of Creeping Discharges on the Surface of Laminated Densified Wood Used in Power Transformers. Technical Report 1999, High Voltage Laboratory, Osnabrück University of Applied Sciences, http://www.et.fh-osnabrueck.de/energie/HochspannungstechnikEMV/index.html
[3]	Comsol	Manuals for FEMLAB 3.0 field simulator, www.femlab.de
[4]	CRGRAPH	Manuals for Visual XSEL 2000 statistical software, www.crgraph.de

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