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Arch. Metall. Mater. **65** (2020), 1, 367-374

DOI: 10.24425/amm.2020.131739

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COMPARATIVE STUDIES ON DEGRADATION OF VARISTORS SUBJECTED TO OPERATION IN SURGE ARRESTERS AND SURGE ARRESTER COUNTERS

The paper presents results of investigation of microstructure and micro-hardness for material of ZnO varistors applied to 110 kV surge arrester and surge arrester counter. The research combined two pairs of varistors, each consisted of one varistor subjected before to operation, while the other one was brand new unit and constituted a reference. All varistors were made of the same material by the reputable manufacture. The tests revealed a different degree of the material degradation for varistors subjected before to operation. This also refers to different degradation mechanism observed for the material of these varistors, if typical effects of degradation of aged ZnO varistors were considered as a reference. Physical state of spinel in the microstructure had a significant impact on the material degradation, however a considerable loosening of the microstructure associated with bismuth oxide was observed too. It was surprising, since the precipitates of the bismuth oxide phase most often showed very good binding to the ZnO matrix and high resistance to associated electrical, thermal and mechanical effects. The degradation effects in the ZnO matrix proved to be limited only.

Keywords: surge arrester, surge arrester counter, MO varistors, microstructure of ceramics, ceramic material degradation

1. Introduction

Varistors are commonly used equipment components protecting power systems against overvoltage. In order for the protection to be effective, the quality of these components should be as high as possible. The varistor manufacturing technology, well-established since long and constantly optimized, is relatively simple and cost-effective [1,2]. These elements are made of a relatively cheap and commonly used material – zinc oxide, with usually small additives of other metal oxides. It is these small additives, however, that determine the properties of the product, and the details concerning the raw material composition and technology are the manufacturer's secret. When leaving the manufacturing plant, varistors fulfill the requirements concerning the current - voltage characteristics [3]. Therefore, they provide appropriate overvoltage protection. However, during operation, varistors are durably loaded with working voltage. But first of all, they take over large currents during random overvoltages and other external factors – such as ambient temperature changes. In consequence, the structure of the varistor material gets gradually degraded [1,3].

Many years of research on the flow of current through varistors, including observations of the electroluminescence effect, showed that it is usually of a pathway nature. The current flow pathways join one another to form hot spots [3,4]. During conduction of large currents in the areas of conduction pathways, particularly in hot spots, a large amount of heat is emitted. This results in local, strong heat up and large mechanical stress – both compressive and tensile – in the material. Large heat flow occurs and the material, which, as in the case of ceramic ware, is brittle, may get punctured or crack. The pathway flow of current is the consequence of local conductivity differences. This results from the inhomogenity of the varistor material microstructure, which is very difficult to avoid. Therefore, the homogeneity of material is very important, mainly in the sense of even distribution of doping oxides in the microstructure. The doping oxides are present in intergranular limit layers, triple points, and they also form separate grains, aggregates and spinel phase. Considering

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the fact that admixtures are most frequently a small percentage of the material composition, it is technologically difficult to obtain its requisite high homogeneity.

A separate issue is the appropriate size of ZnO matrix grains, which should amount to approx. 10 micrometers. The inside of the grains is a good conductor, whereas on their boundaries, as a result of an electrostatic electric-potential barrier, a highly insulating area is formed, with a depth of up to 100 nm – on each side, at a boundary layer thickness of approx. 1 nm [1,5]. Non-linear electric characteristics of joints between the grains are obtained only for appropriately formed grains. In the case of improperly selected sintering parameters or raw material composition, smaller dimensions of grains are formed, with poorly non-linear current – voltage characteristics [1,6]. It shall be remembered that ZnO grains should be similar in size – and thus a narrow size distribution (PSD parameter). It is an important factor, which has a significant impact on the compactness, mechanical and thermo-mechanical strength of the material microstructure, and its operational durability.

The effects of degradation of varistors, and the entire equipment, are the consequence of numerous factors, however, in particular of the untightness and the resulting moisture penetration inside the surge arresters or surge arrester counters [7,8]. These lead to the flow of high short-circuit currents and, after a certain time, to a failure. This study is a contribution to the investigations of the degradation processes of the ZnO varistor material in the course of long-term operation.

2. Subject and methodology of tests

As part of the long-term research conducted by authors of the studies in the field of the aging processes of varistor material in the course of varistor operation [8,9], this paper presents the tests results for varistors presenting different degrees of ceramic material degradation. The comparative tests covered two pairs of varistors for the 110 kV power transmission network. They were produced by the same renowned European manufacturer. Analogous, unused varistors were used as a reference.

The first pair of tested components comprised two smaller varistors, one of which was removed from a surge arrester counter after several years of operation and a significant number – approx. 1000 – of operations. The other one, identical as the first one, was not used and served as a reference sample. The first pair of samples is presented in figure 1. The second pair comprised two varistors with larger dimensions. The first one was removed from a damaged surge arrester. The second one was identical, but was not used and, as in the case of the first pair, served as a reference sample. The second pair of samples is presented in figure 2. Figure 3 presents the close-up of the lateral surface of the used varistor – from a surge arrester working in a 110 kV power transmission network after failure – presenting a loss in the protective layer as a result of strong short-circuit current flow.

Optical microscopy (OM) tests of all four varistors comprised the evaluation of the most important parameters of their microstructure. They mainly related to the micro- and semi-macro homogeneity of the material. The tests covered the size of ZnO grains in the body and the number and homogeneity of the distribution of doping phases – light Bi_2O_3 aggregates and spinel grains. The evaluation covered the compactness and degree of sintering of the material, integration of grains and aggregates and their resistance to chipping during performance of

Fig. 1. First pair of samples – varistor from a surge arrester counter on the left and an analogous – reference varistor that was not used

Fig. 2. Second pair of samples – varistor from a damaged 110 kV surge arrester on the left and an analogous – reference varistor that was not used

Fig. 3. Varistor from a surge arrester after a failure, with a well visible loss in the protective layer which resulted from strong short-circuit current flow

surface microsection. The tests included also the number, size and distribution of chipped off elements of the microstructure and pores, which were, however, very small in number. The parameters of the microstructure of the tested varistors were compared also in order to assess the repeatability of the manufacturer's technological processes.

During the preparation of microsections, it was attempted to minimize the impact of mechanical processing on the material microstructure as to the biggest extent possible. Samples intended for tests were cut out from the varistors with the use of a diamond blade saw with a grain size of 30 μm. The test surfaces were exposed on the samples by cutting them with the use of a jigsaw with a working powder with a grain size of 10 μm, in oil suspension. The samples prepared in this way were flooded in epoxy resin and then ground on abrasive paper with a grain size of 1000 and polished on diamond pastes with a grain size in the range of 1 ÷ 0.25 μm. Final polishing was conducted on colloidal silica – 90 nm. Thus, after the removal of the resin coating, the material layer with a thickness of several dozen micrometers was removed. Grinding and polishing was conducted for both pairs of samples simultaneously – using a six-point grinding and polishing head. The samples were washed in water solutions of micellar liquids in strong acoustic fields.

In the tests performed by means of the optical microscopy method (OM), a microscope equipped with a CLEMEX computer image analyzer was used. A lens with a power of 20x was used, which corresponds to the resolution of 0.1 μm. Visual inspection was conducted at the highest available magnification – i.e. 500 times. Microstructure images were presented in the same magnification. The most frequently the Nomarski phase-interference contrast was used. This allows good distinguishing of phases forming the material, and also of cavities after the chipping – crushed out elements of microstructure and pores. However, in such a case, the boundaries of the individual grains and precipitates remain less visible. In order to register the grains of the spinel phase more specifically, the microstructure was also observed with the use of scanning electron microscopy (SEM).

The tested varistor material indicated a grainy microstructure typical for ZnO oxide materials, in which, apart from the main phase, only the phase of bismuth oxide (Bi_2O_3) and cavities after chipped off grains and their aggregates were visible. Sometimes, larger grains were surrounded by groups of smaller grains, often with a worse cohesion. During the grinding and polishing processes, with the use of slurries with a grain size similar to that of the grains forming the body, the areas with a grain and precipitate geometry similar to that of the polishing agent sometimes degrade. In such a case they form cavities. Optical microscopy is characterized with a relatively small depth of focus as compared to, e.g. scanning electron microscopy. In consequence, the areas of fine-grained ceramic microstructure, deformed by polishing and depressed, are visibly darker – in particular if the Nomarski phase-interference contrast is used. At the same time, the grains and their aggregates show different shades of gray. Therefore, part of the dark areas in the images of the microsections in the Nomarski contrast do not, in fact, represent chipping, but depressed grains, their aggregates and precipitates with diverse spatial packing – present in the microstructure.

In addition to microscopic tests, the microhardness of the sample material was measured. The measurements were a significant supplementation of the results of the optical test method of the material. They also enabled an independent assessment of the homogenity and cohesion of the varistor material. The measurements were performed with the use of the Vickers standardized method, using a typical microhardness tester with 1 kG indenter load. A semi-automatic measurement mode of the stamp diameters was used. It should be emphasized that in addition to the obtained average values, the dispersion of results provides important information, indicating the homogeneity of the material microstructure.

3. Results of reference varistor tests

Figures 4 and 5 present typical images of the reference varistors microstructure. The varistor from the first pair was analogous to the element taken out of the surge arrester counter, whereas the varistor from the second pair corresponded to the element from the damaged surge arrester. The images draw attention to the small size of the surface which is occupied by the microstructure elements chipped off as a result of polishing. In both samples, they constitute approximately 2% of the microsections surface, proving good compactness and cohesion of the body. The more so as the homogeneity of the material at a microscale does not raise any doubts either. This indicates an entirely correct homogenization of the raw mass (powder raw materials) and optimal selection of sintering parameters in the production process.

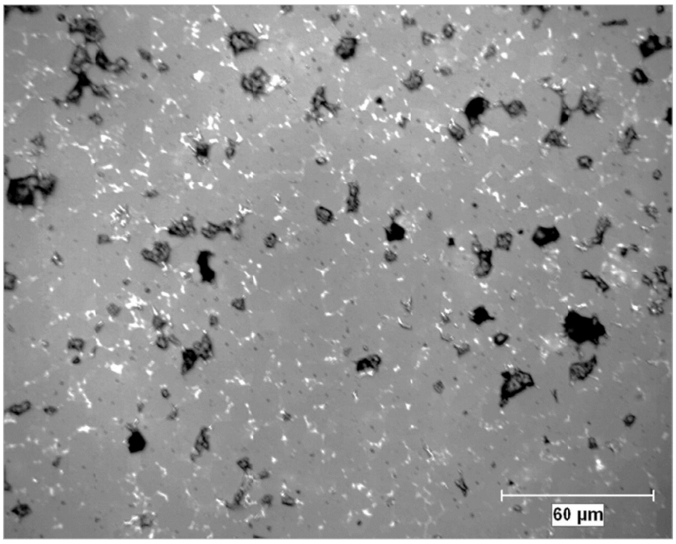

Fig. 4. Typical image of a reference varistor microstructure from the first pair. The precipitates of the light doping phase (Bi_2O_3) and darker gray areas depicting depressed ZnO grain aggregates of diverse packing are quite homogeneous. Black chipping constitutes only approx. 1.5% of the surface

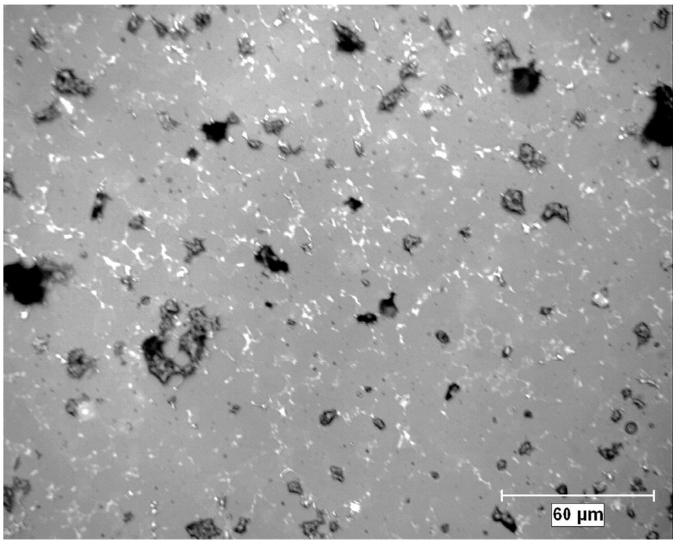

Fig. 5. Image of a reference varistor microstructure from the second pair. A quite homogeneous distribution of the precipitates of the light doping phase (Bi_2O_3) is visible. Black chipping occupies more than 2% of the microsection surface

A visual inspection of the microsections showed that the varistors of both pairs – produced by the same manufacturer – were made of the same material and only slightly differed in terms of the content of doping phases and chipping of microstructure elements caused by polishing. Small differences could result from the fact that the dimensions of the varistors of the first and second pair were different and originated from different manufacturing lots. The images were analyzed with the use of a CLEMEX computer analyzer. After appropriate reformatting at a grayscale – 8 bits and the processing of images from the optical microscope with Photo Paint-Corel, subsequent gray phases in the images of the analyzed varistors could be distinguished. The applied binary masks shown in figures 6 and 7 allowed a quantitative assessment of the phase content in the material. The blue marked phase signifies chipping of grains from the microsection surface and pores, whose amount was, however, marginal. The second – red marked phase comprised light precipitates – bismuth oxide aggregates.

Microscope images of the material of both reference varistor samples were very similar – see figures 4-7. Also within the individual samples, the variability of microstructure parameters was small, which signifies material homogeneity. A detailed visual inspection of the microsections in a special lighting and observation using the SEM method allowed to determine that the size of ZnO grains was typical for varistor materials – approx. 10 µm. However, the ZnO grain size ranged from several to approx. 30 µm. Large grains were, however, small in number and the known abnormal grain growth (AGG) effect did not occur. On the other hand, a significant number of smaller grains occurred, which seem to be more susceptible to separation from the structure than the better formed grains of a typical size. This is proved by the size of dark spots after the chipped off elements of microstructure.

Light precipitates – bismuth oxide aggregates – are the most important doping phase in ZnO varistors. In principle, its content amounts to several percent and very rarely exceeds 10%. However, a significant diversity of the content of Bi_2O_3 and other oxide phases and spinel in the material of varistors produced by different manufacturers should be emphasized [1,8,9]. In general, bismuth oxide in the tested material showed good, homogenous scattering. Its amount in the form of precipitates – in various observation fields – was in the range of approx. 1 ÷ 2%. Slightly more bismuth oxide – of more than 1.5% – was observed in the larger reference sample – from the second pair. Considering the fact that a certain part of the Bi_2O_3 phase was chipped during the preparation of microsections, the total content of bismuth oxide precipitates in the material ranged from less

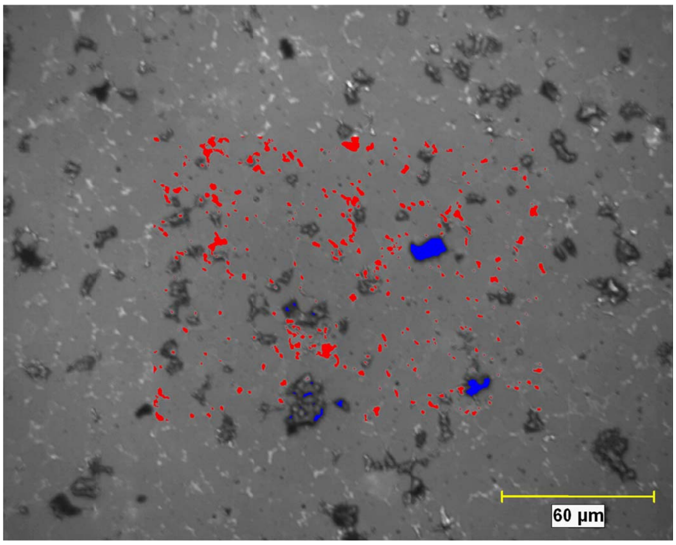

Fig. 6. Image of a reference varistor microstructure from the first pair. A colorful binary mask applied on the central part of the image is visible, showing the precipitates of the doping Bi_2O_3 phase – in red, and the areas of chipping of microstructure elements – in blue

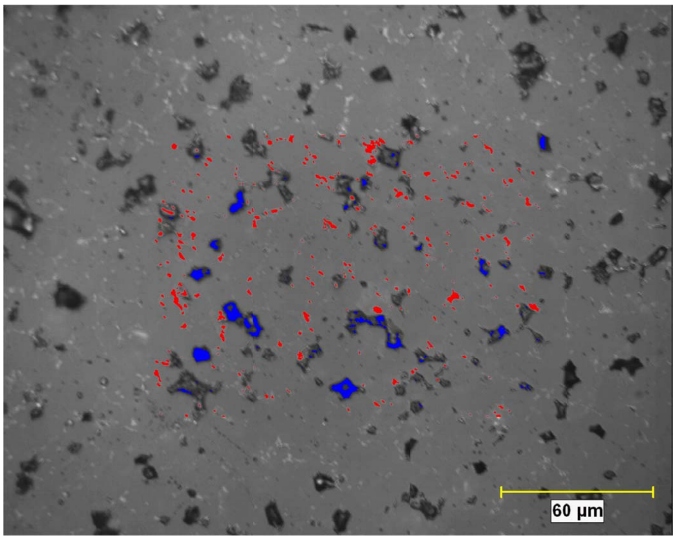

Fig. 7. Image of a reference varistor microstructure from the second pair. A colorful binary mask was applied on the central part of the image. The precipitates of the doping Bi_2O_3 phase are marked in red, and the areas of chipping of microstructure elements are marked in blue

than 2% to approx. 2.5%. The more so that as demonstrated by the tests of the material of the used varistors from both pairs, bismuth oxide in the tested material showed weak integration with the matrix grains. The shape of Bi_2O_3 precipitates was usually slightly extended and their size ranged from micrometer fractions to approx. 7 µm. However, most frequently these were aggregates of spherical particles with a size of approx. 1 mm. Less frequent were concentrations of bound aggregates, whose size was of several micrometers. In addition, SEM images show very fine light bismuth oxide particles present on the surface of ZnO grains – see figure 8.

The zinc–antimony-based spinel phase ($Zn_7Sb_2O_{12}$) in the form of single grains with a characteristic polyhedral shape was very poorly visible under the optical microscope and only in special lighting. With the use of the SEM method it was confirmed that spinel grains were small in number and highly scattered – see figure 8. Spinel grains were small – usually of approx. one micrometer, seldom they exceeded 3 µm and were characterized with a polyhedral shape with quite clearly marked edges. The content of the spinel phase in the material of the tested varistors was difficult to determine. Its amount could be only estimated to be approx. 2%, whereas 0.5% chipped off during the polishing of the microsection surface. Long-term tests proved that microstructure element chipping is often integrated with spinel phase grains [8, 9]. These grains, characterized with a polyhedral, angular shape, are less integrated with the ZnO matrix grains. Consequently they cause a microstructure loosening effect as a result of degradation processes. During the preparation of the microsection, not only get they chipped off relatively easily, but they also facilitate the separation of adjacent ZnO grains, in particular those of a smaller size.

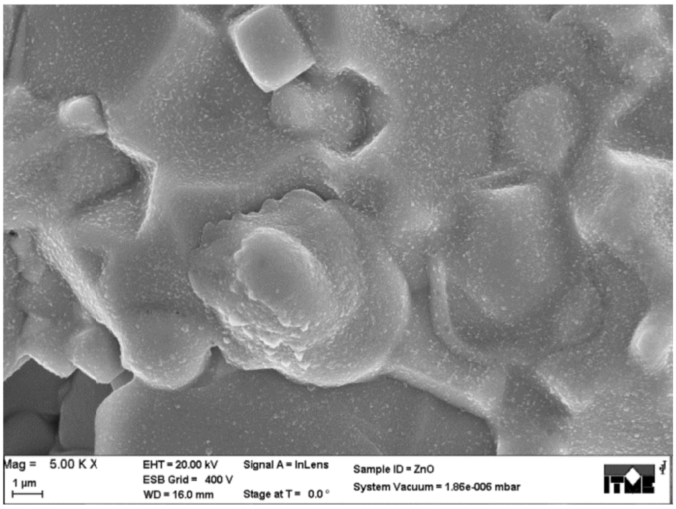

Fig. 8. SEM image of the reference varistor material fracture from the first pair, magnified 5000 times. Among large ZnO grains, at the top of the image, a rectangular spinel grain is visible. The light dots on the ZnO grain surfaces are very fine bismuth oxide particles

The black spots visible on the microsections correspond to microstructure element chipping. Their shape vary, and their size changes from over 1 µm to approx. 20 µm. In terms of quantity, small chipping of several micrometers definitely dominated. During the polishing of microsections, mainly spinel grains and small ZnO grains chipped off. Well-developed grains, with a typical size of approx. 10 µm and more, seemed to be significantly more resistant to separation from the surroundings. Detailed microscopic visual inspection, in particular using the SEM method, indicated that ZnO grains chipped off mainly in the spinel phase presence area. This is confirmed with the results of earlier tests [8,9]. In addition to a significant part of spinel grains, a certain part of the Bi_2O_3 phase at the microsection surface chipped off as well. The areas after the chipped off elements of the microstructure constituted, depending on the observation area, from over 1 to 2.5% of the microsection surface, with their quite homogeneous distribution, proving material homogeneity. Slightly more chipping – of more than 2% – was observed in the larger reference sample – from the second pair. The tested material also showed very small porosity. The shape of the fine, black pores was properly oval and they were present in the amount of a fraction of a percent. They were uniformly distributed and their size remained at a level of fractions, less frequently single micrometers.

As previously mentioned, in addition to microscopic tests, material microhardness was measured for all four varistor samples, and the results were averaged from 10 measurements. The average value for a reference sample from the first pair amounted to HV1 = 128.3±8.2, whereas for the varistor material from the second pair to HV1 = 131.6±4.7. The obtained values are at an average level [8,9] and correspond to varistor materials with a good, although not the highest, cohesion. The level of standard deviations confirms a certain diversity of properties for the individual metering points of the tested varistor material.

The material microstructure may be generally assessed as beneficial, quite homogeneous, compact and completely correct. The sintering process was conducted in an optimal manner, probably in a lower temperature range (1100 ÷ 1200°C). The bismuth oxide uniformly distributed in the original granulate melted, dissolving – at least partially – other doping oxides, and facilitated their uniform distribution in the material. In addition, the liquid phase facilitated grain growth and the compaction process itself. The quite uniformly distributed, although only few in number, spinel grains could have influenced the inhibition of further ZnO grain growth. This enabled them to maintain a similar size [1]. Abnormal grain growth effect – above 20 µm and disadvantageous escape of bismuth and antimony oxides towards the sample edges was avoided.

4. Results of used varistors tests

The used varistors from both pairs were subject to analogous tests as in the case of reference samples. The first one was taken from the surge arrester counter after several years of operation. The sample intended for tests was cut out from the central part of the varistor, which did not show any external traces of short-circuit current impact. The second varistor was removed from the damaged surge arrester and on its lateral surface an overburning with a protective layer loss was visible. This resulted from the flow of strong short-circuit current which damaged the surge arrester. The test sample was cut out from the external varistor area, 5 mm from the overburning trace. It was expected that in this area the material was subject to significant degradation effects.

Figures 9 and 10 present the microstructure of both used varistors, which reveal significant microstructure degradation effects. The microstructure was significantly loosened. The number of chipped off fragments increased more than twofold in relation to the reference condition, and the number of light bismuth oxide precipitates observed on the microsections significantly decreased. This applied in particular to the varistor from the second pair.

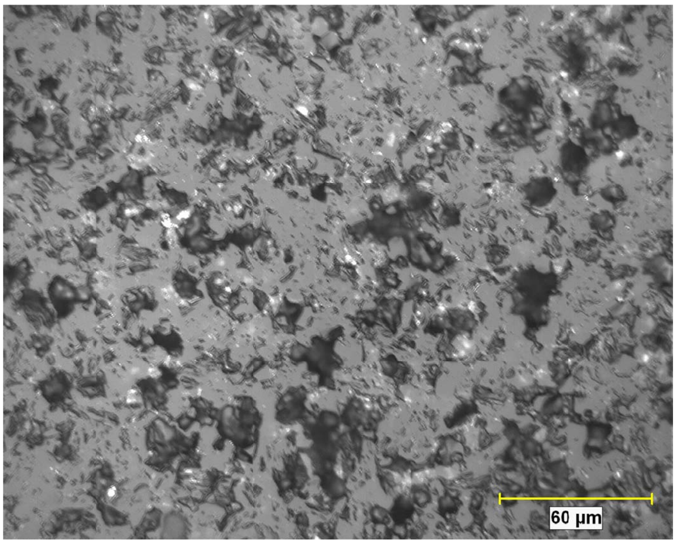

Fig. 9. Typical image of a varistor microstructure from the surge arrester counter (from the first pair). A large amount of black fragments chipped off from the microsection surface – nearly 4.5% and loss of the light Bi_2O_3 doping phase is visible – it takes up only 0.4% of the surface. Darker, gray areas show depressed ZnO grain aggregates in the microsection with diverse packing

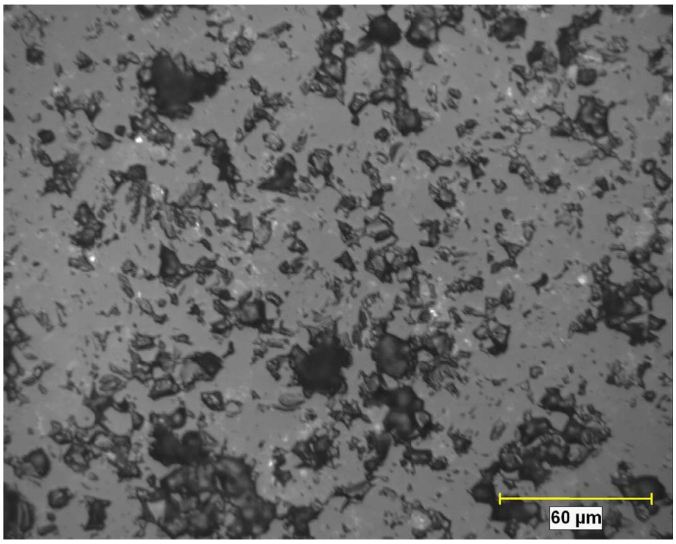

Fig. 10. Image of the microstructure of the varistor from the damaged surge arrester (from the second pair). Visible black chipped off elements of the structure constitute nearly 5% of the surface, whereas quantity of the light Bi_2O_3 doping phase is very small. Darker gray areas show depressed ZnO grain aggregates with diverse packing

Binary masks shown in figures 11 and 12 facilitated a quantitative assessment of the phases in the microstructure of the used varistors. The blue marked phase comprised elements of the microstructure chipped off from the microsection surface and the marginal pores. The red marked phase, on the other hand, comprised precipitates – aggregates of bismuth oxide.

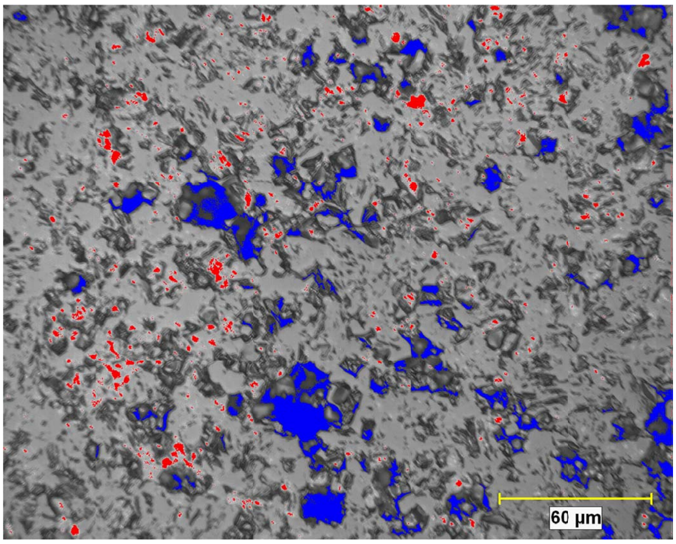

Fig. 11. Image of the varistor microstructure from the surge arrester counter. The colorful binary mask applied is visible. The significant areas of microstructure elements chipping are marked in blue and Bi_2O_3 doping phase precipitates are marked in red

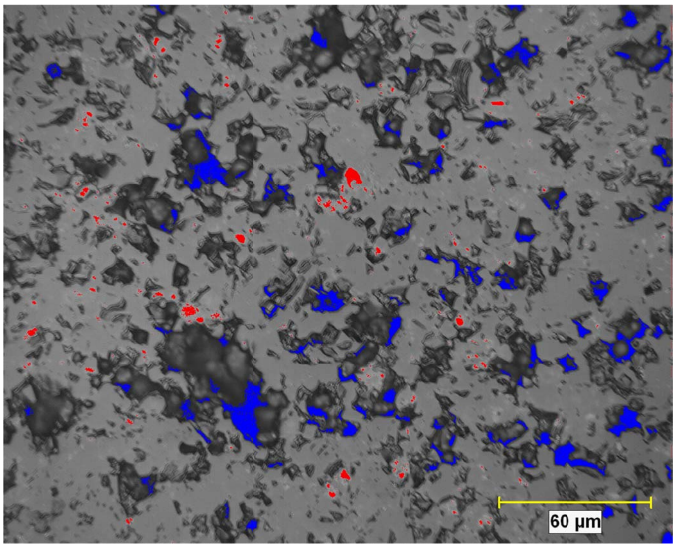

Fig. 12. Image of the varistor microstructure from the damaged surge arrester. A colorful binary mask was applied on the central part of the image. The areas of microstructure elements chipping are marked in blue and Bi_2O_3 doping phase precipitates are marked in red. A significant degradation of the varistor material is visible

The analysis of colored mapping of the areas of chipping from the microsection surface and small size of the remaining

Bi_2O_3 phase in figures 11 and 12 well illustrates the degradation effects in the microstructure of the used varistors. The initially compact material microstructure was significantly weakened and loosened. This was stronger marked in the case of the varistor from the surge arrester after failure (from the second pair). As a consequence of action of short-circuit currents, the number of chipping observed on the microsections increased more than twofold. In the reference samples, they constituted from over 1 to 2.5% of the surface of the microsections in different observation areas. In the case of the varistor removed from the surge arrester counter, depending on the observation area, they occupied from over 4 to approx. 5% of the surface. The varistor from the damaged surge arrester showed a stronger microstructure degradation. In images of its material, chipping constituted from over 4.5% to over 5%. The shape of the areas remaining after the chipped off fragments was often very irregular. Similarly as in the case of reference samples, in terms of quantity, small chipping – of few micrometers – dominated. They mainly corresponded to spinel grains and bismuth oxide precipitates. However, large areas – of even 30 µm – appeared, mapping the separation of few ZnO grains. They also draw the attention when observing the microsections – figures 9 ÷ 12. The chipping areas were located often in places of the spinel phase occurrence and applied to both the spinel grains and the adjacent ZnO grains, in particular those of a smaller size. Spinel grains, whose share on the surface of the reference samples could be estimated at a level of approx. 1.5%, were observed in the material of both of the used varistors only incidentally. A significant majority of spinel grains in the microsections was chipped off, facilitating the chipping of the adjacent grains of zinc oxide and bismuth oxide precipitates. The effect of weaker integration of polyhedral spinel grains with the matrix is known and confirmed by the results of previous tests [8,9]. Therefore, the very large loss of the spinel phase observed on the microsections, resulting from the degradation processes, is not surprising.

However, another, very important effect of the microstructure degradation processes was found, which was not registered previously. It turned out that the amount of bismuth oxide was also largely reduced in the tested microsections. In both reference samples, light Bi_2O_3 precipitates constituted approx. 1.5% of the surface of the microsections. However, the bismuth oxide which remained in the microstructure of the varistor from the damaged surge arrester accounted for less than 0.3%. Only slightly more Bi_2O_3 remained in the varistor microstructure from the surge arrester counter – 0.3 ÷ 0.5%. Therefore, apart from spinel, bismuth oxide was the main phase component which was loosened as a result of the degradation processes. Its precipitates (aggregates of spherical particles) in the tested material were worse integrated with ZnO grains and at their boundaries cracks were formed, resulting in chipping during the preparation of microsections.

Detailed observations of the microsections of other varistors, which were degraded as a result of strong current flow, allowed the determination that chipping often adjoins spinel grains or pores [8,9]. This proves a worse integration of the antimony-zinc spinel grains with zinc oxide. The separation of spinel grains from the microstructure is a known and observed degradation effect and it was an expected effect. In addition, it is known that the factor that weakens the compactness and strength of varistor microstructure are significant differences in the ZnO grain size [1,6]. However, the effect of high degradation of the Bi_2O_3 phase is surprising. In many other tested varistor materials, a strong integration of the bismuth oxide precipitates with the matrix was observed. In principle, they showed high resistance to cracking and separation from the microstructure. The main degradation effect were cracks between the ZnO (or ZnO – spinel) grains and their chipping during the preparation of microsections. Bismuth oxide, if chipped off, was crushed out to a small extent only [8, 9]. Therefore, the effect observed and documented in the tested material is untypical and surprising. The more so that the compactness and cohesion of the material of the tested varistors raises no objections and the ZnO matrix degradation may be deemed moderate. Even in the case of a more weakened microstructure of the varistor from the damaged surge arrester.

Similarly as in the case of reference samples, in addition to microscopic tests, microhardness of the material of the used varistors was measured. The average value for the sample from the surge arrester counter amounted to HV1 = 87.4±19.8. In relation to the reference sample (HV1 = 128.3±8.2) the aging effects caused not only a large decrease in the average value of microhardness (by 32%), but also a nearly 2.5-fold increase in standard deviation – thus largely varying results. In the case of the second sample – taken from the damaged surge arrester – the average value amounted to HV1 = 91.9±27.7. This meant a decrease in microhardness as a result of aging by 30% and nearly 6-fold increase in standard deviation in relation to reference values (HV1 = 131.6±4.7). Despite a slightly higher average microhardness HV1, the dispersion of results for the aged material of the varistor from the surge arrester after failure was significantly higher than in the case of the aged sample from the surge arrester counter. This confirmed a stronger degradation of this varistor material observed under the microscope.

5. Summary

The document presents the results of microscopic tests and microhardness measurements of the material of ZnO varistors which were part of a 110 kV gapless surge arrester and surge arrester counter. The tests covered two pairs of varistors from the same manufacturer, one of which was used and the other was brand new and constituted a reference sample.

The tests showed that the varistors from the surge arrester counter and the damaged surge arrester, as well as the reference elements, were made of the same material. The phase structure of the material of the varistors was typical for such elements. Both in the micro- and semi-macro scale, the material structure can be assessed as compact and homogeneous, whereas the degree of material sintering was entirely correct. The quality of the tested material can be assessed as good and raising no objections.

As a result of strong current flow during operation, degradation effects occurred in the tested varistors in the form of significant weakening and loosening of the material microstructure, whereas it occurred to a significantly bigger extent in the case of the varistor from the surge arrester after failure. The tests showed that regardless of the antimony-zinc ($Zn_7Sb_2O_{12}$) spinel grains, present in the amount of less than 2%, also bismuth oxide is a phase component which gets loose as a result of degradation processes. Bismuth oxide precipitates in the amount of approx. 2% ÷ 2,5% are worse integrated with ZnO grains in the tested material and cracks are formed at their boundaries, resulting in chipping. A large loss of the Bi_2O_3 phase, observed on the microsections of the used samples, is a very significant effect of the material degradation. This is a surprising fact. In the case of a series of tests of other materials of used varistors, even those whose microstructure was strongly degraded, the Bi_2O_3 phase did not weaken the compactness and cohesion of the material and was resistant to chipping. The elements that weaken the varistor microstructure are mainly spinel grains, differences in the size of grains of the main phase (matrix) zinc oxide and – to a small extent pores. The effects observed in the material of the used varistors should be considered untypical. Nevertheless, the ZnO matrix degradation was moderate. The ZnO grains were of similar, correct size and were quite resistant to separation from the microstructure as a result of strong current, mechanical and thermo-mechanical stresses. In combination with good material microhardness parameters, this is a good indication of the service life of the tested varistors.

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