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Influence of shield materials on the Penning effect in a vacuum interrupter

Abstract. *The research conducted in the Tele- and Radio Research Institute (ITR) covers a developing a new portable vacuum gauge for using in a vacuum circuit breaker. Next step will be its integration with new generation of vacuum circuit breakers. The new device is supposed to use the Penning effect. In this effect, glow charge is amplified by an external magnetic field. Vacuum chambers based on a glass insulator, must be made of FeNiCo alloy called Kovar. Kovar has a high magnetic permeability, but its mechanical and magnetic parameters strongly depend on heat and mechanical treatments. The paper presents results of investigation on influence of complex thermal-mechanical treatment on magnetization curve of FeNiCo alloy. Measuring samples have undergone a similar process of heat, chemical and plastic treatment as the structural element of vacuum chambers with glass insulators. In addition, simulation results of magnetic induction in a chamber with Kovar elements are presented. Modelling and simulations were conductedin software based on Finite Element Method (FEM).*

Streszczenie. *Badania przeprowadzone w Instytucie Tele- i Radiotechnicznym (ITR) obejmują opracowanie nowego przenośnego miernika podciśnienia do stosowania w wyłączniku próżniowym. Kolejnym krokiem będzie integracja z nową generacją wyłączników próżniowych. Nowe urządzenie ma używać efektu Penninga. W tym efekcie ładunek żarzenia jest wzmacniany przez zewnętrzne pole magnetyczne. Komory próżniowe na bazie izolatora szklanego, muszą być wykonane ze stopu FeNiCo o nazwie Kovar. Kovar ma wysoką przenikalność magnetyczną, ale jego parametry mechaniczne i magnetyczne są silnie uzależnione od obróbki cieplnej i mechanicznej. W pracy przedstawiono wyniki badań wpływu złożonej obróbki cieplno-mechanicznej na krzywą magnesowania stopu FeNiCo. Próbki pomiarowe poddano podobnemu procesowi obróbki cieplnej, chemicznej i plastycznej jako element konstrukcyjny komór próżniowych z izolatorami szklanymi. Ponadto przedstawiono wyniki symulacji indukcji magnetycznej w komorze z elementami Kovar. Modelowanie i symulacje przeprowadzono w oparciu o metodę elementów skończonych (MES).* ***Badań wpływu złożonej obróbki cieplno-mechanicznej na krzywą magnesowania stopu FeNiCo***

Keywords: Penning effect, Kovar, Vacuum Interrupter.
Słowa kluczowe: wyłącznik próżniowy, efekt Penning, Kovar

Introduction

In vacuum chambers with a glass insulator for vacuum circuit breakers, it is necessary to use a construction elements and a vapour condensation shield made of Kovar. Construction of a vacuum interrupter is shown in figure 1. The condensation screen protects the insulating material from dusting of metal evaporated from the contacts and ensures protection of the internal insulating surfaces against metal sputtering and condensation of metal vapours [1].

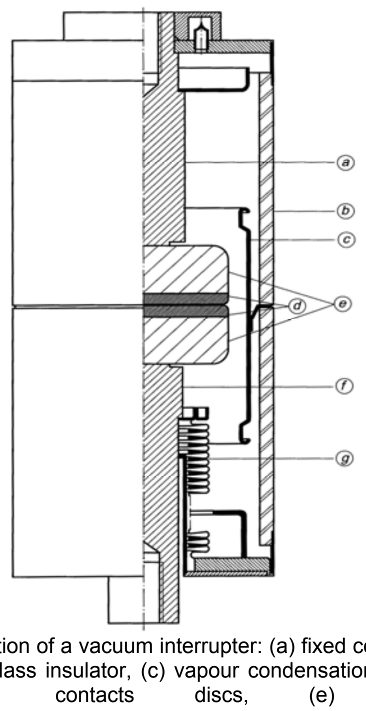

Fig. 1.Cross section of a vacuum interrupter: (a) fixed contact stem, (b) ceramic or glass insulator, (c) vapour condensation shield, (d) copper-tungsten contacts discs, (e) contacts, (f) moving contact stem, g) bellow

Kovar is a nickel–cobalt–ferrous alloy, designed to have substantially the same thermal expansion characteristics as borosilicate glass, in order to allow a tight mechanical joint between two materials over a range of temperatures [2]. Kovar was invented to meet the need for a reliable glass–to–metal seal, which is required in electronic devices such as light bulbs, vacuum tubes, cathode ray tubes, and in vacuum systems in chemistry and other scientific research. It finds application in glass-to-metal seals in vacuum interrupters made in ITR. Composition of Kovar, which is used in ITR, is shown in table 1.

Table 1. Composition of Kovar given in percentages of weight [3]

Element	Minimum	Maximum
Carbon	-	0.06
Chromium	-	0.20
Cobalt	-	17.0
Copper	-	0.20
Iron	Bal	--
Manganese	-	0.50
Molybdenum	-	0.20
Nickel	-	29.0
Phosphorus	-	0.025
Silicon	-	0.20
Sulphur	-	0.025
Zirconium	-	0.10

The research conducted in ITR covers development on line detection of residual gases inside the chamber of a vacuum interrupter. This method uses of the Penning effect.

The Penning effect is used in vacuum gauges, but also for testing vacuum interrupters [4]. The Penning gauge is an ionization gauge with an unheated cathode in which a discharge is maintained between two electrodes with a potential difference of a few kilovolts. Pressure is converted from discharge current. Magnetic field is applied to increase the number of ions produced during discharge.

Ionization is the process by which an atom gain or lose electron after collision with subatomic particle, atoms, molecules and ions or interaction with electromagnetic radiation and acquires a positive or negative charge. More collisions mean more electrons.

The force that affects the ion in the electromagnetic field is described by the equation (eq. 1). It is the sum of the electrical and magnetic forces acting on the particle.

$$\vec{F} = \vec{F_e} + \vec{F_b} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (1)$$

where: q – particle charge, E – intensity of electrical field, B – magnetic induction, V – particle velocity.

The electric field affects the particle to change its kinetic energy. Particle can change the speed and acceleration in the direction of the electric field. The magnetic field has no effect on the change of energy of particle. However, it causes the centripetal force resulting in centripetal acceleration. It curves the particle path causing it to move at a constant angular velocity ω (cyclotron frequency), which is described by equation 2. The radius of this orbit r is determined by equation 3. As q, the value of the electric charge was determined, and as $\upsilon\perp$ the speed component perpendicular to the vector B. The magnetic field influences the particle velocity component, which is perpendicular to the vector $\vec{B}$, does not affect the velocity component parallel to the vector $\vec{B}$. According to formulas 2 and 3, increasing the value of the component B perpendicular to the spinning plane of the particle will increase the angular velocity of the particle and reduce the spinning radius. Summation of the interaction of the magnetic field and the electric field may be the spiral motion of the particle.

$$\omega = \frac{qB}{m} \quad (2)$$

where: ω – angular velocity, q – particle charge, B – magnetic induction, m – mass of the particle.

$$r = \frac{mv_\perp}{qB} \quad (3)$$

here: r – spinning radius, $v_\perp$ – component of the velocity perpendicular to the direction of the magnetic field, q – particle charge, B – magnetic induction.

An axial magnetic fields cause electrons to move in spiral path and increase the ionization current. The longer path length of an electron from cathode to anode increased possibility of generate another electron by impacting on a gas molecule to maintain the discharge.

The vacuum interrupter manufactured in ITR are mainly made of kovar, glass and copper. Kovar from which the housing elements and sometimes screens are made can influence the distribution of the magnetic field during the Penning method test. Research include measurements of magnetization characteristics of samples made of kovar. In addition, Finite Element Method (FEM) simulations of the magnetic field distribution in the chamber with elements made of Kovar were carried out.

Experiments and results

In order to carry out the simulation of magnetic field distribution in a vacuum interrupter, it was necessary to determine the magnetization curve of the materials used. Two specimens made of a Kovar were tested. One sample was made of Kovar without any special treatment. It was a Kovar ring only punched and etched. Second sample was made of Kovar with complex thermal-mechanical treatment with means punching, etching, annealing (860°C) and ironing. The samples was made from Kovar plate made according to ASTM F15 standard. Each plate was cut on rings with size: thickness 0,8mm, external diameter: 66mm and internal diameter: 56 mm. Characteristic of magnetic materials was examined according to IEC 60404-4 standard. Two samples were made, each one was made of six stacked rings.

The measured values of the intensity of the magnetic field and induction are used to draw magnetization curve (fig. 2). It seems that thermal-mechanical treatment worsens magnetic properties of Kovar. A sample after thermal-mechanical treatment have lower magnetic permeability and saturation induction in comparison to a sample without such treatment.

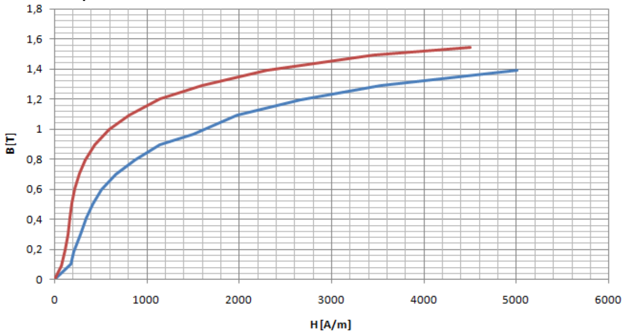

Fig. 2. DC magnetization curves of Kovar: without special treatment – red line, and after complex thermal-mechanical treatment – blue line

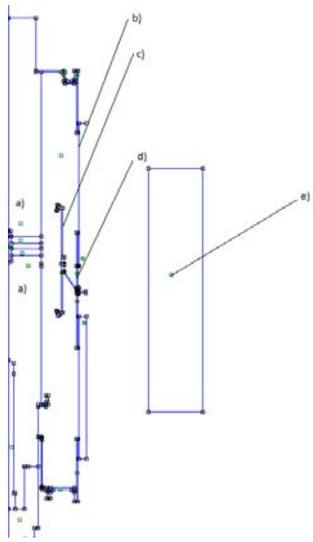

Fig. 3.Cross section of a vacuum interrupter: (a) a fixed contact stem, (b) a ceramic or glass insulator, (c) vapour condensation shield, (d) housing sleeve with flanges, (e) magnet coil

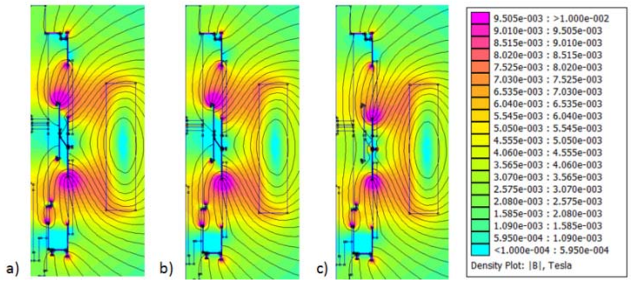

Fig. 4. Magnetic flux density distribution and magnetic flux lines for simulations:(a) with Kovar without special treatment shield, (b) with Kovar with complex thermal-mechanical treatment shield and (c) with copper shield

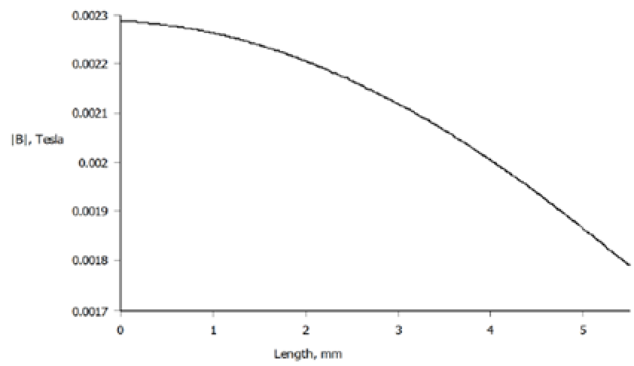

Fig.5. Magnitude of magnetic flux density between contacts with a shield made of Kovar without a special treatment, as a function of distance from centre of a chamber

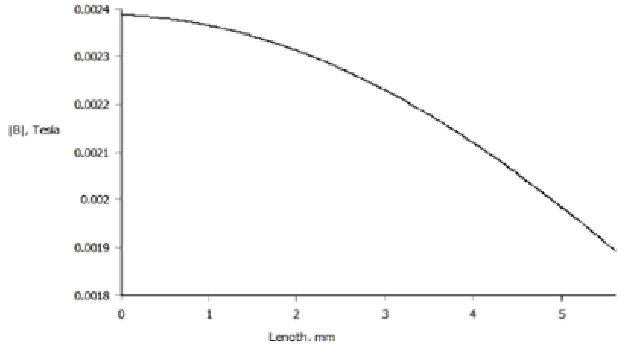

Fig.6. Magnitude of magnetic flux density between contacts with a shield made of Kovar after a special treatment, as a function of distance from centre of a chamber

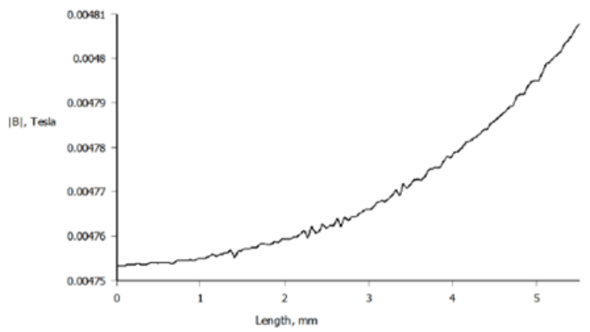

Fig.7. Magnitude of magnetic flux density between contacts with a shield made of copper, as a function of distance from centre of a chamber

The next step of research was simulations of magnetic flux density using FEMM4.2 program [5]. Fig. 3 shows cross section of vacuum interrupter with selected important elements for simulation. The results of simulations are shown on the figures from fig.4 to fig. 7. Fig. 4 show magnetic flux density and magnetic flux lines in vacuum interrupter. During simulations it was assumed the flow of a DC current equal 5 A in a coil with 100 turns. Fig. 5 to fig. 7 shows simulations of magnitude of magnetic flux density between contacts in the chamber in three case using different shield material: (a) Kovar, (b) Kovar after thermal-mechanical treatment, and (c) copper.

Conclusions

Results of research shows the influence of the complex thermal-mechanical treatment on the magnetic properties of Kovar. It can be noticed that special treatment decreases Kovar saturation induction and permeability.

Simulations show that the magnitude of magnetic flux density between contacts in vacuum interrupter is like as in case of using shield with Kovar without thermal-mechanical treatment. It can be noticed that copper used instead of Kovar significantly increases the magnetic field value between the contacts. This increases the effectiveness of measuring the vacuum level in the interrupter.

Application of the copper shield is better than application of the Kovar shield if we think about higher magnetic field between contacts. For investigation the significance of such a difference in the magnetic field to amplify the measuring signal, further experimental studies are necessary.

The research allowed us for a selection of materials to use as a shield in next step of research. After going through simulation results, we can choose copper and Kovar with thermal-mechanical treatment to further study. We can skip study the influence of using Kovar without treatment and the thermal-mechanical treatment Kovar. Difference between this two types of material are neglected in comparison to copper.

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REFERENCES

[1] Sibilski H., Dzierżyński A., Berowski P., Hejduk A., Krasuski K., Grodziński A., Szymański A., AMF contact research in a dismountable vacuum chamber, (in Polish), *Elektronika,*vol. 52, no. 8, 2011, pp. 42-44
[2] Bozorth R. M., Ferromagnetism, *D. Van Nostrand Company*, *3 Edition*, 1955, pp. 160-180
[3] https://www.vincentmetals.com/Kovar_ASTM-F15.html#chemical, access 02.10.2018
[4] Mao H., Chang G., Zhu X., Wang Y., On-line monitoring of pressure in vacuum interrupters, *IEEE Transactions Dielectrics and Electrical Insulation*, vol. 14, no. 1, 2007,pp. 179 – 184
[5] http://www.femm.info/wiki/HomePage, access 02.10.2018