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DETERMINATION OF THE APPLICABILITY OF THE NORMAL AND WEIBULL DISTRIBUTIONS TO THE DIAMETER OF WELDED PORES

The adequacy of the application of the normal and Weibull distributions to the variability of weld pore diameters is analyzed. It is shown that, despite the visual similarity of the Weibull distribution to the visualization of the experimentally obtained distribution of pore diameter values, according to the Pearson agreement criterion, the normal distribution describes the variability of pore diameter values six times better than the Weibull distribution. The obtained results provide grounds for the direct application of standardized statistical tools to the statistical analysis of the variability of weld pore diameter.

Keywords: *weld porosity; variability; statistical distribution; Pearson's criterion; pore diameter.*
Table: 4. Fig.: 4. References: 12.

Urgency of the research. A global trend today is the use of a risk-based approach when making decisions regarding the quality of welded products [1; 2]. One of the methods for reducing the risks of non-compliance with the quality requirements of welded products is to replace the control of actual defect levels with statistical control of quantitative indicators that determine the appearance of defects. Such a quantitative indicator is the pore diameter. At the same time, standardized statistical control tools for continuous features assume that the variability of the controlled indicator is subject to a normal distribution. Thus, determining a statistical distribution that adequately describes the variability of the pore diameter of a weld is a relevant task related to creating conditions for reducing the risks of failure to meet porosity requirements during welding using standardized statistical tools.

Target setting. The allowable porosity in the weld metal is determined by their diameter and number per unit length of the weld [3]. It is the diameter and number of pores that determine the reduction in the cross-sectional area of the weld and, as a result, the reduction in the ability to work under static loads. The diameter of the pores significantly affects their ability to form stress concentrators. Thus, to ensure the uniform strength of the weld metal under static and dynamic loading conditions, it is important to monitor the number of pores per unit length of the weld and their diameter values.

The value of the number and diameter of pores is a random variable. The use of a distribution that adequately describes the variability of a random variable makes it possible to use the entire arsenal of standardized statistical tools available for such a distribution (control charts, reproducibility indices, workability indices, etc.). Pore diameter is a continuous statistical characteristic. The vast majority of statistical tools for analyzing continuous data are based on the normal distribution [4, 5]. At the same time, there are a significant number of arguments in favor of both the application of the normal distribution and the application of the Weibull distribution to the variability of pore diameter. Therefore, determining the distribution that should be preferred when analyzing data on pore diameter variability actually means determining the possibility of directly applying most standardized statistical tools to such an important indicator as pore diameter or the necessary adaptation of these tools to the Weibull distribution.

Actual scientific researches and issues analysis. The variability of the number of pores per unit length of the weld is adequately described by Poisson's law [6]. This allows the use of standardized c-maps and u-maps for statistical control of the number of pores without additional measures [4].

It is generally accepted that the variability of product quality indicators and production processes, which are related to a continuous statistical characteristic, is subject to a normal distribution [7; 8]. This is usually supported by a large number of factors simultaneously influencing the values of such indicators, approximately the same level of influence of each factor, which corresponds well to the conditions of the central limit theorem. As a result, the probability density of the indicator value is determined by the Gauss-Laplace function. In application to the variability of the pore diameter according to the normal distribution:

$$f(d_*;\mu;\sigma) = \frac{1}{\sqrt{2\pi}\sigma} exp - \frac{1}{2}\left(\frac{d_*-\mu}{\sigma}\right)^2. \quad (1)$$

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

μ – mathematical expectation of the pore diameter value, mm;

σ – standard deviation of the pore diameter value, mm;

The normal distribution curve is a symmetrical, bell-shaped Gaussian curve. This distribution is the basis of most statistical tools for analyzing continuous data and in 90 % of cases such tools can be applied to product and welding process parameters without additional measures [9].

A large number of factors and the equivalence of their influence is a prerequisite for symmetry, and therefore normality, of the distribution of the indicator values. If the subject of the study is the indicator of the size (diameter) of the defect, then it is necessary to take into account the fact that measures are being implemented to prevent the appearance of defects in relation to defects. The consequence of such actions is a deviation of the distribution from symmetry towards an increase in the probability of the appearance of defects (pores, slag inclusions) of smaller diameter. Thus, a “deformation”, a deviation from symmetry, of the distribution of defect diameter values occurs.

Studies conducted on ship hulls, fuel and lubricant storage tanks, and large-diameter pipelines [10] have shown that the distribution of pore diameter values deviates from the Gauss-Laplace function. Studies of the variability of pore diameter in the conditions of determining the resistance to pore formation during submerged arc welding have shown the possibility of using the two-parameter Weibull distribution [11; 12].

The value of the Weibull probability density distribution for a given limit value of the pore diameter d_* :

$$f(d_*;a_d;b_d) = \frac{b_d}{a_d}\left(\frac{d_*}{a_d}\right)^{b_d-1} exp - \left(\frac{d_*}{a_d}\right)^{b_d}. \quad (2)$$

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

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

Uninvestigated parts of general matters defining. Recent studies have shown deviations from symmetry in the distribution of pore diameter values in welded joints and the adequacy of the use of the two-parametric Weibull distribution. However, there is no evidence on the applicability of the normal distribution to the analysis of pore diameter variability data compared to the Weibull distribution. Studies on the adequacy of applying statistical distributions to pore diameter variability are constrained by the limited number of pores that appear under constant pore formation conditions.

The research objective is to determine the possibility of applying a normal distribution to the analysis of data on pore diameter variability. Depending on the result obtained, a decision should be made on the possibility of applying standardized statistical data analysis tools without correction for distribution asymmetry.

The statement of basic materials. The initial data for the statistical analysis of the variability of the pore diameter were collected using the method of studying the resistance to pore formation using polyolefin tubes, set out in the work [4]. Table 1 presents experimental data on the distribution of pore diameters in these ranges. The accepted notations are n_i – number of pores registered in the diameter range, N_i - the number of pores whose diameters do not exceed the limit value of the i-th range, N – the total number of registered pores for which the diameter was determined, d_{*i} – upper limit value of the i-th range of pore diameters, d_{*i} – the average value of the i-th range of pore diameters.

Table 1 – Experimental data on pore diameter distribution

№	Pore diameter range, mm	n_i, units	N_i, units	N, units	d_{*i} , mm	$d_{cep,i}$, mm
1	0...0,5	71	71	372	0,5	0,25
2	0,6...1,0	121	192		1,0	0,75
3	1,1...1,5	99	291		1,5	1,25
4	1,6...2,0	53	344		2,0	1,75
5	2,1...2,5	23	367		2,5	2,25
6	2,6...3,0	5	372		3,0	2,75
7	3,1...3,5	0	372		3,5	3,25

Source: developed by the authors.

According to the data in Table 1, a bar chart of the actual distribution of pore diameters was constructed.

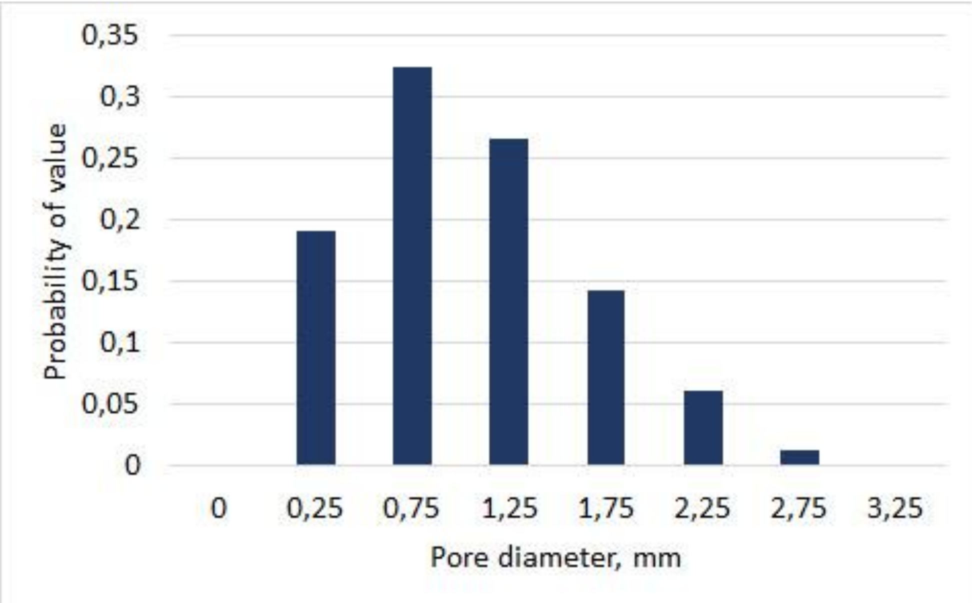

Fig. 1. Bar chart of actual pore diameter distribution

Source: developed by the authors

Visually, the bar chart (Fig. 1) shows the expected deviation from the symmetry of the normal distribution.

Using a probability grid based on experimental data, it is possible to determine the parameters of the Weibull distribution of pore diameter. To do this, you need to perform the following steps [12]:

Divide the range of possible pore diameter values into ranges of 0.5 mm width (see Table 1).

Record the number of pores detected, for each range separately, entering the results by n_i - the number of pore diameter measurements that fall within the range.

For each range limit d_{*i} (defined as the maximum value of the pore diameter falling within the range) determine N_i - the number of pores whose diameters do not exceed the limit value of the range (defined as the sum of all pores whose diameters do not exceed the limit value of the range).

Calculate the estimated probability of not exceeding the limit value of the pore diameter range:

$$F(d_{*i}) = \frac{N_i - 3/8}{N + 1/4} \times 100\%. \quad (3)$$

where N – the total number of registered pores for which the diameter was determined.

Each range in which pores were recorded gives a point on the probability grid. The x coordinate of this point is d_{*i} – to the upper limit of the range of pore diameters, and the y coordinate to the calculated value $F(d_{*i})$ - estimated probability of not exceeding the limit value of the pore diameter range.

If the points on the probability grid are distributed along a straight line, this indicates that the pore diameter is indeed distributed according to the Weibull law. The location of the straight line approximating the position of the experimental points determines the quantitative values of the parameters of the Weibull pore diameter distribution.

To determine the parameters of the Weibull distribution, the data in Table 1 were converted into data for applying the probability grid in Table 2.

Table 2 – Experimental data for estimating the values of the size parameter a_d and form parameter b_d Weibull distribution of pore diameter

№	Pore diameter range, mm	N_i, units	N, units	d_{*i} , mm	$lg(d_{*i})$, mm	$F(d_{*i})$, %
1	0...0,5	71	372	0,5	-0,301	19,0
2	0,6...1,0	192		1,0	0,000	51,5
3	1,1...1,5	291		1,5	0,176	78,1
4	1,6...2,0	344		2,0	0,301	92,3
5	2,1...2,5	367		2,5	0,398	98,5
6	2,6...3,0	372		3,0	0,477	99,8
7	3,1...3,5	372		3,5	-0,301	99,8

Source: developed by the authors.

The data in Table 2 are plotted on a probability grid as points through which an approximating line is drawn. The result is shown in Fig. 2.

The value of the scale parameter ad of the Weibull distribution is determined by the intersection point of the straight line, which approximates the results of the experimental determination of the pore diameter on the probabilistic grid, with the horizontal line $y = 0$. At this point, the probability of not exceeding the given diameter value is $d_* = a_d$ makes up $F(a_d) = 0{,}632$ (see Fig. 2). In the given data set (sample), the intersection point has the coordinate of the horizontal logarithmic scale $x = 0.18$. That is, in the given data set (sample) $lg(a_d)=0{,}18$, therefore, $a_d = 10^{0{,}18} = 1{,}51$ (mm). The resulting value of the scale parameter $a_d = 1{,}51$ mm can be interpreted in such a way that under the investigated welding conditions, 63 % pores, have a diameter of no more than 1,51 mm.

Calculation formula for shape parameter b_d:

$$b_d = \frac{y}{ln\left(d_*/a_d\right)}. \quad (4)$$

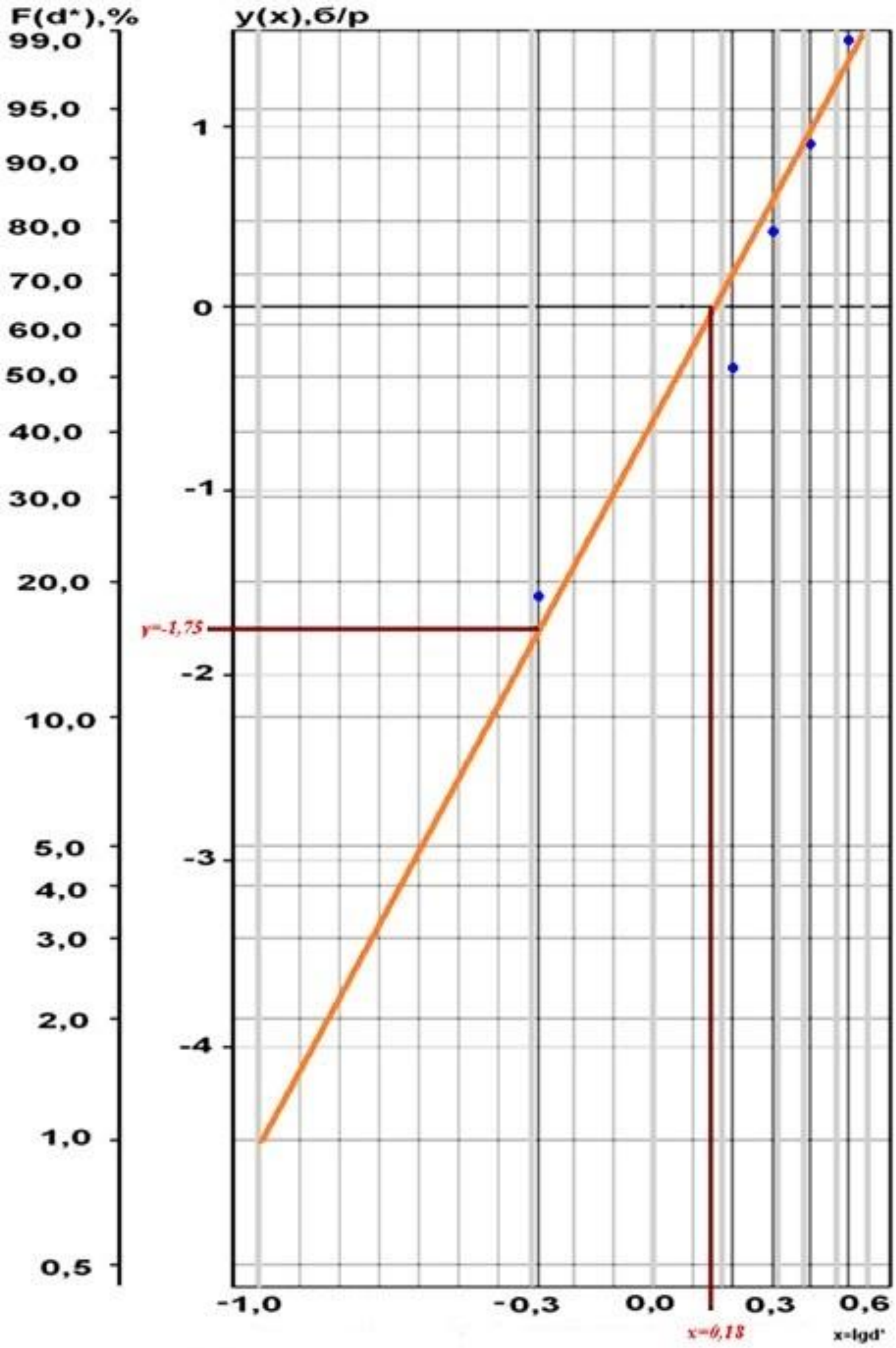

Fig. 2. Determination of pore diameter distribution parameters using a probabilistic grid
Source: developed by the authors.

To determine using a probability grid the value of bd - the shape parameter of the Weibull distribution, it is necessary for any pore diameter (in Fig. 2 the pore diameter is assumed $d_* = 0.5$ mm) find the corresponding value y (in Fig. 2 $y(0.5) = -1.75$). By substitution into the formula (4), taking into account the previously found value of the scale parameter a_d = 1.51 mm, we find the value of the shape parameter for this distribution b_d=1.583 (dimensionless).

At the same time, according to the Weibull distribution, the fraction of pores with a diameter not exceeding a given value d_*, can be found:

$$F(d_*; 1{,}51; 1{,}583) = 1 - exp\left[-\left(\frac{d_*}{1{,}51}\right)^{1{,}583}\right]. \quad (5)$$

The probability that the pore diameter becomes significant d_* (or close to d_*) mm:

$$f(d_*; 1{,}51; 1{,}583) = \frac{1{,}583}{1{,}51}\left(\frac{d_*}{1{,}51}\right)^{1{,}583-1} exp - \left(\frac{d_*}{1{,}51}\right)^{1{,}791}. \quad (6)$$

Among the advantages of the graphical method of determining the parameters a_d and b_d of the Weibull distribution of pore diameters using a probability grid, it should be noted its extreme simplicity, clarity.

The normal distribution is defined by two parameters: μ– mathematical expectation and σ - standard deviation of a random variable.

From a sample of 372 pore diameter values divided into seven ranges (see Table 1), the values of the normal distribution parameters were found.

Mathematical expectation of pore diameter

$$\mu = \sum_{i=1}^{7} d_{\text{cep}i} * \frac{n_i}{N}. \quad (7)$$

The standard deviation of the pore diameter is found as the square root of the variance of the pore diameter as a random variable

$$\sigma = \sqrt{\sum_{i=1}^{7} \frac{n_i}{N}\left(d_{\text{cep}i} - \mu\right)^2}. \quad (8)$$

The data for calculating the parameters of the normal distribution of pore diameters are summarized in Table 3.

Table 3 – Data for calculating the parameters of the normal distribution of pore diameter

№	Pore diameter range, mm	n_i, units	$d_{cep,i}$, мм	$d_{\text{cep}i} * \frac{n_i}{N}$, units	$\frac{n_i}{N}\left(d_{\text{cep}i} - \mu\right)^2$, units ^{2}
1	0...0,5	71	0,25	0,047715	0,121845
2	0,6...1,0	121	0,75	0,243952	0,029079
3	1,1...1,5	99	1,25	0,332661	0,010752
4	1,6...2,0	53	1,75	0,249328	0,070011
5	2,1...2,5	23	2,25	0,139113	0,089181
6	2,6...3,0	5	2,75	0,036962	0,03889
7	3,1...3,5	0	3,25	0	0

Source: developed by the authors.

According to the data in Table 3, the values of the parameters of the normal distribution of pore diameters were established: μ=1,049 mm, σ=0,5998 mm.

In this case, the probability that, according to the Weibull distribution, the pore diameter takes on the value d_* (or close to d_*) mm:

$$f(d_*; 1{,}049; 0{,}5998) = \frac{1}{\sqrt{2\pi}\times 0{,}5998} exp - \frac{1}{2}\left(\frac{d_* - 1{,}049}{0{,}5998}\right)^2. \quad (9)$$

For comparison, Fig. 3 shows the probability density graphs of the pore diameter distribution according to the normal and Weibull distributions. The graphs are constructed using dependencies (6) and (9).

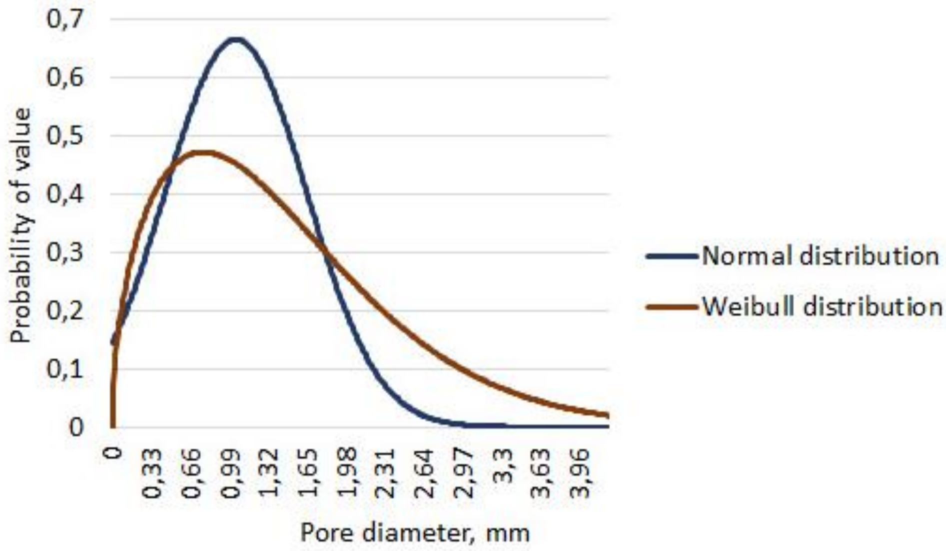

Fig. 3. Probability density of pore diameter according to normal f(d;1.049;0.5998) and Weibull f(d;1.51;1.583) distributions (probability functions)

Source: developed by the authors.

Of the two graphs shown in Fig. 3, the Weibull distribution *f(d;1.51;1.583)* is closer to the bar chart of the actual pore diameter distribution (Fig. 1). Thus, visually, the Weibull distribution in shape better describes the variability of pore diameter and correlates with the results of the experimental study.

However, the adequacy of the application of the Weibull distribution and the normal distribution to the obtained experimental data should be verified using the Pearson consistency criterion.

The value of the Pearson consistency criterion (χ^2 criterion) is calculated:

$$\chi^2 = N\sum_i \frac{\left(n_i{}^{n_i}/_{N} - P_i\right)^2}{P_i} = \sum_i \frac{(n_i - N\times P_i)^2}{N\times P_i}. \quad (10)$$

where N – number of pores for which the diameter was measured, units;

n_i – experimentally registered number of pores in the i-th range, units;

P_i – the probability that the pore diameter is in the i-th range, calculated from the Weibull distribution or normal distribution, in fractions.

The value of P_i from the Weibull distribution can be calculated:

$$P_i = F(d_{*i}; a_d; b_d) - F(d_{*i+1}; a_d; b_d) = F(d_{*i}; 1{,}51; 1{,}583) - F(d_{*i+1}; 1{,}51; 1{,}583). \quad (11)$$

where $F(d_{*i};a_d;b_d)$ – calculated according to the Weibull distribution, the fraction of pores whose diameter does not exceed the pore diameter of the upper (right) boundary of the i-th pore diameter range;

$F(d_{*i-1};a_d;b_d)$ – calculated according to the Weibull distribution, the fraction of pores whose diameter does not exceed the pore diameter of the lower (left) boundary of the i-th pore diameter range.

The value of P_i according to the normal distribution can be calculated:

$$P_i = F(d_{*i}; \mu; \sigma) - F(d_{*i+1}; \mu; \sigma) = F(d_{*i}; 1{,}049; 0{,}5998) - F(d_{*i+1}; 1{,}049; 0{,}5998). \quad (12)$$

where $F(d_{*i};\mu;\sigma)$ – calculated according to the normal distribution the fraction of pores whose diameter does not exceed the pore diameter of the upper (right) boundary of the i-th pore diameter range;

$F(d_{*i-1};\mu;\sigma)$ – calculated according to the normal distribution the fraction of pores whose diameter does not exceed the pore diameter of the lower (left) boundary of the *i*-th pore diameter range.

The results of calculations for the value of the Pearson consistency criterion when applying the Weibull distribution and the normal distribution to the variability of the pore diameter (see Table 1) are given in Table 4.

Table 4 – Data for calculating the value of the Pearson test (χ^2 test)

№	Pore diameter range, mm	n_i, units	According to the Weibull distribution		According to normal distribution	
			P_i	χ_i^2	P_i	χ_i^2
1	0...0,5	71	0,160946	2,068302	0,180016	0,243024
2	0,6...1,0	121	0,232393	13,80775	0,287429	1,853115
3	1,1...1,5	99	0,208896	5,833139	0,306505	1,978527
4	1,6...2,0	53	0,15688	0,492199	0,169627	1,617033
5	2,1...2,5	23	0,104702	6,530908	0,048645	1,329126
6	2,6...3,0	5	0,06379	14,78324	0,007207	2,005718
7	3,1...3,5	0	0,036015	13,3976	0,00055	0,204436
The value of the Pearson test (χ^2 test)			56,91313		9,23098	

Source: developed by the authors.

A larger value of the Pearson consistency criterion corresponds to a larger deviation of the calculated value according to the statistical distribution from the experimental value according to the actual distribution of the random variable (see (10)). According to Table 4, the normal distribution provides a total of six times smaller value of the Pearson χ^2 criterion compared to the Weibull distribution. The marginal ranges of pore diameters make a particularly large contribution to the formation of the χ^2 value for the Weibull distribution (Fig. 4).

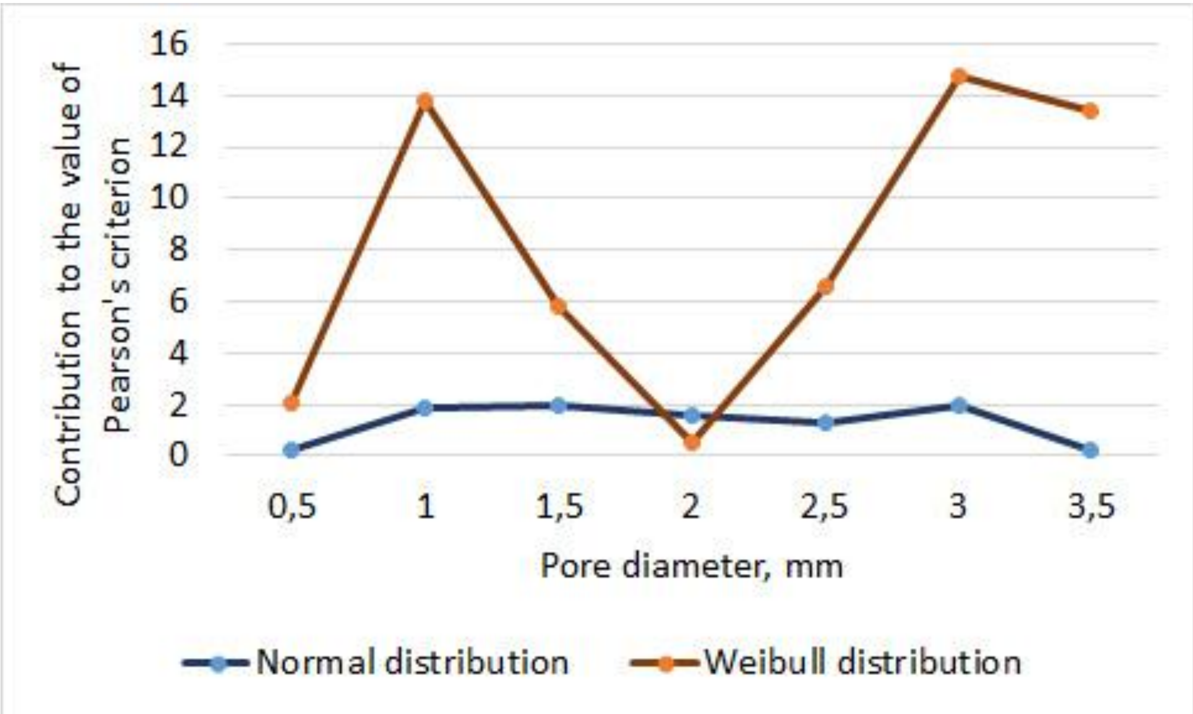

Fig. 4. Contribution of pore diameter ranges to the value of the consistency criterion for the application of the normal distribution and the Weibull distribution

Source: developed by the authors.

The value of the Pearson criterion was determined by f = 7 ranges of pore diameter, therefore the number of degrees of freedom of the studied system:

$$r = f - 1 = 7 - 1 = 6\ . \tag{13}$$

For six degrees of freedom and a significance level of a=0.1 (10%), the maximum allowable value of the Pearson criterion is: 10.645 [5]. For a normal distribution, the value of χ^2 = 9.23098 is less than the maximum allowable value, which indicates the possibility of using a normal distribution for statistical analysis of data on the variability of pore diameter. It should also be noted that for a normal distribution, the χ^2 value is formed uniformly throughout the entire investigated range of pore diameters (see Fig. 4). At the same time, despite the apparent similarity of the Weibull distribution to the actual diameter distribution, its use for quantitative statistical analysis of data on pore diameter variability is undesirable. This is due to the fact that the value of χ^2 = 56.91313 for the Weibull distribution significantly exceeds the permissible 10.645. At the same time, the deviations of the calculated from the actual values are especially significant for relatively small and, conversely, large pore diameters.

Conclusions.

Using experimentally obtained data on weld porosity, a comparison of the possibilities of applying data analysis on pore diameter variability using the normal distribution and the Weibull distribution was made.

An apparent comparison of the probability density graphs of the pore diameter distribution according to the normal, Weibull distribution with the actual experimental distribution of pore diameters shows the closeness of the Weibull distribution in shape to the actual distribution. However, the value of the Pearson consistency criterion for the Weibull distribution is 6 times greater than the value of χ^2 = 9.23098 for the normal distribution. The use of the normal distribution for quantitative analysis of data on pore diameter variability is also supported by the fulfillment of the condition for the adequacy of the application of the normal distribution according to the Pearson consistency criterion, namely $\chi^2 = 9.23098 < 10.645$.

The results obtained make it possible to use standardized tools and methods based on the normal distribution for quantitative statistical analysis of data on pore diameter variability. In fact, this is the entire line of tools for statistical analysis of continuous data.

A possible direction for further research is to define statistical models that adequately describe the variability of slag inclusions in welded joints. The availability of such models will simplify the analysis of risks of extending the service life of potentially hazardous objects.

A statement on the use of generative AI and AI-based technologies in the writing process. In the process of writing the article, generative artificial intelligence and technologies based on generative artificial intelligence were not used.

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ВИЗНАЧЕННЯ ЗАСТОСОВНОСТІ НОРМАЛЬНОГО ТА ВЕЙБУЛІВСЬКОГО РОЗПОДІЛУ ДО ДІАМЕТРА ПОР ЗВАРНИХ ШВІВ

Допустимість пор у зварному шві визначається їх кількістю на одиницю довжини шва та діаметрами пор. Моніторинг кількісних показників допустимості пор дозволяє своєчасно реагувати на їх змінюваність і суттєво зменшувати ризики невиконання вимог до пористості. Такий моніторинг може бути реалізований з використанням стандартизованих інструментів за умови адекватності застосування статистичних розподілів, які відповідають цим інструментам.

Змінюваність кількості пор на одиницю довжини зварного шва адекватно описується розподілом Пуассона. Стосовно змінюваності діаметра пор попередніми дослідженнями аргументовано використання як нормального розподілу, так і розподілу Вейбулла.

Адекватність застосування статистичних розподілів до змінюваності діаметра пор досліджена по даних, отриманих при однакових умовах їх утворення.

Оцінені значення параметрів нормального та Вейбулівського розподілів діаметру пор для вибірки з 372 значень, отриманих при незмінних умовах експериментального дослідження стійкості до пороутворення,. Параметри нормального розподілу визначені як вибіркове математичне сподівання та корінь квадратний від вибіркової дисперсії. Значення параметрів форми та масштабу розподілу Вейбулла знайдені з використанням ймовірнісної сітки. Показано, що візуально Вейбулівський розподіл краще описує фактичний розподіл діаметра пор. Проте значення χ^2 *критерію узгодженості Пірсона для Вейбулівського розподілу у шість разів більше, ніж для нормального розподілу. При цьому виконується умова адекватності застосування нормального розподілу за критерієм узгодженості Пірсона.*

Отримані результати дають можливість використовувати для кількісного статистичного аналізу даних про змінюваність діаметра пор стандартизовані інструменти та методи в основу яких покладено нормальний розподіл. Фактично це вся лінійка інструментів статистичного аналізу даних за безперервною ознакою.

Ключові слова: *пористість зварних швів; змінюваність; статистичний розподіл; критерій Пірсона; діаметр пор.*
Табл.: 4. Рис.: 4. Бібл.: 12.

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