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TECHNOLOGICAL MONITORING OF ELECTRICAL RESISTANCE OF PRESSED CABLE CONDUCTORS IN PRODUCTION CONDITIONS

This paper presents results of control of electrical resistance R production pressed aluminum cable conductors. Control of electrical resistance in manufacturing of cable production is the most massive non-destructive test, which provides a compromise between the manufacturer's costs for a high-conductivity material on the one hand and the user's operating costs from conducting heating losses on the other. For the adoption of technological solutions for the use of hot compression of solid aluminum wires (instead of cold drawing technology) for a specific size, a reliable determination of the probability of unacceptable values of electrical resistance R > Ř (probability of claims) in large masses of products is necessary. The application of statistical analysis of measurement results using the mathematical apparatus of boundary distributions is considered. In this case, the subject matter of the analysis is the distribution of the limit values of the control parameter, which makes it possible to reliably estimate the likelihood of the appearance of inadmissible values (probability of claims). An algorithm for determining the probability of the appearance of impermissible values of the electrical resistance R > Ř (probability of claims) for solid aluminum wires of low and medium voltage cables in the range of the cross-sectional area (120...240) mm² based on the analysis of the results of control of the electrical resistance during a long technological period (18 months) manufacturing in production conditions. The use of the appeal potential of the technological solution as the cost of products, for which R > Ř is used, is proposed. The comparison of the appeal potential of the technology of hot pressing of solid aluminum and the technology of cold drawing (dragging) provided the same level of specific electrical conductivity of the metal is achieved. References 8, figures 5.

Key words: **control of electrical resistance, aluminum cable conductors, technological monitoring, probability of claims, mathematical apparatus of boundary distributions.**

Представлено результати контролю в умовах виробництва електричного опору R пресованих алюмінієвих кабельних провідників. Контроль R в кабельному виробництві є наймасовішим неруйнівним випробуванням, яке забезпечує компроміс між затратами виробника на матеріал високої електропровідності з одного боку, і експлуатаційними затратами користувача від втрат на нагрівання провідників з іншого. Для прийняття технологічних рішень щодо використання гарячого пресування суцільних алюмінієвих жил (замість технології холодної витяжки) для конкретних розмірів жили необхідне надійне визначення ймовірності появи недопустимих значень електричного опору R > Ř (ймовірності рекламацій) у великих масивах продукції. Розглянуто застосування статистичного аналізу результатів вимірювання за допомогою математичного апарату граничних розподілів. При цьому предметом аналізу стає розподіл граничних значень контрольного параметру, що дає можливість надійного оцінювання ймовірності появи недопустимих значень (ймовірності рекламацій). Розроблено алгоритм визначення ймовірності появи недопустимих значень електричного опору R > Ř (ймовірності рекламацій) для суцільних алюмінієвих жил силових кабелів низької і середньої напруги в діапазоні площі поперечного перерізу (120…240) мм² на основі аналізу результатів контролю електричного опору впродовж тривалого технологічного періоду (18 місяців) виготовлення в умовах виробництва. Запропоновано використання рекламаційного потенціалу технологічного рішення як вартості продукції, для якої R > Ř. Виконане порівняння рекламаційного потенціалу технології гарячого пресування суцільних алюмінієвих і технології холодної витяжки (волочіння) за умови досягнення однакового рівня питомої електропровідності металу. Бібл. 8, рис. 5.

Ключові слова: **контроль електричного опору, алюмінієві кабельні провідники, технологічний моніторинг, ймовірність рекламацій, математичний апарат граничних розподілів.**

Представлены результаты контроля электрического сопротивления R в условиях производства прессованных алюминиевых кабельных жил. Контроль R в кабельном производстве являться наиболее массовым неразрушающим испытанием, которое обеспечивает компромисс между затратами изготовителя на материал высокой электропроводности, с одной стороны, и эксплуатационными затратами пользователя от потерь на нагрев проводников, с другой. Для принятия технологических решений относительно использования горячего прессования сплошных алюминиевых жил (вместо технологии холодной вытяжки) для конкретных размеров жилы необходимо надежное определение вероятности появления недопустимых значений электрического сопротивления R > Ř (вероятности рекламаций) в больших массивах продукции. Рассмотрено использование статистического анализа результатов измерений с помощью математического аппарата предельных распределения. При этом предметом анализа становится распределение предельных значений контрольного параметра, что дает возможность надежного определения вероятности появления недопустимых значений (вероятности рекламаций). Разработан алгоритм определение вероятности появления недопустимых значений электрического сопротивления R > Ř (вероятности рекламаций) для сплошных алюминиевых жил силовых кабелей низкого и среднего напряжения в диапазоне площади поперечного сечения (120…240) мм² на основе анализа результатов контроля электрического сопротивления в течение длительного технологического периода (18 месяцев) изготовления в условиях производства. Предложено использование рекламационного потенциала технологического решения как стоимости продукции, для которой R > Ř. Произведено сравнение рекламационного потенциала технологии горячего прессования сплошных алюминиевых жил и технологии холодной вытяжки (волочения) при условии достижения одинакового уровня удельной электропроводности металла. Библ. 8, рис. 5.

Ключевые слова: **контроль электрического сопротивления, алюминиевые кабельные проводники, технологический мониторинг, вероятность рекламаций, математический аппарат граничных распределений.**

Introduction and problem definition. The introduction of technological changes in the production of cable and wire products, which increase the economic efficiency of production, always requires the analysis of the impact of these changes on the relation of interests of the manufacturer and consumer of products. Here, it is a matter of solid aluminum wires made by hot pressing (SSAP – **s**olid **s**oft **a**luminum **p**ressed), instead of the technology of cold drawing, which in practice of cable technology is called dragging. Hot pressing provides the highest electrical conductivity of the metal with the simultaneous elimination of the cost of annealing, which is necessary for recrystallization of the structure of the conductor due to the cold deformation of compression during dragging. Providing a high level of electrical conductivity corresponds both to the interests of the manufacturer and to the interests of the consumer, since this characteristic is the basis for providing the electrical resistance R of conductors. But the value of R is influenced by a number of structural and technological factors. Therefore, the monitoring of the electrical resistance R for conductors is the most massive non-destructive test in the cable industry, which provides a compromise between the manufacturer's costs on the material of high electrical conductivity on the one hand and the user's operating costs from the losses of heating of conductors on the other.

Corresponding maximum limit values $\check{R}$ are normalized to provide a sufficiently small electrical resistance, which determines the energy losses in the cable, and hence the temperature of its elements and by it, the durability and reliability of cable insulation in both operating and emergency modes [1]. In order to make technical decisions on the use of hot pressing of solid aluminum wires (instead of the cold drawing technology) for a specific size of the wire, it is necessary to reliably determine the probability of unacceptable values of electrical resistance $R > \check{R}$ (probability of claims) in large masses of products based on the results of technological monitoring of R.

Analysis of literature. Cable production is characterized by significant lengths of products with high requirements for the uniformity of length parameters, therefore the value of $\check{R}$ per unit of length is standardized [2]. The monitoring of homogeneity of R in length is the subject of technological monitoring. The problem of organizing active technological monitoring is conceptual for automated mass production not only in cable technology, since between the tasks of receiving and current technological monitoring there is a significant theoretical and technical difference [3]. For the key electrical engineering parameters of mass production, one-way restrictions are used: for electrical resistance of conductors – no more than; for electric strength – not less than, etc. Therefore, for the evaluation of the guaranteed level of technical parameters of products that ensure its reliable functioning, it is expedient to use the mathematical apparatus of boundary distributions [4]. The difference in the technological monitoring from the receiving one is that possible changes in the technological process should be recorded by it [4]. That is, the measurement result is an element of an unknown statistical array. Therefore, for the purposes of technological monitoring, it is expedient to use the mathematical apparatus of the boundary distributions. In this case, the subject matter of the analysis is the distribution of the limit values of the control parameter, which makes it possible to reliably estimate the probability of the appearance of inadmissible values (probability of claims).

The number of structural and technological factors that affect the value of R is very significant. The first is the cross-sectional area of the conductor. The larger the area of the section of the continuous wire, the economic efficiency of the application of hot pressing technology is higher because of the unnecessary further annealing. On the other hand, in the process of crystallization of the metal, after compression its density changes and its shrinkage [5] is observed, which depend on the compression mode and the cross-sectional area of the wire. For a specific size of the wire, a reliable determination of the probability of the occurrence of impermissible values of electrical resistance $R > \check{R}$ in large masses of products based on the results of technological monitoring of R is necessary.

Reliable determination of the probability of the appearance of inadmissible values of random variable is still the subject of the search for specific solutions for specialists in the field of mathematical statistics [6]. It is obvious that such a determination in production conditions should take into account the volume of output and be based on sufficiently well-known and indisputable statistical models. Known statistical models of distribution of boundary values correspond to these obvious requirements [4]. The one-time, even massive, statistical stability study can not be practically carried out, the concept of solving applied probabilistic problems is the well-known Mises concept [7]: the frequency $f^*(A)$ of event A is the proportion of the number of events $m^*(A)$ arising from the number of independent attempts n^* under the identical conditions that they may have occurred in: $f^*(A) = m^*(A)/n^*$. Here and further the mark «*» is used for the values determined experimentally. The requirement of reproducibility of a phenomenon with the definition of frequency acquires a quantitative expression in the form of the principle of constancy of frequencies:

$$m_1^*(A)/n_1^* \cong m_2^*(A)/n_2^* \cong m_3^*(A)/n_3^* \cong .. \; m_k^*(A)/n_k^*, \quad (1)$$

that is, the frequency of this event in a series of independent attempts must be sufficiently identical.

The relation (1) is precisely the principle, since sufficient uniformity of frequencies can be accepted only within the framework of a specific problem, but the requirement of constancy of frequencies naturally follows from the requirement of the reproducibility of the event. This requirement is successfully used in practical statistics [8]. Therefore, it is necessary to reliably determine the probability of the occurrence of impermissible values of resistance $R > \check{R}$ that should be performed for the largest cross-sectional area produced and tested during a long technological period in a series of independent attempts.

The goal of the work is the development of an algorithm for determining the probability of the appearance of impermissible values of the electrical resistance $R > \check{R}$ (probability of claims) for solid aluminum wires of low and medium voltage cables in the range of the cross-sectional area (120 ... 240) mm^2 based on the analysis of the results of the electrical resistance monitoring during a long technological manufacturing period in a production environment. Determination of the probability of unacceptable values of electrical resistance in the current production conditions is the basis for establishing economically justified guarantees for the user, first of all, regarding the bandwidth of the cable, which is guaranteed by the manufacturer in nominal operating conditions.

Main results. Figure 1 shows the results of the monitoring of the electrical resistance R under the conditions of production and, in accordance with the current certification documentation, for 18 months of 2017 and 2018, of solid aluminum wires of low and medium voltage power cables made by pressing in the range of the cross-sectional area (120 ... 240) mm^2.

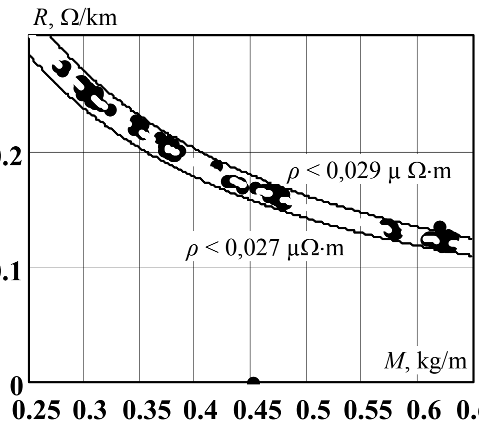

Fig. 1. The dependence of the electric resistance R on the unit length of the aluminum wire, made by hot pressing, from the mass M in the range of the cross-sectional area (120 ... 240) mm^2: points – experimental values; solid curves – the dependencies $R = f(M)$, calculated for the specific electric resistance of 0.027 μΩ·m (lower) and 0.029 μΩ·m (upper)

The dependence $R = f(M)$ of the lateral resistance R on the particle mass of the conductor is universal, inversely proportional and its parameter is the specific electrical resistance ρ of the wire metal. The results of the control over 18 months are in accordance with the current standards regarding the specific electrical resistance of the wire metal, which confirms the starting thesis that pressing provides the necessary electrical conductivity of the metal with the simultaneous exclusion of the cost of annealing.

A feature is the presence of samples with an abnormally low mass for each of the nominal cross sections studied. Such samples appear evenly throughout the long technological observation period, representing a relatively small, but substantial part of the tested samples (from 5 % to 8 %). In accordance with the principle of the reproducibility of the Mises, the technology of manufacturing of continuous aluminum wires by hot pressing ensures the reproducibility of the electrical conductivity of the metal, but in this particular case does not ensure the reproducibility of the particle mass of the metal.

Therefore, in the further development of the algorithm for determining the probability of the appearance of impermissible values of electrical resistance $R > \check{R}$ (probability of claims) for solid aluminum wires of low and medium voltage cables, has been carried out on the basis of analysis of the data array (238 values), which corresponds to the principle of the reproducibility of the event. Data that does not correspond to the principle of reproducibility of an event are used to analyze the reasons for the appearance of specimens with an abnormally low mass.

Figure 2 shows the characteristic functions of the distribution of electrical resistance of SSAP samples. The functions of the distribution of the maximum values of R_{max} are obtained in two ways: analytically by the formula (2) and by the computer statistical experiment as the distributions of the largest values in the corresponding normally distributed random variables. Both methods gave the same result, presented in Fig. 2.

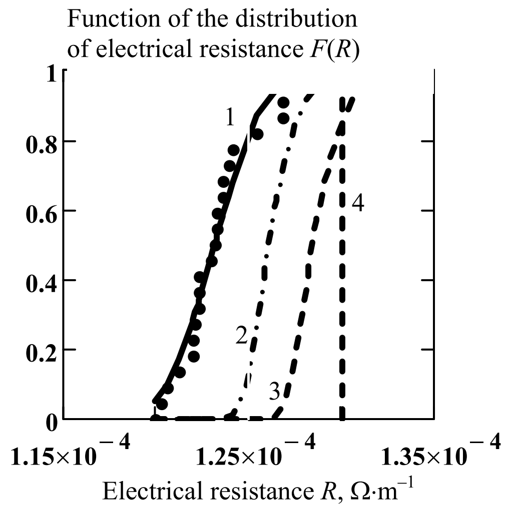

Fig. 2. Functions of the resistance R distribution of SSAP samples: 1 – empirical distribution function (points) and its approximation by normal distribution (solid line); 2 – function of distribution of maximum values R_{max} in 24 samples at 24 normally distributed values; 3 – function of distribution of maximum values R_{max} in the corresponding 250 samples; 4 – arbitrarily selected impermissible value

The results presented in Fig. 2 testify:

1) according to the results of measurements of the electrical resistance, it is possible to determine the probability of the appearance of impermissible values of the electrical resistance $R > \check{R}$ (probability of claims) by means of the known mathematical apparatus of distributions of maximum values R_{max} for solid aluminum wires of low and medium voltage cables;

2) parameters of the boundary function of the distribution of the maximum values R_{max} [4]:

$$F(R_{max}) = \exp\{-\exp[-(R_{max} - B_n)/A_n]\}, \quad (2)$$

where B_n is the shift parameter equal to R_{max}, less than 37 % of the samples with n; A_n is the scale parameter that depends on the initial distribution and does not depend on n; the parameters of the function (2) depend on the division of the batch into statistical groups according to the requirement of constancy of frequencies (1); to determine the parameters we double-log the function $F(R_{max})$, obtain a linear relationship between the double logarithms of the distribution function and the values of R_{max};

3) the larger the statistical groups in accordance with the requirement of constancy of frequencies (1), the greater the number of inadmissible values of the electrical resistance on the curve of the function of the distribution of maximum values (see curves 2 and 3 in Fig. 2), but this increase is rather fast decelerating and there is a limit distribution and, accordingly, the boundary parameters that do not depend on the volume of the batch of products or its division into statistical groups.

Dependencies of the parameters of the distribution function (3) of the maximum values R_{max} on the division of a batch into statistical groups by the results of measurements of electrical resistance (1 in Fig. 2) are presented in Fig. 3.

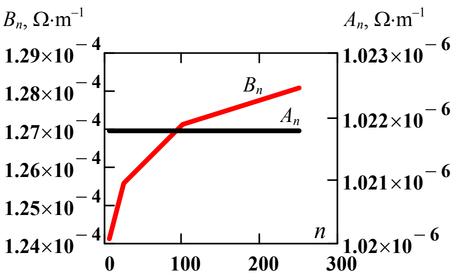

Fig. 3. Dependences of the parameters of the distribution function $F(R_{max})$ (3) on the division of a batch into statistical groups by the results of measurements of electrical resistance: dependence $B_n(n)$ – nonlinear, the value of the parameter B_n reflects the maximum distribution density $F(R_{max})$ (see Fig. 4)

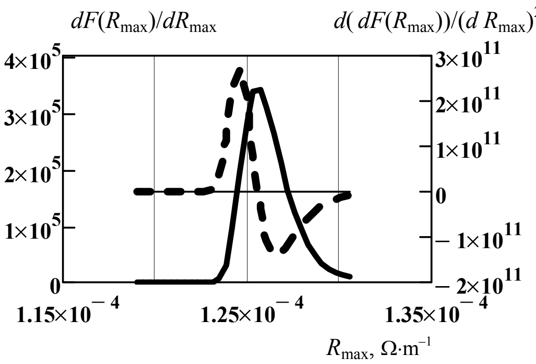

Fig. 4. Characteristic points of the first (solid line $f(R_{max})$) and the second derivative (dashed line $df(R_{max})/dR_{max}$) of the distribution of the maximum values of electrical resistance reflect the unambiguous technical meaning of the corresponding values of R_{max}: the minimum of the second derivative – the appropriate technical characteristic of the upper bound for technological monitoring by R_{max} depends on n, but the corresponding probability of exceeding this bound does not depend on n, which gives an opportunity to analytically assess the appropriate level of technical guarantee

Figure 5 illustrates the application of different upper bounds for technological monitoring of the distribution function of R_{max} in 24 samples with 24 normally distributed values determined experimentally.

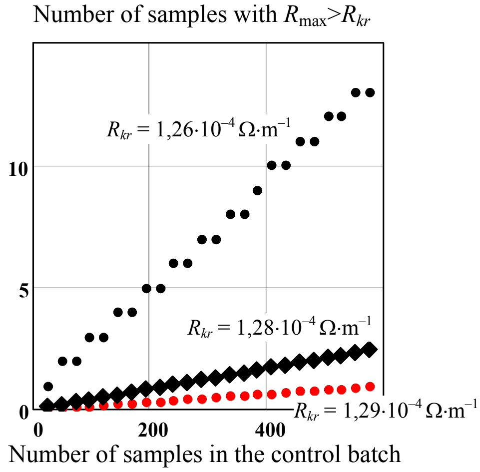

Fig. 5. An illustration of the possible practical application of different upper bounds for technological monitoring of the distribution function of R_{max} in 24 samples at 24 normally distributed samples of SSAP with a cross section of 240 mm²

According to Fig. 5 within the array of a control batch, from several tens to several hundreds, the monitoring sensitivity provides the use of the upper limit for $R_{max} < R_{kr} = 1.26 \cdot 10^{-4}$ Ω·m⁻¹ in sampling for 24 samples. In this case, for batches with a sample size of 50 and larger, the relative number of samples with $R_{max} > R_{kr}$ is stable and remains at 2.5 % if there are no obvious changes in the technological process.

It is important that the limit $R_{kr} = 1.26 \cdot 10^{-4}$ Ω·m⁻¹ is not arbitrarily chosen. This value corresponds to the minimum of the second derivative – an expedient technical characteristic, when the decrease in the density of the distribution is sharply slowing down and practically does not affect the number of violations of the established limit. This gives an opportunity to analytically assess the appropriate level of technical guarantee.

Conclusions.

1. The results of the monitoring over 18 months in the conditions of the production of electrical resistance R of solid aluminum wires made by hot pressing confirmed the starting thesis that hot pressing provides the required electrical conductivity of the metal with the simultaneous exclusion of the cost of annealing.

2. An algorithm for determining the probability of unacceptable values of electrical resistance $R > \check{R}$ (probability of claims) is developed for continuous aluminum wires, made by hot pressing, using the known mathematical apparatus of distributions of maximum values R_{max}. The algorithm includes:

- separation of the control batch into statistical groups in accordance with the known requirement of constancy of frequencies (1);
- determination of the parameters of the initial distribution by standard statistical procedures (in this case, by normal distribution);
- determination of the distribution parameters of the maximum values R_{max} by the least squares method in the linear coordinates of the distribution function of the maximum values;
- determination of the critical value of the electrical resistance R_{kr}, which corresponds to the minimum of the

second derivative – the appropriate technical characteristic, when the decrease in the density of the distribution is sharply slowing down and practically does not affect the number of violations of the established limit (in this case $R_{kr} = 1.26 \cdot 10^{-4}\ \Omega \cdot^{-1}$);

- determination of the level of technical guarantee as the ratio of the number of samples with $R_{\max} > R_{kr}$ to the control batch volume (for example, 5/200 = 0.025 or 2.5 %, see Fig. 5).

3. The developed algorithm, tested in production conditions and in accordance with valid certification documentation during 18 months of 2017 and 2018, makes it possible to technically assess the claim potential of the achieved level of specific technology as a product of the probability of unacceptable values $R_{\max} > R_{kr}$ in the control batch for (3) for the accepted the critical level R_{kr} to the corresponding technological cost of the samples in the control batch.

4. The use of the claim potential of the technological solution as the cost of products, for which $R > \check{R}$ is proposed. The comparison of the claim potential of the technology of hot pressing of solid aluminum wires (0.025×1 = 0.025 USD/km) and the technology of cold drawing (0.025×1.2 = 0.03 USD/km) provided the same level of specific electrical conductivity of the metal is carried out.

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