Improvement of operational properties of parts permanent joints with ultrasound technologies use

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Abstract. The authors consider the improvement of producing permanent joints technology issue due to ultrasonic vibrations use. As a result of main problems the analysis which arising during the permanent joints performance, and effects that occur in liquid and solid bodies under the ultrasound action, options were proposed for using ultrasonic vibrations in technologies for producing welded, riveted, adhesive and press joints. The complex of experimental studies was carried out, which showed using vibrations effectiveness in considered permanent joints. Ultrasonic technology use allows improving obtained joints performance properties and intensifying the processes that ensure assembly quality.

1. Introduction
The permanent joints of machine parts are those the disassembly of which is possible only with parts to be joined destruction or material that was used to connect them. Such connections are welded, brazed, riveted, glue, and press joints. [1-3]. Permanent joints play a crucial role in mechanisms operation ensuring and make up 50-60% of all connections. Their main advantages are:
- obtaining products possibility with complex geometric shape from simple elements;
- tight and durable connections performance without the additional sealing means use;
- low metal consumption, which reduces structure weight;
- enabling assembly operations wide automation;
- relatively low labor input;
- relatively low product cost.

The main disadvantage is obviously impossibility of connection disassembling without damaging the constituent elements [4, 5].

In product repair cases associated with permanent joint breakage, it is necessary to replace the entire joint (rivet, pressing), or joint restore by welding, soldering and gluing (if only material used for the joint is damaged). Consequently, repair time and cost increase. Thus, the working efficiency and maintainability of machine components and mechanisms depend on permanent parts joints performance quality. One of the ways to the improvement of permanent joints quality is ultrasonic technologies use.

2. Research purpose
The purpose of the research is to improve performance properties of the considered permanent joints by technology improvement of their implementation through the use ultrasonic vibrations. This requires
relationships establishment between the effects arising from ultrasonic vibrations imposition in the joints obtaining process, and output parameters characterizing assembly quality and joints properties. Moreover, for each type of joint, it is necessary to choose the optimal type of ultrasonic treatment, the moment of its application and the parameters that determine the joint quality.

Effects arising from the ultrasonic vibrations action

With ultrasonic vibrations introduction in a liquid medium as a result of the discontinuities formation in liquid continuity and subsequent collapse of these cavities, accompanied by intense shocks, cavitation occurs [6, 7]. At high oscillations amplitudes of the oscillatory system end \( \xi_m > 12 \mu m \) (for water), as an energy redistribution result spent on cavitation formation and maintenance, large-scale acoustic flows are formed, which ensure cavitation bubbles transfer through the volume being voiced [8-10]. These mechanical nature primary effects generate a series of secondary effects: heating, mixing, dispersing, coagulating, degassing, chemical reactions accelerating, viscosity changing, polymerizing / depolymerizing, and others [11-14].

The main parameters regulation that determine the ultrasonic treatment mode (amplitude and oscillations frequency, processing time) allows desired effects targeted action depending on the treatment purpose and liquid medium type being treated.

During solids ultrasonic treatment, when the oscillations propagation direction is oriented normally to the surface being treated, surface plastic deformation is performed. Hardening degree and depth are determined by oscillations amplitude, pressing force and type of indenter (connected or free) [15-18]. When ultrasonic frequency oscillations are transmitted parallel to the friction force direction acting in the joint, lubricant presence effect, occurs between the contact surfaces, that is, dry friction is converted to quasi-viscous. This effect underlies the ultrasonic disassembly process [19, 20].

The main problems of making permanent joints technologies

In welding, the main problems are residual stresses, weld porosity and welding deformations. The main causes of stress and deformations are: uneven heating, weld metal shrinkage, metal structural transformations [21-23]. In riveting, the main drawback is high force required to form the joint, as a result of which the residual compressive stresses are distributed unevenly across the package thickness being joined. [24, 25]. The main difficulties in obtaining glued joints are high glue viscosity and joint holding under a certain load to ensure the most complete filling bonded surfaces asperities with glue composition, as well as holding at a certain temperature to create optimal polymerization conditions [26-28]. In assembling press joints, it is required to create large pressing forces, depending on guaranteed tension size, which also increases surface damage likelihood for the parts being joined [29, 30].

As an ultrasound effects analysis result and the main problems for obtaining permanent joints, studies were conducted in the following areas (Table 1). In each case, research is aimed at permanent joint strength increasing, which will increase product reliability and performance properties as a whole.

| Joint type | Ultrasound application | Expected effect |
|------------|------------------------|-----------------|
| Welding    | Vibrations imposition on the welded structure elements | Reduced weld porosity; Welding deformations reduction |
| Riveting   | Rivet deformation under the shock action | Reduced assembly effort; Uniform rivet deformation |
| Glued      | Glue composition preparation | Increased adhesion between glue layer and bonding surface |
|            | Oscillation impact to the glued elements | |
| Press      | Oscillations impact to internal member parts | Reduced assembly effort; Reducing surfaces damage likelihood for assembled parts |

3. Research methods
The studies were carried out using a rod magnetostrictive oscillatory system fed from an UZG 2/22 generator. During the experiment, we measured the main acoustic-technological parameters that determine processing mode:

- transducer end face oscillation amplitude $\xi_m$ according to oscillatory system preliminary calibration with using a dial gauge and millivoltmeter;
- oscillation frequency $f$ (according to frequency meter connected to generator),
- time of processing $t$.

Joints obtained properties were determined by standard methods: tensile and shear tests on UTS-110M-50-U machine, studies on metallographic and multiscan microscopes.

To obtain the considered permanent joints using ultrasound, various experimental schemes were used.

To impose vibrations during welding, the following scheme was used (Figure 1): an oscillatory system consisting of a magnetostrictive transducer and waveguide was connected to one of the welded plates (320x90mm) through a stud pin (Plate material - St 3).

In order to create acoustic contact between the plates, they were welded using a semi-automatic welding machine with a 20 mm butt-jointed seam.

As a result of this design implementation in the transducer (plates), longitudinal and bending waves are simultaneously excited, interacting with each other.

To fix the plates being welded during welding process, special supports were installed with a vibration absorbing material stuck on them.

![Figure 1](image_url)  
**Figure 1.** Experimental setup schematic diagram: 1 - plates, 2 - oscillatory system, 3 - rails, 4 - acoustically impermeable material, 5 - cooling system wires, 6 - generator, 7 - welding tractor

Plate oscillations amplitude distribution in the weld zone and near-weld zone is symmetrical with respect to the oscillation supply place. In the near-weld zone, the amplitude values have a larger scatter (from 3 to 7 $\mu$m) as compared to the weld zone (from 3 to 5 $\mu$m).

The plates were welded in the following mode: $I = 275$ А, $U = 48$ V, $V = 0,26$ cm/min. The generator was turned off 5 minutes after welding end. Next, from the welded plates according to State Standard 9466-75 were cut samples for testing in order to obtain riveted joints as samples of the connection of steel plates with a thickness of 4 mm and a width of 30 mm. In the part of the plates, the holes were countersunk to a depth corresponding to the height of the rivet primary head. The material of rivet is D16.

A hole with a chamfer is formed in the package of parts to be joined, into which a rivet with a primary head is installed. The closing head shaping takes place by the ultrasonic tool blows, at the end of which the crimping is performed, under the semi-stringent sinkage conditions (Figure 2). Clamping force was $F=500$ N.
Figure 2. Riveted joint formation scheme (P - pressing force; ξ - oscillations amplitude): 1 - ultrasonic transducer; 2 – profiled crimping; 3 – rivet; 4 – clamp; 5 - connected parts package; 6 – fixed stop

For glue joint control which obtained under the ultrasonic vibrations conditions, a special device was used - an adhesive tester (Figure 3).

Device is based on principle of nozzle detachment force measuring, which is glued to the surface [24]. Separation force is created by a turning mechanism consisting of a screw-nut pair, cocking the spring mechanism associated with the cap. Separation specific effort value is determined by the body upper face position relative to the scale, corresponding to the nozzle number.

Plate surface and nozzle glued to it were ground to a roughness of Ra=5 μm. Next, the glued surfaces were degreased. A two-component epoxy adhesive with a full polymerization time of 12 h was used as the glue [23]. Moreover, a component mixing was also carried out with vibrations introduction.

During the gluing process to the nozzle, the ultrasonic transducer end was pressed with a force F=100 N. Oscillation amplitude was ξm= 10 μm. Processing was carried out for t=10 s.

A pairs of needle and injection nozzle bodies of the KAMAZ-740 engine, made of 18X2H4MA chromium-nickel steel, grouped in such a way as to obtain a certain tension amount, were used as press joints samples. As a result, several pairs of parts have been selected, the dimensions of which provide a tightness of 4, 6 and 17 microns.

Design model with the forces acting in the pressing process is shown in Figure 4.
Figure 4. Forces acting in the pressing process

Movement condition for internal member part:

\[ F_{us} + (M + m)g > F_{fr} \]  

where \( F_{us} \) – the force created by ultrasonic vibrations,  
\( M \) and \( m \) – oscillatory system and internal member part masses.

The force created by ultrasonic vibrations has a complex effect on the pressing process. First of all, it is the mechanical component responsible for the force transmitted magnitude to the part, and secondly it is friction force reduction at high speed and high frequency of relative displacements. In this case, the friction force is not constant in the oscillation mode and tension magnitude.

4. Results and discussion

For welds tensile testing, samples were selected where the oscillations amplitude in the weld zones was 3, 5 and 7 \( \mu \)m, as well as a control sample obtained without vibrations imposition. The results are shown in Table 2.

| \( \xi_{\text{us}}, \mu \text{m} \) | 0 | 3 | 5 | 7 |
|---|---|---|---|---|
| \( \sigma, \text{MPa} \) | 340 | 377 | 406 | 415 |

Giving oscillations to welded elements leads to an increase in temporal resistance \( \sigma_t \), and this effect increases with an increase in the oscillations amplitude. This phenomenon is explained by the following mechanisms:

- with oscillations increase, the air release process from the molten metal is accelerated, as a result of which the cross-sectional area increases;
- plate oscillation contributes to a more molten metal uniform distribution in the weld pool;
- deflection structure reduction.

Degassing process acceleration is also confirmed by analyzing the sintered flux skin (Figure 5).

Figure 5. Flux skin: a – without ultrasound, b – when applying vibrations
The flux skin formed when vibrations are applied to the plates has a significantly smaller number of pores. This indicates the air exit acceleration from the weld pool under the ultrasound action, which also leads to decrease in weld porosity itself.

Thus, ultrasonic vibrations imposition on the welded elements leads to an increase in joint strength and reduces residual deformations.

During the rivet joints testing for cutting, it was established that with riveting ultrasonic shock method, joint stress on cutting increased from 1600 ... 1650 N / m to 2000 ... 2100 N / m, which is 12 ... 13%.

In addition to the change in shear stress on test chart in force-displacement coordinates, a noticeable decrease in mutual joint elements displacement before failure was noted. Since the rivet begins to work on cut only after mating parts shifting by radial gap amount between the rivet core and the whole walls, displacement reducing with ultrasonic method shows a larger hole filling with the rivet material.

The study of parts bonding strength using an adhesion tester showed that when using ultrasonic vibrations, the separation force was 7 MPa, while without the use of ultrasound - 5 MPa. This is due to a number of factors: glue viscosity decrease with glue components mixing ultrasonic method, a more complete asperities filling of glued surfaces as a result of sound-capillary effect, as well as an processes acceleration of glue setting and polymerization as a result of mechanical heating under the vibrations influence during the gluing process.

For ultrasound effectiveness assess during press joints assembly, we compared the pressing depth values using the calculated parameters $\Delta L_{calc}$ – without taking into account the quasi-viscous friction effect appearance and the depth obtained as a experiments result, $\Delta L_{exp}$, obtained as a experiment result.

$$\Delta L_{calc} = \frac{m l m (2\pi f)^2 (C_D C_d)}{N \eta_{dry}}$$

(2)

where $C_D = \frac{1 + (d_1/d_2)^2}{1 - (d_1/d_2)^2} + \mu_D$ and

$C_d = \frac{1 + (d_1/d_2)^2}{1 - (d_1/d_2)^2} + \mu_d$ – dimensionless coefficients taking into account: $d_1$ – hollow shaft hole diameter (in our case $d_1=0$), $d_2$ – external member part outer surface diameter, $\mu_d$ and $\mu_D$ – Poisson ratios for materials covered and external member part, $N$ – interference, $E_d$ and $E_D$ – covered and external member part materials elastic modulus, $\eta_{dry}$ – dry friction coefficient (for 18X2H4MA is equal to 0,18).

As a result of the comparison, friction coefficient value is obtained, which takes into account the quasi-viscous effect, depending on oscillations amplitude:

$$\eta_{qu} = \eta_{dry} \frac{\Delta L_{calc}}{\Delta L_{exp}}$$

(3)

The results are presented in graph (Figure 6).

![Graph](image.png)

**Figure 6.** Dependence of quasi-viscous friction coefficient $\eta_{qu}$ from the ultrasonic treatment mode for joints with tension: 4,6 and 17 microns
When applying any amplitude ultrasonic vibrations, friction coefficient when vibrations are reported
\( \eta_{qu} \) be lower than dry \( \eta_{dry} = 0.18 \). In this case, regularities arise due to oscillations mode and required interference magnitude.

Thus, with a small tension (\( N = 4 \, \mu m \)), friction coefficient increases with increasing amplitude, and with an average (\( N = 6 \, \mu m \)) and, especially, a large tension (\( N = 17 \, \mu m \)) decreases. Thus, for small tensioners with an increase in ultrasonic vibrations amplitude, ultrasonic action mechanical component begins to predominate: transmitted large accelerations effect increases relative to friction coefficient reducing effect. With an increase in tension, an increase in oscillations amplitude leads to the opposite — friction into quasi-viscous effect begins to prevail.

5. Conclusion
1. As a result of complex conducted studies, ultrasonic technologies use effectiveness in obtaining permanent joints processes is shown.
2. Ultrasound use during the weld formation leads to weld strength increase to values close to base metal strength, which causes loads uniform distribution in welded joint and increases its carrying capacity.
3. Ultrasonic shock use during the riveted joint formation ensures an even distribution of residual compressive stresses over the entire thickness package being joined. This reduces riveted joints formation force, which, in turn, increases riveting use for joining materials with different strengths (for example, Plexiglas and steel joints).
4. Bonding parts technology with glue composition pre-treatment and vibrations transmission to parts to be glued provides an increase in adhesion up to 30%. Also, ultrasound use gives a number of effects that provide gluing process intensification.
5. Ultrasonic frequency oscillations use allows intensifying press joints assembling process. Applying ultrasonic vibrations effectiveness to internal member part is determined by possibility of transmitting significant accelerations, as well as converting dry friction into quasi-viscous effect.

The main direction for the improvement of obtaining permanent joints technology is to increase their operational properties. This task solution will allow increasing units and mechanisms machines reliability; increasing the products service life. One of the ways to solve this problem is ultrasound technology use. Ultrasound effectiveness is due to emergence several specific effects, which, depending on application, allow the joints mechanical properties being improved and to intensify existing technological processes.

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