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DESIGN – TECHNOLOGICAL OPTIMIZATION OF THE LEVEL OF RESIDUAL DEFORMATIONS DURING WELDING OF PIPE SECTIONS FROM PT-7M ALLOY

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Abstract. Application of tubular elements in the chemical industry is widely used. The special properties of materials and their reaction to the welding thermal cycle is quite complex. This is especially true of titanium alloys, which when heated are sensitive to environmental influences, require special welding techniques and undergo residual welding deformations.

The welded joints of tubular elements made of titanium alloy brand PT-7m, which undergo transverse deformations due to welding, are studied. It is necessary to ensure high-quality sealed welds.

Analysis of the literature has shown that to obtain a guaranteed penetration it is necessary to increase the power of the arc discharge or perform multi-pass welding. This will provide larger cross sections of welded parts and should provide the specified strength characteristics. However, this technology, in turn, leads to an increase in residual deformation in the vicinity of the welded joint due to the intensive increase in the coefficient of linear expansion when heating the material. Also, the special thermophysical properties of titanium alloy such as increasing the affinity for gases when heated, increasing the grain size lead to a decrease in strength properties.

In the presented work it is proposed to use a mechanical angular deformer with an indicator head and a reference base for the study of transverse residual deformations. Peculiarities of measuring sockets and methods of their preparation are revealed. A calculation scheme for determining the amount of deformation has been developed, which has been tested on flat welded specimens and transferred to tubular elements. The sequence of deformation measurement process is described and the peculiarities of their formation on flat samples and tubular sections are studied.

The constructive decision of a welded joint of pipes which provides use of a compensation ring is offered. This approach allows to provide reliable protection of the root of the seam and its optimal formation with minimal residual deformation. At the same time it is possible to reach the reproducible form of a dagger of similar penetration in one pass. The result is a welded joint of the lock type, which is sealed and has a free formation of the seam root with high-quality protection by the gas atmosphere. The use of pulsed arc welding with a non-fusible electrode in an argon environment with filler wire allows to minimize the thermal impact on the base metal.

Statistical processing of experimental data on the parameters of the welding mode and their influence on the residual transverse welding deformations is carried out. To obtain an unambiguous statistically reliable answer about the valid law of distribution of experimental data of the results of strain measurement, the balancing procedure and the development of an analytical approximation distribution model are involved. It is shown that the measured values of the residual transverse deformation of the welded assembly are correctly described by the Laplace distribution, which predicts (probability not worse than 90 %) a decrease in the average value of the deformation value by 1.3 times.

Keywords: argon arc welding, pipe section welding, titanium alloy weld, angle deformer, welding deformations, statistical processing of experimental data, distribution probability

Introduction

Titanium alloys, in particular α-alloy PT-7m (σ_B = 600–700 MPa, δ = 8 %) are used in the energy-intensive (pressure, temperature) chemical processes of hydrocarbon products processing as a structural material of the corresponding equipment. The latter is also characterized by a sufficiently high thermal stability, corrosion resistance and acceptable technological weldability [1].

The study of ways to create structural welded elements such as tubular sections using titanium alloys shows that it is necessary to take into account their specific features [1, 2]. This should include a small modulus of elasticity ($E = 1.08 \cdot 10^5$ MPa), which causes to lay in the structure of larger sections of welded parts to ensure strength characteristics. Also, when titanium alloys are heated to temperatures above 400 °C, an intensive increase in the coefficient of linear expansion is observed ($\alpha \cdot 10^6\ K^{-1} = 10$). At the melting temperature of the coefficient of linear expansion is approximately $\alpha \cdot 10^6\ K^{-1} = 15$. As a result, there may be significant deformation of the structure, often there is an unacceptable change in the geometry of the product.

In titanium alloys in the process of heating there is a tendency to grain growth, especially taking into account the low thermal conductivity (λ = 33.1 W / (m · K) and the corresponding development of the thermal impact zone. As a result, the mechanical properties of the material deteriorate.

The above features of welding of titanium alloys lead to the need to solve a number of problems to ensure the required technological strength and performance characteristics of welded joints of tubular sections.

Object and subject of research

The aim of the work is to optimize the design and technological solution for the manufacture of welded pipe sections by argon-arc welding with a non-fusible electrode (gas-shielded argon arc welding), which operate at high temperatures and internal pressure with reliable level of minimum residual deformation.

The main tasks that are set in the work should include:

- constructive execution of joints of tubular sections from the guaranteed penetration;
- reduction of residual deformations as a result of welding;
- development of methods and research of residual deformations in the vicinity of the welded joint;
- statistical processing of the results of measuring the deformations of the welded joints.

Purpose and objectives of the study

The object of research is welded joints of tubular elements made of titanium alloy PT-7m.

The subject of research is the residual welding deformations of tubular elements and structural quality assurance of welded joints.

The practical significance of the obtained results

As a result of performance of work the new constructive decision for a joint of tubular sections is received. It provides assembly of elements through an intermediate compensation ring that provides the best quality of joining and a possibility of the guaranteed penetration. It is shown that for the proposed welded joint provides minimal transverse residual welding deformations, which are correctly described by the Laplace distribution with a probability of not less than 90 %.

Analysis of Literary Sources

It is known [1–3] that the significant technological complexity of welding titanium parts is due to the high sensitivity to the gas composition of the gas stream of arc discharge during fusion welding, structural design of the product (tubular element), choice of welding method, residual deformation and stress in the weld zone.

All other things being equal, the magnitude of welding deformations depends on both welding technology and technological support [4, 5]. In particular, the increase in the cross section of the seam (according to regulatory requirements for the product) causes an increase in the area of penetration of the seam, which leads to an increase in the residual level of transverse deformations. At the same time, the system of rigid clamping objectively contributes to their reduction [5–7].

The study of such stresses and strains requires the use of special methods and equipment based on the measurement of various physical quantities and the use of complex mathematical devices [8–11]. However, when testing welding technology, it is advisable to use methods for determining the linear characteristics of the structure [12].

High surface tension of liquid metal (σ_C = 1.39 Pa) and low viscosity of metal in the range of welding temperatures (1730–1930 °C) provide qualitative formation of a root of a seam. However, violation of the conditions of precision assembly of parts for welding and insufficient protection of the root and its characteristic cross-sectional shape, affect the increased defect of welding (burning, excessive gas saturation of the metal, uneven distribution of residual stresses and strains along the height of the seam). Most of these negative factors are manifested when it is necessary to perform welding in conditions of free deformation of the welded joint (by weight). The latter causes a zone of concentration growth of operating stresses, violation of the shape of the conductive channel when pumping through it the working fluid and, thus, reducing the efficiency of the system.

Results and Discussion

With continuous argon-arc welding with a non-fusible electrode with filler wire, the increased thickness of the product within certain limits provides the rigidity of the structure in the welding zone with free deformation on the weight. Also, this design limits the level of residual deformation due to the need to use multi-pass welding (fulfilling the condition of minimizing the running energy of welding q_P). However, a significant increase in the size of the thermal impact zone leads to increased deformation of the entire welding zone.

Assuming that the level of residual transverse deformations is proportional to the volume of molten metal in the bath, other things being equal, it is possible to reduce it, while ensuring operational requirements (strong-tight seams). This is achieved by developing the technological process of manufacturing welded pipe chains with a shell thickness of 3^{+1} mm with minimizing the size of the post-welded deformation zone of the connection made with free deformation on the weight under the following conditions: 1. transition to pulse-arc welding setting parameters of the mode; 2. ensuring reliable protection of the root of the seam with a standard supply of gas protection only in the combustion zone of the arc; 3. constructive reduction of the thickness of the pipe shell by welding pipe sections with embedded compensation (unloading) rings.

The research was performed on the equipment provided by the Customer: power supply – VSVU-315, welding machine – ADSV-5. Measurement of transverse residual deformations was performed with an analog angle deformer with an indicator head MIG (division price 2 μm, stroke length – 2 mm), which is shown in Fig. 1.

The development of the method of measuring deformations and the establishment of optimal welding modes was carried out initially on planar samples with a thickness similar to the pipe shell and the reference base. The samples and the reference base were made of the same material as the product. Since practical measurements of the amount of deformation are carried out with complete cooling of the metal of the welding zone, the uniformity of the material eliminates the constant temperature error of the measurements.

Fig. 1. Analog angle deformer with indicator head and reference base

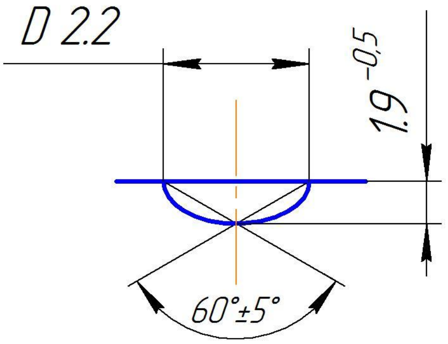


Fig. 2. Profile of the reference point
of the measuring socket

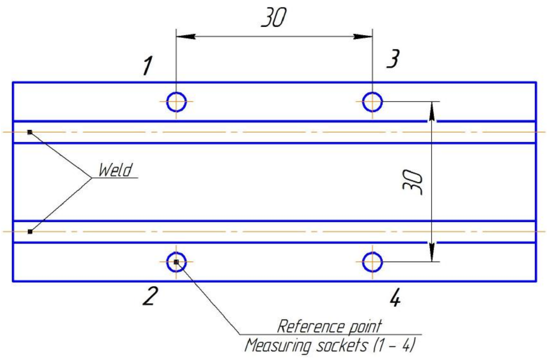


Fig. 3. Measuring socket for determining
the final residual transverse deformation
of the welding zone by two seams of the pipe shells
through the compensation ring

$$(1 - 1^*) = \frac{1}{2}D; \; H = (2 - 2^*) = \sqrt{(1 - 2)^2 - [(1 - 2) - \frac{D}{2})]^2} = \sqrt{(1 - 2)^2 - (1 - 2)^2 + 2\times(1 - 2)\times D - \frac{D^2}{4}};$$

$$H = D\sqrt{2\times(1 - 2) - \frac{D}{4}}$$

where H is the amount of loss of shape of the planar sample due to the action of transverse residual deformations.

Adjustment of the deformometer to the initial state (base "zero") of the head was performed on a reference sample according to standard methods [12].

When transferring the deformometer to the product to measure the amount of deformation, the support legs were alternately installed on the previously applied (Fig. 3) reference points of the measuring socket. The principle of random number generator randomization was used to ensure the same additive measurement error along the entire length of the seams.

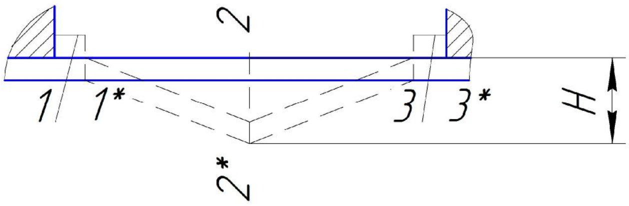


Fig. 4. Calculation scheme for determining the amount of deformation (flat sample)

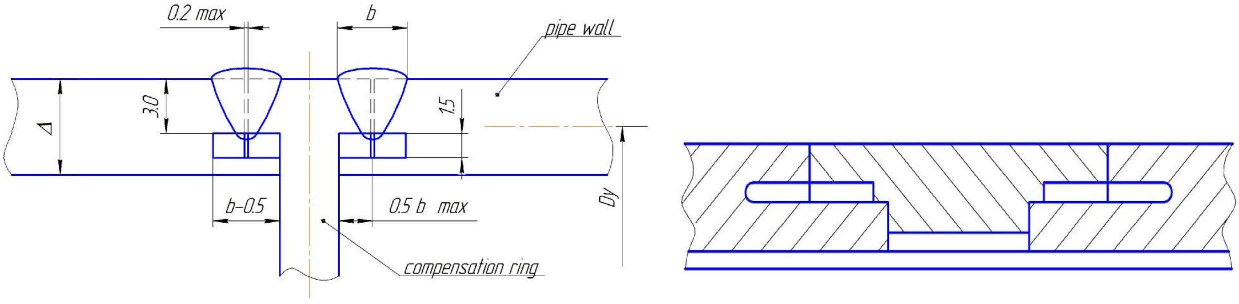
The deformation measurement of the distance between the reference points of the socket is relative, as it demonstrates the difference between the reference points of the reference and the measuring base of the socket.

After completion of welding and complete cooling of the metal of the welding zone, the measurements were performed, according to this method, repeatedly, duplicating the process of studying the base between the reference points of the socket and determining the actual value of residual transverse deformation. To reduce the measurement error, a control check of the deformer setting according to the reference base was performed. The frequency of testing was determined experimentally by comparing the calculated (1) and experimental values.

It is established that during testing of welding modes on planar samples the difference of deformation on surfaces which is caused by uneven cross shrinkage on thickness of a seam (influence of a typical form of section of a seam) is observed. The result is a bend from the plane, because the welding was carried out under the conditions of the technological scheme without rigid fixing of parts. This bending causes a significant difference in the distance of the bases of measuring sockets applied strictly symmetrically on the surfaces of the sample (on the surface, on the side of the arc, the base is reduced, and on the reverse surface of the part on the contrary increases). However, their average value (determined by the sign) goes to zero.

When switching to welding a real product, this systematic error completely disappears. This is due to the curvature of the shell, which acts, in this case, as a stiffness that limits deformation and bending. Thus, the measurement of deformations when applying a measuring socket from the outer surface of the product is statistically significant.

The design of the welded assembly, which provides reliable protection of the root of the seam and its optimal formation with minimal residual deformation is to meet the following conditions: a) the maximum possible, in terms of strength, the cross-sectional area of the seam; b) strict and reproducible form of dagger penetration in one pass; c) formation of a one-piece welded joint of the “lock” type with a simultaneous free formation of the seam root (exclusion of stress concentration and non-uniform deformation from the root to the top of the seam); d) the presence of a compensating insert ring for the coupling of the pipe shells in the welded assembly, which creates additional rigidity and reduces the transverse shrinkage of the parts and the final deformation of the seam. It should be noted that the implementation of the reproducible form of dagger penetration is provided by additional processing of the end of the pipes and, in fact, the body of the ring - the compensator with the formation after assembly of the cavities (Fig. 5).



a

b

Fig. 5. Working form of assembly and welding of pipes: a – through the compensation ring; b – when working out the modes on planar samples

Artificial cavities also perform a protective function for the liquid metal of the weld: with standard gas protection of the welding zone, argon flows through the assembly gaps into the volumes of the cavities, which protects the liquid metal of the weld root. This somewhat limits the intense leakage of metal due to the formation of a pressure balance between the gas and liquid metal phases (the depth of the cavity almost corresponds to the standard width of the seam b).

Also in the process of developing the technology of welding in the pulse mode it is necessary: a) strict need to withstand the vertical displacement from the horizontal plane of the surfaces of the assembly parts within not more than $1^{+0.2}$ mm. Failure to comply with this requirement, there is a partial destruction of pre-installed seizures on the second, in the order of welding, the seam. The destruction process becomes complete when the surfaces are exceeded by 1.5 mm; b) the value of the assembly gap is strictly correlated with the angle of exit of the plane of the mirror of the welding bath normal to the zenith. Thus, when welding "on the rise" with the plane orientation of the bath mirror strictly to the normal of the zenith with accidental fluctuations in the parameters of the mode, the formation of gaps is possible. Since the welding process is a statistically indeterminate system, a guaranteed way to eliminate such a defect is to comply with the assembly gap along the entire length of not more than 0.3 mm. If technically it is not possible to provide, it is recommended to perform welding "downhill". Then at an angle of inclination of the bath within 5°–10° and there is a pause between current pulses, there is a movement of liquid metal of the bath in its main part. The liquid metal effectively flows to the edges, thereby reducing the previous assembly gap, and also creates a certain liquid temperature damper between the pulse of the arc discharge and the hard metal parts.

Optimization of welding modes was performed according to the following parameters: pulse current I_{zv}, time of current t_i, pause time between pulses t_P, time of pulse front t_F, value of base arc support current I_0, welding speed V_{zv}, angle of inclination $\alpha°$ of the welding bath from the plane. In this case, the use of simplex – planning with $K = 7$ factors was performed. In the first steps, the factor is the angle of inclination $\alpha°$, fixed at the level of 100 and taken out of the plan. The current results of the displacement of the 6-factor simplex in the optimization response plane [13, 14] are shown in Fig. 6, and in table 1.

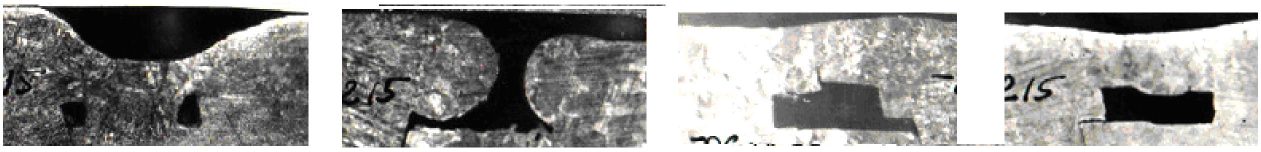


Fig. 6. Macro sections of the weld zone with excess edges, mm: a – 1.4; b – 1.2; c – 0.8; d – 0.25

Table 1

The amount of deformation in the process of optimizing the welding process in simplex planning

Welded macro sections (according to Fig.6)	Excess of edges, mm	Deviation of a welding bath from horizon, °	Deformation, microns
a	1.4	10	940
b	1.2	10	952
c	0.8	10	926
d	0.25	10	935

The result of the optimization experiment is a set of setting parameters of the welding mode (Table 2), in which an acceptable range of oscillations of the deformation value of 932–940 μm is observed.

Table 2

Setting parameters of the welding mode

Capture	Welding	Note
$t_{F,}$ s = 0	t_F, s = 0.02	The diameter of the electrode is 4 mm
t_i, s = 1.0	t_i, s = 0.2	Electrode cone angle 45°
t_P, s = 0.3	t_P, s =0.7	Optimal arc length
I_0, A = 20	I_0, A = 20	2^{+1} mm
I_{zv}, A = 100	I_{zv}, A = 300	Descent welding with angle
$V_{zv,}$ m/h = 65	$V_{zv,}$ m/h = 15	Exit from the horizon not more than 10°

The obtained results made it possible to estimate the level of residual welding stresses from welding. To do this, we use the mathematical apparatus of the computational-experimental method, which is based on the method of plastic deformations [15, 16]. Then, for a width of the plastic deformation zone of 10 mm, the value of residual stresses in the vicinity of the welded joint will look like (Fig. 7).

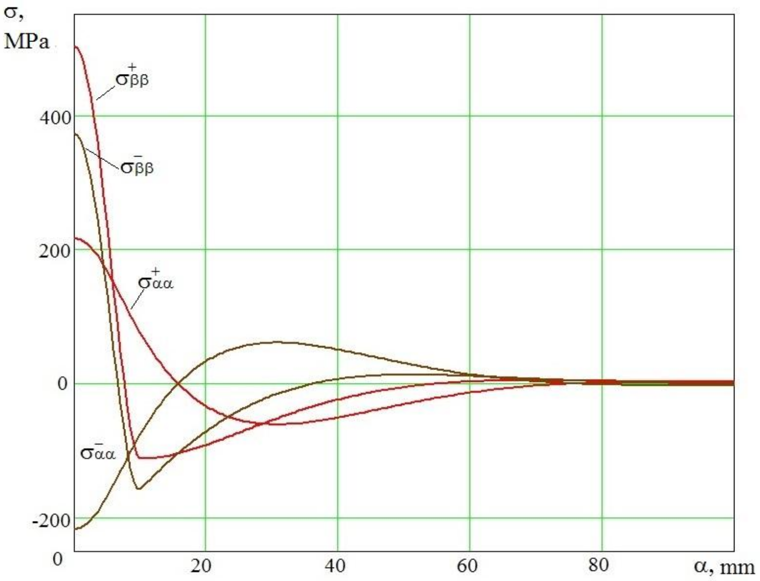


Fig. 7. Distribution of residual stresses in the vicinity of the butt weld of two shells:
α, β – axial and annular directions in the pipe; s_{bb}^{-} ,s_{bb}^{+} , – circular and, s_{aa}^{-} ,s_{aa}^{+} –
axial stresses on the inner and outer surfaces of the pipe, respectively

The analysis of Fig. 7 shows that in the welded joint of two pipes there are two characteristic areas: plastic-deformed and elastic. The first section, near the axis of the weld, is characterized by high circular tensile stresses in the weld metal. In the future, they decrease sharply and in the peri-suture area change their sign to the opposite.

The axial stresses in the first section are tensile on the inner surface and compressive on the inner surface, respectively. As they move away from the weld, they go to zero and change the sign to the opposite.

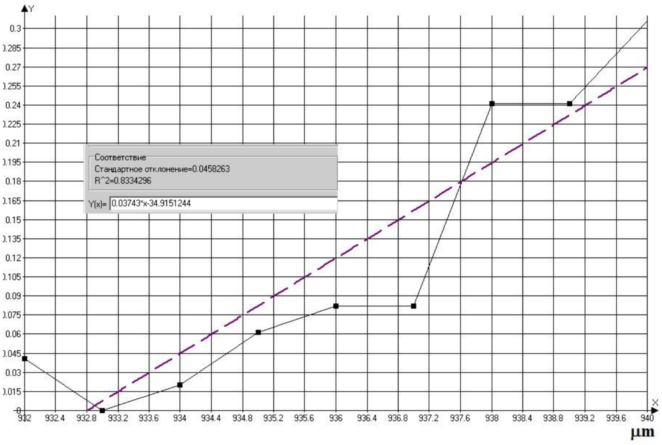
After complete cooling, circular tensile stresses occur at the boundary between the two sections, which leads to a gradual decrease in compressive stresses in the second section. The stresses in the connection depend on the running energy and the welding method.

In order to predict the indicators of the proposed technology when using it, their statistical representation was carried out to determine the type of distribution (Table 3), Fig. 8, 9.

Table 3

Representation and types of distribution of indicators

Statistical parameter	Estimated value of the parameter
Weighted average (sample average) $\overline{x}_{(f)}$	938.061
Mode x_{mod}	940
Median x_{med}	939
The scope of variation x_R	8
Linear deviation d	1.57
Unbiased estimation of variance S^2	4.267
Estimation of standard deviation s	2.066
Coefficient of variation n	0.22 %
Relative linear deviation K_d	0.17 %
Oscillation coefficient K_R	0.85 %
Coefficient of asymmetry A_S	-1.243 (left asymmetry)
the standard deviation of the asymmetry coefficient S_{AS}	$0.592 \leq 3$ (asymmetry is not significant)
Excess E_S	1.13 (distribution elongated - sharp tip)
standard deviation of the excess coefficient S_{ES}	0.735 Because $E_x/S_{Ex} = 1.13/0.735 = 1.538 \leq 3$, then the deviation from the normal distribution law is insignificant
Test hypotheses about the type of distribution 1. Normal law according to the criterion of Pearson's agreement	K_{kp} (0.05; 6) = 12.59159; K_{observ} = 47.49 $K_{approx} > K_{kp}$ – array data are not distributed according to the normal law (significant difference between theoretical and empirical frequencies)
2. Normal law in terms of asymmetry and excess	A condition is fair for normal distribution: $\|A_s\| < 3S_{As}$; $\|A\| < 3S_{As}$; $\|E\| < 3S_{Ex}$ $S_{As} = 0.5916$, $S_{Ex} = 0.7348$ $A_s=-1.243$, $E_x = 1.13$ $\|-1.243\| < 3\cdot0.5916 = 1.7748$ $\|1.13\| < 3\cdot0.7348 = 2.2045$ The condition is fulfilled
3. The normal law according to the rule of 3 sigma	Interval $(x - 3s\ ;\ x + 3s\ )$ (938.061-3·2.044; 938.061-3·2.044) = (931.929; 944.193) All values of the measured deformation lie in the interval x_{min}= 932; x_{max}= 940



Соответствие
Стандартное отклонение=0.0458263
R^2=0.8334296
Y(x)= 0.03743*x-34.9151244

Fig. 8. Distribution of empirical frequencies for measuring strain from a data set

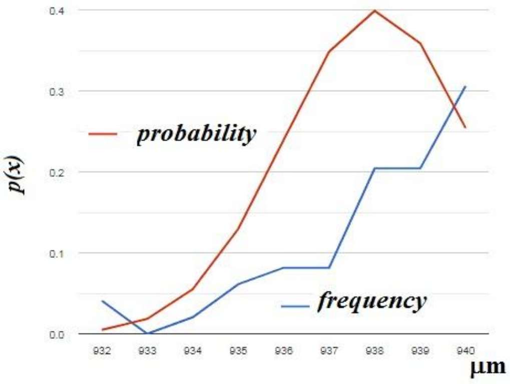


Fig. 9. Empirical frequency polygon and probability for the normal law of distribution of the data array

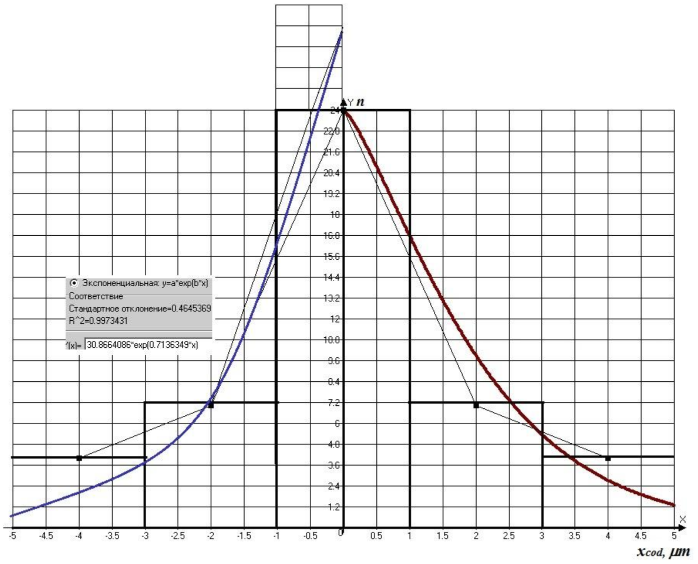
From the given data it follows that the average value of the array of data of deformation measurements practically corresponds to the mode and the median, which confirms the normality of the sample distribution. The homogeneity of the measured data is confirmed by the coefficient of variation (less than 30 %). However, the test of hypotheses about the normality of the distribution of data by Pearson's criterion is rejected if it does not contradict the normal law by estimates of asymmetry and excess, as well as the rule of 3 sigma.

To obtain an unambiguous statistically reliable answer about the valid law of distribution of experimental data of deformation measurement results, the symmetry procedure (centering of the data set) and the development of the analytical approximation distribution model (Table 4) are involved, Fig. 10.

Table 4

Analytical approximation model

Statistical parameter	Estimation of the parameter
Arithmetic mean $\overline{x}$	939.29
Median x_{med}	939
Swing x_R	936
Average for bends (25 % та 75 %) x_Z	939.25
Strongly cut average (50 %) $\overline{x}_{0.5}$	939.1
Estimation of the distribution center by 5 nonparametric parameters (arithmetic mean, median, amplitude, bending average, strongly cut average)x_C	939.1
Number of ejection points from the data set (probability of their significance is less than 90 %) x_n	4
standard deviation of the data s_{x_i}	14.1
the standard deviation of the mean array $s_{\bar{x}}$	3.2
Estimated width of the histogram column d	2
Histogram column centers (natural / coded) x_{ci}	935.02/-4; 937.06/-2; 939.1/0; 941.14/2; 943.18/4
Approximation model $p(x_{cod}) = A\exp(-\lvert x_{cod} / l\,s\rvert^{a})$	$p(x) = 24\exp(-\lvert x_{cod} / 2.2\rvert^{1.3})$



● Экспоненциальная: y=a*exp(b*x)
Соответствие
Стандартное отклонение=0.4645369
R^2=0.9973431
f(x)= 30.8664086*exp(0.7136349*x)

Fig. 10. Histogram and polygon of experimental data of deformation measurement during centering and symmetry of their values and representation: 1 – density of distribution by analytical model (right branch); 2 – distribution density according to the model corresponding to the Laplace distribution (left branch)

Conclusions

A design solution of the welded unit is proposed, which provides, depending on the requirements of the technology, the formation of a connection with a guaranteed specified level of final deformation of the welding zone.

Technological methods and modes of welding with a reliable probability of not less than 90 % provide a residual deformation value at the level of 939 μm and a limiting (95 % distribution quantile) value of 940 μm.

The measured values of the residual transverse deformation of the welded assembly are correctly described by the Laplace distribution, according to which it is predicted (probability not worse than 90 %).

The distribution of residual welding stresses in the vicinity of the welded joint of pipe sections is calculated. It is shown that the stresses have an oscillatory character with smooth attenuation at a distance from the axis of the weld. The maximum tensile stresses are localized in the vicinity of the weld.

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