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Experimental evaluation of resistance to degradation of modern C 120 type porcelain

***Abstract**. The paper presents mechanoacoustic and microscopic testing of degradation processes of modern C 120 electrotechnical porcelain of domestic medium voltage line insulator. Samples of small dimensions, cut off from the rod of insulator, were subjected to compressive loading, with recording of acoustic emission descriptors. Microscopic analysis enabled determining the advancement of degradation effects. Results of experiments revealed high long-term mechanical resistance of tested material, when compared to typical C 120 porcelains.*

***Streszczenie**. W pracy przedstawiono mechanoakustyczne i mikroskopowe badania procesów degradacji w nowoczesnym tworzywie porcelanowym rodzaju C 120 liniowego izolatora SN. Małogabarytowe próbki, wycięte z pnia izolatora, były quasi-statycznie ściskane z jednoczesną rejestracją deskryptorów emisji akustycznej. Badania mikroskopowe ściskanych próbek wykorzystano do opisu mechanizmu degradacji tworzywa. Stwierdzono wysoką krótko- i długotrwałą odporność materiału izolatora w porównaniu do typowych tworzyw rodzaju C 120. (**Eksperymentalna ocena odporności nowoczesnej porcelany rodzaju C 120 na procesy degradacji**).*

Keywords: ceramic insulators, porcelain degradation, acoustic emission (AE), microscopic analysis.
Słowa kluczowe: izolatory ceramiczne, degradacja tworzyw porcelanowych, emisja akustyczna, badania mikroskopowe.

Introduction

The aluminous porcelain of C 120 type has at present wide application in the production of reliable electroinsulating elements of power systems. Line and station MV insulators, hollow insulators as well as bushings are produced using this kind of ceramic material. The reliability of power supply is determined primarily by the durability, closely connected with the long-term mechanical strength of insulators. That is why these properties are the most important in the case of such objects. The evaluation of operating time of the porcelain material is based mainly on the analysis of the formation and development of aging degradation effects in their structure.

From the reports concerning an older type C 120 insulator porcelain, it has been known that about 35 years long period of exploitation causes 30.5% decrease of the mean mechanical strength of insulating material. Besides that, the dispersion of the strength of the exploited insulators is about 2.5 times greater than that of the new elements [1, 2]. In instance of ceramic insulators, degradation of the mechanical and electric parameters is of great importance, because it decreases the reliability of the power supply. The experience obtained during the exploitation of older type insulators has revealed a relatively quick development of the ageing processes [1-4]. This refers to the objects being in operation for some decades of years on domestic and foreign power lines and stations. The factor which had essential influence on the degradation of the material of older type, in the process of time, was a high content of quartz, exceeding 20 %. This component, present often in the form of large grains, caused serious internal stresses in the porcelain body. The quartz phase sometimes showed also a weak joint with precipitates of needle-shaped mullite. An additional problem was the dispersion of the properties, resulting from insufficient repeatability of parameters of technological processes, which was observed still in the nineteen-eighties.

The results of different tests showed that the parameters of the insulator ceramic material seriously deteriorate after a long period of service. This applies particularly to the rods of line insulators, but also to the post insulators, whose porcelain demonstrated significantly worse properties. In the case of post insulators, internal stresses had a crucial influence on the degradation processes. The stresses were specifically connected with the quartz phase in the porcelain structure. The degradation processes in the rod area of line insulators were mainly the result of the service load, but also the ageing played an important role, as indicated by the number of breakdowns – similar for strain and suspension insulators. Technological defects, however, proved to be the primary cause of damage. The material of the domestic insulators showed high diversity in its phase composition and parameters. Also the ageing contributed to the variation in the material properties. In comparison with the line insulators, the porcelain of the post insulators had generally worse parameters. Surprisingly, serious differences were also found within groups of insulators of the same type.

The investigations have amply confirmed the limited resistance of the C 120 material to degradation. On the basis of different research and the operational data, its service life was estimated at maximum 35 years, provided the insulator does not contain any significant inhomogeneities or technological defects [1, 2, 4, 5]. In the work, modern C 120 type material is presented. This porcelain was taken from the domestic MV line insulator LP 60/8 produced in 1999. The aim of study was to compare the structural composition, mechanical parameters and especially the resistance to degradation of the new material with a typical insulator porcelain of the same type.

Ultrasonic control of the acoustic properties of the tested material revealed better parameters than in the case of typical ones. Velocities of the longitudinal c_L and the transverse c_T waves, measured along the lengthwise axis of insulator, were equal to 6420 m/s and 3780 m/s, respectively. The calculated value of Young's modulus E was 86 GPa at density of the material ρ=2.44 g/cm^3 [6]. The uncertainty of measurements for c_L and c_T was ±30 m/s and ±40 m/s respectively, whereas for the calculated value of Young's modulus it was about ±2.0 GPa. In the case of typical material C 120 kind of line insulators, the measured parameters fitted within the ranges: 5790÷6180 m/s for c_L, 3410÷3660 m/s for c_T and 69÷79 GPa for E value ($\rho\approx$2.41 g/cm^3) [4].

Study of material structure and degradation effects

The microscopic phase analysis of examined samples of the insulator material revealed generally satisfying homogeneity along the length of the rod (macro-scale) as well as in the semi-macro scale. Grains of corundum, pores and particles of cullet were uniformly distributed in a glassy matrix in the micro-scale. The typical image of the material structure was presented in figure 1.

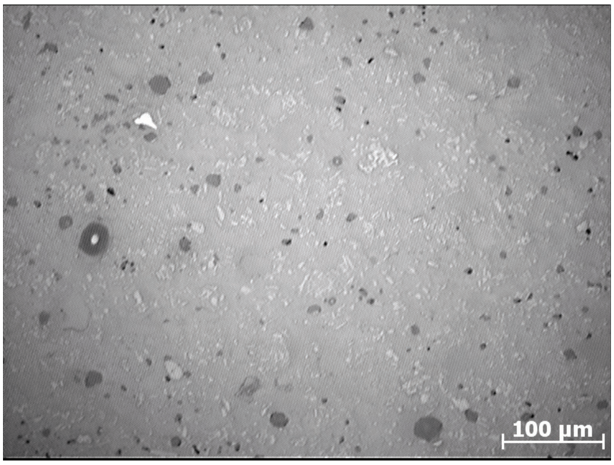

Fig.1. Image of the structure of examined insulator material, magnification 200x. Fine, bright grains of corundum, a little greater quartz grains and white particles of cullet are visible. Darker precipitates of mullite are almost indistinguishable from glassy matrix. Dark areas of crushed out cullet and quartz as well as fine black pores can be observed

The important crystal phase constitutes fine-grained corundum, in amount of 7.5% by volume. Needle-like crystals of mullite form elongated precipitates, 20–30 μm in size. The content of mullite phase was about 26 %. In the glassy matrix, in amount of 52–55 %, several percent of dispersed crystals of mullite were present. The quartz grains, with the diameter from a few to almost 50 μm, occupied 8–9 % of the porcelain surface. The majority of grains were sufficiently melted at the boundaries and adhered to the glassy matrix. The initial content of cullet was 5%. Approximately half of it fell out during the preparation of polished sections. The particles of cullet had different size, they were about 6 μm on average. Small pores (the most frequently below 3 μm) occupied 0.7% of the surface.

The representative C 120 material, especially of the older line insulators, was characterized by a moderate homogeneity. The quartz content ranged usually between 20 and 30 %. It often occurred in the form of larger grains. This phase was mainly responsible for internal stresses and the initiation and development of cracks, as a consequence of ageing processes. A significant amount of the quartz grains fell out during the preparation of surface of the samples. The mullite phase content was about 33–35 %. Relatively large precipitates, mostly 25–40 μm, were usually uniformly distributed in the material. The corundum phase was present only incidentally as single small grains. The pore content was in a range of 2.8–7.0% (about 5% on average). The glassy matrix content in the material amounted to 40–60 % (usually over 50 %). The matrix was strongly bonded with the mullite precipitates. Small and very small cracks appeared in the neighborhood of quartz grains. The material did not contain any cullet.

Tested material clearly differs from the typical C 120 type porcelain. It contains much less quartz, a little less mullite and pores. The material structure includes 7.5% of corundum, 5% of cullet, and the amount of glassy matrix is considerably higher. The main difference consists in the presence of dispersive structure reinforcement. Structural strengthening is represented by fine grains of corundum and needle-like crystals of mullite dispersed in the matrix, apart from the precipitates,. Such a phase composition is considered to be more resistant to ageing processes.

The mechanoacoustic method, together with a comparative microscopic analysis of the ceramic structure, were earlier employed to investigate porcelain and corundum materials [7]. This method was described in details in paper [8]. The examinations of electrotechnical porcelain C 120 had significant practical importance. By comparing the structural degradation of the material of the insulators removed from service and that of laboratory compressed samples, a close similarity was established. The structural effects of slowly increasing compressive load applied to the material, and the aging processes being the result of many years long service on a power line appear to be similar.

The specimens, cut off from the central part of the insulator rod, were subjected to mechanoacoustic measurements, using the technique of acoustic emission (AE) on a special two-channel measuring system. Pieces of small dimensions (8x8x10 mm) were put to slowly increasing compressive stress at the velocity v=0.02 mm/min, with a simultaneous registration of the force in one channel, and AE descriptors in another. The investigations enabled the recording and description of correlation between the increasing external load and processes of structure degradation, which are reflected in the AE activity. It was necessary to apply a quasi-static, very slow increase of stress, a precise registration of the AE descriptors and accurate preparation of the geometry of the samples [8].

The compressive strength of five samples, loaded until a complete destruction, showed relatively low dispersion: 469, 491, 512, 557 and 563 MPa. The lowest value of strength was unreliable because of surface defects of the sample and was neglected. The mean value of strength was equal to 531 MPa. This value is relatively very high. The typical strength of C 120 type material is usually about 400 MPa. The obtained resistance is slightly lower than in the weaker C 130 type porcelain (about 580 MPa). Besides the damaged samples, a group of specimens was selected for the microscopic investigation. The compression process of these samples was stopped at different levels of stresses: 100, 250, 460, 521 and 541 MPa. Greater pieces of destroyed samples were also subjected to microscopic study. The applied procedure enabled a detailed study of progress of degradation process in the porcelain material, subjected to increasing load. The obtained mechanoacoustic characteristics of the particular samples showed considerable differentiation. Figure 2 shows the typical course of acoustic activity for the sample, whose loading was stopped at 541 MPa, just before destruction. The comparative microscopic investigation of compressed samples and the analysis of known mechanism of structural degradation of electrotechnical porcelain enabled the interpretation of obtained mechanoacoustic patterns [4, 8]. On the basis of these results three successive stages of degradation of the studied material could be recognized.

The first - preliminary stage of material degradation occurs as a result of the internal stresses, created during the manufacturing processes and existing mainly on the micro-scale in the ceramic body. Defects may start to develop at a relatively low energy threshold and under small stresses acting on the sample. The propagation of microcracks in service conditions is slow and takes many years. The preliminary stage of material degradation usually takes place up to about 100 MPa and for some samples only to 60 MPa. This stage is characterized by a low intensity of AE signals and a considerable differentiation among individual samples. The microscopic analysis of prepared specimen surface of loaded to 100 MPa confirmed that preliminary stage of degradation corresponded to the crushing out a greater part of cullet. The particles underwent fracture and separation from the porcelain matrix without any recordable acoustic activity. However, the degradation of significant part of the quartz phase was the source of AE signals. In quartz grains initiated and developed cracks in the perimeter and to a lesser extent - internal cracks. No more than half of the quartz phase and especially small grains of size below 10 μm underwent destruction and crushing out. The degradation did not affect the corundum and mullite phases. The destroyed elements of structure comprised 3–4 % of the surface of compressed samples. Figure 3 presents the material of the sample loaded up to 250 MPa, in which almost only effects of the preliminary stage are visible.

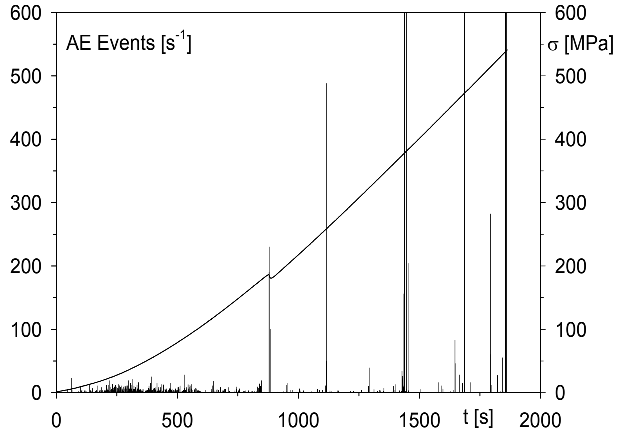

Fig.2. Typical course of the rate of AE events versus the increase of compressive stress for the sample, which loading was stopped at 541 MPa, just before destruction. Only the preliminary and subcritical stages of degradation in the stress range 0÷538 MPa are displayed. Strong signals of the last – critical stage are not included

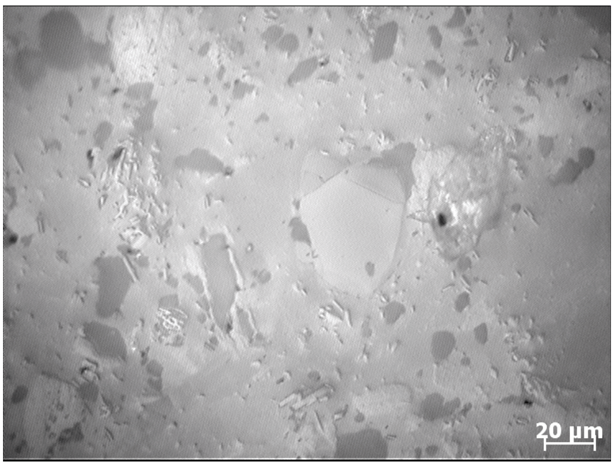

Fig. 3. Representative structure of the sample loaded up to the early subcritical stage of degradation, magnification 500x. Dark areas remaining after crushed out particles of cullet and quartz grains constitute about 4 % of the surface. Fine bright grains of corundum and grey mullite precipitates are not affected by degradation

The second – subcritical stage of structure degradation is closely connected with the homogeneity of the sample structure in the micro and semi-macro scales. The subcritical stage follows the preliminary stage and lasts to the beginning of the critical stage. This phase of destruction varies considerably for particular samples and shows single or series of acoustic signals of low or moderate intensity of AE activity. Intervals of longer AE activity occur rarely. The strongest signals follow the fracture and splitting off the walls and corners from the sample. During this period further damage of cullet particles (without acoustic effects) and quartz grains (weak AE signals) takes place. Peripheral and internal cracks in grains are created. A slow degradation of mullite phase was registered too. The stresses of advanced subcritical stage, especially in the central section of the samples, caused the initiation of internal cracks and sometimes crushing out parts of precipitates. They were strongly bonded with the glassy matrix and peripheral cracks occurred very rarely. In the case of the samples, which were stressed up to the end of subcritical stage (460 and 521 MPa), the area of damaged, separated and crushed out elements of structure comprised about 8 % of the surface. This value included almost the whole cullet (below 5 %), a part of quartz grains (especially of small size) and less than 1 % of the mullite phase. Figure 4 presents the structure of the sample containing moderate effects of subcritical degradation.

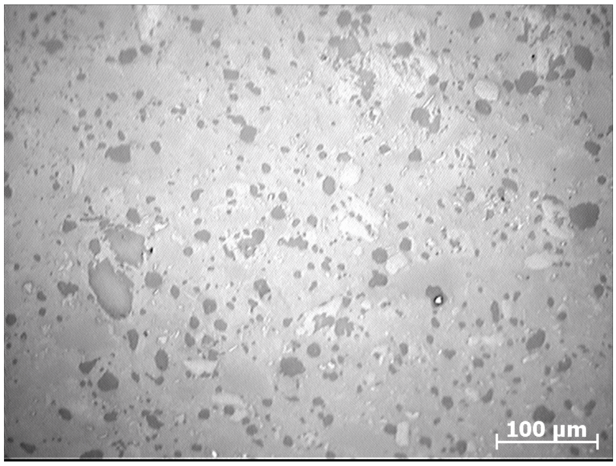

Fig.4. Image of the structure at the boundary part of the sample stressed up to 460 MPa, magnification 200x. Dark areas remaining after crushed out particles of cullet and quartz grains of different size constitute about 7.5 % of surface. Almost all bigger quartz grains contain internal cracks. Damage of mullite and corundum phases are only incidental.

The last one – critical interval, showing the highest level of the acoustic activity, begins at loading from several to dozen or so of megapascals lower than the destructive stress for the particular sample. It lasts up to the destruction of the specimen. This interval is characterized by generally good repeatability of the level of AE signals, which have the highest intensity. Some samples generated signals from the fracture and splitting off greater pieces of the specimen. This effect is visible in the stress curve as characteristic steps – like faults (abrupt decreases). During the critical stage the remaining quartz grains undergo the peripheral and internal fracture. The degradation of the mullite precipitates is continued as well. Grains of corundum are separated from alumina agglomerates. However, such agglomerates were observed very rarely. During the critical stage, just before the destruction, the area of damaged, separated and crushed out elements of structure comprised about 13 % of the analyzed surface. It included almost the whole cullet, about 3/4 of quartz, a small part of mullite as well as corundum. However, the formation and growth of cracks in the porcelain body is the most important and destructive effect, accompanied by strong AE signals. The propagation of cracks is facilitated by previously destroyed elements of structure. These cracks are elongated and in general not branched – see figure 5. They grow initially among the damaged particles of cullet, quartz grains and other crushed out elements of the structure. Similarly, as in the case of C 130 type porcelain, the dispersive and fibrous reinforcement of the material structure hamper their increase. For that reason cracks are usually unbranched. In the case of typical aluminosilicate ceramic materials, including the C 120 type porcelain, single cracks join together and even form a network of cracks. Such effect is observed in the traditional insulator porcelain [4]. At sufficiently high stress, the rapid growth of critical cracks in the porcelain body takes place and the sample undergoes irreversible destruction.

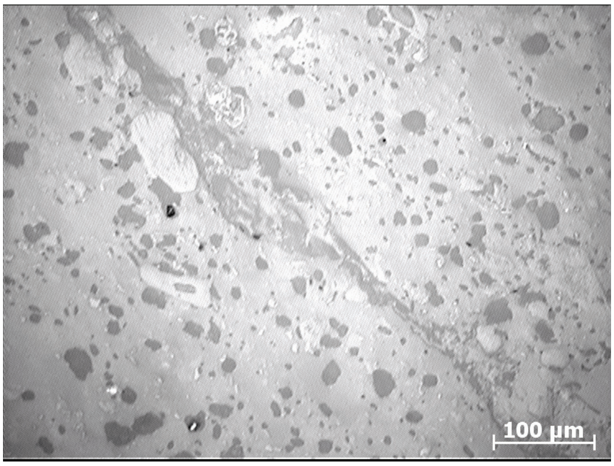

Fig.5. Image of the structure of the piece of destroyed sample, magnification 200x. Large crack and bright fractured grains of quartz are visible. Damages of mullite phase are small and negligible in the case of corundum. Dark areas remaining after crushed out elements of structure exceed 13 % of the surface

The results of the mechanoacoustic study showed clear differences in the degradation process of the tested material, when compared with the typical porcelain C 120 kind. This was the result of different phase composition, and especially the presence of dispersed strengthening of the material structure. There was greater mechanical resistance of mullite precipitates and glassy matrix, which contained scattered grains of corundum and single mullite crystals. As a result, the resistance to the processes of formation and growth of cracks of the tested material was considerably higher, when compared with the typical porcelain of the same kind.

Final remarks

The microscopic, ultrasonic and mechanoacoustic examination of the tested insulator material showed that its properties are intermediate between those of typical kind of material C 120 and a much stronger type of porcelain C 130. Like the latter, the tested material contains dispersed reinforcement of the material structure. Scattered grains of corundum and single crystals of mullite are not as numerous as in the material C 130 type. However, they constitute the factor which effectively hinders creation and growth of cracks. In addition, the glassy matrix of the tested material contains more alumina than the typical 120 type porcelain. Consequently, the glassy phase has a higher mechanical strength. It should be noted that the porosity of the tested porcelain is relatively very low. Therefore, the mechanism of the degradation process is similar to that of C 130 type material. It concerns especially the last – critical stage of degradation. Then, at sufficiently high stress, elongated cracks, usually not branched, undergo fast growth and lead to the damage of the compressed sample.

The structural effects of slowly increasing compressive loading applied to the insulator material, and the ageing processes being the result of many years service on a power line are regarded to be similar [4, 8]. Therefore, these tests can be used to evaluate the operational durability of insulators. “Life time” of a typical C 120 type material was evaluated at 30-35 years [1, 2, 4, 5]. In the case of C 130 type porcelain “life time” was assessed to be approximately 50 years [5]. On the basis of described examinations, it can be assumed that the insulator made of this material, may operate for about 40 years. The crucial condition for such estimation is the lack of significant inhomogeneities or technological defects in the structure of insulator.

Obtaining a significant improvement in the properties of C 120 type porcelain was made possible mainly through the use of ceramic alumina instead of metallurgical Al_2O_3 in the raw material composition. It was also necessary some modification of the technological process of insulator porcelain production.

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