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STUDY OF THE VARIABILITY OF THE NUMBER OF PORES PER UNIT LENGTH OF THE WELD

The variability of the number of pores that appeared under the influence of additional introduction of the pore-forming material into the welding zone was analyzed. The Pearson test showed that Poisson's law adequately describes the variability of the number of pores in a unit area of the weld. At the same time, the experimental distribution is very close to the theoretical one calculated according to Poisson's law. The mathematical expectation of the number of pores in a unit area of the weld unambiguously determines the distribution of the number of pores. The form of the distribution depends significantly on the value of the mathematical expectation.

Keywords: *porosity of welds; porosity indicators; Poisson distribution; Pearson's test; mathematical expectation.*
Table: 2. Fig.: 3. References: 8.

Urgency of the research. The presence of gas pores in the metal of the weld reduces the area of the metal of the welded joint in the cross-section, acts as a stress concentration factor, which can lead to the destruction of the welded product during operation. In the case of through-pores (gas channels), there is a possibility of loss of tightness of welded products. Ensuring the absence of pores is especially relevant for pressure vessels, welded products that are under the influence of dynamic loads.

The process of pore formation is quite complex and multifactorial. The formation of a pore in a weld involves the simultaneous presence of a seed in the weld pool and a supersaturated solution of hydrogen or nitrogen as a gas that saturates the pore. The appearance of a pore may be the result of a heterogeneous reaction with the formation of carbon monoxide. The weld pool usually contains a large number of potential pore nuclei. But not all embryos develop, because there is not enough gas in the place where the embryo is located. In addition, even if a gas bubble has formed in the metal of the welding bath, it can float to the surface and a pore will not form. The main efforts to prevent the appearance of pores are aimed at limiting the content of hydrogen and nitrogen in the metal of the weld pool and preventing the formation of carbon monoxide before the crystallization front of the metal of the weld pool. However, the complexity and multifactorial nature of the process of pore formation leads to the fact that their appearance has a pronounced statistical character [1]. Despite measures to prevent the formation of pores, they are a fairly common defect, the absence of which cannot be guaranteed [2]. Therefore, the study of statistical distributions that describe the variability in the formation of pores is an urgent task.

Target setting. Depending on the load conditions of the welded joint, modern standards limit the permissible diameter and number of pores per unit length of the weld [3]. Thus, the acceptability of each individual controlled section of the welded joint is determined by the diameter and number of pores found in this section. To determine the acceptability of the welding process, it is necessary to focus on the statistical characteristics of the variability of the diameter and the number of pores, which are characteristic of the process under study. At the same time, the main characteristic is a statistical law (distribution), which adequately describes the variability of the controlled porosity indicator. In real welding conditions, pores do not occur frequently enough to combine pore data into representative volume samples. Therefore, statistical studies should be conducted in laboratory conditions with the additional introduction into the welding zone of materials that lead to the appearance of pores. The data obtained in this way must be statistically analyzed using the criteria of adequacy of statistical models. Data on the statistical regularities of variability of porosity indicators will allow us to draw conclusions about the propensity of welding processes to porosity on much smaller sample volumes under production conditions.

Actual scientific researches and issues analysis. According to the generally accepted classification in mathematical statistics, the main indicators of porosity, namely the pore diameter d and the number of pores x per unit area of the weld, are random values.

The possibility of applying statistical regularities to porosity indicators is largely determined by which statistical feature the indicator belongs to. The value of the pore diameter is determined by measurements using appropriate measuring equipment. The accuracy of measurements can be different and depends significantly on the method of measurements and the used measuring equipment. Therefore, the pore diameter is considered a continuous feature. The variability of an indicator attributed to a continuous feature can be described by a uniform distribution, a normal distribution, and a Weibull distribution. A uniform distribution adequately describes variability for relatively simple objects with a well-known complete event space, which is characteristic of game theory and is practically not encountered in industrial situations. The normal distribution is the most common distribution for controlled production, process, and product indicators. However, the normal distribution better describes the variability of indicators that are purposefully and actively formed by production processes [4]. The appearance of a pore is a random, undesirable phenomenon, so its diameter is purposefully approached to zero, which leads to the deviation of the distribution of diameter values from the symmetrical form corresponding to the Weibull distribution [5]. There are three-parametric and two-parametric Weibull distributions. According to published research results [6, 7], the variability of the pore diameter is described by a two-parametric Weibull distribution

$$f\left(d_*, a_d, b_d\right) = \frac{b_d}{a_d}\left(\frac{d_*}{a_d}\right)^{b_d - 1} \times e^{\left[-\left(\frac{d_*}{a_d}\right)^{b_d}\right]} \qquad (1)$$

where d_* – is the value of the pore diameter, mm;

a_d – scale parameter (size) of the Weibull distribution of pore diameter, mm;

b_d – shape parameter of the Weibull distribution of pore diameter, dimensionless.

Characteristic ranges of values of parameters of the Weibull distribution of pore diameters in weld metal during submerged arc welding - a_d = 1,2÷2,6 mm; b_d = 1,0÷1,6.

The number of pores in a unit area of a weld seam is determined by the registration method and refers to an ordinal feature as the number of events registered per unit [8]. The variability of an indicator assigned to an ordinal characteristic is often described by the Poisson distribution. However, it is necessary to determine the possibility and adequacy of applying this distribution precisely to the variability of the number of pores per unit length of the weld.

Uninvestigated parts of general matters defining. Recent studies have shown the adequacy of the application of the Weibull distribution to the variability of the pore diameter. Determining the distribution that adequately describes the variability of the number of pores per unit length of the weld requires specialized laboratory research.

The research objective is the definition of a statistical distribution that adequately describes the variability of the number of pores per unit length of the weld.

The statement of basic materials. To provoke pores, surfacing was performed on a plate with grooves into which two polyolefin tubes with a diameter of 0.8 mm filled with distilled water were inserted (Fig. 1).

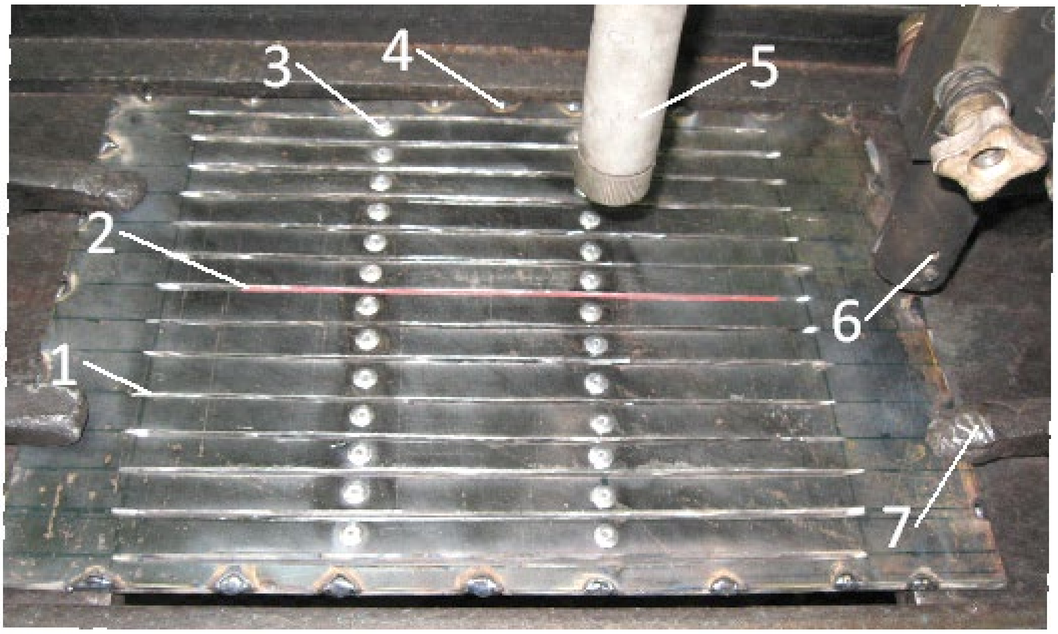

Fig. 1. Laying of polyolefin tubes with a pore-forming liquid:
1 – groove; 2 - polyolefin tube with a pore-forming liquid; 3 – rivet; 4 – tack;
5 – joint monitoring system; 6 – mouthpiece; 7 - clamp

The source: authors have developed

In the 0214 series of experiments, four rollers with a length of 280 mm each were welded. 35 mm remained on the roller at the beginning and at the end for igniting the arc and welding the crater. The length of each polyolefin tube with water was 210 mm. Thus, the total length of the welded roller, which was under the influence of the water introduced into the tube, was 210 mm. This length was divided into seven single sections of 30 mm in length. Thus, in the series, experimental data were obtained regarding the porosity of the deposited rolls on 28 single sections, deposited under the same conditions with the introduction of distilled water in two polyolefin tubes with a diameter of 0.8 mm. The surface pores detected by visual inspection were recorded in the table. 1. In the same table, the data for checking the adequacy of the application of Poisson's law for the analysis of the obtained experimental data are given.

Table 1 – Application of Poisson's law for the analysis of experimental data

i	1	2	3	4	5	6	7	8	9	10	11	12	13
x_i	8	9	10	11	12	13	14	15	16	17	18	19	20
k_i	1	2	2	3	4	3	3	3	2	2	1	1	1
k_i/K	0,036	0,071	0,071	0,107	0,143	0,107	0,107	0,107	0,071	0,071	0,036	0,036	0,036
$g(x_i,\mu)$	0,041	0,060	0,080	0,097	0,107	0,110	0,104	0,092	0,077	0,060	0,044	0,031	0,020
K	28												
$\mu=x_{cep}$	13,29												
χ_k^2	1,454												

The source: authors have developed

According to the table 1, the number of pores per unit area of the weld varied from 8 to 20. Thus, x_i took one of 13 values, and the number of ranges in which pores were recorded was f = 13. According to the number of pores per unit area of the weld, the system had r = 13-1 =12 degrees of freedom.

What is the proportion of unit sites that have a pore count x* or what is the probability that the pore count is equal to a given value x*? The answer to this question is given by the unit probability of the Poisson distribution for a given value of the number of pores x*:

$$g(x_*, \mu) = \frac{\mu^{x_*}}{x_*!} \times e^{-\mu}, \tag{2}$$

where μ - is the mathematical expectation of the number of pores per unit area of the weld, as a parameter of Poisson's law.

The only parameter of the Poisson distribution of the number of pores per unit area of the weld is μ - the mathematical expectation of the number of pores, found as the arithmetic mean of the number of pores per unit area of the weld in a series of K experiments:

$$x_{cep} = \frac{\sum_{i=1}^{K} x_i}{K} \quad . \tag{3}$$

According to the table 1 mathematical expectation of the number of pores per unit area of the weld, found as the arithmetic mean number of pores per unit length of the weld is 13.29 pores/30 mm length. In fig. 2. A bar chart of the comparison of the experimentally obtained and calculated values of Poisson's law for the probability of obtaining a given number of pores on a unit area of the deposited metal is given.

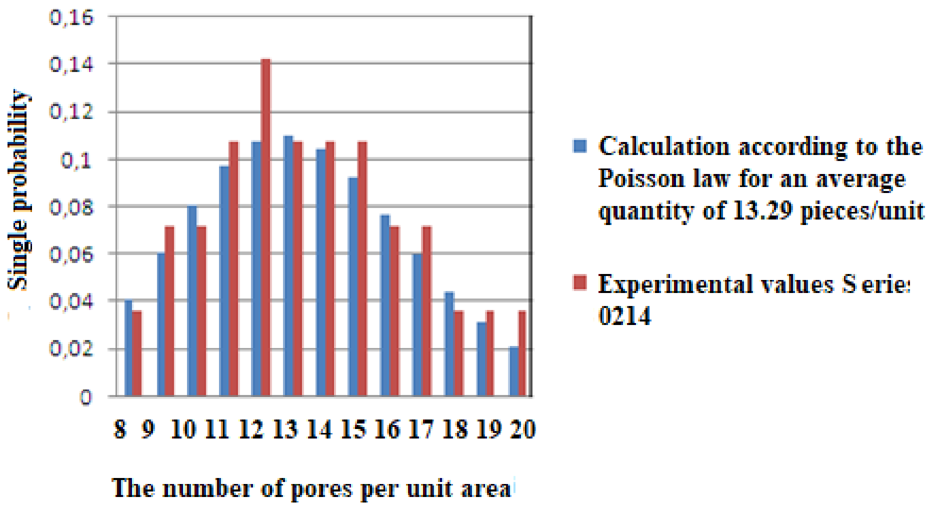

Fig. 2. Comparison of experimental data with the results of the calculation of the statistical distribution of the number of pores on a unit area of the weld

The source: authors have developed

As can be seen from fig. 2, the deviation of the experimental data from the calculated data is relatively small.

To check the adequacy of the Poisson's law model of the distribution of the number of pores on a unit area of the weld with experimental data, the Pearson agreement criterion (χ^2 criterion) can be used. Calculation of the Pearson agreement criterion for the Poisson distribution:

$$\chi_k^2 = K\sum_i \frac{\left(k_i/K - g(x_i,\mu)\right)^2}{g(x_i,\mu)} \ , \qquad (4)$$

where K - is the number of sites where pores were recorded;

x_i - the number of pores registered on the i unit section of the weld;

k_i – the number of sites on which x_i pores are registered, units;

$g(x_i,\mu)$ – calculated by the Poisson distribution (2), the probability that with an average number of pores μ, x_i pores will be registered in a unit area.

For 12 degrees of freedom at $\alpha = 0.5$, which corresponds to the maximum possible consistency of the data obtained experimentally with the results of calculation according to Poisson's law, the maximum permissible value is $\chi^2_{max} = 11.340$. The actually obtained value of the Pearson criterion $\chi_k^2 = 1.454$ (Table 1) is significantly less than the maximum permissible value.

Thus, Poisson's law adequately describes the experimentally obtained statistical distribution of the number of pores on a unit area and can be used for practical problems.

However, it is important to understand and take into account that the average value of the number of pores found in a series on a unit weld area is only an estimated value and the next series of experiments conducted under the same conditions may give a different value of the average number of pores. Taking this into account, the estimated value of the average number of pores found in the sample should be supplemented by the value of the width of the interval in which the average number of pores can be with a 95% probability (width of the 95% confidence interval), which is calculated:

$$\Delta_{(x)0,95} = 1{,}960 \times \frac{\sigma_x}{\sqrt{K}} \ , \qquad (5)$$

where σ_x - the mean square deviation of the number of pores per unit area of the weld in a series of experiments;

K - the total number of single sections of the weld where pores were found, thing.

The root-mean-square deviation of the number of pores per unit area of the weld seam can be calculated as the standard deviation from x_{cep} - the average number of pores per unit area of the weld seam, found from a sample of volume K:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{K}\left(x_{cep} - x_i\right)^2}{(K-1)}} \ . \qquad (6)$$

According to the 0214 series according to the data in the table. 1, the average number per unit area of the weld seam and the corresponding width of the 95% confidence interval are calculated. The results of the calculations for the considered example are given in the table. 2.

Table 2 – The average number of pores per unit area of the weld and the width of the 95% confidence interval (series 0214)

x_{cep}, mm	K, thing	σ_x, mm	$\Delta_{(x)0,95}$, mm
13,29	28	3,287	1,218

The source: authors have developed

According to the table 2, it can be concluded that in the considered series of experiments 0214, the average number of pores per unit area of the weld is 13.29±1.218. That is, according to the available experimental data formed into a sample of 28 unit areas, the estimated value of the average number of pores per unit area x_{cep} = 13.29±1.218 pores per 30 mm of weld. The actual value of the average number of pores per unit area with a probability of 95% is in the range of 14.508 to 12.072 pores per 30 mm of weld.

The form of the Poisson distribution of the number of pores in a unit area of the weld depends significantly on the value of the average number of pores. An increase in the values of the average number of pores per unit area of the weld shifts the peak of the distribution towards larger values and contributes to the symmetry of the distribution (Fig. 3). Without taking into account the actual values of the parameters of the distribution of the number of pores per unit length of the seam, it is impossible to predict the values.

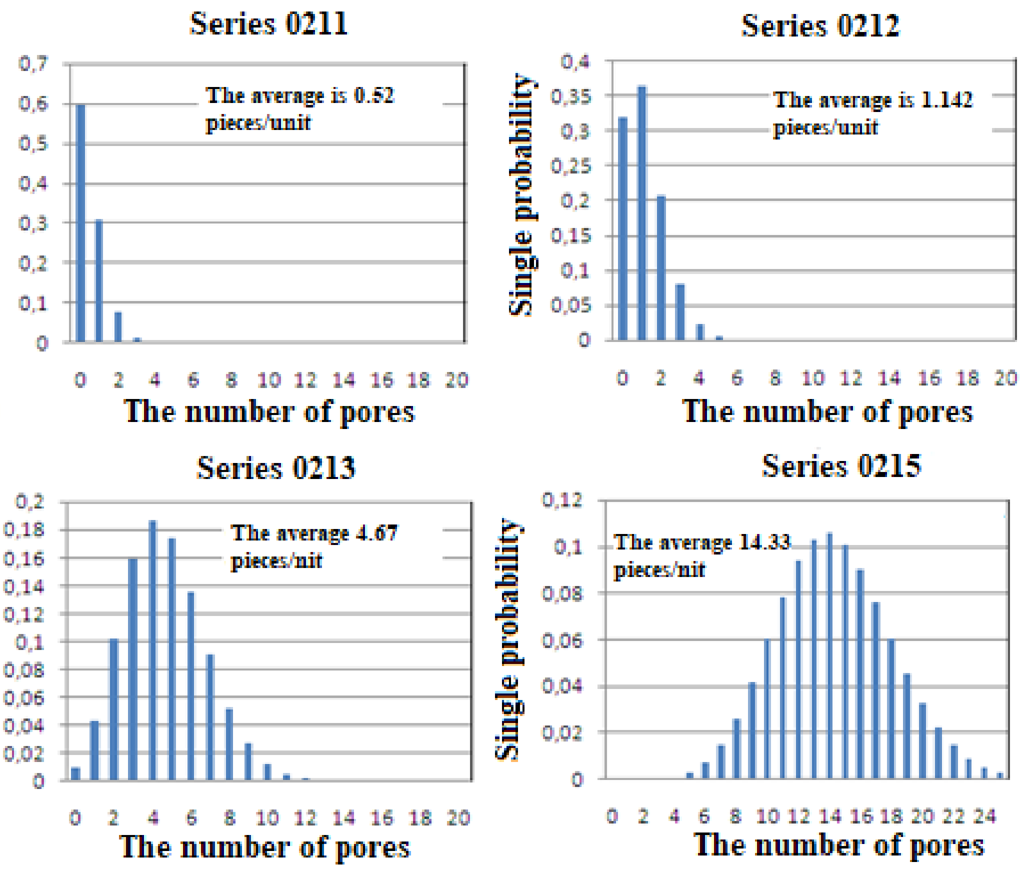

*Fig. 3. Single probability of the number of pores on a unit area of the weld x**

The source: authors have developed

The 0211-0215 series differ in the number of polyolefin tubes introduced into the welding zone, and, accordingly, in the average number of pores per unit area of the weld.

The demonstrated adequacy of the application of Poisson's law to the variability of the number of pores on a unit area of the deposited roll (weld) makes it possible to predict the probability of meeting the requirements for the porosity of the weld metal.

Conclusions. The statistical distribution is defined that adequately describes the variability of the number of pores per unit length of the weld. Using the Pearson test, it is shown that the actual value of χ_K^2 = 1.454 obtained by applying Poisson's law is significantly less than the maximum allowable χ_2^{max} = 11.340. This indicates the adequacy of the application of Poisson's law to the variability of the number of pores per unit length of the weld.

The main parameter of the Poisson distribution necessary for its application to the analysis of the variability of the number of pores per unit length of the weld is the mathematical expectation of the number of pores μ, found as the arithmetic mean of the number of pores per unit area of the weld in a series of K experiments. In further calculations, one should focus on the confidence interval for the value of the mathematical expectation of the number of pores per unit length of the weld.

The obtained results make it possible to take into account the characteristics of the statistical distribution of the number of pores per unit length of the weld when predicting the possibility of meeting the requirements for the porosity of the weld. Can be used in assessing the acceptability of welding technology, predicting quality costs associated with weld porosity.

A possible direction of further research is the definition of statistical models that adequately describe the variability of slag inclusions in welded joints.

Literature

1. Otsuka, H. Quality assurance of welded steel of Tokyo sky tree / H. Otsuka, Y. Minoda, K. Nagayama // Journal of the Japan Welding Society. – 2013. – № 82(4), – P. 252-257. DOI: https://doi.org/10.2207/jjws.82.252

2. Gaievskiy, V. Limitation of risks of non-compliance of weld metal porosity / V. Gaievskiy, V. Prokhorenko, M. Ziberov // Graduaзгo em Engenharia Mecвnica. – 2014. – Vol. 1. – P. 4-7.

3. ISO 5817:2023 Welding — Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) — Quality levels for imperfections[Electronic resource]. – Geneva : International Organization for Standardization, 2023. – 26 p. – Access mode : https://www.iso.org/standard/80209.html

4. Weld defect frequency, size statistics and probabilistic models for ship structures / P. Amirafshari, N. Barltrop, M. Wright, A. Kolios // International Journal of Fatigue. – 2021. – Vol. 145. – P. 106069. DOI: https://doi.org/10.1016/j.ijfatigue.2020.106069

5. Гаєвський, В. О. Застосування ймовірнісної сітки для визначення параметрів вейбулівського розподілу діаметру пор / В. О. Гаєвський, О. А. Гаєвський, К. О. Зворикін // Іноваційні технології та інжиніринг у зварюванні PolyWeld–2019 : зб. доп. Міжнар. конф. – Київ : КПІ ім. Ігоря Сікорського, 2019. – С. 35-36.

6. Гаєвський, В. О. Визначення параметрів Вейбулівського розподілу діаметру пор [Electronic resource] / В. О. Гаєвський, О. А. Гаєвський, К. О. Зворикін // Technological Systems. – 2019. – № 1(86). – С. 75-80. – Access mode : http://technological-systems.com/index.php/Home/article/view/703/735

7. Amirafshari, P. Estimation of weld defects size distributions, rates and probability of detections in fabrication yards using a Bayesian theorem approach / P. Amirafshari, A. Kolios // International Journal of Fatigue. – 2022. – Vol. 159. – P. 106763. DOI: https://doi.org/10.1016/j.ijfatigue.2022.106763

8. Ling, M. Weld Quality Assessment and Control in Steel Structure Fabrication [Electronic resource] / M. Ling // Journal of Steel Structures and Constructions. – 2023. – Vol. 9:1. – P. 1-2. – Access mode : https://www.hilarispublisher.com/open-access/weld-quality-assessment-and-control-in-steel-structure-fabrication.pdf

References

1. Otsuka, H., Minoda, Y., Nagayama, K. (2013). Quality assurance of welded steel of Tokyo sky tree. *Journal of the Japan Welding Society, 82(4),* 252-257. doi: https://doi.org/10.2207/jjws.82.252

2. Gaievskiy, V., Prokhorenko, V., Ziberov, M. (2014). Limitation of risks of non-compliance of weld metal porosity. *Graduaзгo em Engenharia Mecвnica, 1,* 4-7.

3. International Organization for Standardization. (2023). Welding — Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) — Quality levels for imperfections (ISO 5817:2023). https://www.iso.org/standard/80209.html

4. Amirafshari, P., Barltrop, N., Wright, M., Kolios, A. (2021). Weld defect frequency, size statistics and probabilistic models for ship structures. *International Journal of Fatigue, 145,* 106069. doi: https://doi.org/10.1016/j.ijfatigue.2020.106069

5. Haievskyi, V.O., Haievskyi, O.A., Zvorykin, K.O. (2019). The use of a probability grid for determining the parameters of the Weibull diameter distribution. PolyWeld–2019: Proceedings of the international conference "Innovative technologies and engineering in welding. Kyiv: KPI im. Ihoria Sikorskoho, 2019. P. 35-36.

6. Haievskyi, V.O., Haievskyi, O.A., Zvorykin, K.O. (2019). Determination of the parameters of the Weibull diameter distribution. *Technological Systems, 1(86),* 75-80. http://technological-systems.com/index.php/Home/article/view/703/735

7. Amirafshari, P., Kolios, A. (2022). Estimation of weld defects size distributions, rates and probability of detections in fabrication yards using a Bayesian theorem approach. *International Journal of Fatigue, 159,* 106763. doi: https://doi.org/10.1016/j.ijfatigue.2022.106763

8. Ling, M. (2023). Weld Quality Assessment and Control in Steel Structure Fabrication. *Journal of Steel Structures and Constructions, 9:1,* 1-2. https://www.hilarispublisher.com/open-access/weld-quality-assessment-and-control-in-steel-structure-fabrication.pdf

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ДОСЛІДЖЕННЯ ЗМІНЮВАНОСТІ КІЛЬКОСТІ ПОР НА ОДИНИЦЮ ДОВЖИНИ ЗВАРНОГО ШВА

Поява пор у металі зварного шва має ймовірнісний характер і може приводити до негативних наслідків. Ці наслідки пов'язані з втратою виробами функцій та загрозою для життя і здоров'я людей. Тому дослідження змінюваності пористості зварних швів є актуальною задачею для прикладної механіки, зварювального виробництва.

В реальних умовах зварювання ускладнене формування вибірок даних з достатнім для статистичного аналізу об'ємом. Тому необхідна постановка спеціалізованого експерименту з введенням у зону зварювання матеріалу, який викликає появу пор і подальшим статистичним аналізом даних про пористість зварних швів. Визначення статистичних закономірностей змінюваності пористості дозволить прогнозувати значення показники пористості з врахуванням їх варіативності.

Вимоги до пористості зварних швів задаються по двох показниках – діаметру та кількості пор на одиничній довжині зварного шва. Діаметр пор відноситься до безперервної ознаки, а кількість пор на одиничній довжині зварного шва до порядкової статичної ознаки. Аналіз опублікованих досліджень показує, що змінюваність діаметру пор адекватно описується двох параметричним розподілом Вейбулла. Визначення розподілу, який адекватно описує змінюваність кількості пор на одиничній довжини зварного шва потребує спеціалізованих лабораторних досліджень.

Метою статті є визначення статистичного розподілу, який адекватно описує змінюваність кількості пор на одиничній довжині зварного шва. Для досягнення мети належить статично проаналізувати дані щодо змінюваності кількості пор при додатковому введенні у зону зварювання матеріалу, який сприяє утворенню пор.

Для сприяння утворенню пор у зону зварювання вводили поліолефінові трубки діаметром 0,8 мм, заповнені дистильованою водою. З використанням ступінчатої діаграми візуально порівнювали експериментально отриманий розподіл кількості пор і теоретично розрахований по закону Пуассона. Адекватність застосування закону Пуассона до змінюваності кількості пор на одиничній довжині зварного шва оцінювалась за критерієм Пірсона.

Фактично отримане, при застосуванні закону Пуассона, значення критерію Пірсона $\chi_k^2 = 1,454$ *значно менше ніж максимально допустиме* $\chi^2_{max} = 11,340$. *Це свідчить про адекватність застосування закону Пуассона до змінюваності кількості пор на одиницю довжини зварного шва. Отримані результати дають можливість враховувати характеристики статистичного розподілу кількості пор на одиницю довжини зварного шва при прогнозуванні можливості виконання вимог щодо пористості зварного шва. Вони можуть бути використані при оцінюванні прийнятності технології зварювання, прогнозуванні витрат на якість, які пов'язані з пористістю зварного шва.*

Ключові слова: *пористість зварних швів; показники пористості; розподіл Пуассона; критерій Пірсона; математичне очікування.*

Табл.: 2. Рис.: 3. Бібл.: 8.

Haievskyi V., Haievskyi O., Puzik O. Study of the variability of the number of pores per unit length of the weld. *Technical sciences and technologies,* (3 (33)). С. 68-75.