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METALLURGY
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Principal Distinction of the Methods of Low-Frequency and Ultrasonic Effects on Melts

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Abstract—Factors that determine the difference between low-frequency and ultrasonic treatments methods are discussed: cavitation phenomena, dissipative losses, and the possibility for the turbulent mixing of the melts. The independence of each method is proven.

Keywords: low-frequency treatment of melts, ultrasonic treatment of melts, cavitation, pseudocavitation
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The method of action on the melt by low-frequency piston vibrations belong to vibrational treatment methods of melts and is intended for the fabrication of composite metallurgical alloys. Having common features with the ultrasonic method in the action mode on the melt and tools performing this action, it considerably differs by the behavior of particles in the melt. A considerable barodynamic influence on the melt particles is characteristic of ultrasonic treatment [1], especially due to the cavitation. In this case, the melt is mixed in small volumes localized around collapsing gas bubbles. In the course of the low-frequency treatment [2–5], melt particles are subjected to a much weaker acoustic pressure; however, turbulent mixing of the entire melt volume is performed at definite geometric and amplitude-frequency parameters, which leads to the homogeneity of the alloy structure. The causes of the difference in behavior of melt components during its treatment by low-frequency and ultrasonic vibrations under the identical specification of the perturbation—by means of a piston—need the theoretical substantiation. The target of this study is to enclose the mentioned causes and prove the independence of each of these methods for the vibrational treatment of the melt.

ABILITY TO CAVITATIONAL BREAK OF LIQUID

Let us say that the sound treatment of the melt is performed in an immobile crucible by a mobile piston moving with amplitude A and frequency μ (with cyclic frequency $\omega = 2\pi\mu$). In the ultrasonic method, the result of the sound pressure on the melt

$$p_s = \rho_l c \omega A \sin\omega(t - z/c), \tag{1}$$

where c is the sound speed, ρ_l is the melt density, and z is the distance from a piston, is the displacement of melt particles along the sound wave with the formation of compression and tension zones. This causes breaks in continuity over the melt volume and, as a consequence, cavitation. The intensity of the sound pressure of longitudinal waves on the melt particle, which is proportional to the square of the module of vibration velocity, is by essence the specified power. To make further evaluation and comparison possible, let us accept the equality of intensities of low (index "lo") and ultrasonic (index "u") frequencies:

$$J \sim (A_{lo}\omega_{lo})^2 = (A_u\omega_u)^2 \tag{2}$$

and, as an example, take the following values: A_{lo} = 1 mm, ω_{lo} = 50 Hz, A_u = 1 μm, and ω_u = 50000 Hz.

The points of the melt where the cavitation break of continuity is most probable are distributed along the wave-propagation direction by one at each segment of the action of tensile stresses, i.e., through the interval equal to wavelength $\lambda = v/\mu$ (where v is the wave speed in the medium), or between the antinodes. The force directed to the cavitation collapse or deformation of the gas bubble that is present in the melt, according to the Newton law, is proportional to the acceleration of melt particles rather than to sound pressure (1); the former is in turn proportional to the piston acceleration: $f \sim A\omega^2$. This is valid since deformational stresses in the isolated melt element with size d along the wave direction are determined by the difference between the pressures in the isolated volume relative to the break plane, i.e., $\sigma_b \sim d\text{grad}(p_s) \sim d\rho A\omega^2$. Therefore, at equal intensities, the breaking force of the ultrasound is larger than for low frequencies by a factor ω_u/ω_{lo} = 1000 and break points are distributed, for example, in water at frequency $\omega_u = 50000$ Hz through each $\lambda = 0.03$ m. At the same time, at low frequencies they are arranged through each $(\omega_u/\omega_{lo}) \times 0.03$ m $= 30$ m, which is much larger than the crucible size. Therefore, the cavitation at ultrasonic frequencies in the absence of amplitude damping of the sound wave is distributed uniformly over the entire liquid volume, while a weak place at low frequencies is the interface between liquid and piston. Thus, the force effect of ultrasound on the liquid particles is larger than the low-frequency one by a factor of $\omega_u/\omega_{lo} = 1000$.

DISSIPATIVE LOSSES

Irreversible losses for internal friction, thermal conductivity, and radiation always occur during the propagation of the sound wave in the medium. The presence of gas bubbles or solid particles in the liquid abruptly increases the dissipation. The variation in the amplitude of a plane sound wave is determined [1] as $A = A_0\exp(-a_t)$, where $a = a_1 + a_2$, $a_1 = 2\eta\omega^2/(3\rho c^3)$ is the sound absorption coefficient and a_2 is the coefficient corresponding to thermal conductivity and constituting to 10% of a_1 (values of a_2 for ultrasound are higher than for low frequencies). It follows from the comparison of magnitudes of a_1 for ultrasonic and low frequencies that a distance from the vibration source, at which the amplitude decreases by a factor of 2, is shorter for ultrasound by a factor $(\omega_u/\omega_{lo})^2 \approx 10^6$ than for the low-frequency effect. This means that the effectively treated volume of liquid is smaller at least by the same factor.

CAVITATION AND PSEUDOCAVITATION

For the appearance of cavitation, it is necessary to fulfill the condition of occurrence of a time interval when the discontinuity zones, i.e., cavitation voids, are not filled with the melt. If we suddenly extract a certain ball-like volume from the melt, the void will be filled for certain time $\breve{t}$. The authors of [6] give the solution of such a problem in the form

$$\breve{t} = r\sqrt{\frac{3\pi\rho_l}{2\Delta p}\frac{\Gamma(8.33)}{\Gamma(0.33)}} = 1.12r\sqrt{\frac{\rho_l}{\Delta p}}, \qquad (3)$$

where r is the radius of the extracted volume, ρ_l is the liquid (melt) density, Δp is the pressure difference, and Γ is the gamma-function. In our case, which somewhat differs by the boundary conditions, cavitation is possible when the piston lifts from the bottom position into the top position to the height of two amplitudes $2A$ for half-period $\bar{t} = (2\mu)^{-1}$, where $\mu = \omega/(2\pi)$ is the piston vibration frequency. Liquid can enter the void under the piston, which is formed upon its motion, only from the side not confined by a piston. For this case, the authors of [2] proposed a formula

$$\breve{t} = 0.917r\sqrt{\frac{\rho_l}{\Delta p}}. \qquad (4)$$

However, it is known from the experiments [3, 4] on the low-frequency treatment that the pressure difference is partially lost in the gap between sidewalls of the piston and working vessel. The narrower the gap is and the longer the piston generatrix (height) is, the larger this loss is, and we can attain the cavitation situation at a low frequency due to the corresponding selection of the mentioned geometric parameters.

It is shown in [5] that flow velocities can be discontinued and there can be a jumplike pressure drop in the gap because of the excessive length of the piston generatrix. Therefore, the lack of liquid for filling the formed vacuum void under the piston is formed and gases from the liquid itself have no time to replenish this lack (delay of true cavitation due to a large void size concentrated in one place). The void is filled with gas from the liquid surface. This means that the pressure drop in a narrow and long gap leads to the inflow of gas bubbles from the melt surface through the melt depth and the gap under the piston. We call such gas ingress from outside into the liquid volume pseudocavitation.

However, this does not explain why cavitation is observed during ultrasonic treatment, while pseudocavitation is observed under the effect of low frequencies. Let us consider the equation of motion of the gas bubble with radius r and density ρ in a liquid medium during the treatment of the medium by vibrations with sound pressure $p_s = \rho_l cA\omega\sin\omega$ under conditions of partial locking the flow in the gap between the piston and crucible and, consequently, with the influencing factor of the pressure under the piston equal to $p_0\frac{1+\hat{a}\sin\omega t}{1+\hat{a}}$. The equation will be written as

$$\dot{u} = -\frac{12\eta u}{d^2\rho} + g\left(\frac{\rho_l}{\rho} - 1\right) + 3\omega A\frac{\rho_l c}{\rho d}\sin\omega t - \frac{3}{\rho d}p_0\frac{1+\hat{a}\sin\omega t}{1+\hat{a}}. \qquad (5)$$

where c is the sound speed; P_0 is the modulus of the pressure drop between the sections above and below the piston; $\hat{a}$ is the coefficient larger or smaller than unit depending on the values of turbulent viscosity and thickness of the boundary layer in the gap and, consequently, on the magnitude of pressure losses in the gap; and u and $\dot{u}$ are the bubble acceleration and velocity, respectively. The first summand of the right side of (5) expresses the resistance of the medium and the second summand expresses the Archimedean force. Solution of (5) relative to velocity allowing for initial condition $u(t = 0) = 0$ has the form

$$u = \frac{g}{B}\left(\frac{\rho_l}{\rho} - 1\right)[1 - \exp(-Bt)] - \frac{3p_0}{B\rho d}\frac{1}{1 + a}$$
$$\times [1 - \exp(-Bt)] + \frac{1}{B^2 + \omega^2}\left(3\omega A\frac{\rho_l c}{\rho d} - \frac{3p_0}{\rho d}\frac{a}{1 + a}\right) \quad (6)$$
$$\times [B\sin\omega t - \omega\cos\omega t + \omega\exp(-Bt)],$$

where $B = 3\eta/(r^2\rho)$.

In Eq. (6), exponent $\exp(-Bt)$ tends to zero with time. The first summand in the right side of (6) is positive, being the Archimedean component of velocity directed upward. The second summand, being negative, is responsible for bubble immersion. The third summand describes the bubble oscillation near its current position in the liquid volume. The motion of the gas bubble downward correspond to the negative difference of the first and second summands, and the smaller the bubble size is, the higher its immersion velocity into the melt is. The modulus of pressure drop p_0 is proportional to the size of the cavitation cavern under the void for the time of piston motion upward:

$$p_0 \sim 2A\pi R^2 - \bar{v}\pi(R^2 - R_0^2)\frac{1}{2\mu}$$
$$= \frac{\pi R^2}{2\mu}\left\{2A\mu - \bar{v}\left[1 - \left(\frac{R_0}{R}\right)^2\right]\right\}, \quad (7)$$

where $\bar{v}$ is the average piston velocity for the time of motion upward, R_0 is the piston radius, and R is the vessel radius.

With the same intensity of the low-frequency and ultrasonic effects, value $\{2A\mu - \bar{v}\lfloor 1 - (R_0/R^2)\rfloor\}$, which characterizes the insufficient void filling, will be identical for both impact methods. Consequently, $p_0 \sim 1/\mu$, and p_0 will be larger at low frequencies than for the ultrasound by a factor of ω_u/ω_{lo}. Therefore, velocity u during low-frequency treatment is negative and formed cavitation caverns are filled with gas from the liquid (melt) surface; during ultrasonic action, this velocity is positive and full-value cavitation occurs. Thus, the phenomenon of just pseudocavitation during low-frequency treatment is quite regular.

Gas bubbles are collected immediately under the piston since the direct pressure-drop zone is formed at its lower face: it follows from the Bernoulli equation that, as the flow turns from the gap (flowing around of the angle), the velocity, which is proportional to the curvature radius, tends to infinity while the pressure drops abruptly. As a result, the air cushion is accumulated under the piston from the bubbles, which is partially dissolved in liquid. Therefore, the average density in the working volume decreases, which causes the sedimentation of the particles with density higher than the density of the liquid–air mixture into the precipitate and a decrease in the load on the piston in view of the pressure drop.

Thus, the cavitation, which appears during the ultrasonic treatment, is the tool of the barodynamic effect on the liquid, while pseudocavitation, which is characteristic of low-frequency treatment, is a phenomenon that causes the fallout of heavy particles from mixing and gassing; therefore, it should be avoided by lowering the treatment intensity.

It should be also noted that, in order for the motion of the gas bubble in liquid to be possible, we should take into account the state of the gas–liquid surface interface. The state at the interface alone (values of the wetting angle and viscosity) explains, for example, the absence of gas bubbles during operation with glycerol at frequencies $\omega < 60$ Hz and amplitude $A = 1.5$ mm: glycerol viscosity is considerably higher than that of water, while the transportation velocity of the gas bubble is lower according to expression (6).

TURBULENT MIXING

Fluid mixing under the ultrasonic effect is localized near the coalescing gas bubbles; therefore, even though mixing of any component through the entire treated region occurs, it occupies considerable time. Turbulent mixing is the tool of barodynamics for the low-frequency treatment.

Turbulent mixing of liquid during its vibrational treatment with piston [2–4] appears due to the flow from the gap between the piston and the vessel wall into the chamber under the piston, as well as to due to pressure drop p_0 between the zones above and below the piston. It is necessary for the full-value turbulent mixing that the jet flow rate from the gap for the half-period of piston motion upward would be sufficient in order to impart valuable motion and velocity to each liquid particle. This is necessary for the reserve of the motion inertia, since mixing is damped upon the piston motion downward. It is shown above (a consequence of Eq. (7)) that pressure drop p_0 at low frequencies will be larger than for ultrasound by a factor of ω_u/ω_{lo} and the liquid flow rate for the half-period of vibrations will be larger by the same factor. This means that the flow rate during ultrasonic treatment is too small to form turbulence. Therefore, the ultrasound power is consumed for the compression–tension of the melt and cavitation; the low-frequency power is consumed by turbulent mixing and the fraction of the dynamic effect on melt particles following from the turbulence of flows rather than from the sound pressure is high at low frequencies.

CONCLUSIONS

Thus, the causes of distinctions in the behavior of melt components under its treatment with low-frequency and ultrasonic vibrations with the same method of specifying the perturbation, notably by a piston, are considered. These causes are conditioned by various factors: the different ability to the force effect on the melt particles and mixing of the treated volume, dissipative losses, and cavitation phenomena. Distinctions turn out to be substantial and principal and, consequently, these methods can be considered principally different and independent.

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