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Research Article

A STUDY OF THE INFLUENCE OF CAVITATION STRUCTURES ON THE FACIAL LAYERS OF STRUCTURAL MATERIALS

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ABSTRACT

The effect of ultrasonic cavitation is widely used in some technological processes, for example, ultrasonic cleaning. Along with the positive effects, cavitation leads to deformation and destruction (erosion) of treated materials' surface. Controlling the effects caused by ultrasound in a liquid requires a detailed study of the cavitation structures' impact on the facial layers of work-pieces. Proposed methodology includes the processing of metal samples in liquid under the impact of ultrasonic field. The process dynamics were recorded using high-speed video camera. Samples' characteristics were measured before and after treatment. The article presents a study on the effect of cavitation structures on the facial layers of structural materials, as well as modification regularities of physical, mechanical, and geometrical parameters of the metal sample surfaces under the impact of cavitation. The authors revealed the quantitative characteristics of structure transformations, as well as changes in microhardness, roughness, and subroughness of the samples.

INTRODUCTION

In the technological processes associated with ultrasonic processing in liquid, the main physical phenomenon influencing the processing object is cavitation (Kazantsev, 2008). Cavitation is the formation of cavities in the bulk of liquid, which are filled with steam, gas or their mixture, and the collapse of these cavities, accompanied by intense shocks. Cavitation alters the rate of chemical reactions, promotes emulsification and dispersion, and also causes a variety of other effects. Effect of erosion caused by the cavitation is widely used in the processes associated with the removal of dirt from the surface of work-piece (ultrasonic cleaning) (Prikhodko, *et al.*, 2015). But along with the advantages cavitation leads to the destruction of the surface of the treated work-piece (Sirotjuk, 2008). Controlling the effect of ultrasonic treatment is one of the development paths in ultrasonic technology (Fatyukhin, 2012).

Cavitation occurs at the oscillation of the bubbles, the radii of which are within a wide range from Rcr to Rres. The least critical radius can be approximately determined from the formula (Aculichev, 1984):

$$R_{cr}^{\ 3} + 2\sigma \cdot \frac{R_{cr}^{\ 2}}{P_{st}} - \frac{32\sigma R_{cr}^{\ 2}}{27 P_{st}(P_{st} - P_0)^2} = 0 \qquad (1)$$

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where R_{cr} is the smallest critical radius of the bubble; σ is the surface tension at the liquid – gas interface; P_{st} is the static pressure; P_0 is the external hydrostatic pressure.

The resonance radii of the bubbles are radii that correspond to the frequency of the applied sound wave. There is a formula (Aculichev, 1984) to determine the size of the bubbles oscillating in resonance with the point emitter oscillations:

$$f = \frac{1}{2\pi R_{res}} \sqrt{\frac{3\gamma(P_0 + 2\sigma / R_{res})}{\rho}} \quad (2)$$

where R_{res} is the resonance radius of the bubble; γ is the ratio of the gas specific thermal capacities in the bubble; P_0 is the external hydrostatic pressure; ρ – is the liquid density.

Bubbles with the radii smaller than the R_{cr} will not be involved in the ultrasonic cavitation (at a given static pressure P_{st}). If the radius of the bubble is greater than R_{res}, no collapse will occur, and the bubble will pulsate in a sound field with a complex change of its shape.

Thus, by nature of the produced action and the duration of existence in a sound field, pulsating and collapsing bubbles are considered to be the main cavitation structures (Rozenberg, 1970; Seo, *et al.*, 2010; Agranat, *et al.*, 1987).

The existence of an isolated bubble is very unlikely. Most researchers concur that strong ultrasonic radiation causes the formation of many bubbles interacting with each other. The bubble swarm is called cavitation region (Rozenberg, 1970; Agranat, *et al.*, 1987).

At ultrasonic treatment in the liquid, pulsating and collapsing cavitation pockets produce work to change the structure and properties of work-piece's facial layer. In addition, high velocities of microflows, formed by the bubbles, serve also the mechanism of surface deformation.

Due to the small sizes of the working bodies and the small generated local loads, changes occurring on the work-piece surfaces can be accurately controlled and proportioned. The main surface properties, which are essentially influenced by cavitation erosion, include physical and mechanical properties of the facial layer (type of structure, microhardness, and the magnitude and sign of internal residual stresses) and geometrical parameters (roughness and submicroroughness).

METHODS

Steel 45, steel 20, steel 3, and aluminum AL4 served the tested materials in the current study.

Processing was performed with the use of the LEFMO-5M ultrasonic test bench. Ultrasonic generator UZG2-22 served as vibration source. Three-half-wave oscillatory system with rod-shaped magnetostrictive transducer connected to the ultrasonic generator allowed implementing the vibrational displacement amplitudes within the range from 2 to 70 µm. The operation frequency of oscillations was 22 kHz. The exposure time was chosen within the range from 1 to 90 minutes. Gas-free tap water at room temperature served as processing medium.

To enable observation and quantification of ultrasound exposure we used the Fastec HiSpec 1 camera, which provided images with shooting speed up to 112000 fps at max resolution of 1280 × 1024 pixels.

Studies of the facial layer were conducted using light microscope Axiovert 25 CA Carl Zeiss. Subroughness was measured using an electronic multi-microscope SMM-2000 in tunnel and atomic force modes.

Alloys' hardness measurements (durometric measurements) were carried out using AFFRI Dm-8 microhardness tester.

RESULTS

In the context of technological application, at least three fundamentally different modes of ultrasonic impact in the liquid are distinguished.

1. Precavitation mode, where there are no breaks of fluid continuity, i.e., cavitation. The main impact mechanism in this mode is alternating sound pressure. This mode is characterized by specific acoustic power of 1-2 W/cm^2.

2. The increase in specific acoustic power over 1-2 W/cm^2 leads to the formation in the fluid continuity of cavities filled with vapor, gas, or gas-vapor mixture, as well as the collapse of these cavities, i.e., cavitation.

3. High-amplitude processing mode takes place when exceeding power to 10-12 W/cm^2. The transition to high-amplitude processing is characterized by the formation of large-scale hydrodynamic flows, which quantitatively and qualitatively alter the distribution of the cavitation phenomena in the volume exposed to sonic vibrations.

When creating technology, mainly 2nd and 3rd mode are used, since a tangible effect on work-piece properties requires a sufficient level of emitting power.

The obtained video records show that the shape of the cavitation cavities at various stages of oscillations is quite far from spherical one. At that, it should be noted that larger volume of cavitation area is occupied not by single bubbles, but their conglomerates, the dimensions of which amount to an average of 200-600 μm, while the size of the bubbles is considerably less, up to 50 μm.

Negligibly small difference between the flow velocity generated by a single bubble and the velocity of the wall of the next bubble V_{fl}/V_b <<1 can be considered as the condition for the lack of dynamic interaction between single bubbles (Agranat, *et al*., 1987). In this case:

$$R_{cr} = 3R_{max} \; ; \; a_{cr} = 4R_{max} \tag{3}$$

where R_{cr} is the critical radius of the bubble;

R_{max} is the maximum radius of the bubble;

a_{cr} is the critical distance between the bubbles centers.

When creating powerful ultrasonic fields in a bath filled with liquid, we observed cavitation region in the form of white clouds connected by threads of fast moving bubbles. This region was observed under the oscillator at the amplitude of oscillatory displacements of 1.0 μm.

The structure and dynamics of the cavitation region has a significant influence on the intensity of ultrasonic impact. The analysis of high-speed filming of cavitation processes allowed revealing the nature of generation and pulsations of complex bubble structures.

Collapsing cavitation bubble exists during very short time. The analysis of high-speed filming and the results of several studies e.g. (Kazantsev, 2008) show that after the collapse the bubble is divided into many fragments, which in turn are pulsing in-phase. At that, the process is accompanied by the formation of complex bubble structures. Let's call them clusters (Fig. 1).

Bubbles, formed under the impact of the alternating acoustic pressure and located at a small distance from each other, are merged. At that, two processes occur simultaneously, namely collapse of bubbles (coalescence) and merging of small bubbles into larger under the effect of the adhesion forces that is followed by the formation of common structures (coagulation). Coalescence is accompanied by a transition of the system into a state with lower free energy.

For a clear description of the phenomena occurring in the region of acoustic cavitation it is necessary to distinguish concepts of the cavitation bubble and cavitation cluster.

A bubble is an element of cavitation impact. Cavitation bubble is a single vapor-gas cavity formed due to pressure reduction under the effect of oscillations. Usually, the description of the phenomena that occur in the liquid under the effect of ultrasound is reduced to the behavior of cavitation bubbles.

In relation to cavitation formations, the following definition of a cluster is most suitable: Cluster is the association of several homogeneous elements, which can be regarded as an independent unit with certain properties.

The study of clusters' dynamics has been conducted in a series of papers (Birkin, *et al*., 2011; Nigmatulin, *et al*., 2000; Lele and Tryggvason, 2010; Ashokkumar and Grieser, 2007; Ushikubo, *et al*., 2010). However, the issue concerning the impact of clusters on the facial layer of metallic materials still remains open.

The association of bubbles into clusters occurs both in the liquid and at the interface. Besides the pulsations, cavitation clusters progressively move in the volume exposed to sonic vibrations sufficiently long time corresponding to the period of 10-100 thousand oscillations of the ultrasonic source.

It should be noted that the cluster size over the whole time of its existence varies slightly. When the cluster moves, some of the bubbles are scattered due to their collapse, while the other bubbles are moved away under the action of the liquid resistance. At the same time the cluster absorbs other nearby bubbles and clusters that leads to an increase in its volume.

Analysis of high-speed filming shows that the impact of the cluster does not cause a noticeable shock action. Bubbles, forming a cluster, periodically merge, pulsate, and are disconnected. However, the high rate of pulsations and movements of the clusters leads to the strain effects.

Under the impact of the cavitation, over time the structure of the material is separated into facial layer, pre-facial layer, and the core.

Under the effect of fluctuations on the microstructure of the material the latter is subjected to both transcrystalline and intercrystalline destructions. Deformation and crushing of the grains, observed in the course of cavitation-erosion effect, result in a change of the microstresses.

Characteristic feature is the presence of clearly defined hardened-deformed layer. For high quality structural carbon steel such as steel 45, the depth of this layer is 3-5 µm. At that, we revealed an increase in hardness of the facial layer by 2-2.5 times in comparison with the hardness of the core material. The study of materials different in properties (non-ferrous metals and steels) has shown similar distribution pattern of hardness and stresses.

DISCUSSION

Since the forces created by the working bodies are of microscopic value and repeated at very high frequency, the impact on the material is of cumulative nature. Momentary change in pressure and temperature in the treatment area affects facial layer just within a limited depth and leads to the fact

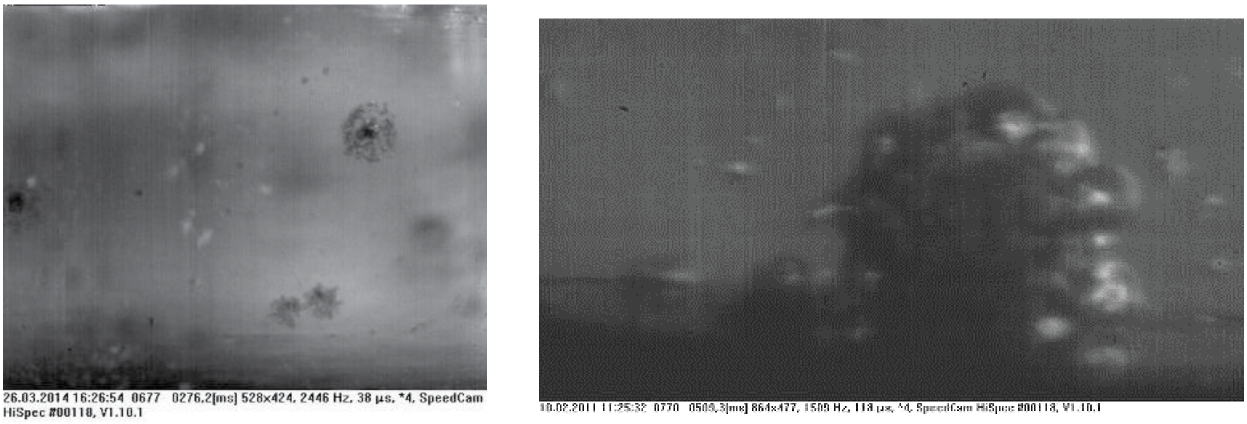
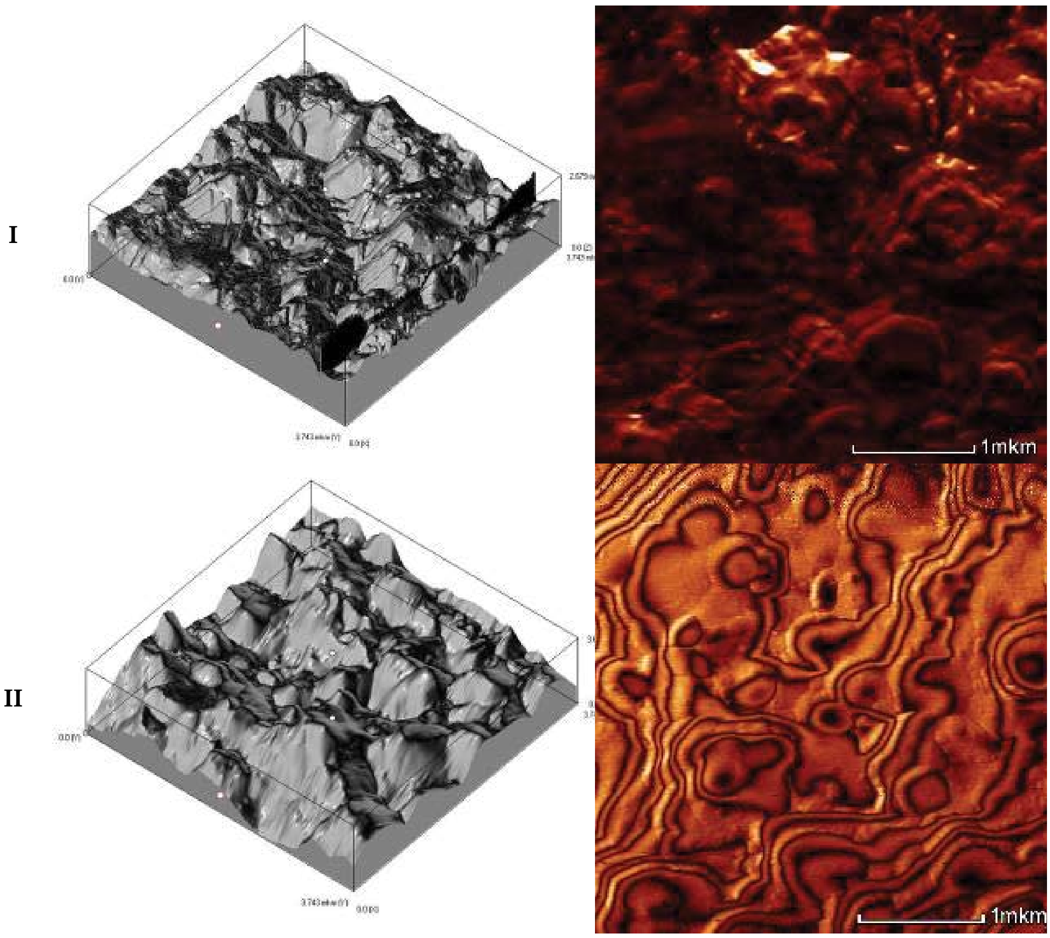


Fig. 1 The cavitation clusters: a – in the liquid, b – on the liquid-sample interface.



a b

Fig. 2 Samples of steel 45 before (I) and after (II) impact of cavitation: a – 3D image of the surface; b – distribution of the lateral friction contact.

that the physical and mechanical properties of the facial layer differ from those of the base metal.

Dynamic pattern of microhardness shows that at the beginning of ultrasonic treatment of the sample, elastic strain is dominated that does not lead to noticeable changes in the subsurface layer. The stresses exceeding elastic limit of the test material cause occurrence of the yielding phenomena resulting in increased hardness of the material. Conducted studies have shown that there exists a steady state which is characterized by the relative microhardness index equal to 1.5 (the ratio of microhardness after and before treatment). When this value is reached, the effect of cavitation does not lead to any significant changes.

The effects of cavitation erosion cause an increase in the values of the major parameters that determine the characteristics of the microrelief. Basically, the numerical values of the roughness parameters change by 1.1-1.2 times.

In addition to change of microroughness under the impact of cavitation, the nature and size of submicroroughness change as well. Using the electron and atomic force microscopy methods we have evaluated the changes of submicroroughness, lateral forces, and the granulometric composition of particles' distribution (Fig. 2).

(Fig. 2) shows surface images of steel 45 sample before and after the impact of cavitation. Despite the increase in the greatest height of roughness of the profile irregularity, the protrusions of the treated surface are smoothed. The subroughness parameters were determined in the surface topography cross-section from the upper left corner of the frame to the bottom right corner. The measurements showed a significant decrease in the heights of the irregularities from 130.1 nm (without the effects of cavitation) to 60.6 nm (after cavitation treatment). The force of the lateral frictional contact also changed from 6.2•10-10 to 4.4•10-10 H. In consequence of the granulometric composition analysis we revealed that the impact of cavitation led to reduction in particle size and smoothing of their dimensional characteristics.

CONCLUSION

The effect of cavitation on the surface of metal samples consists in the relative increase of microhardness by 1.5 times. Similar effect in changes of hardness was revealed when studying materials with different properties (steel and non-ferrous metals). The roughness parameters increased by 1.1-1.2 times, while subroughness was reduced twice.

Analysis of conducted experimental studies allows stating that the cavitation structures' impact leads to a significant change in the basic physical, mechanical, and geometrical parameters of the material surface directly affecting the operating properties of the work-pieces.

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