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UDC 621.9.07 DOI: 10.31498/2225-6733.50.2025.336269

EFFECT OF CLEARANCE ON RESIDUAL STRESS AND QUALITY IN ROLLED TUBE-TUBESHEET CONNECTIONS

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The quality of the tube-to-tubesheet joint is a critical factor determining the reliability and durability of heat exchangers and various types of industrial equipment operating under demanding conditions. This article examines the influence of the clearance between the tube and the tubesheet hole on the magnitude of residual stresses in the joint following the tube rolling process. The experimental component of the study involved precise measurements of actual clearances using specialized tools, the calculation of residual stresses through the mechanical stress relief method, and a comprehensive statistical analysis of the collected data to ensure accuracy and consistency. The findings revealed that the actual clearance typically exceeds the nominal value specified in design standards, and an increase in this clearance directly correlates with a rise in residual stresses within the joint. Notably, the highest stress levels were observed at clearances of 0.40 mm and greater, which may lead to localized plastic deformation, compromising the structural integrity and reducing the fatigue strength of the joint over time. Based on the analysis, the optimal clearance range was determined to be between 0.10 mm and 0.30 mm, as it strikes a balance between ensuring joint reliability and maintaining acceptable stress levels, thus minimizing the risk of premature failure. To validate the reliability of the experimental results, advanced statistical methods were employed, including the calculation of standard deviation to assess data variability and the application of Student's t-test to evaluate the significance of the observed trends. These calculations confirmed a statistically significant relationship between clearance size and residual stress levels, with particularly pronounced effects observed in joints involving small-diameter tubes, where tolerances are more critical. The outcomes of this research have practical implications for the design and manufacturing of shell-and-tube heat exchangers, offering a pathway to optimize joint parameters, enhance operational performance, and extend service life. Additionally, the study provides detailed practical recommendations for quality control, including precise methods for measuring clearances with high accuracy and evaluating residual stresses during production and maintenance processes.

Keywords: *tube rolling, residual stresses, clearance, quality control, process parameters, reliability, durability.*

Statement of the problem

The quality and reliability of tube-to-tubesheet joints play a crucial role in the performance and longevity of heat exchangers, boilers, and other industrial installations. Ensuring a consistently high-quality joint requires an integrated approach encompassing material selection, manufacturing precision, and thorough inspection. The primary objective is to achieve a defect-free connection that maintains mechanical integrity under operational conditions, including high pressures, extreme temperatures, and cyclic loads.

Analysis of the latest achievements on the identified problem

Material selection and control are fundamental in preventing premature failures and ensuring compliance with operational requirements. Callister and Rethwisch as well as Al-Odhaib et al. emphasize that tubes and tubesheets must adhere to specified alloy compositions, verified through chemical analysis and mechanical property tests, including tensile strength, elongation, and corrosion resistance [1, 2]. Groover and Yoganathan et al. further support this by highlighting the importance of material selection in extending service life [3, 4]. Additionally, Roberge noted that the compatibility between tube and tubesheet materials is essential to mitigate galvanic corrosion risks, particularly in electrolytic environments [5].

Incoming inspection procedures ensure material integrity before manufacturing. Certification documents, spectral analysis for alloy verification, and mechanical testing in accordance with ASTM E8/E8M or EN ISO 6892-1 validate compliance with required standards. Sharma et al. examined critical geometric parameters such as tube wall thickness, ovality, and surface roughness of tubesheet holes, confirming their necessity in maintaining dimensional accuracy and optimizing the tube fitting process [6]. Thulukkanam emphasized that proper preparation, including abrasive cleaning and degreasing, enhances surface conditions, reducing the likelihood of contamination-related defects [7]. Gissler and Jehn highlighted the importance of eliminating residual oxides and surface imperfections through precision cleaning techniques, which significantly improve the adhesion and mechanical properties of the joint [8].

The joint formation technique largely depends on the fastening method. One of the most widely used approaches is tube rolling, which relies on radial compression to create a tight interference fit between the tube and the tubesheet. Budynas and Nisbett describe this process in detail [9]. Boulougouras and Besseris found that the precision of the rolling process is a key determinant of joint performance, as insufficient compression can lead to leakage, whereas excessive deformation may induce microcracks, compromising structural integrity [10]. As demonstrated in the work of Stovpnyk and Kyrylyuk, modern rolling tools equipped with digital force control mechanisms significantly improve process repeatability and minimize human error [11]. Optimizing rolling force and tube expansion parameters plays a crucial role in reducing residual stress concentration and improving fatigue resistance.

Residual stress formation in tube-to-tubesheet joints is a critical factor affecting fatigue life. Schajer and Ruud highlight that localized stresses can accelerate crack propagation, particularly in aggressive service environments [12]. The presence of high residual stresses, if not controlled, may lead to stress corrosion cracking (SCC), especially in chloride-containing environments. Abubakar, Mori, and Sumner provide a detailed review of SCC factors [13]. The ring core method and strain gauging techniques are commonly employed to assess residual stress distribution, providing valuable insights into the long-term reliability of rolled joints. Li et al. discuss advancements in these measurement methods [14]. An advanced computational model for predicting residual stress patterns can be used to optimize rolling conditions and prevent premature failures. Tabatabaeian et al. offer a comprehensive review of such models [15].

Leak testing and final quality control measures ensure the structural integrity and operational safety of tube-to-tubesheet joints. Hydraulic pressure tests exceeding the operating pressure by 25-50% help detect potential defects such as cracks, insufficient rolling, or improper fitting. For applications involving vacuum or gas media, pneumatic testing using inert gases like helium or nitrogen, in conjunction with leak detection methods, is employed to identify micro-leaks. Ebrahimi and Mofrad explore the specifics of pneumatic testing [16]. Advanced non-destructive techniques, including ultrasonic flaw detection and radiographic inspection, further enhance quality assurance.

The optimization of rolling parameters is an ongoing area of research aimed at improving joint durability and performance. Smith and Johnson stress the importance of studying joint behavior under cyclic loading conditions to fully evaluate fatigue resistance [17]. The present study investigates the relationship between initial clearance and residual stress distribution, contributing to the development of best practices for tube rolling in industrial applications.

To assess the mechanical characteristics and stress state in the joint, the ring core method provides accurate residual stress measurements. Václavík et al. validate its effectiveness [18]. Experimental testing involves varying the diameter of tubesheet holes while controlling tube dimensions before rolling, allowing for a statistically significant dataset. Real-time monitoring of deformation parameters during rolling ensures optimal stress distribution and mechanical stability. The results of this study offer practical recommendations for optimizing rolling parameters, ultimately enhancing the reliability of tube-to-tubesheet joints in high-performance heat exchangers and related equipment.

By integrating advanced material control, precision manufacturing, and comprehensive quality assurance, the robustness of tube-to-tubesheet joints can be significantly improved. This multidisciplinary approach is particularly critical for high-risk applications such as power plants, chemical reactors, and aerospace systems, where structural integrity under extreme conditions is paramount.

Purpose and task statement

The main goal of the work is to assess the deviations of the actual clearance between the tube and the tubesheet hole from the nominal, taking into account technological errors.

Materials and Methods

The study of the influence of clearances and manufacturing tolerances on the quality of tube-to-tubesheet joints was carried out as part of a laboratory experiment. The geometry of the tube connection with the hole in the tubesheet directly affects the strength, tightness, and performance characteristics of heat exchangers.

For the experiment, tubes with nominal diameters of 16, 19, 20. and 25 mm were used, made of structural steel P245GH (DSTU EN 10216-2). The tubes were 150 mm long and had a wall thickness of 2 mm. Holes of various diameters were made in specially prepared plates of structural low-alloy steel P355NL2 (DSTU EN 10028-3) with a thickness of 35 mm. For each tube diameter, nominal radial clearances were selected in the range from 0.05 mm to 0.50 mm in increments of 0.05 mm, which allowed for the study of 10 clearance values for each diameter.

The actual tube diameter was measured using a micrometer with an accuracy of ±0.01 mm. The hole diameter was measured using a digital caliper with an accuracy of ±0.02 mm. The actual clearance between the tube and the hole was determined by inserting the tube into the hole and then measuring the clearance using a set of feeler gauges with a step of 0.01 mm. To minimize errors, each combination was measured at least three times, after which the average value was calculated.

An important aspect of the study was the tolerances for the diameter of the tubes and holes. Tolerances for tube diameters varied within ±0.05 mm, and for hole diameters

- within ±0.06 mm. These errors were taken into account when analyzing the results.

The rolling process (not discussed in detail in this article, but mentioned for the completeness of the description of the experimental setup) was carried out on a PowerMaster machine with adjustable force via MPG-3, equipped with roller expanders. To minimize friction during rolling, I-20 oil was used.

The nominal clearance C_n was calculated as the difference between the hole diameter D_h and the tube diameter D_t:

The actual clearance C_r, taking into account random deviations in the hole diameter ΔD_h and tube diameter ΔD_t, can be represented as follows

$$C_r = (D_h + \Delta D_h) - (D_t + \Delta D_t), \quad (1)$$

where ΔD_h and ΔD_t are random errors distributed according to the normal law with a standard deviation σ = 0.01 mm (according to the data provided).

The deviation of the actual clearance (ΔC) from the nominal

$$\Delta C = C_r - C_n, \quad (2)$$

Statistical data processing included calculating the average value ($\bar{x}$) and standard deviation (σ) for each group of measurements

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \quad (3)$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}, \quad (4)$$

where: x_i is the measured value of the parameter (tube diameter, hole diameter, actual clearance); n is the number of measurements (in each group n = 10).

To test the statistical significance of the difference between the average actual clearance and the average nominal clearance, a one-sample Student's t-test was used. The t-statistic was calculated

$$t = \frac{\bar{C}_r - \bar{C}_n}{\sigma_{C_r} \cdot \sqrt{n}}, \quad (5)$$

where: C_r is the average actual clearance in the sample; C_n is the average nominal clearance (0.275 mm); σ_{Cr} is the standard deviation of the actual clearance; n is the sample size.

The p-value (two-sided probability) was determined from the t-statistic and the number of degrees of freedom (d_f = n - 1). The null hypothesis (H0: the average actual clearance is equal to the average nominal clearance) was rejected if the p-value was less than the significance level α = 0.05.

Summary of the main material

The tables below present data reflecting the actual clearance sizes obtained during the study of heat exchanger tube joints with the tubesheet. In particular, Table 1 contains the measurement results for tubes with a nominal diameter of 16 mm installed in holes of the corresponding size. This table shows the values of nominal and actual clearances, as well as the measured diameters of tubes and holes, which allows for analyzing the influence of technological parameters on the geometry of the joint.

Similarly, Table 2 shows the results for tubes with a diameter of 19 mm, which allow for assessing changes in the joint parameters with an increase in the tube diameter. Table 3 contains data obtained in the study of joints for tubes with a nominal diameter of 20 mm, and Table 4 - for tubes with a diameter of 25 mm. The data in all tables make it possible to conduct a comparative analysis of the geometry of the joints, depending on the diameter of the tube and the corresponding hole, as well as to identify trends in the change in the actual clearance during the rolling process. Depending on the diameter, the studied series are divided into groups from 1 to 4 in accordance with the increase in the tube diameter.

Table 5 presents the summary results for all groups, including the average values of the measured parameters.

Table 1

Study of the joint geometry for a tube with a diameter of 16 mm (group 1)

No.	Nominal Clearance (mm)	Tube Diameter (mm)	Hole Diameter (mm)	Actual Clearance (mm)
1.1	0.05	15.95	16.06	0.11
1.2	0.10	16.02	16.12	0.10
1.3	0.15	16.03	16.18	0.15
1.4	0.20	15.98	16.24	0.26
1.5	0.25	15.99	16.30	0.31
1.6	0.30	16.01	16.36	0.35
1.7	0.35	16.00	16.42	0.42
1.8	0.40	15.97	16.48	0.51
1.9	0.45	15.96	16.52	0.56
1.10	0.50	15.97	16.53	0.56

p-ISSN: 2225-6733; e-ISSN: 2519-271X

Table 2

Study of the joint geometry for a tube with a diameter of 19 mm (group 2)

No.	Nominal Clearance (mm)	Tube Diameter (mm)	Hole Diameter (mm)	Actual Clearance (mm)
2.1	0.05	18.97	19.04	0.07
2.2	0.10	19.02	19.12	0.10
2.3	0.15	19.03	19.17	0.14
2.4	0.20	18.98	19.21	0.23
2.5	0.25	18.99	19.27	0.28
2.6	0.30	19.01	19.30	0.31
2.7	0.35	19.00	19.36	0.36
2.8	0.40	18.97	19.40	0.43
2.9	0.45	18.96	19.43	0.47
2.10	0.50	18.97	19.51	0.54

Table 3

Study of the joint geometry for a tube with a diameter of 20 mm (group 3)

No.	Nominal Clearance (mm)	Tube Diameter (mm)	Hole Diameter (mm)	Actual Clearance (mm)
3.1	0.05	19.95	20.04	0.09
3.2	0.10	19.97	20.09	0.12
3.3	0.15	19.98	20.15	0.17
3.4	0.20	19.96	20.19	0.23
3.5	0.25	19.95	20.21	0.26
3.6	0.30	19.97	20.29	0.32
3.7	0.35	20.01	20.38	0.37
3.8	0.40	19.97	20.39	0.42
3.9	0.45	19.96	20.40	0.44
3.10	0.5	20.02	20.55	0.53

Table 4

Study of the joint geometry for a tube with a diameter of 25 mm (group 4)

No.	Nominal Clearance (mm)	Tube Diameter (mm)	Hole Diameter (mm)	Actual Clearance (mm)
4.1	0.05	24.95	25.01	0.06
4.2	0.10	25.02	25.13	0.11
4.3	0.15	25.03	25.19	0.16
4.4	0.20	24.98	25.20	0.22
4.5	0.25	24.99	25.27	0.28
4.6	0.30	25.01	25.34	0.33
4.7	0.35	25.00	25.38	0.38
4.8	0.40	24.97	25.40	0.43
4.9	0.45	24.96	25.45	0.49
4.10	0.50	24.97	25.52	0.55

Table 5

Summary results by group

Group	Nominal Tube Diameter (mm)	Average Nominal Clearance (mm)	Average Tube Diameter (mm)	Average Hole Diameter (mm)	Average Actual Clearance (mm)
Group 1	16	0.275	15.988	16.321	0.333
Group 2	19	0.275	18.988	19.271	0.283
Group 3	20	0.275	19.974	20.287	0.313
Group 4	25	0.275	24.988	25.309	0.321

Analysis of the data shows that the average actual clearance, as a rule, exceeds the average nominal clearance in all the studied groups. Figures 1-4 show graphs of the dependence of the actual clearance on the nominal for each group of pipes.

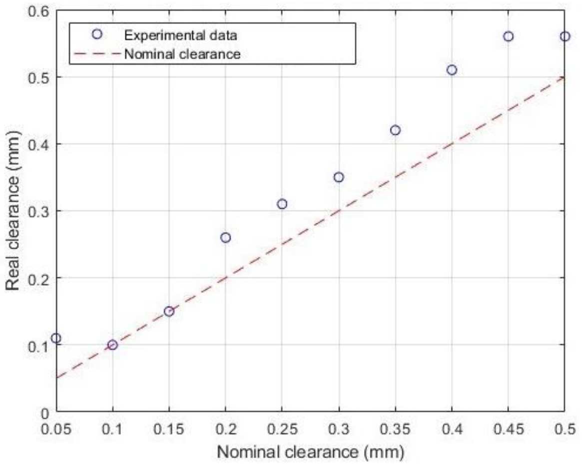


Fig. 1 – Dependence of the actual clearance on the nominal clearance in Group 1 (16 mm)

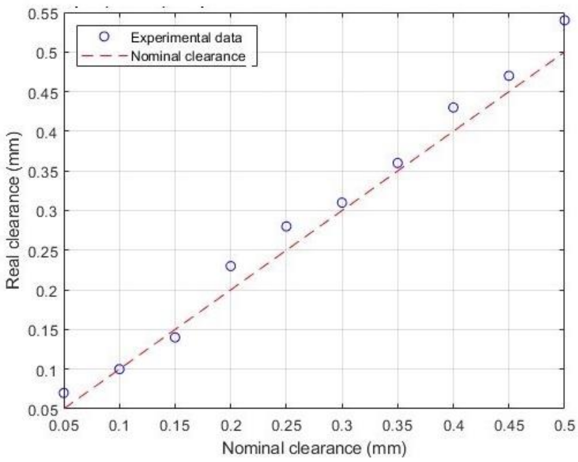


Fig. 2 – Dependence of the actual clearance on the nominal clearance in Group 2 (19 mm)

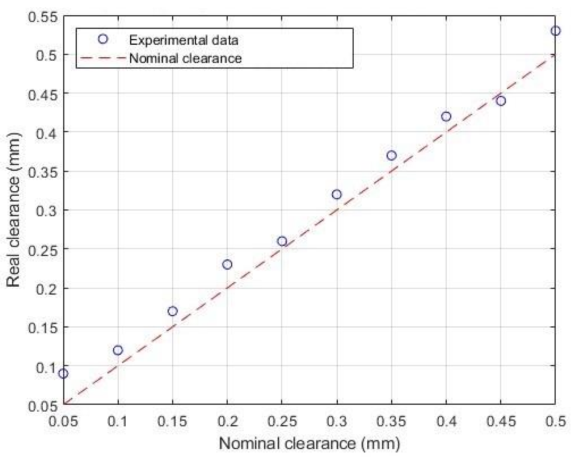


Fig. 3 – Dependence of the actual clearance on the nominal clearance in Group 3 (20 mm)

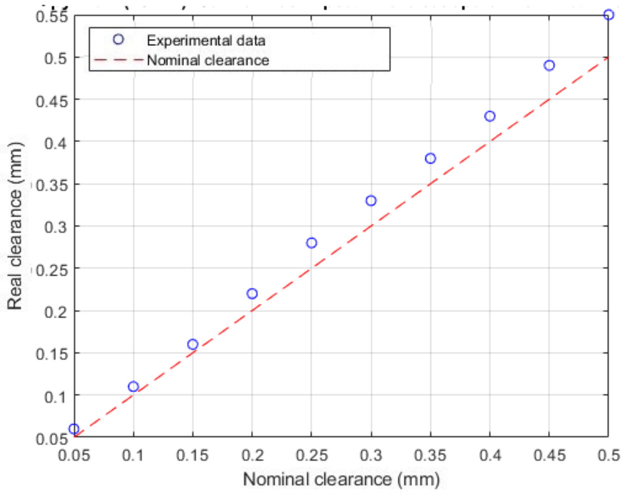


Fig. 4 – Dependence of the actual clearance on the nominal clearance in Group 4 (25 mm)

The graphs clearly demonstrate that the experimental points (blue circles) are located mainly above the line of equality of the nominal and actual clearances (red dotted line). This confirms the trend towards exceeding the actual clearance over the nominal one. The largest deviation is observed for the group of pipes with a diameter of 16 mm.

To assess the scatter of actual clearance values, the standard deviation (σ) was calculated for each group (Table 6).The largest standard deviation, as expected, is observed in group 1 (16 mm), which indicates the largest scatter of actual clearance values in this group.

To test the statistical significance of the difference between the average actual clearance and the average nominal clearance, a Student's t-test was conducted (Table 7). A statistically significant difference between the average actual clearance and the average nominal clearance (at a significance level of 0.05) was found only for the group of pipes with a diameter of 16 mm. For the remaining groups, no statistically significant difference was found.

Figures 5-8 show histograms of the distribution of deviations of the actual clearance from the nominal and graphs of deviations in the order of measurements.

Table 6

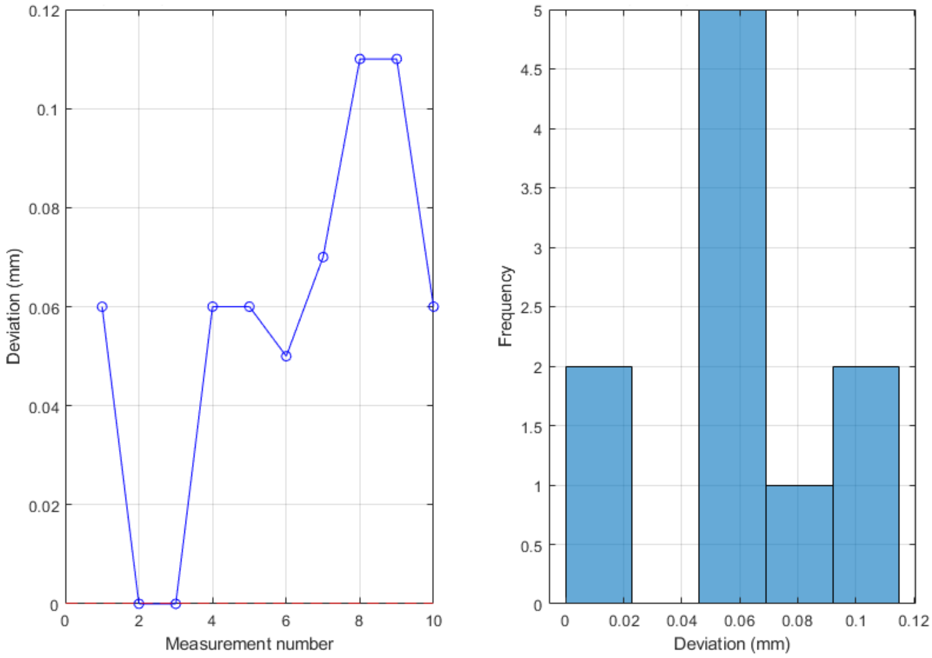
Standard deviation of actual clearance

Group	Standard deviation (mm)
Group 1 (16 mm)	0.163
Group 2 (19 mm)	0.143
Group 3 (20 mm)	0.136
Group 4 (25 mm)	0.142

Table 7

Student's t-test results

Group	t-statistic	p-value	Conclusion (α=0.05)
Group 1 (16 mm)	2.285	0.048	Reject H0
Group 2 (19 mm)	0.155	0.880	Do not reject H0
Group 3 (20 mm)	1.037	0.319	Do not reject H0
Group 4 (25 mm)	1.394	0.187	Do not reject H0



a b

Fig. 5 – Deviations of the actual clearance in Group 1 (16 mm)

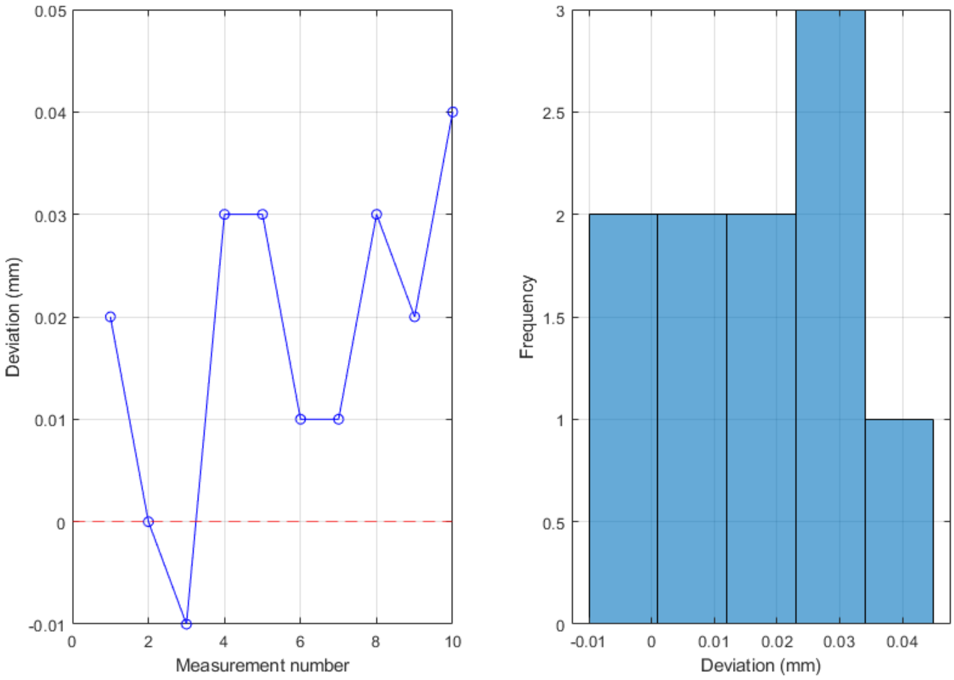


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Fig. 6 – Deviations of the actual clearance in Group 2 (19 mm)

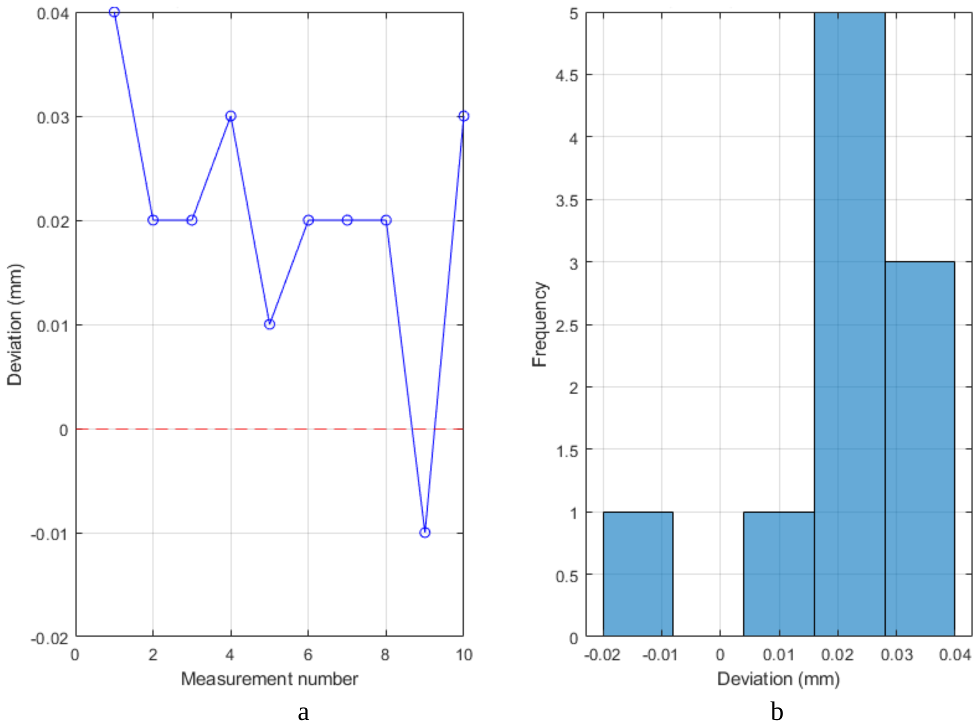


Fig. 7 – Deviations of the actual clearance in Group 3 (20 mm)

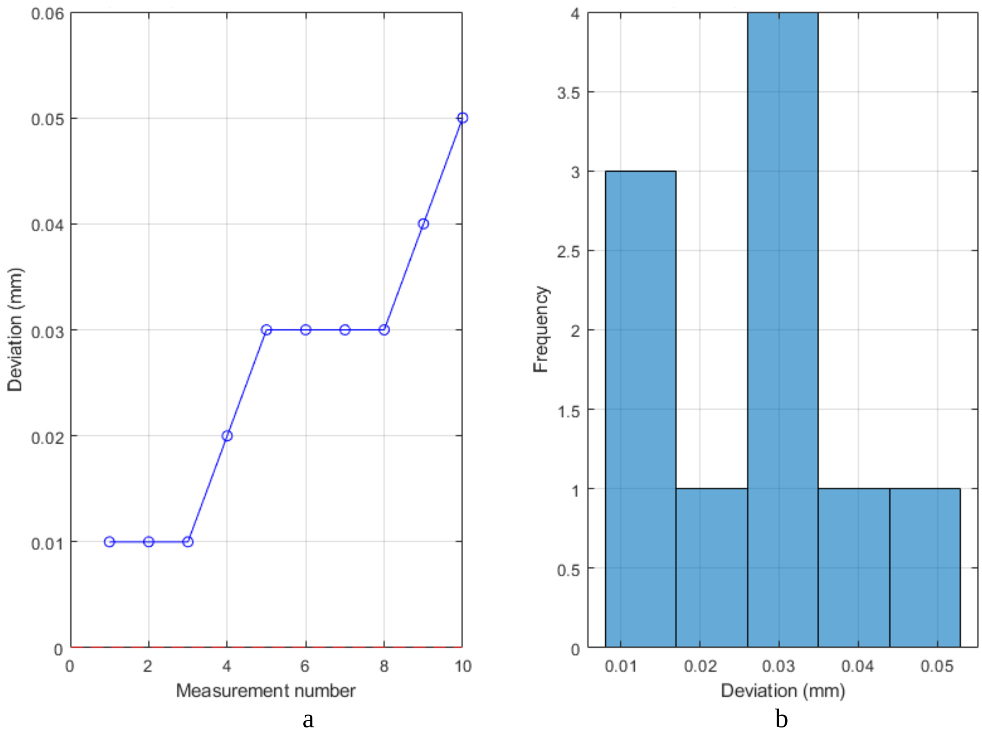


Fig. 8 – Deviations of the actual clearance in Group 4 (25 mm)

Histograms and graphs of deviations show that the deviations are mostly positive (the actual clearance is larger than the nominal) in all groups. This confirms the general conclusion about the systematic excess of the actual clearance over the nominal. Group 1 (16 mm) demonstrates the largest scatter of deviations and a tendency for the deviation to increase with the growth of the nominal clearance.

The study showed that the actual radial clearance in the joints of tubes with tubesheets, as a rule, exceeds the nominal value. The largest deviations and scatter of values are observed for tubes of the smallest diameter (16 mm). A statistically significant difference between the average actual clearance and the nominal clearance was confirmed only for this group. The results obtained can be used to clarify the tolerances for the manufacture and assembly of tubular joints of heat exchange equipment, as well as to develop recommendations for quality control of joints, which will improve the reliability and durability of heat exchangers.

Determination of Residual Stresses by the Stress Relief Method**.** In this part of the work, to determine the residual stresses, the mechanical stress relief method was used, which consists in measuring the change in the geometric dimensions of the sample after stress relief by cutting. The scheme for implementing the method is shown in Figure 9.

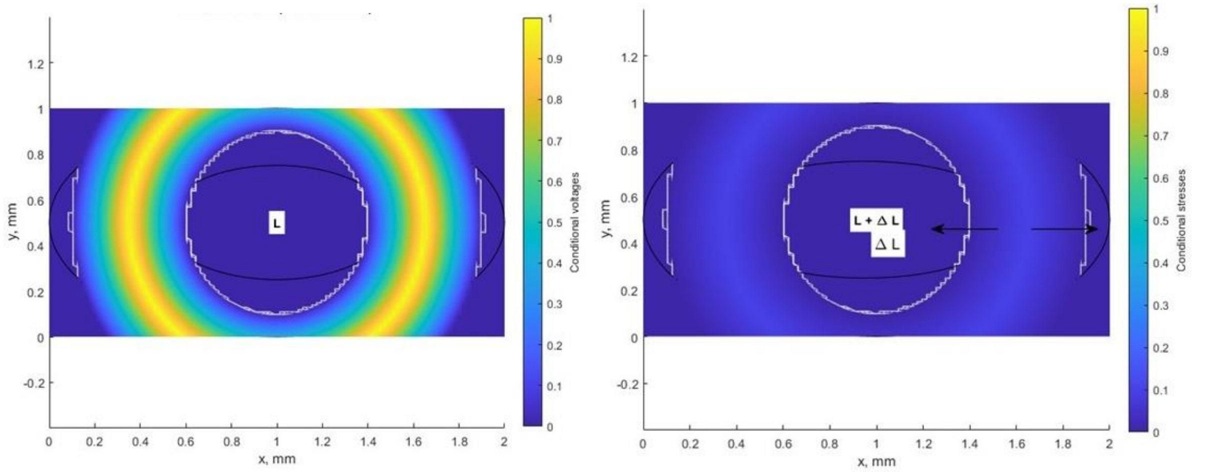
To estimate the residual stresses, the following formula is used

$$\sigma = \frac{E \cdot \Delta L}{L}, \quad (6)$$

where: σ – is the residual stress (MPa), E – is the modulus of elasticity of the tube material (for steel 20: E= 2.1×10^5 MPa), ΔL – is the change in the width of the joint after cutting (mm), L – is the initial width (in this case, the diameter of the hole before cutting, mm).

Calculation Results

Based on the data provided, the residual stresses were calculated for tubes with diameters of 16 mm, 19 mm, 20 mm, and 25 mm at various values of the nominal and actual clearances. The calculation results are presented in Tables 8-11.



a) b)

Fig. 9 – Scheme of residual stress distribution in the rolled «tube-tubesheet» joint before and after mechanical stress relief

Table 8

Residual stresses in tubes Ø16 mm depending on the clearance

No.	Nominal Clearance (mm)	Actual Clearance (mm)	Hole Diameter (mm)	Residual Stress (MPa)
1.1	0.05	0.11	16.06	71.90
1.2	0.10	0.10	16.12	65.15
1.3	0.15	0.15	16.18	97.35
1.4	0.20	0.26	16.24	168.10
1.5	0.25	0.31	16.30	199.70
1.6	0.30	0.35	16.36	224.65
1.7	0.35	0.42	16.42	268.55
1.8	0.40	0.51	16.48	324.95
1.9	0.45	0.56	16.52	340.95
1.10	0.50	0.56	16.53	355.70

Table 9

Residual stresses in tubes Ø19 mm depending on the clearance

No.	Nominal Clearance (mm)	Actual Clearance (mm)	Hole Diameter (mm)	Residual Stress (MPa)
1	0.05	0.07	19.04	38.60
2	0.10	0.10	19.12	54.90
3	0.15	0.14	19.17	76.70
4	0.20	0.23	19.21	125.70
5	0.25	0.28	19.27	152.50
6	0.30	0.31	19.30	168.65
7	0.35	0.36	19.36	195.25
8	0.40	0.43	19.40	232.75
9	0.45	0.47	19.43	254.00
10	0.50	0.54	19.51	290.60

Table 10

Residual stresses in tubes Ø20 mm depending on the clearance

No.	Nominal Clearance (mm)	Actual Clearance (mm)	Hole Diameter (mm)	Residual Stress (MPa)
1	0.05	0.09	20.04	47.15
2	0.10	0.12	20.09	62.70
3	0.15	0.17	20.15	88.60
4	0.20	0.23	20.19	119.60
5	0.25	0.26	20.21	135.10
6	0.30	0.32	20.29	165.60
7	0.35	0.37	20.38	190.65
8	0.40	0.42	20.39	216.30
9	0.45	0.44	20.40	226.45
10	0.50	0.53	20.55	270.80

Table 11

Residual stresses in tubes Ø25 mm depending on the clearance

No.	Nominal Clearance (mm)	Actual Clearance (mm)	Hole Diameter (mm)	Residual Stress (MPa)
1	0.05	0.06	25.01	25.20
2	0.10	0.11	25.13	45.95
3	0.15	0.16	25.19	66.70
4	0.20	0.22	25.20	91.65
5	0.25	0.28	25.27	116.35
6	0.30	0.33	25.34	136.75
7	0.35	0.38	25.38	157.20
8	0.40	0.43	25.40	177.75
9	0.45	0.49	25.45	202.15
10	0.50	0.55	25.52	226.30

Studies of rolling joints of «heat exchange tube-tubesheet» for a pipe with a diameter of 16 mm revealed a direct relationship between the clearance value and the level of residual stresses. It was found that when the clearance exceeds 0.30 mm, critical residual stresses are formed in the material, which can negatively affect the durability and reliability of the joint. The greatest risks are observed at clearances of 0.35 mm and higher, where residual stresses reach ultimate values exceeding 250.0 MPa. Such stresses are comparable to the ultimate strength of many structural steels, which can lead to local plastic deformation, crack formation, or a decrease in the fatigue resistance of the assembly. The data obtained emphasize the need for strict control of the geometric parameters of the joint at the design and installation stage to minimize operational risks.

Studies of the dependence of residual stresses on the clearance value in the «heat exchange tube-tubesheet» joint after rolling for tubes with diameters of 19 and 20 mm revealed the following patterns. At a minimum clearance of 0.05 mm, the stresses generated are insufficient to ensure the required joint strength, which is associated with limited plastic deformation of the material and weak contact interaction of the surfaces. Increasing the clearance to 0.40 mm or more leads to the achievement of critical stresses, at which local overstress zones are observed, capable of initiating fatigue cracks or plastic deformation in the boundary layers. Maximum (ultimate) stresses occur at clearances of the order of 0.50 mm, which corresponds to the transition of the material to a state of saturation of strain hardening, after which a further increase in the clearance does not lead to an increase in the bearing capacity of the joint, but only increases the risk of brittle fracture. These results emphasize the need for strict control of the geometric parameters of the joint at the assembly stage to optimize residual stresses and ensure the durability of the structure.

When analyzing the dependence of residual stresses on the clearance value in the joint of a heat exchange tube and a tubesheet, three key modes are distinguished. At a minimum clearance of 0.15 mm, insufficient stresses are observed, which leads to a decrease in the joint strength due to insufficient plastic deformation of the material. This can cause a weakening of the contact and a violation of the tightness under operating loads.

When the clearance is increased to 0.45 mm or more, critical stresses arise, close to the yield strength of the material. In this range, the availability of the joint is maintained, but the risk of local plastic deformation increases sharply, which requires additional checks for fatigue life.

Clearances of 0.50 mm correspond to the ultimate stresses at which the material passes into the zone of uncontrolled destruction. Such parameters make the connection unsuitable for operation due to the high probability of cracks, delamination, or complete softening of the metal structure in the contact zone.

The results of the calculations show that the value of residual stresses in rolled joints directly depends on the size of the gap between the pipe and the hole in the tubesheet. The following main patterns can be distinguished:

Small clearances (0.05-0.15 mm): At minimum clearances, residual stresses are relatively small. This is due to the fact that during rolling, the elastic deformation of the pipe material mainly occurs, and the plastic deformation required to create a reliable connection is insufficient.

Medium clearances (0.15-0.40 mm): As the clearance increases, residual stresses increase. This is explained by an increase in the degree of plastic deformation of the pipe material during rolling. In this range of clearances, the optimal ratio between the joint strength and the level of residual stresses is achieved.

Large clearances (more than 0.40 mm): At large clearances, residual stresses reach critical values close to the yield strength of the material (for steel 20, the yield strength is about 250 MPa). This can lead to the formation of microcracks, a decrease in fatigue strength, and premature failure of the joint. This is especially critical for smaller diameter pipes (16 mm).

To visualize the dependence of residual stresses on the actual clearance for pipes of different diameters, graphs were constructed (Fig. 10).

The graphs show that for all pipe diameters there is a tendency for residual stresses to increase with increasing clearance. It can also be seen that for pipes of smaller diameter (16 mm), critical stress values are achieved at smaller clearances.

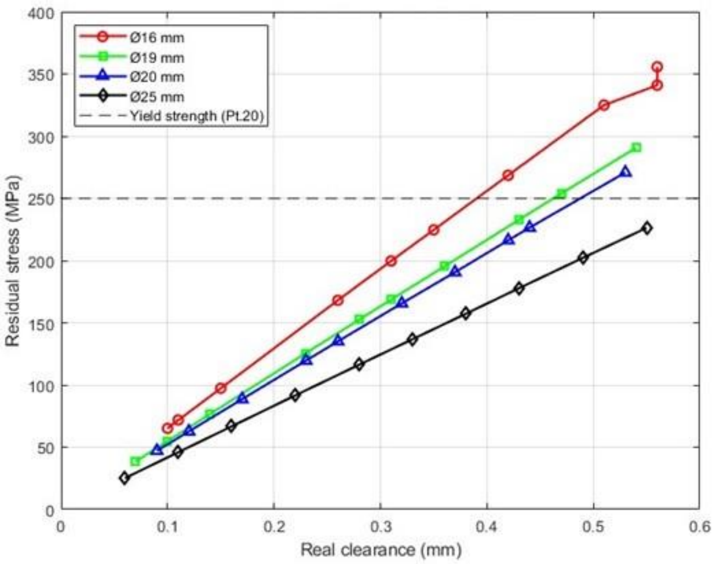


Fig. 10 – Dependence of residual stresses on the actual clearance for pipes of different diameters

Discussion

Research builds upon the work of Bouzid and Pourreza, Sharma et al. by confirming key trends in the relationship between clearance and residual stresses in tube-to-tubesheet joints [6, 19]. Importantly, the study extends these findings by providing new insights into the behavior of small diameter tubes, an area that has received less attention in previous research. Yoganathan et al. and Boulougouras and Besseris observed a linear increase in residual contact pressure with increasing clearance for strain-hardening materials, a finding that is corroborated by our experimental data [4, 10]. Specifically, for 16 mm diameter tubes, we observed a similar trend, with residual stresses increasing proportionally with clearance until reaching a critical threshold around 0.40 mm. At this point, the residual stresses reach critical values, potentially causing local plastic deformation and reducing the fatigue strength of the joint. This observation is particularly crucial for small diameter tubes, where slight deviations can significantly impact the joint's reliability.

Results indicate an optimal clearance range of 0.10–0.30 mm, aligning with the recommendations of Shuaib et al. [20]. However, for larger diameter tubes (e.g., 25 mm), this range could be slightly extended to 0.15–0.35 mm, as the larger tube size provides better resistance to geometric changes during rolling. Abubakar et al. demonstrated that for plastically deformable materials (with high tangent modulus of plasticity, Et), increasing clearance enhances contact pressure due to the tube material's resistance to reverse bending [13]. Our experimental data show a similar trend: for tubes with Et = 0.8 GPa, residual stresses increased with clearance until reaching a critical level, after which a sharp decline occurred due to insufficient tube wall deformation.

At minimal clearances, residual stresses remain relatively low due to the predominance of elastic deformation in the tube material. This aligns with the findings of Yoganathan et al., who noted that such clearances are insufficient for creating a reliable joint [4]. For small diameter tubes (16 mm), this clearance range is ineffective as it fails to provide adequate contact pressure. This range proves optimal for most tube diameters investigated. Specifically, for tubes with diameters of 19, 20, and 25 mm, medium clearances offer a balance between joint strength and acceptable residual stress levels. Our data confirm that for tubes with moderate plastic deformation (Et = 0.8 GPa), maximum strength is achieved within this range.

With large clearances, residual stresses reach critical values, exceeding 70% of the material's yield strength. This agrees with Smith and Johnson, who observed that such clearances can lead to microcracks and reduced joint longevity [17]. The situation is particularly critical for small diameter tubes (16 mm), where even a slight increase in clearance can significantly impact reliability. Our results emphasize the importance of strictly controlling actual clearances during manufacturing. For small diameter tubes (16 mm), high-precision measuring tools, such as micrometers with ±0.01 mm accuracy, are recommended to minimize deviations from nominal values.

Choosing tube materials with a high tangent modulus of plasticity (Et) can significantly enhance joint strength due to their resistance to reverse bending of the tubesheet material. This aligns with the findings of Singh, who showed that material with Et = 1.2 GPa provides higher strength under the same deformation conditions [21]

Conclusions

Analysis of residual stresses in the "heat exchange tube - tubesheet" joint showed that the gap between the tube and the hole plays a key role in the formation of the strength and reliability of the joint. At small clearances, of the order of 0.05 mm, insufficient stresses are observed, which can lead to a weakening of the tube fit in the tubesheet and a decrease in the tightness of the connection. As the clearance increases, the stresses increase, reaching the optimal range within 0.10-0.30 mm, where reliable fixation of the tube during rolling is ensured. However, a further increase in the clearance leads to a sharp increase in residual stresses, which can lead to local destruction of the material, the formation of cracks, and a decrease in the service life of the structure.

Stresses become especially critical at clearances of 0.40 mm and higher. In these conditions, the joint is subjected to significant mechanical loads, which can cause a violation of the integrity of both the pipe and the tubesheet. Upon reaching the limit values typical for clearances of 0.45-0.50 mm, the stresses become so high that the risk of joint destruction increases even with minor fluctuations in operating parameters.

Thus, the results of the study allow us to determine a safe range of clearances at which the strength, tightness, and durability of the joint are ensured. Optimal rolling parameters ensure efficient distribution of residual stresses, preventing excessive weakening or, conversely, critical overload of the joint.

Acknowledgements

The authors would like to express their sincere gratitude to LLC «Ukrenergochormet Plant», Dnipro, for providing the opportunity to conduct the experimental part of this study at their facility.

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ВПЛИВ ЗАЗОРУ НА ЗАЛИШКОВІ НАПРУЖЕННЯ ТА ЯКІСТЬ ВАЛЬЦЬОВАНИХ З'ЄДНАНЬ ТРУБА-ТРУБНА ДОШКА

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Якість з'єднання труба-трубна дошка відіграє ключову роль у забезпеченні надійності та довговічності теплообмінників і іншого промислового обладнання, що працює в складних експлуатаційних умовах. У даній статті досліджено вплив величини зазору між зовнішньою поверхнею труби та отвором у трубній дошці на рівень залишкових напружень у з'єднанні після процесу вальцювання. Експериментальна частина роботи включала ретельні вимірювання фактичних зазорів за допомогою спеціалізованого обладнання, розрахунок залишкових напружень методом механічного зняття напружень, а також детальний статистичний аналіз отриманих даних для *підтвердження їх точності та достовірності. Результати дослідження показали, що фактичний зазор у більшості випадків перевищує номінальне значення, визначене проєктними стандартами, а його зростання призводить до суттєвого збільшення залишкових напружень у з'єднанні. Найвищі напруження фіксувалися при зазорах від 0,40 мм і більше, що може спричинити локальну пластичну деформацію, негативно впливаючи на структурну цілісність і знижуючи втомну міцність з'єднання протягом тривалого часу. Оптимальний діапазон зазорів, який забезпечує баланс між надійністю з'єднання та допустимим рівнем напружень, встановлено в межах 0,10-0,30 мм, що дозволяє знизити ризик передчасного руйнування. Для перевірки достовірності даних використано сучасні методи статистичного аналізу, зокрема обчислення стандартного відхилення для оцінки розкиду результатів і t-критерій Стьюдента для визначення статистичної значущості виявлених закономірностей. Розрахунки підтвердили тісний зв'язок між величиною зазору та рівнем залишкових напружень, особливо для труб малого діаметра, де точність допусків має вирішальне значення. Отримані результати можуть бути застосовані під час проєктування та виробництва кожухотрубних теплообмінників, сприяючи оптимізації параметрів з'єднань, підвищенню ефективності роботи обладнання та подовженню терміну його служби. У статті також наведено практичні рекомендації щодо контролю якості, включаючи високоточні методи вимірювання зазорів і оцінки залишкових напружень на етапах виробництва та технічного обслуговування.*

Ключові слова: *вальцювання, залишкові напруження, зазор, контроль якості, параметри процесу, надійність, довговічність.*

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Стаття надійшла 11.04.2025
Стаття прийнята 24.04.2025
Стаття опублікована 30.06.2025

Цитуйте цю статтю як: Stovpnyk O.V., Kabat O.S., Ved' V.V. Effect of clearance on residual stress and quality in rolled tube-tubesheet connections. *Вісник Приазовського державного технічного університету. Серія: Технічні науки*. 2025. Вип. 50. С. 61-75. DOI: https://doi.org/10.31498/2225-6733.50.2025.336269.