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COMPUTER-AIDED DESIGN OF STRESS-RELIEF HOLES IN THE MEDIUM VOLTAGE PRODUCTS MADE OF EPOXY RESIN

MATEUSZ AMBROZIŃSKI[1*], TOMASZ NOWAK[2]

[1] AGH University of Science and Technology, Kraków, Poland
[2] ABB Corporate Research, Krakow, Poland
**Corresponding author: mambroz@agh.edu.pl*

Abstract

The aim of the presented work was to study the method reducing the stress level in epoxy-based products, by application of stress-relief holes. The optimal geometry of relief holes, as well as their locations were found by numerical simulations. Two design variants (with drilled– and cast holes) were considered in numerical analysis, and selected geometrical configurations were also tested by experimental tests. The obtained results allowed formulate the number of practical recommendations for production of medium voltage devices. It was shown that proper application of relief holes in case of brittle material can bring positive effects and reduce the probability of material failure.

Key words: epoxy resin, electrical equipment, stress relief holes, numerical simulations

1. INTRODUCTION

Development of new products often requires an extensive research in the area of material science. In many cases, the demanded materials should offer an innovative and unique combination of different physical properties. For this reason composites and polymers are frequently the selection of choice in various branches of the industry. In electrical power business, which requires good insulation materials, epoxy resin systems play an important role. Thanks to their good mechanical strength and excellent dielectric properties epoxy resins replace standard ceramic products. During manufacturing process of epoxy-based electrical products, when a cast thermoset material starts to polymerize, the internally developed thermo-chemical strains lead to an extensive stress build-up. This may have a damaging effect on the quality of the product, since epoxy resins are normally a very brittle materials (Nowak, 2011). This situation causes several technical problems during the production, and on the later stage during the product life-time, when electrical apparatuses are exposed to various temperature and atmospheric conditions. Due to the presence of the residual stresses, complexity of the reactive molding process, and variety of parameters influencing the final product quality it is very difficult to define the product design and manufacturing process characteristics in such a way, that cracks and warpage problems are eliminated. For this reason costly experiments are often performed, or the application of numerical simulations has to be foreseen as valuable and effective alternative (Roger et al., 2007).

The aim of the presented work was to study the method for reduction of residual stresses caused by manufacturing process. Application of specially designed stress-relief holes, which were introduced into critical areas of medium voltage devices, was selected to reach this goal. The products of epoxy resins used in industrial environments are exposed to

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a large change in temperature. As a result, they are subject to destruction. Authors of the paper present a solution to this problem using numerical physical simulations.

Resins are commonly used in composite materials, where they are combined with other materials such as steel or aluminum. A number of studies on composite resin have been done, including numerical simulations and application of the relief hole method, see for example (Lijuan Liao, 2011). These applications are in various areas engineering, but to the Authors knowledge there are no such applications to electrical equipment. Therefore, in the present work the numerical simulations were applied to find the best combination of hole geometry and its position in the electrical epoxy resin systems. The computer results have been validated by experiments – the resin samples were produced and tested by thermal cycling.

The work was performed at ABB Research Center in Krakow, Poland.

2. PHYSICAL MODEL

The geometrical model of the product under study was simplified to the metal core, which represented the electrical conductor, and epoxy sleeve, which worked as protective insulation (Tang et al., 2004). The assembly model is shown in figure 1. The specimen exhibits two radii at the edges of the metal core: R10 (smooth), and R1 (very sharp). Such a design is normally used by resin suppliers, since it promotes material fracture during mechanical tests.

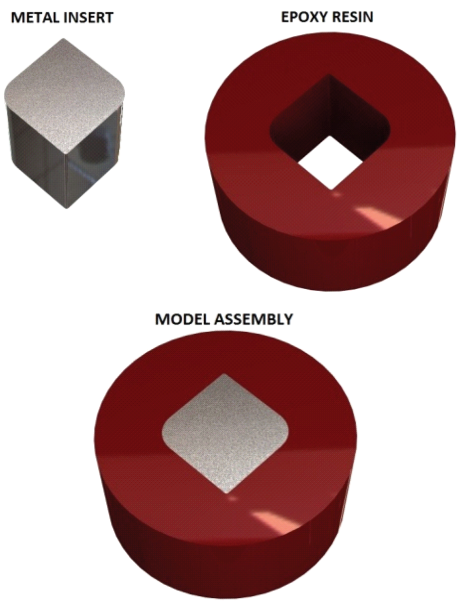


Fig. 1. Schematic representation of the specimen used in the analysis.

The epoxy system was based on Araldite CY228 resin, CW 229-3 filler, and hardener HW 229-1 (Vantico, 2000). This material is commonly used in medium voltage transformer business. The material properties were delivered by system supplier. The Young modulus and Poisson ratio dependent on the temperature, as shown in figure 2, where used in calculations.

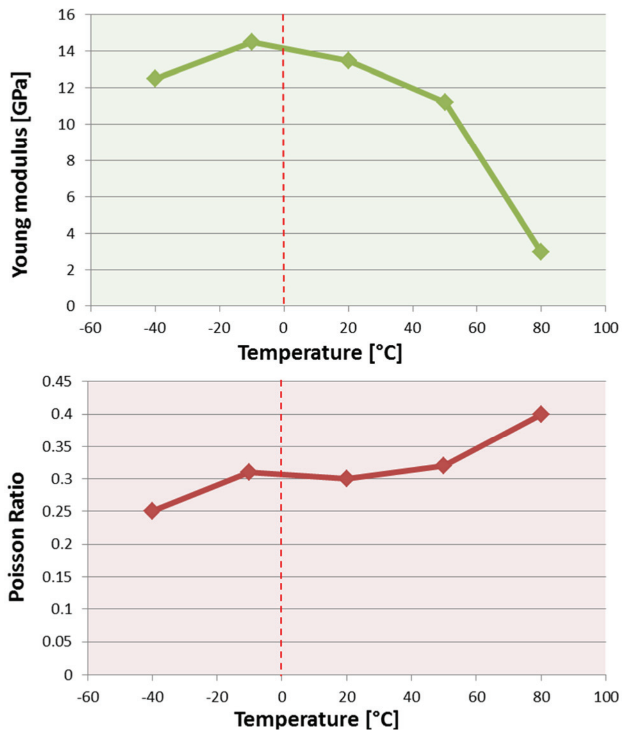


Fig. 2. Temperature-dependent material data.

3. AN IDEA OF RELIEF HOLES

For brittle materials even a very small crack initiation drives directly to the product failure, thus epoxy-based components are very sensitive to the fracture phenomena. Sharp corners, geometrical discontinuities or presence of small features, as well as interfaces between different material phases, and changes in wall thickness are typical examples of stress concentrators (Braoek, 1988; Peres 2004). They are especially seen in electrical devices, where metal inserts of complex shape are embedded within the fragile material.

In case of elastic materials exposed to high stresses, the relief holes may be used to reduce the probability of crack initiation. This approach is cheaper than application of an additional reinforcements. The stress-relief holes not only give stress relaxation, but also cause decrease of the weight of the device, which is very important in some applications (Young, Budynas, 2002). The motivation of the work described by this paper was to apply the same solution into brittle materials, which is not a common approach. Mistakes made in design of hole's geometry and its position leads to increase of the tendency to material fracture. Costly experiments can be performed to find the optimal design and location of the holes, however numerical simulations can also be applied.

In order to explain how the relief holes work, the fluid flow analogy is often used (Saouma, 1998).In the case of the plate with the cylindrical hole, which is exposed to the uniaxial load, the maximum stress occurs at the edge of the orifice. However, if the shape of the circle is changed to the ellipse, or additional openings are added, lines of the flow along the sample are smoothed, and stress concentrations are balanced and reduced. The graphical illustration of these two cases is shown in figure 3 (*Machine Design Databook*, 2004).

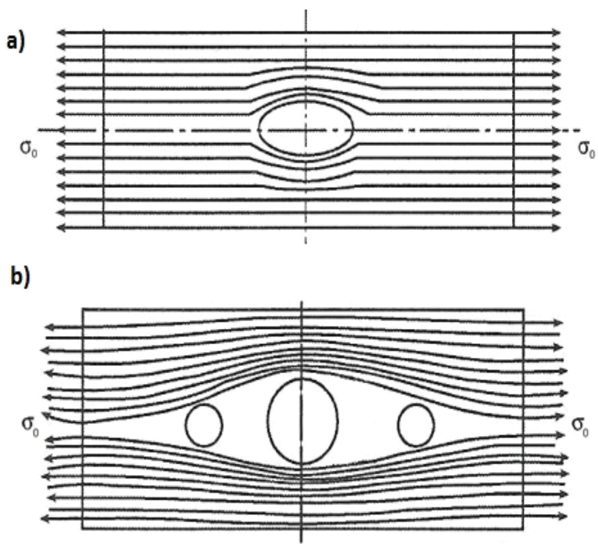


Fig. 3. *Two examples of stress-relief holes: a) in form of an elliptical shape, b) two additional openings.*

4. MODEL USED IN FEM ANALYSIS

The classical thermo-mechanical theory is based on Hook's Law with thermal component introduced, which can be expressed in the direct tensor notation as:

$$\boldsymbol{\varepsilon} = \frac{1}{E}\boldsymbol{\sigma} - \frac{\upsilon}{E}\left[tr(\boldsymbol{\sigma})I - \boldsymbol{\sigma}\right] + \boldsymbol{\varepsilon}_{\mathbf{T}} \qquad (1)$$

where: $\boldsymbol{\varepsilon}$ and $\boldsymbol{\sigma}$ are strain and stress tensors respectively, $\boldsymbol{I}$ is the second-order identity tensor, E represents Young's modulus, ν is Poisson's ratio, and $\boldsymbol{\varepsilon}_T = \{\beta\Delta T, \beta\Delta T, \beta\Delta T, 0,0,0\}^T$ is the vector, which contains thermal strain, β is the thermal expansion coefficient, ΔT – temperature change.

The thermo-mechanical analysis managed by this study covered two stages of the process. During the first stage, which is not described in the present work, the sample manufacturing process was simulated. In that process the temperature load was driven by the epoxy polymerization. That step ended at glass transition temperature, *Tg*. The results of those simulations were the input for the second stage discussed in the present work. This phase was ranging between *Tg* and sub-ambient temperatures. The linear elastic model with parameters shown in figure 2 was used.

4.1. Chemical behaviour

The epoxy resin under study, as every thermoset material, undergoes polymerization process, in which, monomer molecules form three-dimensional polymer networks. The progress of the reaction - the polymerization kinetics, is frequently described by Kamal's model:

$$\frac{d\alpha}{dt} = (A_1 e^{-E_1/T} + A_2 e^{-E_2/T}\alpha^m)(1-\alpha)^n \qquad (2)$$

where α – the degree of polymerization, t – time, T – temperature, A_1, E_1, A_2, E_2, m, and n – material constants.

Degree of reaction, α, is a common manufacturing parameter defined by equation:

$$\alpha = \frac{H(t)}{H_U} \qquad (3)$$

in which, $H(t)$ – the heat released by the exothermic cross linking reaction up to the time t, H_U – the ultimate heat of reaction.

4.2. Hermal and mechanical behaviour

Thermoset materials exhibit strong dependence of physical properties on the temperature, especially near glass transition temperature, *Tg*. Below *Tg* the epoxy material is hard and brittle, having the Coefficient of Thermal Expansion on the level of 35-40 ppm [1/K], while above *Tg*, resin becomes significantly softer (Young modules is lowered about 2 orders of magnitude), and *CTE* reaches the level of 100-105 ppm [1/K].

Moreover, if the epoxy-based product is kept in elevated temperatures, slightly above *Tg*, the viscoelastic properties have to be used in this area. Thus, material modules (Young and Kirchhoff) are not only the functions of temperature, but also the time. Both dependencies are covered by the principle known as the time-temperature superposition, which simply states that the relaxation modulus at any given temperature, $G(T)$, can be derived if the relaxation modulus at the reference temperature, $G(T_{ref})$, and horizontal shift factor a_T, are known (Nowak, 2012).

$$G(T) = a_T G(T_{ref}) \tag{4}$$

The temperature shift factor, relating time to temperature, may be expressed in form of commonly used Williams-Landell-Ferry (WLF) equation:

$$\log a_T(T) = \frac{C_1(T - T_{ref})}{C_2 + T - T_{ref}} \tag{5}$$

where C_1 and C_2 are material constants.

Well below *Tg* level, the viscoelastic properties do not play the major role and may be neglected in analysis.

5. NUMERICAL SIMULATIONS

5.1. Numerical model and calculation procedure

Two alternative versions of the relaxation holes were prepared for the numerical analysis. The hole was spaced away from the sharp edge of the metal insert, and the hole was placed at the edge. Both cases are shown in figure 4. Used for the calculation of the linear hexahedral elements of type C3D8R. The number of elements was changing slightly depending on the shape of the relief maintaining the same size. Assembly model is shown in figure 5. Mesh refinement was applied near the sharp notch to improve accuracy of results.

Two variants of manufacturing of holes were considered (figure 4). The first was drilling the holes and the second was casting. Simulations of these two variants of manufacturing were not performed in the present work. Due to the technological and manufacturing limitations, various configurations and dimensions of holes were obtained. The investigated combinations are shown in Table 1. The orifices were dimensioned by three parameters: distance from the notch, *D*, as well as depth, *H*, and radius of the hole, *R*. Each parameter could be applied at three geometrical levels, thus as many as 27 (3^3) different models were analyzed for each variant.

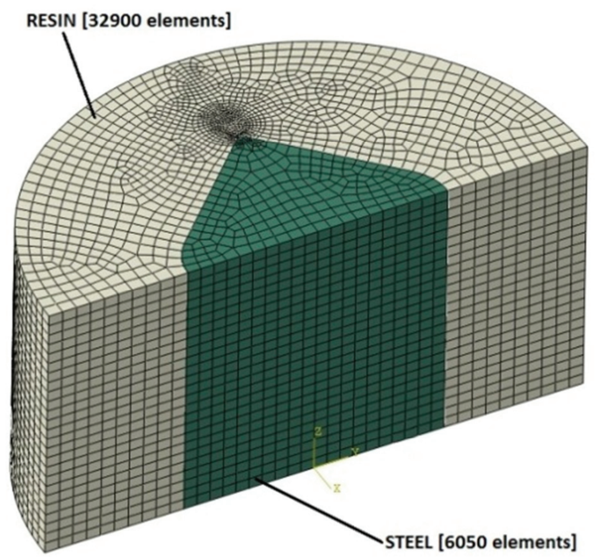


Fig. 5. **Cross-section of the model with the FE mesh for one shape of the relief hole.**

The specimens were subjected to thermal loading. The thermal cycle was composed of cooling from glass transition temperature (80°C) to subambient temperature (-50°C). The uniform tempera-

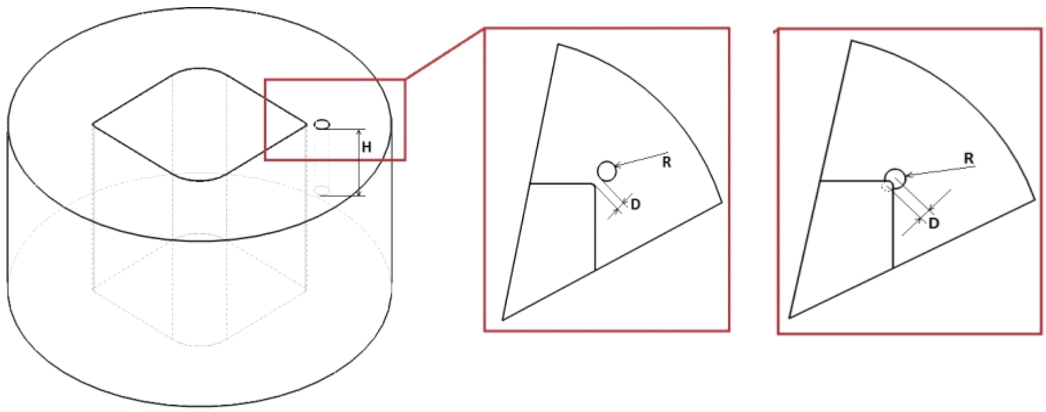


Fig. 4. *Two variants of relief holes investigated in the paper.*

ture changing with time use assumed in the whole volume. Ideal connection between resin and steel was assumed.

Table 1. *All configurations of relief holes used in simulations: a) first variant, b) second variant.*

a)

MODEL NR.	R [m]	H [m]	D [m]
1	0.002	0.010	0.004
2	0.002	0.010	0.006
3	0.002	0.010	0.008
4	0.002	0.025	0.004
5	0.002	0.025	0.006
6	0.002	0.025	0.008
7	0.002	0.050	0.004
8	0.002	0.050	0.006
9	0.002	0.050	0.008
10	0.003	0.010	0.004
11	0.003	0.010	0.006
12	0.003	0.010	0.008
13	0.003	0.025	0.004
14	0.003	0.025	0.006
15	0.003	0.025	0.008
16	0.003	0.050	0.004
17	0.003	0.050	0.006
18	0.003	0.050	0.008
19	0.004	0.010	0.004
20	0.004	0.010	0.006
21	0.004	0.010	0.008
22	0.004	0.025	0.004
23	0.004	0.025	0.006
24	0.004	0.025	0.008
25	0.004	0.050	0.004
26	0.004	0.050	0.006
27	0.004	0.050	0.008

b)

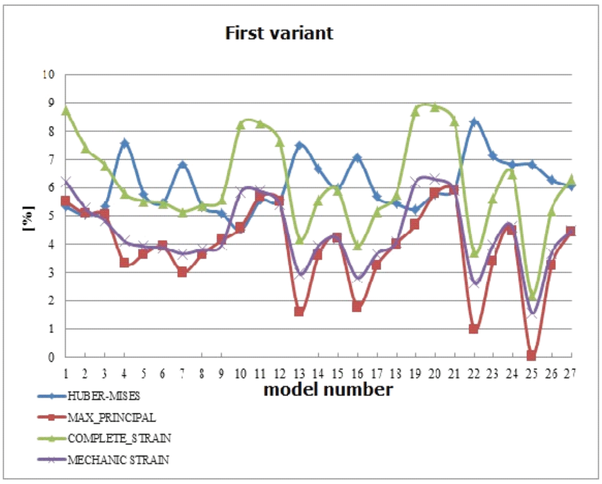
MODEL NR.	R [m]	H [m]	D [m]
1	0.002	0.01	0
2	0.002	0.01	0.0005
3	0.002	0.01	0.001
4	0.002	0.025	0
5	0.002	0.025	0.0005
6	0.002	0.025	0.001
7	0.002	0.05	0
8	0.002	0.05	0.0005
9	0.002	0.05	0.001
10	0.003	0.01	0
11	0.003	0.01	0.0005
12	0.003	0.01	0.001
13	0.003	0.025	0
14	0.003	0.025	0.0005
15	0.003	0.025	0.001
16	0.003	0.05	0
17	0.003	0.05	0.0005
18	0.003	0.05	0.001
19	0.004	0.01	0
20	0.004	0.01	0.0005
21	0.004	0.01	0.001
22	0.004	0.025	0
23	0.004	0.025	0.0005
24	0.004	0.025	0.001
25	0.004	0.05	0
26	0.004	0.05	0.0005
27	0.004	0.05	0.0011

flecting the sample preparation procedure, the user subroutine used HETVAL function to describe the exothermic polymerization process. Later, in main part of the simulation work, the subroutine utilized *Phyton* scripting language to automate all of the tasks of model building, meshing, analysis and result extraction.

5.2. Results of simulations

Full set of simulation results can be found in (Ambroziński, 2011). The calculations results of the calculations are summarized in figure 6, which shows the reduction of respective stress and strain levels in comparison to the reference solution. It is worth to note, that all analyzed design combinations of first variant allowed reduce the stress values, however the reduction is rather small (few percent). The configuration nr. 1 (R = 2 mm, D = 4 mm, H = 10 mm) was selected, as the most promising one, for further experimental validation. The second design variant (figure 4, right) offered much larger decrease in stress and strain levels, but one can also observe configurations with negative results. The configuration nr. 26 (R = 4 mm, D = 0.5 mm, H = 50 mm) was designated for experimental verifications.

Based on achieved numerical results and performed Analysis of Variance (ANOVA), which is not shown in this paper, one could conclude that



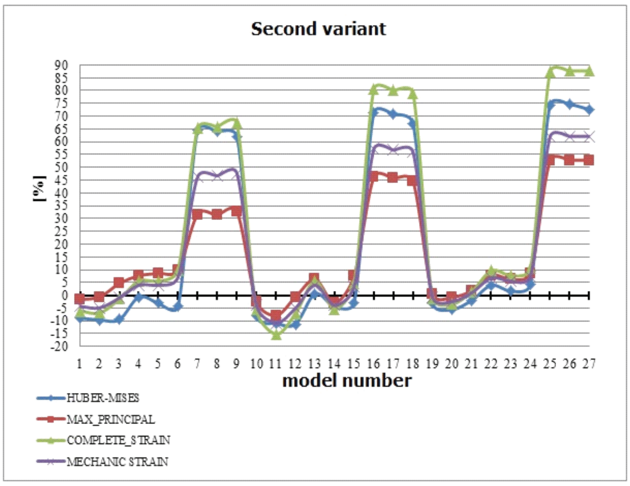


Fig. 6. *Strain reduction for all design configurations.*

The reference simulation without the relief holes was performed first. The equivalent Mises stress level, max principle stress, as well as strain results were computed and stored for comparison. All numerical calculations were managed with help of ABAQUS software package, supported by user defined subroutines. In preliminary calculations, re-

reduction of the stress level Δσ [%] in first design variant, may be described by simple equation (with 85% of the confidence):

$$\Delta\sigma = -3.8 + 27.3H + 10.3R^2 + 22.1H^2 + 9.6D^2 - 8.4R^2H^2 - 8.6R^2D^2 - 6.6H^2D^2 \quad (6)$$

with hole depth H being the most sensitive design factor (over 65% of importance).

6. EXPERIMENTAL VALIDATION

6.1. Sample preparation procedure

As many as 17 samples were prepared for experimental tests. Seven of them represented first design variant (configuration nr. 1), while the others were used for the second design variant (configuration nr. 26). All specimens were cast first, next polymerized, and finally post-cured, according strictly to the procedure specified by epoxy resin supplier (Vantico, 2000). After cooling to the room temperature, the relief holes were drilled in the case of the first design variant. At the end of the preparation process, the resin members were equipped in strain gauges (tensometers), and calibrated. The samples ready for the first experiment are shown in figure 7.

Fig. 7. *The samples prepared for the experiments.*

6.2. Testing procedure

The experimental equipment consisted of StrainBook 616 by IOtech, the strain gauge bridge, 120-Ohm strain sensors, as well as climate chamber with temperature and moisture control, see figure 8.

All the samples were subjected to thermal cycling, which is schematically presented in figure 9. Two temperature gradients were used: 2 and 5°C/min (not shown in the figure). The thermal cycle was repeated three times, in order to increase the probability of epoxy cracking.

Fig. 8. *The experimental equipment: the strain bride and the climate chamber.*

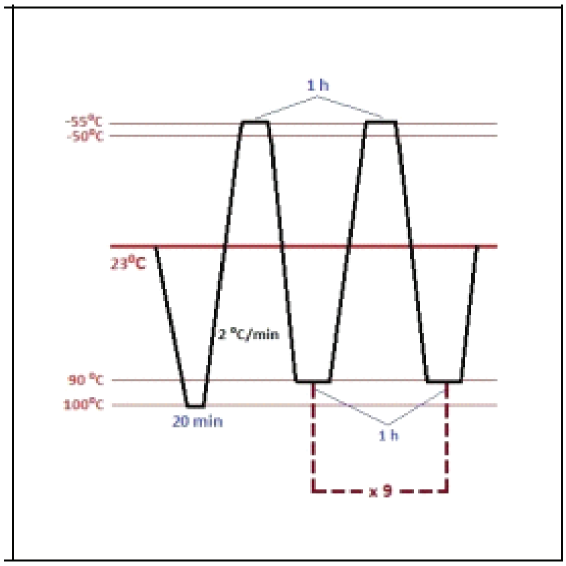


Fig. 9. *Thermal cycles used in the experiments.*

6.3. Results of experiments

The results of the experiments performed for variant 1 are summarized in table 2. One can see that application of stress relief holes has a positive effect on decrease of the failure probability. However, the influence is not dramatic. In general, 3 sharp edges (out of 7) with relief holes survived the experimental tests, while no one without the relief holes remained crack-free.

Table. 2. *Experimental results: R - notch with the relief hole, WR - notch without relief hole, V – no fracture, X – fracture.*

Test	Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		Sample 7	
	R	WR	R	WR	R	WR	R	WR	R	WR	R	WR	R	WR
3	V	X	V	X	V	X	X	X	X	X	X	X	X	X

The selected plots showing the evolution of strains near the sharp notch during experiment are shown in figure 10. A moment of time, when the fracture happens, is clearly seen. The typical samples at the end of the experimental procedure are depicted in figure 11.

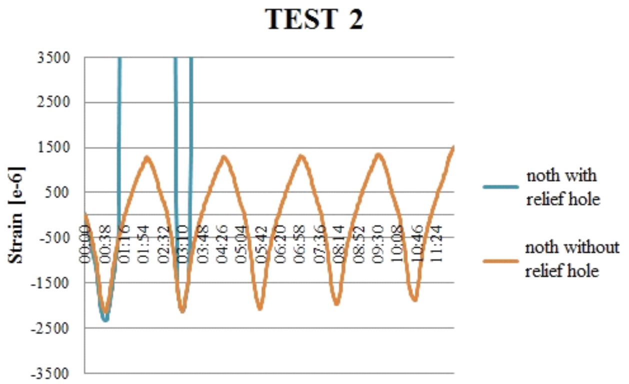


Fig. 10. *Evolution of strains during experimental tests – design variant 1.*

The design variant 2 resulted in different observations. Contrary to the previous experiment, all the tests were successful and none of the samples was destroyed. It suggests that relief hole located near one stress concentrator only worked so well that it protected the whole sample. The strain levels recorded during experiments are presented in figure 12.

7. DISCUSSION AND CONCLUSIONS

The results of performed simulation and experimental work allow concluding that application of stress-relief holes into brittle material, such as epoxy resin, brings positive effects. It was observed in numerical analysis and confirmed via validation tests that probability of material failure is reduced, if stress-relief holes are properly designed and located in the product under study. However, also manufacturing aspects and methods of making the holes are important, thus they should always be considered in

Fig. 11. *Samples number 5 (variant 1) and 9 (variant 2) after all three tests.*

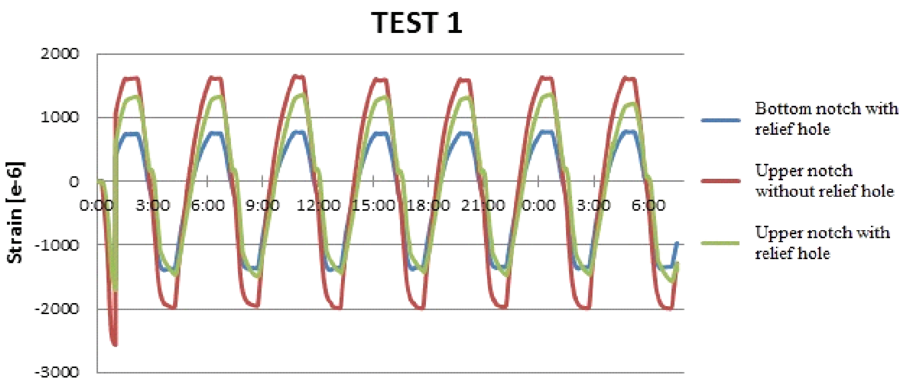


Fig. 12. *Evolution of strains during experiment – design variant 2.*

analysis. If relief holes are made by drilling after the product was cast, there is a probability of introducing some stress concentrators. In this case, the benefits of relief holes can be partly jeopardized by residual stresses made by the hole making operation. Experimental work confirmed that this design option is not totally free of cracks, but samples without holes were destroyed earlier (in higher temperatures – at lower loads). The other design option assumed, that relief holes are cast during the manufacturing process, thus no additional drilling was needed. This approach resulted in significant improvement of material failure probability. Experimental tests were performed for 10 samples, and none of them cracked during demanding tests. In general, these observations give very practical hints and suggestions for production of the medium voltage apparatuses. It became clear now, that relief holes should be produced directly during the casting process and, in the case of brittle materials, drilling operations are not recommended. It must also be pointed out that optimal geometry of the relief holes was found by numerical analysis, which helped to explore the large number of design configurations.

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KOMPUTEROWE WSPOMAGANIE PROJEKTOWANIA OTWORÓW ODPRĘŻAJĄCYCH W WYROBACH ŚREDNICH NAPIĘĆ Z ŻYWICY EPOKSYDOWEJ

Streszczenie

Celem pracy była weryfikacja metody redukcji poziomu naprężeń szczątkowych, występujących po procesie produkcyjnym, poprzez zastosowanie otworów odprężających. Obiektem badań był model reprezentujący urządzenie średniego napięcia, składający się metalowego rdzenia oraz zewnętrznej izolacji odlanej z żywicy epoksydowej. Wykorzystano analizy numeryczne do wskazania optymalnej geometrii otworu odprężającego, oraz jego usytuowania względem karbu. Przeanalizowano dwa różne warianty konstrukcyjne (stosując otwory wiercone oraz odlewane). Wyniki symulacji numerycznych posłużyły do zaprojektowania próbek testowych, które poddano badaniom eksperymentalnym. Na podstawie przeprowadzonych analiz możliwe było wyciągnięcie wniosków praktycznych i rekomendacji dla stosowania metody otworów odprężających w produkcji aparatów średniego napięcia. W szczególności wykazano, że prawidłowe zastosowanie w/w metody przynosi pozytywne efekty, nawet w przypadku materiałów kruchych, jakimi są żywice epoksydowe.

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