ENGINEERING TRANSACTIONS • Engng. Trans. • 46, 1, 131–139, 1998
Polish Academy of Sciences • Institute of Fundamental Technological Research
10.24423/engtrans.662.1998

EXPERIMENTAL METHODS OF DETERMINATION OF SHORT AND LONG-TERM MECHANICAL STRENGTH OF CERAMIC INSULATORS

F. REJMUND and P. RANACHOWSKI (WARSZAWA)

The subject of this paper are the properties of ceramic insulators responsible for transmission of mechanical stresses due to their construction and destination. Taking into account the information about failure of the insulators, the effect of electrical stresses imposed on the insulator structure by the electric field can be neglected. In view of this fact, our considerations concern the parameters characterising short and long-term mechanical strengths and the method of forecasting the minimal time to the mechanical failure.

1. Introduction

The mechanical strength of ceramic materials and engineering objects made of ceramics, such as for example a long-rod insulator, is influenced mainly by the presence of fissures and pores inside the microstructure of the material. Most dangerous are the sharply ended cracks and pores elongated in one direction, because they increase the mechanical and electrical stresses. The high stress appearing at the edge of a microcrack or at the tip of an elongated pore causes further growth of the defect. As a result of this process occurring in a ceramic material under mechanical stress, the crack of critical size is created which in turn leads to damage of the whole object. The creation of a defect of critical length is included in the Weibull model of mechanical strength by supposition of the existence of a weak link in a chain of elements in the material structure [1].

2. Short-term mechanical strength

Short-term mechanical strength depends on the number of defects per unit volume of the material, and on the orientations and size distribution of the defects. The final failure (long-term mechanical strength) depends on the occurrence and the growth of the critical defect. Determination of the dependence of the long-term mechanical strength on the appearance of a defect of critical size for brittle materials, especially for ceramics, needs a statistical approach. The most common brittle failures are based on the Weibull's theory, admitting the appearance of a weak link within the chain of elements in a given volume of the structure. According to Weibull's assumptions, the probability of occurrence of a brittle failure P_f can be determined from the relation:

$$P_f = 1 - \exp\left[-V\left(\frac{\sigma_z - \sigma_u}{\sigma_0}\right)^m\right], \tag{1}$$

where σ_z – fracture stress, σ_u – threshold stress for which $P_f = 0$ (often $\sigma_u = 0$), σ_0 – characteristic fracture stress for $P_f = 63.2\%$, m – Weibull's module, V – volume of the material.

The factor m, known as Weibull's module, is related to the probability density of the occurrence of failure. The higher is the value of m, the narrower becomes the range of magnitudes of the critical failures, resulting in a lower probability of fracture of the tested material (material sample). Consequently, the failure probability of samples is lower. Moreover, the result of formula (1) is the dependence of the mean mechanical strength during tension on the sample volume as $\sigma_z \sim V^{-1/m}$. For the m value approaching infinity, the mechanical strength is no longer a statistical quantity. In the case of electrical porcelain, the value of the Weibull module m is ranging from 5 to 12. The distributions of the brittle fracture probability for different values of the Weibull's module m, as well as for various parameters obtained from the fracture tests of the insulator material, are shown in Figs. 1 a and 1 b. Values of Weibull's coefficient m for different materials are given in Table 1.

Table 1. Values of the Weibull's module m for different materials.

Lp.	Material	Value of m parameter
1	aluminium	20
2	steel	30
3	electrical porcelain	5 – 12
4	alumina ceramics: 99% Al_2O_3 97% Al_2O_3 90% Al_2O_3	– 30 15 – 20 10
5	steatite	8 – 9

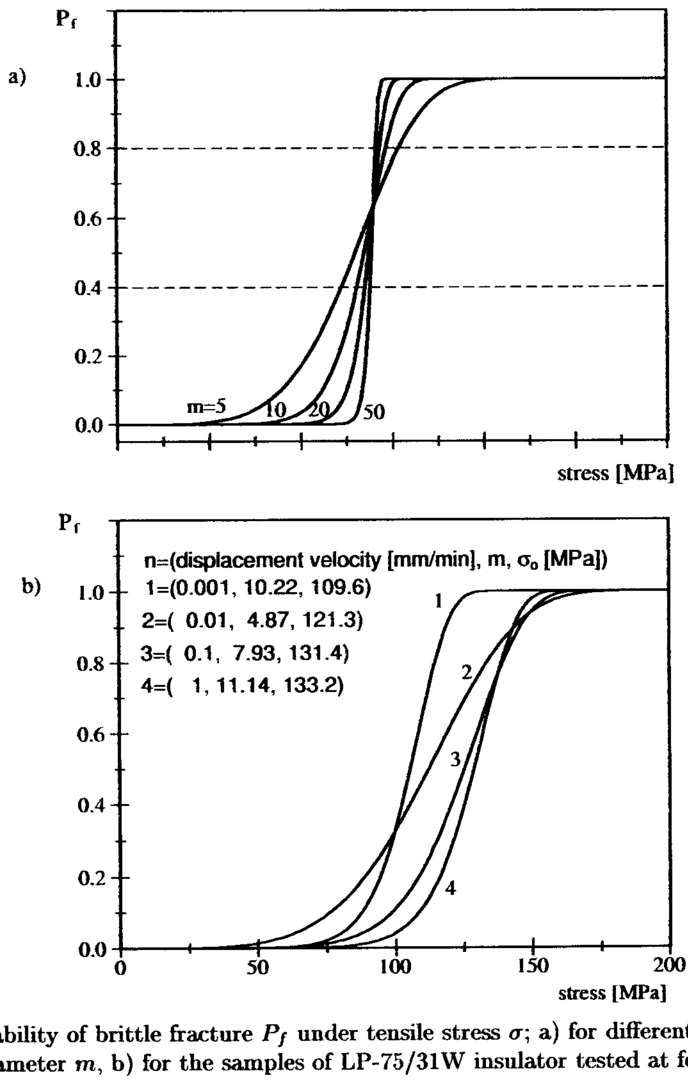

FIG. 1. Probability of brittle fracture P_f under tensile stress σ; a) for different values of the Weibull parameter m, b) for the samples of LP-75/31W insulator tested at four velocities of displacement during a three-point bending.

3. LONG-TERM MECHANICAL STRENGTH

The effect of lowering of the mechanical strength of glasses and ceramic materials during operation under static stress has been known for a long time. Hence this effect has to be taken into consideration when ceramics is used as material for construction purposes, and when either

(a) mechanical properties of particular types of ceramic materials are compared, or

(b) mechanical properties of the ceramic objects made by different producers are compared, or

(c) the time limit to failure during operation under static stress is evaluated.

Modelling of a slow growth of the fissure characteristic for the long-term mechanical strength is based on the relation of the stress intensity factor K_I to the velocity of growth of the fissure used for forecasting the life-time of a ceramic product. The velocity of growth of microcracks for most ceramic materials is described by the relation:

$$V = AK_I^n, \tag{2}$$

where coefficient A and exponent n are parameters of propagation of subcritical cracks.

They depend on the material, the test conditions, temperature and the ambient conditions – hence they must be determined experimentally. Dependence of the velocity of the crack growth V on the stress intensity factor K_{Ic} can indicate the toughness of the ceramic material subject to the growth process of subcritical cracks. Only this relation can be used to compare the toughness of the same type of ceramic materials made by different factories, and subject to microcracking process. An example of such experimental analysis is shown in Fig. 2.

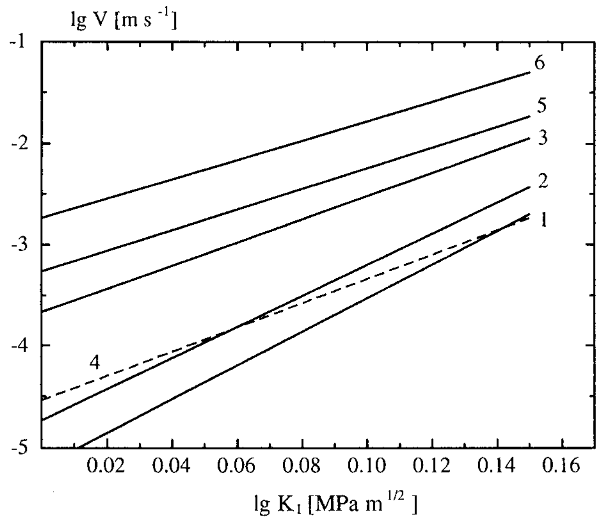

FIG. 2. Dependence of the velocity of crack growth V on the stress intensity factor for insulator porcelain made by different European producers.

Equation (2) is essentially used to evaluate a so-called "lifetime" of engineering objects made of ceramics. It describes the change of the propagation velocity of a crack as a function of the stress intensity factor variation K_I. The time necessary for a subcritical crack to achieve the critical length during the growth process is defined as "lifetime" of the material. The mechanism of brittle cracking proves that the destructive stress σ_f of the sample (a standard notch-less bar of dimensions $30 \times 7.4 \times 3$ mm) depends on the rate of growth of the stress according to the formula:

$$\sigma_f^{n+1} = R\sigma_c^{n-2}\frac{d\sigma}{dt}, \tag{3}$$

where n – exponent from Eq. (2), σ_c – maximum stress at which the growth of cracks does not appear, $R = B(n+1)$, where B is determined from the formula

$$B = \frac{2}{[(n-2)AY^2K_{Ic}^{n-2}]}. \tag{3'}$$

The constant value of Y for a given configuration of the fissure is assumed to be 1.29. K_{Ic} – is the critical value of the stress intensity factor at the moment of catastrophic propagation of cracks in the material. This factor is a constant related to the resistance or, in other words, to the toughness of the material structure subject to the brittle fracture process. The simplest way of determining the value of K_{Ic} is the Vickers indentation method. However, this method can not be used in the case of electrical porcelain of porosity above 3%. For this material the method of three-point bending of a bar with a notch, according to ASTME 399-90 and PN-87/H-04335, was used.

Taking logarithm to base 10 of Eq. (3) we obtain:

$$\lg\sigma_f = \frac{1}{n+1}\lg\left(\frac{d\sigma}{dt}\right) + \frac{1}{n+1}\lg\left[B(n+1)\sigma_c^{(n-2)}\right]. \tag{4}$$

In logarithmic coordinates $x = \lg\sigma_f$ and $y = \lg(d\sigma/dt)$, Eq. (4) represents a straight line with slope $(n+1)^{-1}$. This slope enables the determination of the exponent n. For this purpose, bending tests on four groups of samples, having the shapes of bars without a notch should be carried out. Every group contained at least 30 samples. These samples should be broken in the three-point bending process at the displacement velocity (dy/dt) of 0.001, 0.01, 0.1 and 1 mm/min [2].

Next, the following quantities are determined for every sample:

$S_i = \sigma_i$ – fracture stress of sample number i expressed in [MPa] units;

$$P_i = \frac{i}{\text{number of samples} + 1}$$ – fracture probability;

$$X_i = \lg S_i\,, \qquad Y_i = \lg\ln\left(\frac{1}{1-P_i}\right).$$

The samples in every investigated group are numbered according to the growing fracture stresses. The obtained values X_i and Y_i allow for the determination, for each of the tested group of the bending velocity, the values of Weibull's parameters m and $J = -m \lg \sigma_0$. These factors are characteristic for the inclination angle of the straight lines and the points of intersection with the vertical axis in the system of coordinates (X, Y). Straight lines are obtained by the approximation of the point patterns with coordinates (X_i, Y_i) by means of the least squares method.

Knowing the distribution probability parameters m, J and σ_0, the medians of the distribution $\sigma_{0.5}$, i.e. $P_i = 0.5$, are calculated for the particular velocities. The values of n and A from Eq. (2) are determined basing on the formula (4). Assuming $\sigma_f = \sigma_{0.5}$, equation (4) represents a straight line with a slope $(n+1)^{-1}$ in the coordinates $\lg \sigma_f$ and $\lg(d\sigma/dt)$, and its point of intersection with the vertical axis lies at the elevation:

$$\frac{1}{n+1} \lg \left[B(n+1)\sigma_c^{(n-2)} \right].$$

For every bending velocity, the values $\sigma_f = \sigma_{0.5}$ and $d\sigma/dt$ are found. The value of σ_c is the mean strength at the bending velocity of 1 mm/min.

The straight line, approximating the above mentioned four points, enables us to obtain the values of n and B, and next, basing on the relation (3′), also the parameter A can be determined. Knowing the parameters needed for forecasting the "lifetime" of the insulator material: n, $\lg A$, $\lg B$, m, J and K_{Ic}, it is possible to determine the relation of the minimum time of failure versus the operation stress σ_a admitting a given overstress σ_p/σ_a:

$$\lg t_{\min} = \lg B - 2 \lg \sigma_a + (n-2) \lg \left(\frac{\sigma_p}{\sigma_a} \right). \tag{5}$$

The minimum "lifetime" of the material of the tested insulator at a chosen value of probability P_i, is given by the relation:

$$\lg t_f = \frac{n-2}{m} \lg P_i - n \lg \sigma_a - \frac{n-2}{m} J + \lg B. \tag{6}$$

Representing graphically the relations (5) and (6), usually an overstress σ_p/σ_a of 1.5 to 3.0 is admitted and probabilities $P_i = 0.01$ (1%) and $P_i = 0.001$ (1‰).

Application of the outlined above methodology based on Eqs. (1) and (2) provides the possibility to evaluate the so-called minimal "lifetime" of a new ceramic insulator, or of a one taken from a high-tension line. To obtain the values of the parameters which appear in both the equations, it is necessary to perform the three-points bending tests up to fracture with different velocities of the stress growth. A group of samples used for the tests should contain not less than 120 samples. It is also required to measure the value of the critical stress intensity factor utilising typical samples having the shape of a parallelepiped with a central notch. In case of low porosity ceramics, below 3% per volume, the Vickers indentation method can be used to provide values of the critical stress intensity factor. Both the procedure of obtaining the samples suitable for measurements, and the method of necessary analysis are difficult and expensive.

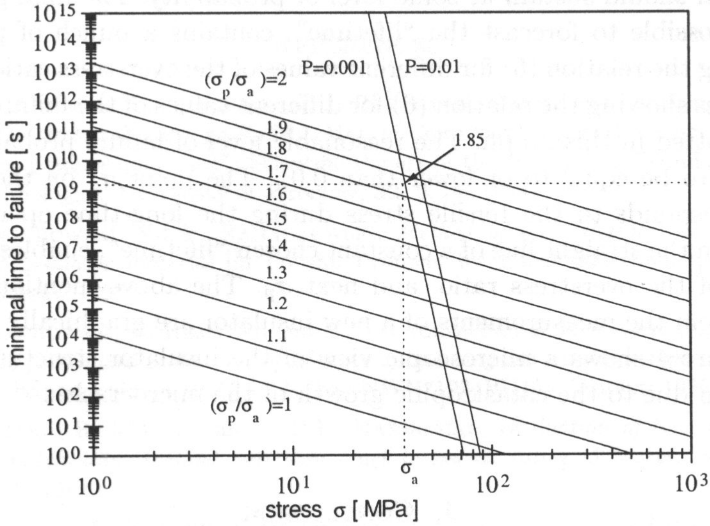

FIG. 3. Diagram of the minimal time of failure for the Polish insulator LP-75/31W (produced in 1995).

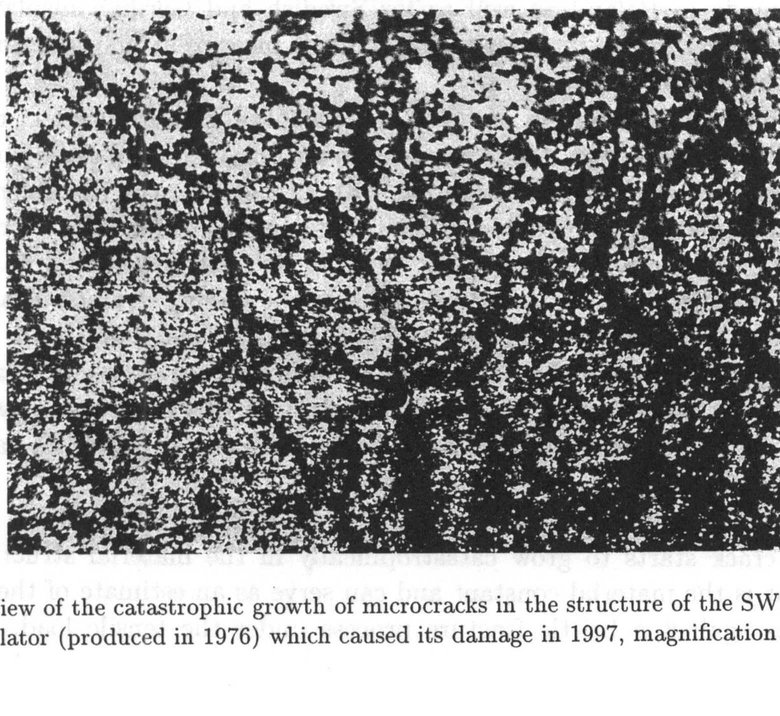

FIG. 4. View of the catastrophic growth of microcracks in the structure of the SWZPAK-110 insulator (produced in 1976) which caused its damage in 1997, magnification ×10.

Also a very specialized apparatus is necessary. Assuming any limited time ("lifetime") during which an insulator should work in a high-tension line without crash, and knowing the stress in the insulator (the maximum tensile load in the insulator), one can determine the value of the short-time overstress ratio which the material should sustain at some level of probability. The final graph, which makes it possible to forecast the "lifetime", contains a bunch of parallel lines representing the relation (5) for different values of the overstress ratio σ_p/σ_a. The parallel lines showing the relation (6) for different values of the failure probability are also plotted in this graph. The reasonable level of failure probability can be considered to be equal to or lower than 0.01. The point σ_a on the stress-axis, which corresponds to the tensile stress during the long-time operation, when projected on the straight line of a constant chosen "lifetime", enables us to obtain the value of the overstress ratio, and next σ_p. The above mentioned relations obtained from the measurements of a new insulator are graphically presented in Fig. 3. Figure 4 shows a microscopic view of the insulator structure which has been broken due to the catastrophic growth of the microcracks.

4. Conclusions

The method described in this paper of evaluating the shortest time of the insulator operation during long-term service has been practically verified for insulators made in Poland as well as for Swedish and German insulators. The experimental technique includes rather difficult measurements, necessary to determine the following quantities.

• Weibull's parameters m and J of the probability distribution of the short-term mechanical strength. These parameters are obtained from three-point bending strength tests of standard samples without notches, the displacement rate growth during a test being held constant and equal to 1 mm/min. To determine the other parameters, the three-point bending strength test should be made for four groups of samples (at least 30 samples in one group) strained at a constant displacement velocity growth equal to 0.001, 0.01, 0.1 and 1 mm/min.

• Next, to determine the parameters n, B and A appearing in relations (4) and (3′), it is necessary to evaluate the velocities of the stress growth $d\sigma/dt$ [MPa/s] and the medians of the strength distribution $\sigma_{0.5}$ [MPa] for each group of the measured samples.

• K_{Ic}, the critical value of the stress intensity factor at the time when the greatest crack starts to grow catastrophically in the material structure. This coefficient is the material constant and can serve as an estimate of the material toughness against a brittle fracture process under the tensile load. A simple method of determining the value of K_{Ic} is the indentation method [4]; however this method should not be applied in the case of insulator porcelain with porosity above 3%. For such material the value of K_{Ic} is measured by three-point bending test of standard samples with a notch [5].

REFERENCES

1. J. RANACHOWSKI, F. REJMUND and J. BERTRAND, *Quality and reliability of insulators applied to electrical power* [in Polish], Mat. of Conf. "Outdoor high voltage insulation for electrical power engineering", Scientific Papers of the Institute of Found. El. Engng. of the Technological University of Wrocław, **32**, 9, pp. 19–41, 1997.
2. J. RANACHOWSKI and P. RANACHOWSKI, *Method of the "lifetime" determination of ceramic insulator material* [in Polish], Protocol for Polish Electroenergetic Networks S.A., Warsaw 1997.
3. J. RANACHOWSKI, F. REJMUND and P. RANACHOWSKI, *Determination of critical stress intensity factor and evaluation of lifetime of line long-rod insulator type LP-75/31W* [in Polish], Expert opinion IPPT-PAN, No. NWN/193/BU/95, Warsaw 1996.
4. K. NÜHARA, R. MORENA and D.P.H. HASSELMAN, *Evaluation of K_{Ic} of brittle solids by the indentation method with low crack-to-indent ratios*, J. Mater. Sci. Letters, 1, pp. 13–16, 1982.
5. J. RAABE and E. BOBRYK, *Determination of Weibull factor m and stress intensity coefficient K_{Ic} of ceramics for electronics* [in Polish], Electronic Materials, 3, 75, 1991.

POLISH ACADEMY OF SCIENCES
INSTITUTE OF FUNDAMENTAL TECHNOLOGICAL RESEARCH.
e-mail: frejmund@ippt.gov.pl

Received January 26, 1998.