Theoretical foundations for modeling the occurrence of attached, vortex and vibration cavitation during heat treatment of machine parts in a cavitating coolant

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Abstract. The effect of cavitation can increase the efficiency of the stability of the cooling process of machine parts during their heat treatment. The article defines the geometric parameters of the installation for carrying out the process of heat treatment of machine parts, as well as the external influence necessary for the appearance of the effect of vortex cavitation in the full volume of the liquid technological medium.

The existing methods of heat treatment of machine parts do not fully ensure its required stability and high efficiency.

A significant effect on the properties of the ordered alloy is exerted by the rate of its cooling from the high-temperature state, which is necessary to suppress the diffusion decomposition of austenite with the formation of a ferrite-cementite mixture and to provide the possibility of overcooling austenite and its transformation into martensite. The critical rate of hardening decreases most strongly with the simultaneous introduction of several alloying elements [1].

Heat treatment of low-carbon and high-alloy alloys, welded joints of cutting tools, side surfaces of gear wheels, etc. in some cases it requires high stability and maximum cooling rate of the part.

To increase the cooling rate, salts, caustic soda and other substances are added to water-based technological media that require additional measures to comply with labor protection and environmental safety conditions.

The achievement of the required cooling rate depends not so much on the grade of the alloy, but also on the geometric dimensions (wall thickness) and the shape of the parts or workpieces. In the works of L.M. Shevelev, G.L. Shneider, Yu.V. Shchelbanin, G.G. Shadrin, V.M. Bryksin it is shown that it is possible to exceed the critical quenching rate of alloy D16T (550 °C/s) during cooling in cold water over the entire section only at a thickness of up to 10 mm or a larger diameter of hollow bodies of axisymmetric shape, which promotes rapid heat removal.

Heat treatment of the cutting tool weld does not provide its required strength due to the fact that the zone of complete decarburization of structural steel, formed during annealing of the workpiece, is not eliminated. At the same time, the low intensity of the process of redistribution of carbon in the weld leads to an increase in the heating duration, which reduces the labor productivity in the manufacture of the tool, and also promotes the formation of cracks during hardening, and as a consequence of the
decrease in the wear resistance of the tool made of high-speed steels with cobalt and molybdenum, which are especially sensitive to decarburization [2].

In order to increase the productivity and quality of processing by eliminating the decarburization of the welded seam, A.V. Ivanaiskiy proposed to perform final cooling during hardening of the cutting tool in a liquid medium with the imposition of vibration in the mode of its cavitation.

Ultrasonic and vibration action on liquid media has a significant effect on the results of heat treatment, contributing in most cases to obtaining effects that are unattainable under normal conditions without the use of ultrasonic treatment. F.B. Pickering, S.A. Golovanenko, Yu.I. Matrosov, S.S. Gorelik made a great contribution to the study of the effect of the cooling rate on the properties of parts and increasing the stability of processing results.

At the same time, the use of ultrasound is associated with high energy costs and the complexity of technological equipment. In addition, the efficiency of using ultrasonic devices to increase the cooling rate of machine parts decreases with an increase in the coolant temperature due to changes in the magnetostrictive properties of the emitter. Therefore, despite a number of positive effects that are achieved with this processing of alloys, this method has not found wide application in the heat treatment of machine parts. The study of L. D. Rosenberg is devoted to the problems of the efficiency of using ultrasonic devices to increase the cooling rate of machine parts.

According to S. Sow's research, the activation of the dynamic parameters of liquid media based on the effect of the cavitation effect is possible due to the following hydrodynamic processes:

- high-energy flows of cavitation cavities;
- formation of turbulent zones in the flow behind the moving cavity;
- the occurrence of intense disturbance waves, with the pulsation of steam-gas caverns;
- kinetic action of cumulative microstructures arising in the final stage of collapse of the cavity [3].

Effective use of heat treatment of machine parts with the use of the effect of attached, vortex or vibration cavitation is possible when the effect under consideration is obtained in the entire volume of the working fluid [4].

For this purpose, the design of the device has been developed, consisting of a body filled with liquid and activators of cavitation action, performing rotational motion in opposite directions. The scheme of a technological installation for cooling machine parts using the effect of vortex or attached cavitation is shown in figure 1.

![Diagram of a device for cooling machine parts during their heat treatment.](image-url)
Let us determine the parameters of external influence to ensure the appearance of the effect of associated cavitation. Based on the performed transformations of the Stokes differential equation and in accordance with the design scheme shown in figure 2, the condition for the appearance of the effect of added cavitation in a liquid region bounded by radius \( r \) around a rotating body with radius \( a \) has the form:

\[
P_{st} > \frac{\rho}{(R^2 - a^2)^2} \left\{ \frac{(RV_n - \omega_a a)^2}{2} (r^2 - a^2) + 2aR(\omega_a R - v_n a) \right\} \\
(RV_n - \omega_a a) \ln \frac{r}{a} - \frac{R(\omega_a R - v_n a)^2}{2}(1 - \frac{r^2}{R^2})
\]

where: \( P_{st} \) is the saturated vapor pressure of the base liquid; \( a \) - the radius of the rotor; \( R \) is the radius of the inner surface of the device body; \( v_n \) - speed of movement of the medium on the inner surface of the device body; \( n \) is the rotor speed at which the added cavitation effect develops in the volume of the device [5].

Figure 2. Design scheme. The section of the device is perpendicular to the rotor axis.

The condition for the formation of an extensive vapor-gas region around the surface of a rotating body, i.e. the condition under which the liquid is capable of transmitting maximum energy through its own viscous friction can be determined as follows, where \( P_a \) is the atmospheric pressure:

\[
n > \frac{P_a}{16\mu R^2 r^2}
\]

If the rotor in the receipt machine is wheels with blades, the following numerical simulation of vortex cavitation is valid for them. In order to simplify the mathematical formulation of the problem of fluid motion in a closed cylindrical vessel caused by a stirrer, we will assume that the stream function satisfies the biharmonic equation in polar coordinates

\[
(\Delta \Delta \psi(r, \varphi)) = 0
\]

Then the radial and angular velocities of the liquid particles are found by the formulas:
\[ v_r (r, \varphi) = \frac{1}{r} \frac{\partial \psi (r, \varphi)}{\partial \varphi}, \quad v_\varphi (r, \varphi) = -\frac{\partial \psi (r, \varphi)}{\partial r} \]  \tag{3}

Let us designate \( 2n \) as the number of sectors into which the agitator blades divide the circle, and we will look for the stream function in the following form:

\[ \psi (r, \varphi) = Ar^2 + B \ln r + \sum_{k=2}^{\infty} \left( A_k r^{k} + B_k r^{k+\frac{1}{2}} + C_k r^{-k} + D_k r^{-k+\frac{1}{2}} \right) \sin 2kn\varphi \]  \tag{4}

Let’s construct a rapidly decaying local part of the solution. Let’s assume that the speed:

\[ v_\varphi (R_1, \varphi) = f (\varphi), \quad \left( |\varphi| \leq \frac{\pi}{2n} \right) \]  \tag{5}

Speeds here will be discontinuous. Analysis shows that it is along the directions of multiples of \( \varphi = \frac{\pi}{2n} \) that the perturbations of radial velocities propagate most deeply, forming a narrow zone of the boundary layer.

Thus, solution \( f (\varphi) \), as the determination of the threshold for the development of cavitation, is defined as:

\[ f (\varphi) = dV \frac{2n}{\pi} \left\{ |\varphi| - \frac{\pi^2}{2} \left( \frac{\pi}{2n} - |\varphi| \right) \right\} \]  \tag{6}

where: \( d \) is a certain coefficient, measured in fractions of \( V \) so that the maximum value of the speed at the end of the blade is \( d \) \[6\].

To solve certain problems in the field of heat treatment, it is necessary to ensure the appearance of the effect of vibration cavitation, which, in particular, helps to reduce the size of austenite grains.

Let us determine the parameters of external influence to ensure the occurrence of the effect of vibration cavitation.

The cavitation process is unsteady and is accompanied by strong pulsations, and when the frequency of one of the pulsating components coincides with the natural frequency of the part, its vibration occurs. The frequency of cavitation vibration is 5-10 times higher than that of the low frequency vibration drive.

The oscillation amplitude for the threshold velocity at different frequencies was determined from the relation:

\[ V = 2 \pi f A \]  \tag{7}

where: \( \pi = 3.14; f \) – vibration frequency; \( A \) – vibration amplitude.

When calculating the height of the column of the cavitating liquid, let us assume that the energy absorption in the layer is proportional to the amount supplied to this layer and its thickness.

\[ dJ = -\alpha J dx \]  \tag{8}

from here:

\[ J = Cl^{-\alpha} \]  \tag{9}

where: \( \alpha \) - коэффициент поглощения звука в вязкой среде равен:

\[ \alpha = \frac{\omega^2}{2\rho \cdot c^3} \left( \frac{4}{3} \eta + \xi \right) \]  \tag{10}

where: \( \rho \) - density of the medium, kg/m\(^3\); \( c \) – speed of sound in the medium, m/s; \( \omega \) - circular frequency, s\(^{-1}\); \( \eta \) - kinematic viscosity, m\(^2\)/s; \( \xi \) - bulk viscosity, m\(^{-1}\).
Let us select on the wave distribution line section 1 and 2 at a distance $X_1$ and $X_2$ from the source of oscillations.

For these sections we have:

\[ J_1 = CI^{-\alpha X_1} \]  
\[ J_2 = CI^{-\alpha X_2} \]  
\[ J_1 = CI^{-\alpha X_1} \]  
\[ J_2 = CI^{-\alpha X_2} \]  
\[ \frac{J_2}{J_1} = l^{-\alpha (X_2-X_1)} \]  

(11)  
(12)  
(13)  
(14)  
(15)

It is known that the vibration energy is proportional to the square of the amplitude, therefore:

\[ \left( \frac{z_2}{z_1} \right)^2 = l^{-\alpha (X_2-X_1)} \]  

where: $z_1$ and $z_2$ vibration amplitudes in the liquid at a distance $X_1$ and $X_2$ from the bottom of the tank. Or:

\[ \left( \frac{z_2}{z_1} \right)^2 = l^{-\alpha (X_2-X_1)} \]  

(16)  
(17)

substitute 1.4, get:

\[ \left( \frac{z_2}{z_1} \right)^2 = l^{-\alpha / 2 (X_2-X_1)} \]  
\[ \left( \frac{z_2}{z_1} \right)^2 = l^{-\alpha / 2 \rho c (\frac{4}{3} \rho + \gamma) (X_2-X_1)} \]  

(18)

According to the formula (18), it is possible to determine the amplitude of oscillations at any distance from the body of the device or container.

In the case when the vibration amplitude is less than its threshold value $V$, product $\omega \cdot z$ will be $\approx 0.25$ m/s, then the vibration cavitation process does not proceed at this height. Then an increase in the amplitude of oscillations will be required, which would provide the cavitation mode in the liquid at the design height.

**Figure 3.** Graph for determining the "threshold" values of the oscillation parameters.
One of the promising directions for using the cavitation effect for cooling is the production of alloys with an amorphous structure. The technology for producing alloys with a crystal structure is associated with the antagonism of the properties of the components at the crystallization stage. At the same time, during ultrafast cooling, the amorphous alloy solidifies before the antagonist components have time to show their properties. Amorphous ferromagnetic alloys based on iron, nickel and cobalt, which have high hardness, wear resistance and corrosion resistance, are of practical importance.

At present, the impossibility of carrying out the process of rapid cooling of alloys makes it possible to produce amorphous materials in the form of ribbons less than 40 μm thick [7].

Stabilization of the cooling rate during heat treatment of machine parts due to the cavitation effect is based on the following hydrodynamic processes:

- creation of unsteady vortex flows of high intensity;
- an increase in the throughput of capillary openings and small diameter openings (up to 1000 times, according to the research results of R. F. Ganiev) [8].

Thus, the use of the proposed device with the established parameters of mechanical action creates the prerequisites for stabilizing and increasing the cooling rate of machine parts during their heat treatment due to the use of the effect of attached, vortex or vibration cavitation.

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