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Assembly of threaded and adhesive-threaded joints with the application of ultrasonic vibrations

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ABSTRACT

Introduction. The main problem in the use of threaded joints is the reduction of the preliminary force under the influence of workloads, which contribute to stress relaxation in the joint elements. The main directions of intensifying assembly operations in order to improve the performance properties of a threaded joint are improving the design of joints, using adhesive compositions that, after polymerization, prevent unscrewing. One of the ways to modernize the assembly is the use of ultrasonic vibrations, which makes it possible to influence the distribution of forces arising during assembly, as well as to process treat the adhesive to improve its properties. **Research methodology.** Experimental studies were carried out in three stages. At the first stage, the influence of shear ultrasonic vibrations on the threaded joint assembly process was assessed. As a complex indicator that determines the effectiveness of the impact, a relative unscrewing torque is proposed, which takes into account the change in the tightening torque under vibration conditions and the increase in the unscrewing torque after assembly. At the second stage, studies were carried out on the effect of ultrasonic treatment on the properties of epoxy adhesive in the liquid (viscosity) and polymerized state (submicrostructure, microhardness, shear stress). At the third stage, the adhesive threaded joint was assembled with the simultaneous addition of adhesive and the application of vibrations. **Results and discussion.** The application of shear ultrasonic vibrations with an amplitude from 5 to 9 μm leads to an increase in the relative unscrewing torque by 1.5 times, which is associated with the creation of an additional force that promotes tightening and a decrease in friction, which acquires the characteristics of quasi-viscous. At the same time, ultrasound increases the uniformity of load distribution along the thread turns, which is confirmed by the absence of its deformation at a higher tightening torque. Ultrasonic treatment of the adhesive at amplitudes of 8...12 μm leads to a decrease in viscosity to 70–80 % and an increase in strength to 24 %, which is explained by the action of cavitation and acoustic flows. The assembly of an adhesive threaded joint at vibration amplitude of 9 μm combines effects that promote tightening and increase the properties of the adhesive. As a result, such a connection has a relative unscrewing torque 1.95 times greater compared to the control one.

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Introduction

In modern conditions, in order to ensure the competitiveness of mechanical engineering products strict requirements are imposed on the quality of products and increase the its manufacturability. Special attention is paid to mechanical engineering products that operate in various extreme operating conditions, in particular, in regions such as the Arctic. In these cases, the reliability of the equipment is especially important, which is largely determined by the quality of the assembly of the joints.

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One of the most common types of joints is threaded, which allows the assembly and disassembly of products without damaging it. Threaded joints make up about 70 % of all connections, which account for 25...30% of the labor intensity of assembly and 25...64 % of the labor intensity of disassembly work [1, 2]. According to various estimates, up to 15–20 % of equipment failures during operation are due to threaded joints. Accordingly, ensuring the assembly quality of threaded joints is one of the main tasks in production conditions [3, 4].

The reliability of a threaded joint is determined by the force interaction of its elements. During assembly, it is necessary to create stresses in the fasteners and jointed parts, leading to elastic and plastic deformations, to ensure the rigidity and strength of the joint, as well as to prevent its self-loosening. These stresses are determined by the tightening force of the thread, which standard values are found in accordance with [5].

During operation, stress relaxation occurs in the elements of the threaded joint under the influence of static and dynamic loads, which leads to a decrease in the pre-tightening force and loosening of the thread. This is related to one of the most common causes of failures of threaded joints [6, 7].

In order to reduce the likelihood of loosening the thread during operation, the joint is done using lock nuts, wedge lock washers, and locking washers, which provide additional grip on its support surfaces. However, these methods do not provide reliable locking under vibration and cyclic loads [8–9].

Another significant problem in the assembly of a threaded joint is the uneven distribution of forces along the turns of the thread, which is proved in [10]. Thus, more than 70 % of the load falls on the first three turns of the thread, which, with an increase in the tightening torque, can lead to thread failure on these turns [11]. In this regard, an increase in the strength of the joint is possible only by increasing the diameter of the threaded parts, and, accordingly, increasing its holes.

The scope of using threaded joints and its importance in the assembly of products determines the relevance of research aimed at improving assembly operations and the operational properties of joints.

A significant number of scientific research and design studies have been devoted to solving issues related to the assembly of threaded joints.

A number of works are aimed at improving the elements of threaded joints or adding new ones [12–16].

The patent [12] proposes a solution to reduce the bending stresses that occur in a threaded joint when the bolt head is transversely displaced due to the force at the end of the tightening device. At high loads, these stresses lead to an increased likelihood of loosening the tightening. In order to reduce stresses, it is proposed to apply an antifriction coating on the spherical surface of the washer and a friction coating on the support surface. In this case, the friction force on the bottom surface of the washer will be greater than the friction force on the spherical surface of the bolt.

The authors [13] proposed a method for redistributing the load along the turns of the thread, which implies cutting grooves in the bolt and then pressing plates of titanium nickelide into it. Next, the threaded parts are cooled to a temperature below –80 °C, which leads to superplasticity of the inserts, and assembly is done. After the temperature increases, the plates regain its elasticity, which allows the load to be distributed from the first turns to the rest.

It is proposed to place a shrink cap on all fasteners of the joint, followed by heating it to the shrinkage temperature to increase the reliability of locking [14]. An additional effect is the corrosion protection of the joint.

For the same purpose, ref. [15] proposed to place a thin-walled tube between the outer and inner threads, which deforms axially during assembly, providing resistance to thread loosening.

The study [16] indicated that the most difficult load to loosen the nut was the load directed perpendicular to the axis of the bolt. In order to increase the reliability of the joint, a lock nut design with a spring inside has been developed, which further increases the axial force.

A number of studies are devoted to the effect of ultrasonic vibrations on threaded joints titanium nickelide, which have proven itself well both during assembly and disassembly operations.

Ultrasonic vibrations of various types superposed on the threaded joints significantly reduce friction in the thread elements during assembly and disassembly operations, which reduce the likelihood of surface setting during assembly [17–19]. Ultrasound can also improve the quality of the joint by creating a greater axial force in it [20–23].

Most of the work in this field is aimed at creating ultrasonic instruments that ensure effective transmission of vibrations to a threaded element [24, 25].

Ref. [26] considers the influence of longitudinal ultrasonic vibrations on the assembly quality of threaded joints. It has been found that low-amplitude vibrations increase the reliability of tightening, while an increase in the amplitude of vibrations does not increase the torque of loosening without ultrasound. It also indicates that in the case of small tightening moments, ultrasound provides a gap, which indicates a decrease in assembly quality.

The study [27], which was also carried out with a longitudinal orientation of vibrations, shows that after reaching a certain level of the vibration amplitude (6 μm), ultrasound practically does not affect the joint reliability.

Refs. [24, 28] consider the application of ultrasonic vibrations of a different polarization — torsional and longitudinally bending. The studies showed that with torsional vibrations with an amplitude of only 1 μm applied to the joint, the torque of loosening was reduced by 2 times. The application of longitudinal bending vibrations also reduces the torque of loosening. No studies of such types of vibrations in the thread assembly have been found.

Another widely used method that prevents the loosening of the threaded joint is using polymer materials in the joint, for example [29–35]. The method consists in applying adhesive or sealant to the screw surface, which, when twisted, is distributed over the gaps between the shapes of the external and internal threads. After curing, the polymer prevents the thread from loosening under the influence of operational loads. This method suggests no lock nuts, spring and locking washers, cotter pins, or other mechanical locking elements, which facilitates and simplifies the assembly and disassembly of units, equipment, and machines.

The analysis of scientific papers identifies the following features:

– using additional threaded joint elements complicates the design of the product and increases the complexity of assembly, while the main effect is resistance to loosening without increasing axial force;

– the advantages of using ultrasonic technologies are no need to complicate the design of the joint and an opportunity to increase the axial force, while the disadvantage is the limited use due to the need to position the oscillating system coaxially with the thread, which is not always possible due to the dimensions and design of the product;

– using polymers is the easiest way to lock threaded parts, but it does not make it possible to increase the axial force.

In this regard, the purpose and objectives of the study are defined.

The aim is to develop a technology for creating an adhesive threaded joint with high performance properties, using ultrasonic vibrations in the assembly process.

In order to achieve the goal, the following tasks have been solved:

– investigating the effect of ultrasonic vibrations of shear polarization (perpendicular to the thread axis) on the parameters of the threaded joint;

– investigating the effect of ultrasonic treatment on the properties of the polymer;

– investigating the process of making a threaded joint assembled by the application of ultrasonic vibrations.

Procedure of experimental research

The experimental studies were conducted in three stages. The *first stage* evaluated the influence of shear ultrasonic vibrations on the assembly of the threaded joint. The *second stage* studied the effect of ultrasonic treatment on the properties of epoxy adhesive. In the *third stage*, the joint was assembled while adding adhesive and imposing vibrations at the same time.

The experimental results were processed using the *Statistica* program.

Superposition of shear vibrations on the assembled threaded parts

The experimental studies used an *M8* bolt-nut pair of normal accuracy with a strength class of 5.8 as specimens. The standard torque for this joint size was 24.5 Nm.

The experimental stand is shown in Fig. 1.

In order to create shear polarization vibrations, an ultrasonic rod three-half-wave oscillatory system *PMS 2.0/22* was used, consisting of a magnetostrictive transducer, a waveguide, and an emitter **1**. The oscillatory system was powered by an ultrasonic generator *UZG5-1,6/22*. A device for fixing the nut was screwed to the end of the radiator through a stud, which consists of two brackets **2** and **3** with slots for a hexagon and has the ability to adjust the size. After installing and fixing the nut, the bolt **4** was screwed into it with a wrench **5**. A dynamometer **6** was used to measure the torque, and a helical gear **7** was used to smoothly change it.

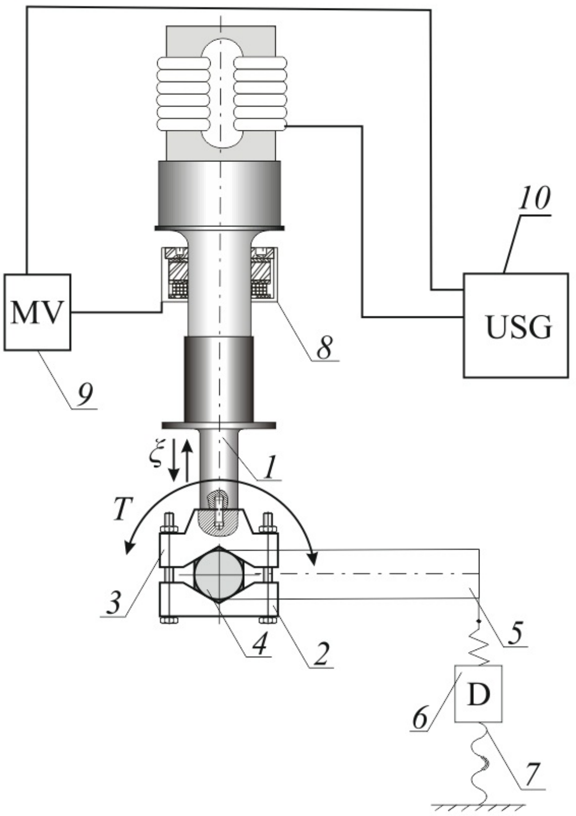


Fig. 1. Experimental stand:

1 – ultrasonic emitter; *2*, *3* – brackets of the fastening device; *4* – bolt; *5* – wrench; *6* – dynamometer; *7* – screw drive; *8* – electrodynamic sensor; *9* – millivoltmeter; *10* – ultrasonic generator

When the ultrasonic generator is turned on, vibrations are transmitted to the nut, the direction of which is perpendicular to the axis of the threaded joint.

According to this scheme, the main factor determining the nature of the thread assembly is the vibration amplitude ξ_m of the ultrasonic instrument surface, which is the end surface of the bracket.

During the experiment, the amplitude values were set according to the readings of a millivoltmeter *VZ-28B* connected to an electrodynamic sensor **8**, previously correlated with the readings of an hour-type indicator with a division price of 0.001 mm.

The amplitude varied in the range of 1 to 9 μm. This range was chosen based on preliminary experiments because after exceeding 9 μm, the joint heats up above 50 °C, which in turn significantly affects the assembly conditions and polymerization of the adhesive composition. The resonant vibration frequency was $f = 22{,}000$ Hz.

The study was carried out as follows: after tightening with a torque wrench to the standard level and checking the torque T_{close}, the vibration source was switched on. Ultrasonic vibrations decreased the tightening torque ΔT_{close}. Further, under vibration conditions, the joint was re-tightened to the standard level of T_{close}, after which the vibrations were turned off. Then the joint was disassembled and the loosening torque T_{open} was measured without imposing ultrasonic vibrations. This torque was compared with the loosening torque of the test joint obtained without ultrasonic treatment – T_{lwut}.

As a result, the effect of vibrations on the threaded joint was estimated by the relative loosening torque T_l, which was calculated using the equation:

$$T_l = \frac{T_{open}}{T_{lwut}} \times 100\ \% . \tag{1}$$

Five joints were assembled for each vibration mode.

The axial force change during tightening was estimated by measuring the roughness parameters on the bearing surface of the nut, which affects the friction force on the bearing surface and the thread turns. The measurement was carried out using a model 130 profilometer, which is based on probing the surface with a diamond needle as it moves along the measured surface and further converting its movements into a digital signal that is processed on a computer.

After disassembling the joint, the screw profile of the bolt was measured to determine possible deformations caused by an increase in the actual torque. For this purpose, the contour measuring station model 220 was used, intended to measure the geometric parameters of items of various shapes.

Ultrasonic treatment of epoxy adhesive

A two-component adhesive *EDP* was used as an experimental specimen (the base is *ED-20* resin, and the hardener is polyethylene polyamine). Before treating, the components were mixed manually in a mass ratio of 1 : 10.

Ultrasonic treatment was done by introducing an oscillatory system emitter into a container with an adhesive composition with a volume of 50 ml (Fig. 2). The adhesive was preheated to 25 °C. The vibration system and ultrasonic generator were used the same as in the previous series of experiments.

The treatment mode was set by the vibration amplitude ξ_m, which determines the intensity of ultrasonic effects in a liquid medium, and time. The resonant vibration frequency was 21,900 Hz. After sounding, a 10 ml sample was taken from the adhesive container to find the viscosity by rotational viscometry using a *Fungilab Expert L*. viscometer. During the measurement process, the software records the viscosity every second. According to the instructions, the average of 10 readings was taken as the result, if the difference between them does not exceed 3 %.

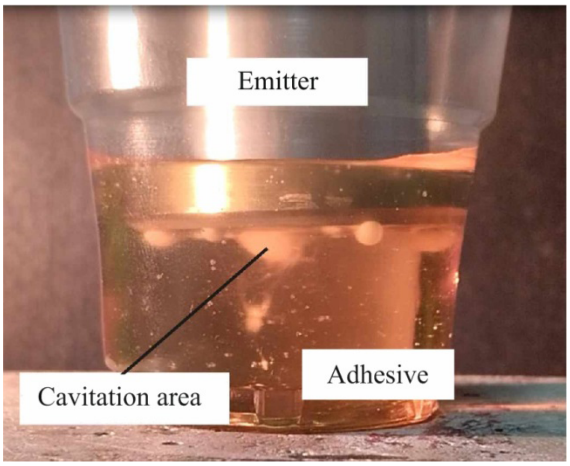


Fig. 2. Ultrasonic treatment of adhesive

Also, after processing, the heating of the adhesive was controlled using an infrared thermometer *Testo 810*.

The optimal treatment mode was chosen according to the greatest decrease in viscosity with the least heating of the adhesive.

Next, using adhesive prepared in the selected modes, 5 specimens of overlapping adhesive joint (20×20 mm) were prepared for tensile testing. The surfaces to be bonded were polished until a roughness of ***Ra*** = 0.32 μm was achieved. Thus, the results are primarily influenced by changes in the properties of the adhesive, and not by the condition of the surface. The specimens were subject to tensile tests using a universal tensile-testing machine *TCB-110M-50-0U* designed to measure the normalized force during mechanical tests while stretching or compressing specimens of structural materials.

In addition, the polymerized adhesive specimens were evaluated for submicrostructure parameters and microhardness.

The submicrostructure was evaluated using the *SMM-2000* microscope in atomic force microscopy mode by the constant height method, and the microhardness using the *PMT-3* device.

Assembly of the adhesive-threaded joint by superposing shear vibrations

As a result of the analysis of the previous stages of the study, ultrasonic treatment modes were selected that provide the greatest increase in the relative torque of loosening and improve the properties of the adhesive composition.

An adhesive in a volume of 5 ml was applied to the bolt at the future location of the nut. First, the joint was tightened to the nominal standard torque, and then ultrasound was turned on, followed by additional tightening. Five joints were assembled in this way.

The resulting specimens of threaded joints were kept for 24 hours, and then were sorted out, and the loosening moment was recorded.

Results and discussion

Effect of shear vibrations on the assembly process and the threaded joints properties

Processing the experimental results found the dependence of the change in the relative torque of loosening on the amplitude of vibrations $\boldsymbol{T_l(\xi_m)}$ (Fig. 3), where **ε** is the standard error of evaluation.

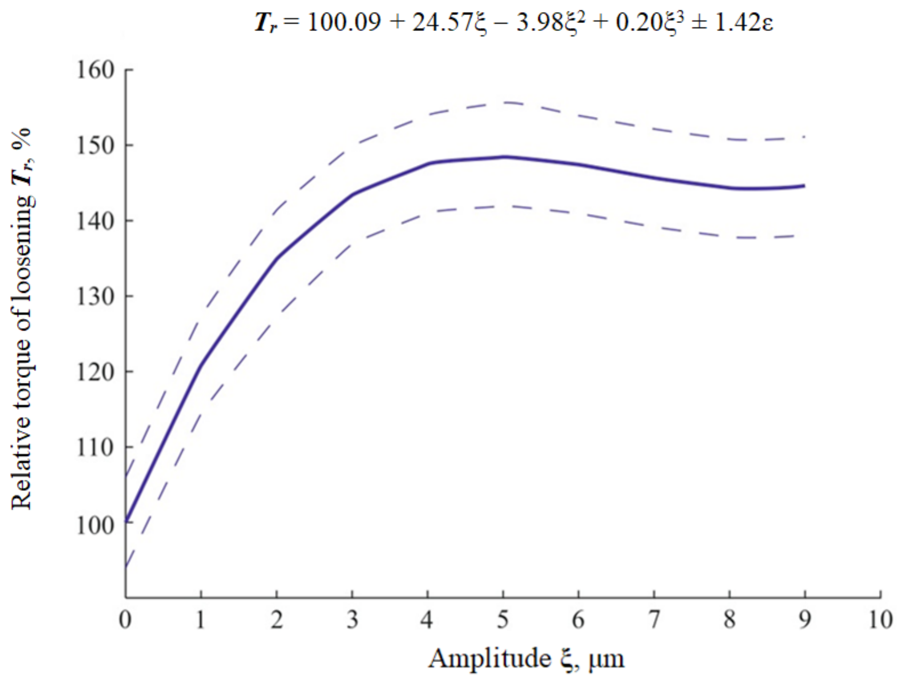


Fig. 3. Dependence of the relative unscrewing torque on the amplitude of shear ultrasonic vibrations for size *M8*

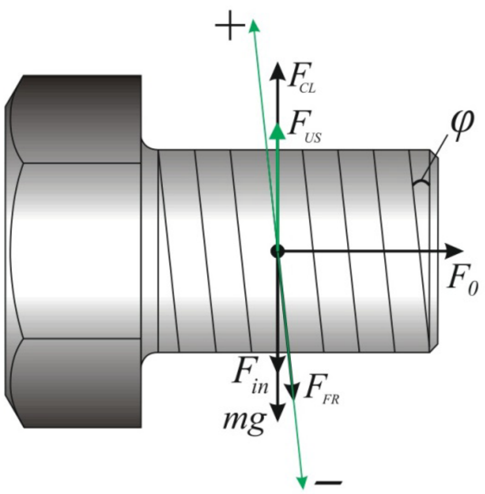


Fig. 4. Diagram of forces when shear vibrations are applied to a horizontal joint

Shear vibrations of any amplitude lead to an increase in the $\boldsymbol{T_l}$. Active growth occurs before the amplitude of $\boldsymbol{\xi_m}$ increases to 5 μm – the relative torque of loosening increases by 1.5 times. In this case, $\boldsymbol{T_{open}}$ is about 30 Nm, which exceeds the value without vibrations by 48 %. With a further increase in the amplitude above 5 μm, no significant changes occur, the increase in $\boldsymbol{T_l}$ is in the range of 1.4–1.5 times.

The increase in $\boldsymbol{T_l}$ under ultrasonic vibrations can be explained by a change in the balance of forces during assembly. When shear vibrations are applied with a horizontal arrangement of the assembled joint, the diagram of the forces acting on the joints looks as follows (Fig. 4):

The main forces acting on the joint during assembly are such forces as the wrench tightening force $\boldsymbol{F_{close}}$; the friction force $\boldsymbol{F_{fr}}$ directed in the projection in the opposite $\boldsymbol{F_{close}}$ direction; the axial force $\boldsymbol{F_0}$ directed from the bolt head; gravity ***mg***; the force excited by the movement of the joint with an ultrasonic frequency $\boldsymbol{F_{us} = F_{cos\omega t}}$, where **ω*t*** is the vibration phase (**ω = 2π*f***, where ***f*** is the vibration frequency); inertia forces $\boldsymbol{F_{in}}$. Inertia forces are understood as centrifugal force $\boldsymbol{F_{cf}}$ and *Coriolis* force $\boldsymbol{F_k}$ [36]. In this case: $\boldsymbol{F_{in} = F_{cf} + F_k}$.

According to the diagram in Fig. 4, the equation of motion has the following form (2):

$$F_{close}\cos\varphi + F\cos\omega\sin\varphi - mg\sin\varphi - F_{fr} - F_0\sin\varphi - F_{in}\cos\varphi = ma, \quad (2)$$

where φ is the angle of thread elevation.

In this case, ultrasonic vibrations lead to two effects that contribute to the tightening of the threaded joint:

1. Occurrence of an additional mechanical force F_{us} arising from the vibration of the assembled element, which increases with increasing amplitude of vibrations;

2. Reduction of the friction force under conditions of ultrasonic vibrations due to its transformation into a quasi-viscous one (this effect is described in detail in [37–39]).

The same factors can explain the absence of significant changes in the dependence of $T_l(\xi_m)$ after reaching 5 µm. This amplitude value seems to be optimal for reducing friction for these experimental conditions. A further increase in amplitude leads to an increase in F_{us} and a simultaneous increase in F_{fr}.

In addition, the factors affecting T_l will be the joint temperature, which increases due to heating with increasing amplitude of vibrations, and the friction force on the contact surface of the nut.

Temperature measurements after the assembly of the joint showed that an increase in amplitude above 9 µm leads to heating to ≈ 50 °C, which will affect the conditions of polymerization of the adhesive and at the same time will not provide an increase in T_l. Therefore, studies at high amplitudes have not been conducted.

The change in the friction force of the contact surface of the nut can be indirectly found by the amount of crushing the profile of the micro-dimensions when tightening the joint. For this purpose, roughness was measured on the support surface of a nut tightened without ultrasound and a nut tightened with imposing shear-type ultrasonic vibrations, as well as a nut before tightening. The main height and step roughness parameters are presented in Table 1; examples of profilograms obtained as a result of measurements are shown in Fig. 5.

The results showed that when assembled with ultrasound, the surface underwent deformations and changes in microrelief more heavily than when assembled without ultrasound. So, if during conventional assembly, the altitude parameters decreased by 30 %, then during assembly with ultrasound, there was

Table 1

Values of the roughness parameters of the nut bearing surface

Parameter roughness	Nut before tightening	Nut tightened without vibration	Nut tightened with vibrations
Ra, µm	0.47	0.32	0.28
Rz, µm	3.05	1.94	1.56
R_{max}, µm	5.65	3.19	2.98
S_m, µm	47.30	63.91	72.83
t_p, %	2.77	4.13	12.22

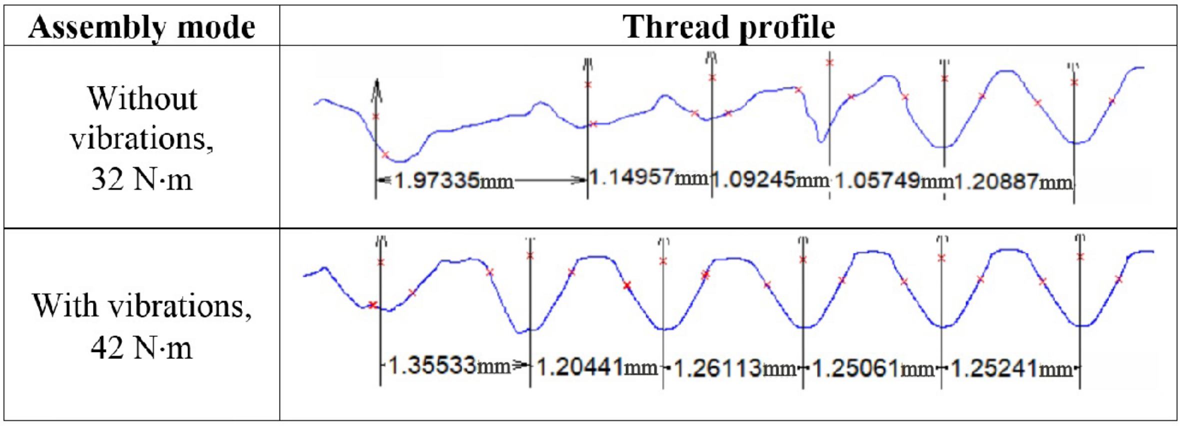


Fig. 5. Bolt thread profile after assembly with different T_{close}

a decrease of 40 %. At the same time, the step parameters increased by 35 % and 54 % for conventional assembly and assembly with ultrasound, respectively. These changes indicate an increase in the friction force on the support surface, as a result of which the loosening force becomes greater. Also, the profile crushing shows an increase in the axial force, which prevents the joint from loosening.

Studies have also been conducted on the effect of shear ultrasonic vibrations on the deformation of thread turns with an increase in torque.

To do this, the joints were assembled with a gradual increase in $\boldsymbol{T_{close}}$ from 24.5 to 27; 29.5; 32; 42 Nm. After assembly, under the influence of vibrations, the joint was disassembled without ultrasonic treatment, after which the bolt thread profile was evaluated using a contour measuring station. The vibration amplitude was 6 µm. The results obtained were compared with profiles obtained by tightening without ultrasound.

When tightening without vibration up to 24.5 Nm, the thread profile is not deformed. The first signs of exceeding the deformation limit are found at 27 Nm, while at 29.5 nm, the deformation is more pronounced. At 32 Nm, the final thread failure occurs on 2–4 turns with severe deformation of the 5^{th} turn (Fig. 5).

When ultrasonic treating at 29.5 and 32 Nm, there are no signs of deformation, and the deformation limit is shifted to 42 Nm.

This confirms an increase in the permissible T_{close} in the absence of damage to the assembled joint, and, as a result, an increase in the quality of the joint. A comparison of the change in the length of the thread turn by turns at the maximum T_{close} is shown in Fig. 6.

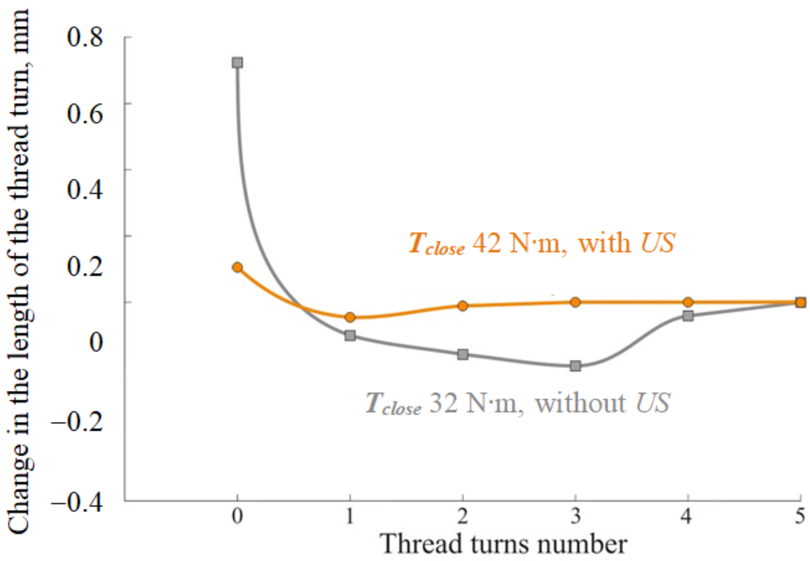


Fig. 6. Graph of the dependence of the length change of the thread turns on the number of the thread turn

This dependence shows that using ultrasound leads to increased uniformity of load distribution along the turns of the thread, which practically does not change from the 1^{st} to the 5^{th} turn, while without ultrasound, the main load is experienced by the first three turns. This makes it possible to increase the torque while significantly reducing the probability of deformation of the thread turns, which leads to an increased strength of the joint.

Effect of ultrasound on the properties of epoxy adhesive

The dependence of the viscosity change on the ultrasonic treatment mode $\boldsymbol{\eta_i/\eta_0(\xi_m, t)}$ is shown in Fig. 7. The initial viscosity before treatment was η_0 = 4,400 MPa·s.

Ultrasonic treatment at any amplitude leads to a change in the viscosity of the epoxy adhesive. At the same time, for each of the considered modes, the change occurs in three stages: the *first* is a sharp decrease in viscosity by 50–80 %; the *second* is the treatment period without significant changes; the *third* is a sharp increase in viscosity, up to levels above the initial one.

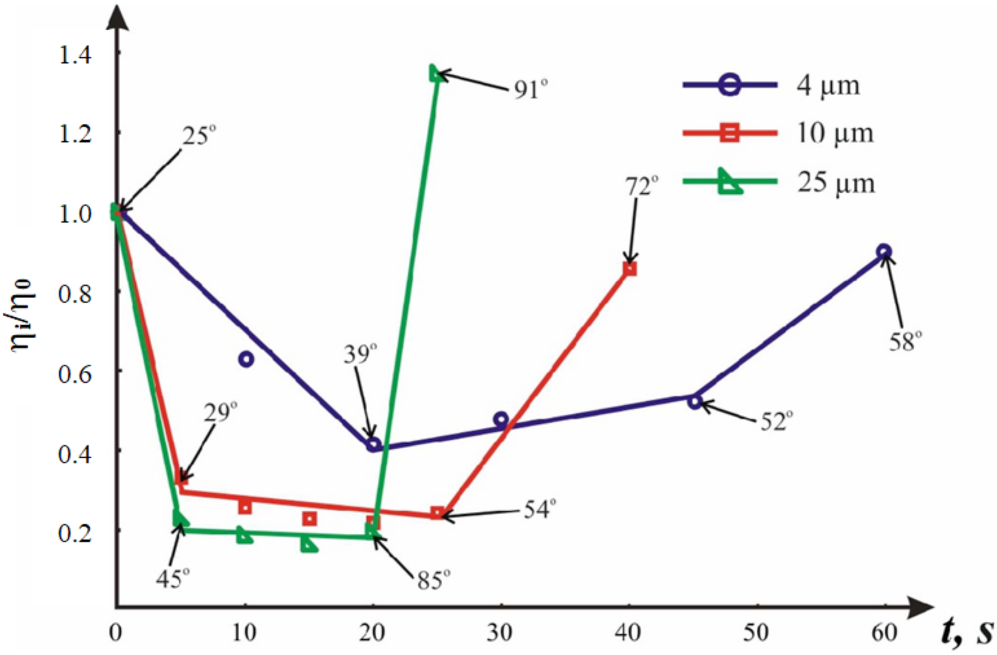


Fig. 7. Change in adhesive viscosity depending on the ultrasonic treatment mode

Such changes are associated with the effects that occur in a liquid medium when ultrasonic frequency vibrations are introduced into it.

First of all, these are cavitation and acoustic flows. Cavitation bubbles cause shock waves and cumulative jets upon collapse, which is accompanied by instantaneous pressures up to hundreds of megapascals and temperatures up to several thousand degrees [40–44]. Acoustic flows of various scales mix the treated liquid medium and transfer cavitation bubbles through it [45–47].

Under the influence of cavitation and flows, a number of secondary effects occur, among which the greatest influence on the change in viscosity is played by heating, which occurs when acoustic energy is absorbed by a liquid medium. To assess the effect of heating, the temperature of the adhesive at this moment is indicated on the graphs (Fig. 7) at the beginning and end of each stage of viscosity change. It has also been previously found that the critical heating temperature of the *EDP* adhesive, after which the polymerization reaction is sharply accelerated, is 45–50 °C.

As a result, the processing can be described as follows: after the onset of ultrasonic vibrations under the influence of cavitation and acoustic flows, macromolecules and polymer chains are destroyed and the adhesive composition is uniformly mixed, which is accompanied by slight heating. These processes occur until a certain limit state is reached, at which an almost minimum viscosity is achieved. Next, the second stage begins, in which the work of cavitation bubbles and acoustic flows is spent on additional heating of the adhesive composition. At this point, two opposite processes occur, associated with an increase in temperature – a decrease in viscosity and an acceleration of polymerization. When the acceleration of polymerization begins to prevail, the third stage begins, characterized by a sharp increase in viscosity and heat release during the exothermic reaction.

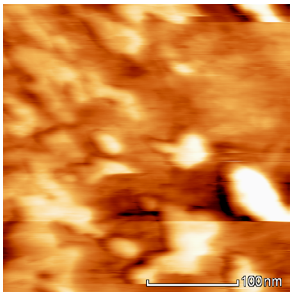
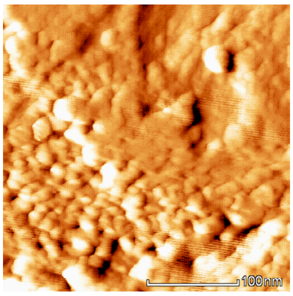
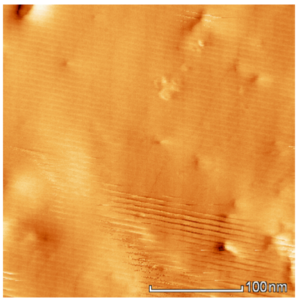
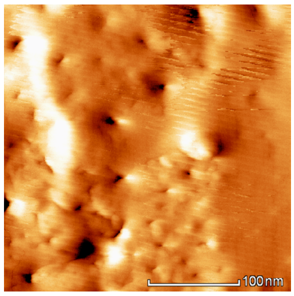
The different dynamics of dependencies are related to processing conditions. With an increase in the amplitude of vibrations, the number of cavitation bubbles increases, and acoustic flows increase, so that the three stages of viscosity change become faster.

The optimal conditions are those in which the greatest decrease in viscosity is achieved with the least heating, which corresponds to the end points of the first (beginning of the second) stage.

Further, specimens were prepared in the selected conditions to determine microhardness, analyze the submicrostructure, and test the adhesive joint for tensile strength. The results of the studies are presented in Table 2.

Table 2

Properties of adhesive under various treatment modes treatment mode

No treatment	ξ_m = 4 мкм, t = 20 с	ξ_m = 10 мкм, t = 5 с	ξ_m = 25 мкм, t = 5 с
Surface image 308×308 nm (constant height method)			
			
Average height of profile irregularities at the submicrolevel Ra_c, nm			
2.63	1.67	0.98	1.35
Microhardness, kg/mm^3			
0.77	0.75	1.01	0.92
Shear stress τ, MPa			
5.5	5.1	6.8	6.2

Changes in the submicrostructure characterize the adhesive polymerization process. A decreased height of the profile irregularities indicates that the polymer chain formation process is uniform and the chains further grow after ultrasonic treatment. The treatment conditions of 10 and 25 µm resulted in the greatest smoothing of the submicrostructure by 2.7 and 1.92 times, respectively. In these processing conditions, a sufficient number of cavitation bubbles are formed and stable large-scale acoustic flows arise, which are necessary for uniform processing of the entire adhesive volume. The large height of the irregularities obtained at 25 µm is associated with heating the adhesive to a temperature of 45 °C, which accelerates the polymerization process. Low-amplitude processing ξ_m = 4 µm occurs with a significantly smaller volume of the cavitation region localized under the radiator, and the absence of large-scale flows does not allow bubbles to spread rapidly through the treated volume. As a result, ultrasound does not process the entire volume of adhesive, which is illustrated in the image of the submicrostructure, with a clear boundary between the treated and untreated parts of the adhesive. This leads to anisotropy of the properties of the hardened polymer.

Changes in microhardness and shear stress correlate with changes in the polymer structure. The maximum results were achieved when processing at an amplitude of 10 µm for 5 seconds. Microhardness increases by 30 %, while shear stress by 24 % during stretching.

Effect of ultrasonic vibrations on the assembly of a threaded joint

The analysis of these studies makes it possible to find the optimal mode of ultrasonic treatment during the assembly of a threaded joint.

When shear vibrations are communicated, the maximum increase in the relative torque of loosening $\boldsymbol{T_l}$ is achieved in the conditions of ξ_m = 5–9 µm.

The best results in ultrasonic treatment of epoxy adhesive were achieved at an amplitude of ξ_m = 10 µm.

As a result, vibration amplitude of 9 µm was selected for the assembly of the adhesive-threaded joint, at which the threaded parts do not heat up above 50 °C, and which, according to the effects occurring in a liquid medium, corresponds to a transient processing mode (8–12 µm).

The assembly was done according to the scheme in Fig. 1 with 5 ml of adhesive applied to the bolt thread. First, tightening to the nominal torque was done, then vibrations were turned on and additional tightening was done. The ultrasound was turned off after 5 seconds after re-tightening.

A comparative diagram of the T_{open} depending on the assembly conditions is shown in Fig. 8.

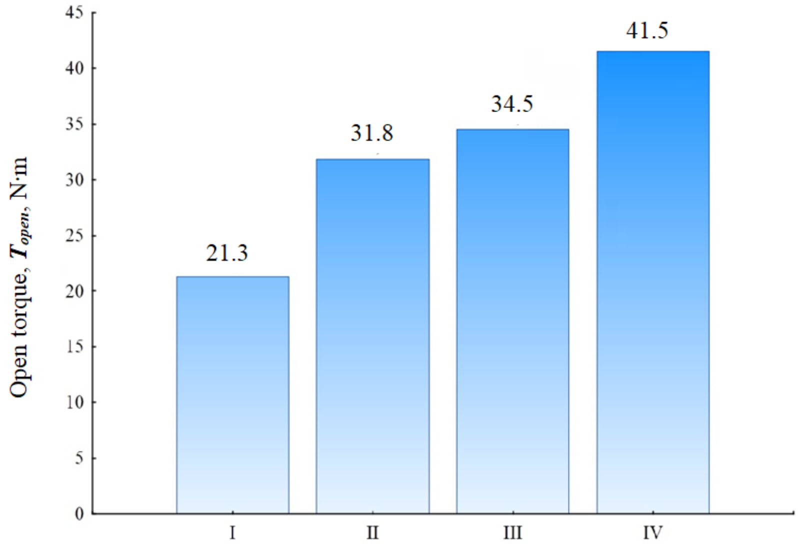


Fig. 8. Diagram of the dependence of the unscrewing torque on the assembly method:

I – assembly without ultrasonics and adhesive; **II** – assembly with ultrasonics without adhesive; **III** – assembly without ultrasonics with adhesive; **IV** – assembly with ultrasonics and adhesive

According to method **III**, adding a liquid medium reduces the friction force, which leads to an increase in the actual torque compared to **I**. After tightening, the adhesive fills the gaps in the joint area of the bolt and nut and polymerizes, creating a strong threaded joint. At the same time, a significant increase in the loosening torque compared to **I** is provided to a greater extent due to the forces of molecular adhesion of the polymer to the parts. That is, this method, compared with **II**, has a greater resistance to loosening, but at the same time creates a lower axial force, which ensures that the location of the parts joined by the thread is preserved. With an increase in the torque, the deformation of the thread turns begins, as in **I** with 32 Nm. The proposed assembly method **IV** combines the advantages of ultrasonic action both to increase the torque and uniform stress distribution along the turns of the thread, and to increase the properties of the epoxy adhesive. As a result, this method allows creating the greatest axial force while simultaneously creating the maximum loosening torque.

Conclusions

The completed theoretical and experimental studies have allowed obtaining the following results:

1. A scheme for applying ultrasonic vibrations perpendicular to the thread axis to a threaded joint has been developed;

2. Imposing shear ultrasonic vibrations during the assembly of the threaded joint creates an additional force that promotes tightening and leads to a decreased friction force, which ensures an increase in the relative loosening torque;

3. The maximum efficiency is achieved with a vibration amplitude of 5 to 9 µm. The relative loosening torque increases by 1.5 times;

4. A comparative analysis of the thread profile after disassembling the test joint and with vibrations shows the uniformity of load distribution along the turns of the threaded part with a higher torque;

5. Ultrasonic treatment of epoxy adhesive leads to a decrease in viscosity and a change in its structure after polymerization.

6. The optimal treatment mode is vibration amplitude of 10 μm, at which the viscosity decreases by 70 % with slight heating of the mixture, and the shear strength increases by 24 %.

7. The vibration amplitude of 9 μm during the assembly of the adhesive-threaded joint allows combining ultrasonic effects that lead to a maximum increase in the relative torque of loosening and provide the greatest increase in the properties of the epoxy adhesive;

8. The adhesive-threaded joint assembled according to the proposed method has a relative loosening moment 1.95 times greater than that of the test joint;

9. The proposed assembly method is intended for highly loaded threaded joints operating under conditions of vibrations and cyclic loads. Also, this method allows increasing the axial force by increasing the torque without damaging the thread elements and using larger diameter threads.

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Conflicts of Interest

The authors declare no conflict of interest.