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Enhanced Performance of Zinc Oxide Arrester by Simple Modification in Processing and Design

Karim ANM[1] and Shahida Begum[2]*

[1]Department of Manufacturing and Materials Engineering, Faculty of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia
[2]Department of Mechanical Engineering, Centre for Advanced Materials, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, Putrajaya, Malaysia

Abstract

Reliable performance of a Zinc Oxide surge arrester is highly dependent on its energy absorption capability. This paper presents two simple but promising approaches for enhancement of this property: one with an alternative sintering orientation and the other with the changed geometry of arrester discs to provide higher surface to volume (S/V) ratio. Several sintering orientations including the control (or conventional) process were tried and assessed. Some of these attempts have demonstrated quite superior results which might be linked to lower level of contamination during sintering. Study conducted to observe the effect of the higher surface to volume (S/V) ratio through geometrical modification of the discs from cylindrical to hexagonal shape has also demonstrated improved outcome. Average energy absorption capability for the hexagonal discs was found to increase markedly which might be attributable to faster heat dissipation aided by higher S/V ratio preventing the discs from premature failure. Thus by combining the appropriate sintering orientation and the change in geometrical shape for higher (S/V) ratio, substantial enhancement of the arrester block capability is achievable which would be eventually helpful for improved protection of electrical system.

Keywords: ZnO arrester block; Energy absorption capability; Surface-to-volume ratio; Sintering orientation

Introduction

Zinc oxide arresters are electronic ceramic devices, the primary function of which is to protect the electrical systems by sensing and limiting transient surges [1]. This metal-oxide varistor technology is widely applied now-a-days for voltage stabilization or transient surge suppression in electronic circuits and electrical power systems [2-5]. Owing to the improvements of non-ohmic properties and functional reliability, use of ZnO varistors has expanded quite rapidly. Moreover, with the advent of advanced manufacturing technology, varistors having new designs and configurations are expected to have wider application.

In addition to some finishing operations, varistor manufacture basically follows the route of conventional ceramic processing. Ceramic materials have been produced and used for centuries. However, compared to the long history of ceramic materials, use of electronic ceramic as transient over-voltage suppression device is a recent development [6].

Processing of arrester block

Zinc Oxide varistors produced in the form of cylinder are often called arrester blocks. These are fundamentally ceramic materials, processed from a number of metal oxide powders. The basic material is pulverized and very finely grained ZnO with particle sizes of about 1μm, to which as many as 10 or more doping elements are added in the form of fine oxide powders. Its actual composition differs from manufacturer to manufacturer. To achieve the required homogeneity the powder is treated in several processing steps, after which the mixture in the form of slurry has to be spray-dried to obtain the dry granulates necessary for pressing. Majority of the varistor devices are processed from this kind of powder. The whole manufacturing process relevant to fabrication of arrester blocks is illustrated in a flow diagram as depicted in Figure 1.

Spray dried powder in the form of granulates is compressed into disc-shaped blocks with approximately 55 to 65 percent of their theoretical density. Pressing is performed by a uniaxial double action compaction technique. Sintering of the discs was performed by a sintering profile with a peak temperature of about 1120°C requiring a cycle time of about 70 hours. The ceramic body undergoing a liquid phase sintering process takes the shape of a rigid cylinder with a theoretical density of more than 95 percent.

Researches in the varistor technology have been primarily aimed at improving the fundamental properties. As the performance and reliability of electronic ceramic were thought to depend on the grain and the grain boundary phenomena [7,8], much of the research works are related to the investigation of material composition, micro-structure, and the grain and grain boundary [9-15]. Maximum attention of the research publications is related to the I-V curve characterized by the nonlinear coefficient, α. But, reliable performance of arrester blocks is also largely dependent on their energy absorption capability, considered as the second most important property.

As observed in earlier study [16] the contact zone of a disc remaining in the vicinity of the liner material during the sintering process is more susceptible to failure and even after deeper grinding of the bottom face, most of the failures were found to originate from this zone. In this respect effect on the change in the orientation of sintering support on the energy absorption capability would be interesting. Moreover, as reported earlier [17], since in testing the energy absorption capability a disc becomes momentarily very hot being subjected to electrical pulses,

***Corresponding author:** Shahida Begum, Department of Mechanical Engineering, Centre for Advanced Materials, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, Putrajaya, Malaysia, Tel: +6-0196345570; E-mail: Shahida@uniten.edu.my

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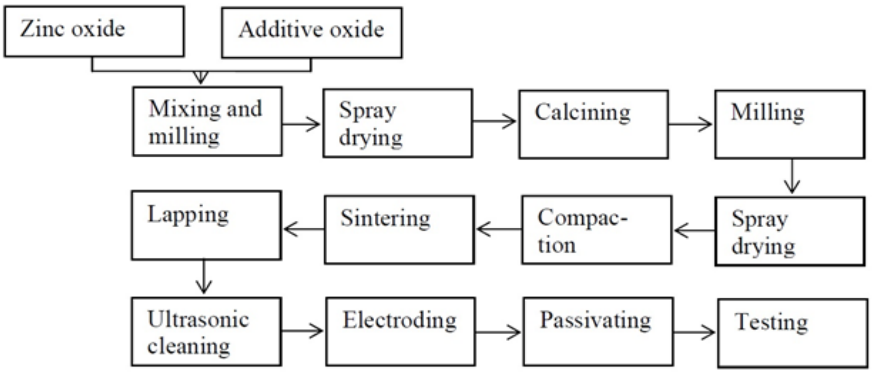

Figure 1: Fabrication procedure of the ZnO arrester discs or blocks.

quicker dissipation of heat from the arrester body having greater surface area should be helpful. In this respect a hexagonal disc having greater surface to volume ratio is thought to perform better.

Experimental Procedure

Sample preparation of the cylindrical arrester blocks through different sintering orientations and hexagonal shape blocks is described. To minimize the undesirable effect at the bottom, a number of alternative orientations have been attempted [18] by changing the sintering orientation i.e. placing the disc on different kinds of support. The orientation in control process is shown in Figure 2.

Figure 2a shows the positions of discs placed in a sagger. As shown in Figure 2b, a disc remains in a vertical condition on a liner to separate from direct contact of sagger. Modified arrangements for are presented in Figures 3 and 4.

A fired smaller support system shown in Figure 3a was chosen to keep the edges free from the liner material to ensure good edge quality. A green support of the same diameter made from the standard varistor material as presented in Figure 3b was to aid the bottom edges unaffected from the adverse effects of sliding during the shrinking process in sintering. As practiced in control process, the green discs in these are kept separated from the direct contact of the supporting liner by sparsely spreading ZnO powder.

As illustrated in Figure 4, the Vee-groove support was made from the fired arrester discs. To prevent sticking of the discs in sintering the supports were made wet by spraying water and covered by sparsely spreading spinel powder, known to have an inhibiting effect on the grain growth. The Vee-groove support could facilitate to keep the edges free from any physical contact during the sintering process.

Thus these three orientations were anticipated to have enhanced edge quality.

The discs are categorized into different cells according to the description given in Table 1 to facilitate to refer in the subsequent sections.

The shape of hexagonal cross-section was obtained by modifying the C-surface of the cylindrical discs [19]. A production-line diamond grinding wheel rotated along a vertical axis was used. Cylindrical arrester discs were passed under the flat face of the diamond wheel by placing them horizontally on the conveyor belt. A small depth of cut was used to remove material in one pass. Several passes were needed to complete one of the six flat sides of the hexagonal discs. After one flat plane was obtained, the other two adjacent flat surfaces were developed at angle of 60 degree. The remaining three flat surfaces were ground one by one by placing the disc on the conveyor belt making contact with the already developed flat surfaces. As shown in Figure 5, a cylindrical disc was thus transformed into a hexagonal shape by progressively generating all the six flat surfaces. A 41 mm diameter cylindrical disc having a cross-section of 13.2025 cm^2 is ground to a hexagonal disc with cross-section reduced to 10.9184 cm^2. Since the disc height of 42 mm remained unchanged, the volumes of the cylindrical and hexagonal discs became 55.45 cm^3 and 45.86 cm^3 respectively with the corresponding surface areas of 80.5032 cm^2 and 73.7887 cm^2.

As a result the S/V ratio of hexagonal disc is increased to a value 1.609 cm^{-1} compared to that for the cylindrical disc of 1.452 cm^{-1}. Thus an increase of about 11% in S/V ratio was achieved for the hexagonal discs. To minimize the effect of the process variables the other necessary operations were conducted in a single run under the same set conditions.

Evaluation of energy absorption capability and high current performance

Energy absorption capability is measured by millisecond rectangular pulses whereas high current performance is analyzed by high amplitude short duration (HASD) pulses of microseconds' duration. In both the cases highly accurate and reliable impulse test systems (Trigatron type 94 for energy and Impulse current test system WO 4924 for high current) were used. This characteristic of a varistor is determined by the maximum energy density injected into the ceramic body up to which it can sustain without failure for a cycle of three shots, expressed in terms of $Joule.cm^{-3}$.

Definition of the rectangular impulse current as derived from Figure 6a is a 2-millisecond pulse, conventionally termed as long wave. This kind of pulse is usually experienced in switching surges.

Energy injected by such a pulse is the integrated value of the product of the voltage and current passing through the disc over the pulse duration. So the amount of energy can be expressed mathematically with the following relationship:

$$Energy = \int_0^t vidt \quad (1)$$

However, the instantaneous values of the voltage, v and current, i are not practically recorded. To evaluate the integrated energy the peak values of the clamping voltage and peak current passing through

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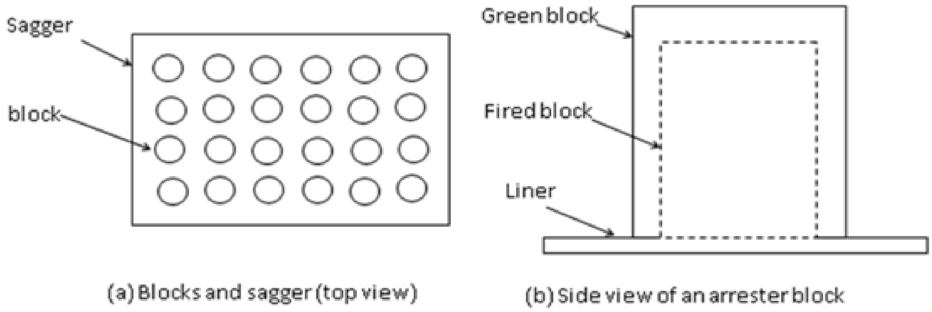


Figure 2: Control orientation of arrester blocks on sagger for sintering (CSS).

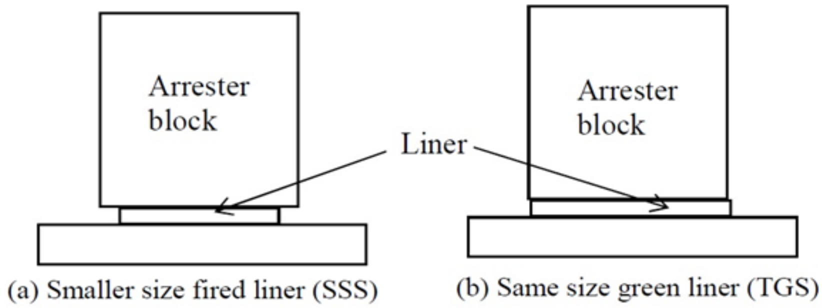


Figure 3: Circular disc liner intended to improve the bottom edge (modified).

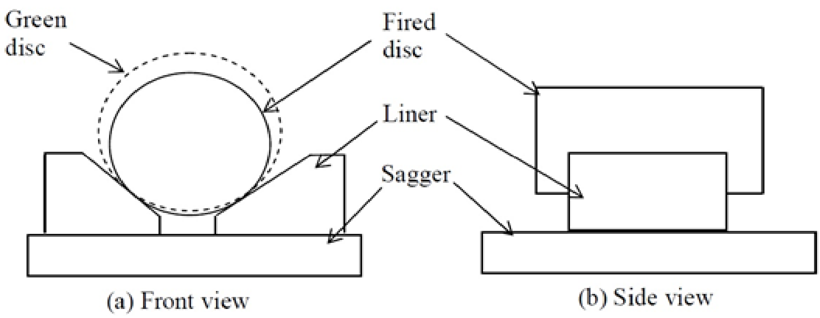


Figure 4: Vee-groove support (VSS) for horizontal sintering orientation.

Cell ID	Description of the support system
CSS	Control Support System (fired ZnO flat liner and spread ZnO powder)
SSS	Smaller Sintered Support system (keeping bottom edge free from contact)
TGS	Total Green Support System (allowing the bottom to smooth shrinkage)
VSS	Vee-groove Support System (keeping both flat surfaces from contact)

Table 1: Identification of four different groups or cells.

the arrester block are used. For a pulse of quasi-rectangular shape as demonstrated in Figure 6a, the relationship can be expressed in terms of the peak voltage, V_{pk} (KV) and peak current, I_{pk} (A) for a duration of time T in millisecond as follows:

$$Energy = \int_0^t vidt = KV_{pk}I_{pk}T \quad (2)$$

where K is a constant, dependent on the wave-shape. For a pulse as shown in Figure 6, the value of K is taken as 1.14. Thus the total injected energy by is estimated as $2.28.V_{pk}\ I_{pk}$

Unlike the measurement of mechanical strength, the test for the energy absorption cannot be performed in a single step. Testing is initiated with a lower charging voltage so that injected energy remains in the lower range, say, about 200 $Joule.cm^{-3}$, to minimize the likelihood of failure at the first cycle. The testing by discrete increment of charging voltage and cooling of the discs is a tedious process which is continued until all the discs of the fail at a certain stage.

The High Amplitude Short Duration (HASD) pulses are in the range of microseconds' duration. This is a simulated pulse of the actual lightning stroke. Typical short pulse used for evaluating high current performance is 4x10µs where the first value (virtual front time) indicates

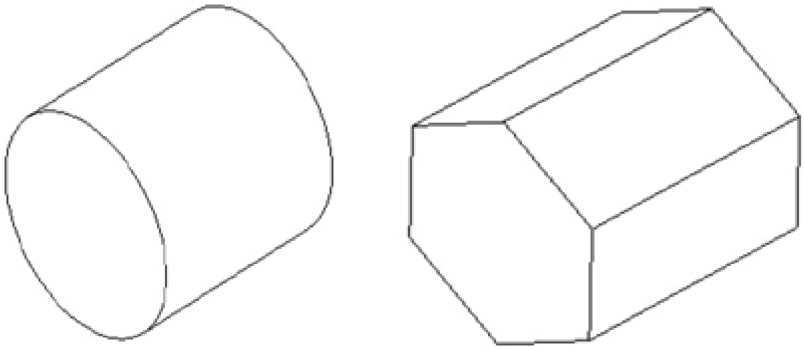
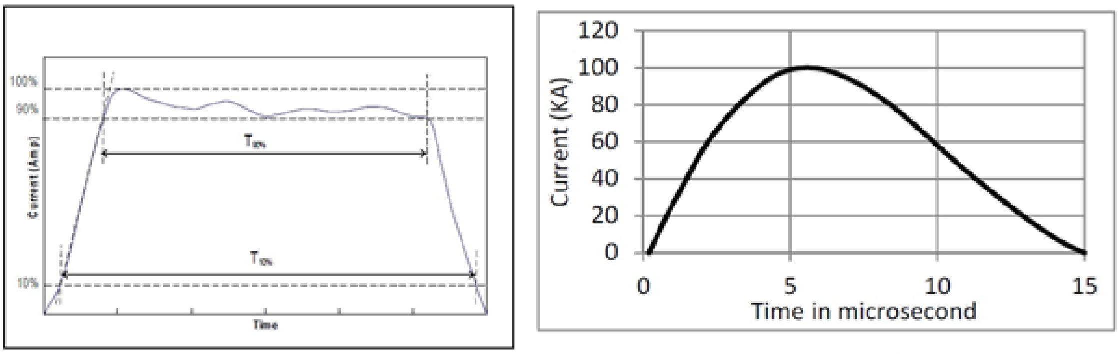


Figure 5: Hexagonal shape disc as obtained by grinding a cylindrical arrester block.



(a) (b)

Figure 6: (a) Long (ms) pulse for energy absorption and (b) HASD (4x10μs) pulse for high current performance.

the rise time from 10% to 90 % of the peak current and the second value (virtual time to half value) is the duration to reach to 50% of the peak during fall. Since this is a destructive test a sample of few discs is taken from a lot. Unlike the test for the energy absorption capability, only one shot is applied at a time for the high current capability. The failure mode in this case is predominated by cracking rather than by the thermal runaway or puncture as observed in long pulse test.

A parameter to express the high current performance of a particular cell can be defined mathematically [16] in the following form:

$$HIgh\,current\,performance\,(\%) = \frac{\sum n_i x_i}{\sum NX_i}(100) \qquad (3)$$

Where N = initial sample size of discs to be tested

X_i = rated peak current at the ith pulse

n_i = number of discs successfully passing the ith pulse and

x_i = actual peak current in the ith pulse

Results and Discussion

The test for energy also known as the 'strength test to destruction' is usually conducted on the discs being passed by visual inspection. Reasonably large sample sizes were used. Arrester blocks tested were 10, 12, 14 and 16 respectively for the CSS, VSS, SSS and TGS cells. The results are plotted in Figure 7a with the error bar. In terms of the energy absorption capability there is no significant difference among the first three cells with slightly higher value for SSS category. But, the mean energy absorption capability for the discs sintered on the same size green support (cell TGS) is about 10 percent less compared to the other cells.

It may be mentioned here that both the faces of a disc are cleaned by grinding operation. Regrinding of a disc face is necessary when defects such as pinhole and chipping of edges are observed by the visual manual inspection following the initial grinding. In the context of material, labor, equipment use, and production cycle time of a batch, regrinding is obviously an undesirable operation. As recorded and shown in Figure 7b, the category (SSS) looks promising followed by (VSS) and (TGS) in the context of the need of minimum regrinding frequency of the faces.

According to the level of energy absorption capability and regrinding frequency the discs belonging to SSS cell are superior. But due to the smaller size of the support, placing of discs on top of it and subsequent handling of the saggars to position in the furnace for sintering purpose are to be difficult. Thus this unstable support system cannot be recommended.

For high current performance multiple discs from each of the cells for sintering orientation were tested. The rated current was selected with an increment of 5 kA for every subsequent shot for every disc. The starting current was 100 kA and there were no survivor after 115 kA shot. Based on the values of high current performance parameter as defined by equation (4) the relative performance is presented graphically in Figure 8a. So according to the combined performance

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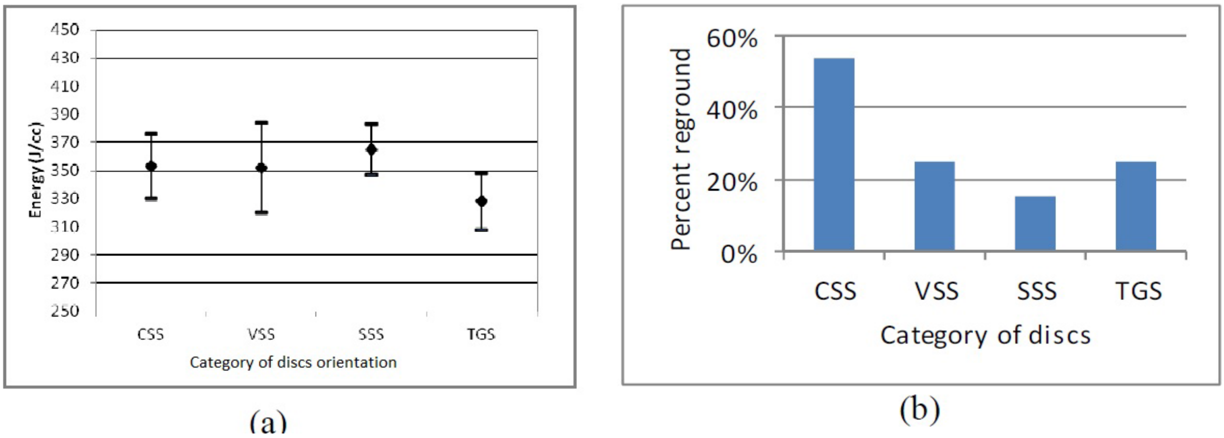

Figure 7: (a) Mean energy absorption capability of different cells (b) Percentage of discs needing regrinding as change of sintering orientation.

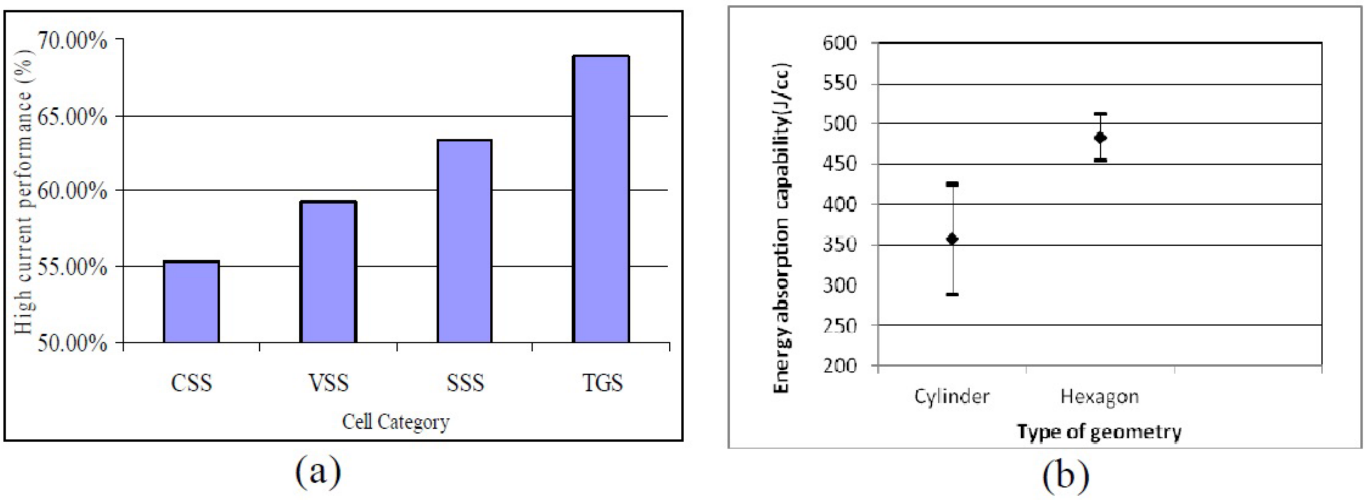

Figure 8: (a) High current performance as affected by sintering orientation (b) Energy absorption capability as influenced by arrester geometry.

on three characteristics such as energy absorption capability, frequency of regrinding and high current performance, the choice horizontal sintering on Vee- groove support (VSS) looks reasonable.

To investigate the effect of surface to volume ratio on the energy absorption capability a total of 20 arrester blocks (10 cylindrical and 10 hexagonal) was taken. Figure 8b illustrates the energy absorption capability for the cylindrical and hexagonal discs by error diagram representing the mean and standard deviation. The discs having hexagonal shape exhibited an average of 483 J.cm^{-3} while the discs having the cylindrical shape yielded an average of only 357 J.cm^{-3}. Thus, about 35% increase in the mean energy absorption capability was observed for the hexagonal discs.

The energy injected by the electrical pulses only of 2 milliseconds' duration may be assumed to follow an adiabatic heating process. But the hexagonal discs having higher surface to volume ratio is found to sustain higher level of energy absorption capability. This phenomenon can be attributable to the effect of increased surface to volume ratio of arrester block refuting the assumption of adiabatic heating.

It may be mentioned here that failure of arrester blocks in the energy test is usually dominated by occurrences of pinhole and flashover. The failure mode and the location of damaged marks for each of the discs were tracked. Pinhole accompanied by a flashover was observed to be the common mode of failure for both categories. In a very few cases discs failed with crack or fracture alone. Since the hexagonal discs were prepared by grinding the side surface of the cylindrical discs, variation in energy absorption capability could likely be linked with the removal of the presumably contaminated surface of the cylindrical discs. But no such indication was found from the observations of the failure patterns and their distribution. So the findings on the influence of S/V ratio in enhancing the energy absorption capability can be taken into consideration in designing the geometry of the device for improved functional reliability.

Conclusions

Through this investigative study on sintering orientation and change of disc geometry leading to higher S/V ratio, some interesting results are obtained. Sintering keeping the discs horizontally on Vee-groove support is found to be more attractive compared to the current practice. With the improved edge quality of the sintered discs, there is a remarkable reduction in the frequency of regrinding. Moreover, the horizontal sintering technique produces arresters with less density gradient and better geometry which could lead to prevent earlier failure. Additionally, the liners could possibly be used for more cycles as these are to be minimally affected at the contact zone. So the horizontal sintering technique is deemed to be significantly beneficial in terms of improved process capability as well as reduced cost for the processing of arrester blocks. Regarding the design with change in geometry, higher S/V ratio of the hexagonal disc is found to be more conducive in transferring heat leading to enhanced life in energy test. With an increase of about 11% in S/V ratio, the average energy absorption capability for the hexagonal discs was found to improve by about 35%. Since there was no other variation in processing except the geometry of the disc, the significant increase in energy absorption capability can be attained with the modification in the design of die for compaction. Thus, with simple changes in geometric shape and sintering processing, surge arresters with enhanced performance are achievable.

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