Impulse and DC breakdown strength of polypropylene thin film

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Abstract. The paper presents the results of a study of the electric strength of a polypropylene film with a thickness of 2 μm. The breakdown voltage of the film was determined under the influence of electric pulses and with a slowly increasing voltage. The rate of increase in voltage at the pulse front varied from 1.8 to 78 GV/s, and with a slowly increasing voltage it varied from 28 to 1100 V/s. A statistical analysis of the breakdown voltage data was performed. For both modes of electrical testing and at all rates of voltage increase, the most probable breakdown voltages $F_{br.exp}$ were calculated. The effect of the voltage rise rate on the value of $F_{br.exp}$ was not detected. The obtained values $F_{br.exp}$ were approximately the same for both test modes and amounted to 550 MV/m for DC and 570 MV/m for pulses.

Keywords: breakdown, polymers, films, polypropylene, impulse, DC, Weibull distribution.

Introduction

The electrical strength of polymer dielectric materials has been studied for many decades. However, due to the great scientific and practical importance of the phenomenon of electrical destruction and breakdown of dielectrics, studies on the electrical strength of polymers remain relevant.

Numerous experiments have shown that the electrical destruction of polymer dielectrics is not a critical event that occurs when a certain field strength is reached. The lifetime of dielectrics in an electric field (durability) τ decreases exponentially with increasing field strength. The kinetic nature of electrical strength of polymers is due to the gradual accumulation of various kinds of damage of macromolecules in them, which is initiated by an electric field. The rate of damage accumulation depends on the electric field strength F (Li, Yin, Wang et al. 2003; Liufu, Wang, Tu et al. 1998; Zakrevskii, Sudar, Zaopo, Dubitsky 2003).

Thus, when determining the electrical strength characteristics of polymer dielectrics it is necessary to take into account the peculiarities of the electric test mode, i.e. to take into account the dependence τ(F) when the polymer is exposed to a constant electric field, or the dependence of the breakdown intensity F_{br} on the rate of electric field strength increase dF/dt. Here $F = U/d$, where U is the stress on the sample, d is its thickness, t is time. The F_{br} value is determined by the voltage on the sample at the time of breakdown.

As a result of the kinetic nature of electrical destruction of polymers, the F_{br} values of polymer materials measured at different values of dF/dt may differ significantly (Zakrevskii, Sudar 1996). Therefore,

the electrical strength of different polymers may only be compared by comparing the F_{br} dependencies on dF/dt established for these polymers.

Difficulties also occur when comparing impulse breakdown strength and breakdown strength determined in a slowly increasing electric field (quasi-constant electric field) for the same polymer dielectric.

The known data on the pulse electrical strength of polymers are quite contradictory. For example, prior research (Watson 1971; Watson 1972) on the impulse breakdown of polymethylmethacrylate has established the existence of a maximum on the F_{br} (dF/dt) dependence. By contrast, the minimum breakdown voltage on F_{br} (dF/dt) is set for polymers such as PET, PTFE and polyimide (Vazhov, Moldobaev 2009). The authors of (Krivko, Lekht 1970; Zakrevskii, Pakhotin, Sudar 2018) recorded only the increase of F_{br} for polyethylene terephthalate when the edge steepness of the pulse increases.

At the same time, a number of works show a decrease in the breakdown voltage of polymers on impulses in comparison with F_{br} value at slow (100–1000V/s) increasing voltage (Artbauer, Griač 1965; Cooper, Rowson, Watson 1963; Watson 1971). It should be noted here that the F_{br} values obtained by the authors of these works may have statistical variation. Therefore, conclusions about the difference in the electrical strength of polymers in the pulsed and quasi-permanent electric fields should be statistically justified; however, in the cited publications there is no statistical analysis of the results. Thus, the indicated difference in F_{br} values cannot be considered conclusively proven.

The purpose of the present work was to determine the value of the impulse breakdown strength of polypropylene (PP) film and F_{br} values of this film in the quasi-static mode of electrical influence at different rates of voltage rise on the sample, as well as provide comparison and statistical substantiation of the obtained results.
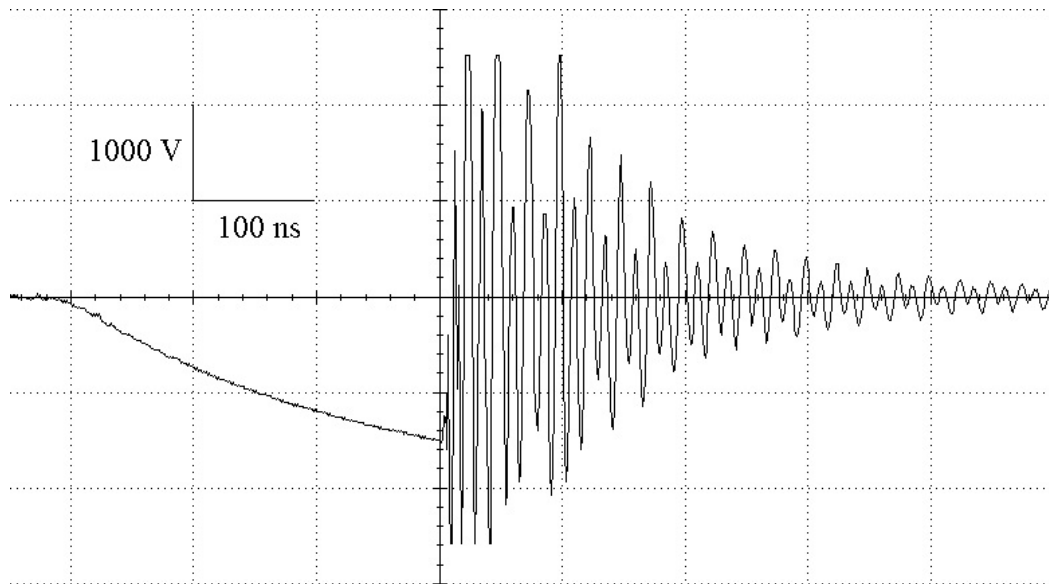

Fig. 1. Oscillogram of the signal recorded at the breakdown of PP film

Experiment design

The object of investigation was an oriented industrially produced PP film with the thickness of $d = 2$ μm. It was fixed in a special mandrel between two steel electrodes and placed in capacitor oil, which prevented the occurrence of edge and surface discharges. One of the electrodes (flat) was under the ground potential. The second spherical (6 mm in diameter) electrode was supplied with either a high voltage pulse of negative polarity with duration of ~10 μs or an increasing negative voltage. Both at impulse and quasi-stationary electric influence on film samples, the voltage increased by exponential law, $U(t) = U_{max} [1 - \exp(-t / \tau)]$, where $U_{max} = 2000$ V, and τ is the time constant, varied in the experiments. The value of U_{max} was chosen so that the breakdown of the polymeric film occurred at a single exposure of a sample to an electrical pulse. It was usually observed at the pulse front.

It should also be noted that with exponentially rapid voltage rise, the rate of voltage growth on the sample decreases as the voltage increases. Therefore, further on, when comparing the experimental data, the largest value dF/dt was used, which was defined at $t = 0$ and equal to $U_{max} /(\tau d)$.

The moment of the polymer film breakdown was recorded by a digital oscilloscope fixing the high voltage on the sample at any given time. High voltage was supplied to the oscilloscope input via a TT-HV-250 1:100 voltage divider with a 300 MHz band and a maximum operating voltage of 2500 V. When determining F_{br} the oscilloscope "Velleman" PCS-500 was used in the quasi-stationary mode, and the oscilloscope "Aktakom" ASD-2332 was used in the pulse mode.

A typical oscillogram of the impulse breakdown development in the investigated film is presented in Fig. 1. The moment of breakdown corresponds to the moment when oscillations arise.

Experiment results and discussion

The breakdown voltage values U_{br}, experimentally determined in both electrical test modes, demonstrated statistical variance. So, with each fixed value of dF/dt, 55 breakdowns were made in different areas of the polymer film. On the basis of the obtained U_{br} values, the breakdown voltage distribution function (DF) $f(U)$ was calculated, defined as

$$f(U) = \frac{n}{N} , \tag{1}$$

where N is the number of tests performed ($N = 55$) and n is the number of samples that broke through when the voltage U was reached. Thus, the DF shows the probability that the U_{br} value does not exceed the specified U value.

For approximation of the empirical DFs calculated by equation (1), we used the Weibull distribution (Weibull 1951):

$$f(U) = 1 - \exp\left[-\left(\frac{U}{U_0}\right)^m\right], \tag{2}$$

where m is a form parameter and U_0 is a scale parameter. Fig. 2 presents typical empirical DFs obtained from impulse electrical breakdown for $dF/dt = 2.7 \cdot 10^{15}$ V/(m·s) (line *1*) and quasi-stationary breakdown $dF/dt = 3.4 \cdot 10^7$ V/(m·s) (line *2*) on the Weibull probability paper. In the coordinates under consideration, they can be approximated by straight lines whose parameters are determined using the least squares method. Based on the values of the angular coefficient and the initial ordinate of these lines, the values of the form and scale parameters were calculated. Their values are presented in the Table. It should be noted that in all cases the correlation coefficient of approximating lines was no less than 0.9, which indicates the validity of the Weibull distribution.
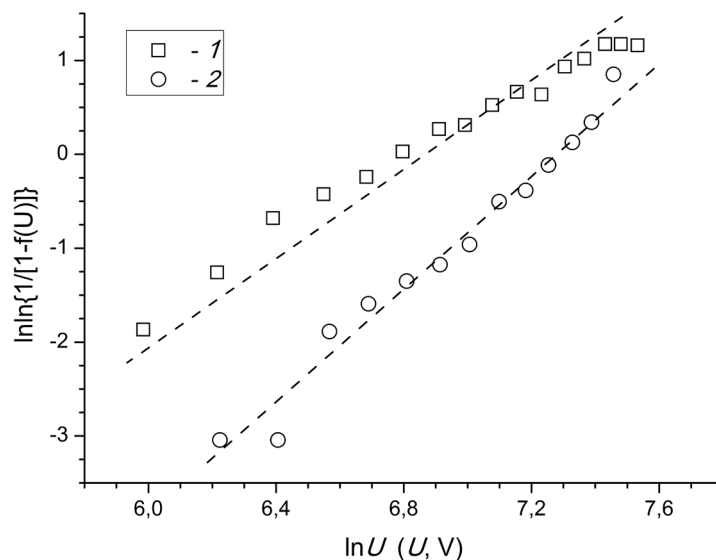

Fig. 2. Linearized DFs for the breakdown stresses of PP film at different values of field strength increase rate: *1* — 2.7·10^{15} V/(m·s); *2* — 3.4·10^7 V/(m·s)

Table. Values of the scale and form parameters of DF for different values of *dF/dt*

Quasi-stationary testing mode			Pulse testing mode		
dF/dt, V/(m·s)	m	U$_0$, V	*dF/dt*, V/(m·s)	m	U$_0$, V
5.6·10⁸	2.7	1300	3.9·10¹⁶	2.9	1010
4.2·10⁸	2.5	1050	1.2·10¹⁶	2.3	1160
1.6·10⁸	2.7	1260	4.6·10¹⁵	3.1	1260
6.8·10⁷	2.0	1150	2.7·10¹⁵	2.3	980
3.4·10⁷	3.1	1410	1.9·10¹⁵	2.0	1290
1.4·10⁷	1.9	1560	9.0·10¹⁴	1.8	940

The values m and U_0 were used to calculate the mathematical expectation of the breakdown voltage $U_{br.exp}$ and the variance σ, defined as follows

$$U_{br.exp} = U_0 \Gamma\left(1 + \frac{1}{m}\right) \qquad (3)$$

and

$$\sigma^2 = U_0^2 \left[\Gamma\left(1 + \frac{2}{m}\right) - \Gamma^2\left(1 + \frac{1}{m}\right)\right]. \qquad (4)$$

Fig. 3 presents the dependence of the most probable breakdown strength $F_{br.exp}$ on the electric field intensity increase rate. We can see that the values $F_{br.exp}$ determined in quasi-stationary and impulse modes of electrical tests are close in value, but are characterized by a significant variation. The rate of the voltage increase does not affect the value of $F_{br.exp}$. It should be noted that the fact that there is no dependence for the PP film at a slowly increasing voltage is well-known (Zakrevskii, Sudar 1996) and is believed to result from the peculiarities of bulk charge accumulation in the PP film.
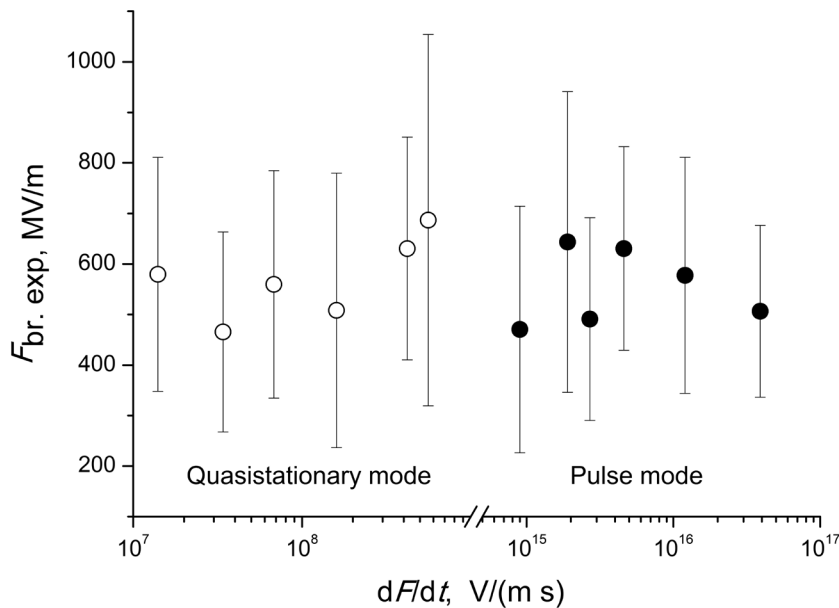

Fig. 3. A plot of the most probable breakdown strength of the PP film vs the electric field strength increase rate, established in quasi-stationary and impulse modes of electrical testing

Conclusion

In the present paper, experimental data on the values of breakdown strength of thin film of PP at various modes of electrical tests, namely pulse and quasi-stationary modes, were obtained. Grounds for applying Weibull distribution for the analysis of the received values of breakdown voltage of a film were established. The statistical analysis of the results of electrical tests performed in the paper allowed comparison between the values of the most probable breakdown strength determined in various modes of electrical tests. The results do not indicate a difference in the electric strength of the investigated film in various test modes.

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