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THE USE OF SURFACE ACOUSTIC WAVES TO EVALUATE OF THE NEAR-SURFACE LAYERS OF METAL PROCESSED SHOT PEENING

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Abstract

The surface layers of low-carbon steel metal subjected to shot peening were studied. The velocity of Rayleigh surface waves of various frequencies in the range of 3-9 MHz by the phase-pulse method using contact piezoelectric transducers measured. The study of the distribution of residual mechanical stresses in depth was carried out using the etching of the surface layer of the metal and the use of a strain gauges. The characteristics of the roughness of the surface layer of the metal, which has arisen as a result of shot peening, have been determined.

The effect of roughness and plastically deformed layer on the velocity of surface acoustic waves (SAW) is estimated by the method of layer-by-layer grinding of the surface layers of the metal.

Based on the determination of the magnitude of the residual mechanical stresses and the known acoustoelastic coefficients, the magnitude of the change in the velocity of SAW under the action of these stresses is estimated.

Keywords: shot peening, Rayleigh surface wave velocity, residual mechanical stresses, roughness.

1. INTRODUCTION

Currently, various methods are widely used to change the physical and mechanical properties of metals in order to improve their performance. One of them is shot peening of metal, which consists in treating the surface with a jet of abrasive particles. This technology is used to clean the metal surface and improve its fatigue strength and other performance characteristics. As a result of the impact of abrasive particles, plastically deformed microsections appear on the surface, and a plastically deformed layer is formed in the near-surface regions of the metal. Another result of shot peening is a change in surface roughness and a deformed surface layer, as a result of which compressive stresses arise in it. There are a number of works that consider the processes occurring in metal as a result of shot peening [3, 12, 15], its effect on fatigue strength [22], as well as the effect on increasing the adhesion strength with the base of single-layer coating [4, 5, 8, 9, 20].

The technological mode of shot peening significantly affects the characteristics of the surface layer, and therefore there is a need to control them. Acoustic studies of the condition of the material occupy an important place. Among them are acoustic emission methods based on the Barkhausen effect [17] and nonlinear acoustic effects [16].

Methods for studying the state of a material are effective, in which measurements of the velocity of SAW are used [6, 7, 11, 16, 19, 23]. The velocity of SAW depends on the elastic characteristics of the material and its density and is sensitive to the occurrence of plastic deformation [18], as well as mechanical stresses [2, 13, 14] in the material. Another feature of them is that they propagate in a near-surface layer ~ 1.5Λ thick, where Λ is the wavelength of the surfactant. On this basis, the value of the SAW velocity can be used to effectively control the state of the surface of the metal treated by the shot peening method. In addition, it is convenient that the wavelengths of SAW, which are traditionally used in non-destructive testing (0.15-3 mm), roughly correspond to the depth of the layer that is modified during processing. The technique for measuring the SAW does not require bulky equipment and allows high-precision research required to assess the state of the metal.

At the same time, the difficulty at this stage is the interpretation of the results obtained, since there are various mechanisms that arise in the process of plastic deformation, leading to a change in the velocity. Therefore, there is a need for comprehensive studies of the effect of shot peening on SAW velocity. In this work, we experimentally study the effect of shot peening on the change in the properties of the near-surface layers of the metal, as well as the velocity of SAW of various frequencies.

2. MATERIALS AND METHODS

We investigated samples of low-carbon steel with a size of 55×55×9.8 mm, which were subjected to shot peening at a compressed air pressure of 0.6 MPa, an abrasive jet particle diameter of 2 mm, and a distance from the nozzle to the processing surface of 100 mm. Shot peening was carried out in one, two and three passes of the nozzle over the treated surface, thus providing different depths and stress levels in the work-hardened layer. The velocity of the SAW was determined by the phase-pulse method, in which an acoustic signal was used in the form of a radio pulse with high-frequency filling. The time taken by the acoustic signal to travel a distance equal to the base of measurements. The transducer used for the measurements is shown in Fig.1.

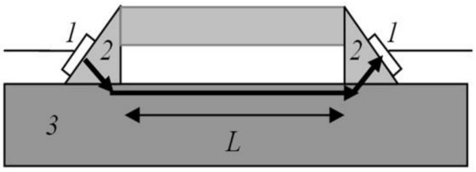

Fig. 1. A transducer for determining the speed of a surfactant: 1 - piezoelectric element, 2 - prism, 3 - test sample, L - measurement base

The constancy of the magnitude of the base of measurements was ensured by using a transducer in which the exciting and receivering parts are rigidly connected to each other [10]. SAW was excited and receivering using wedges, in which a longitudinal bulk acoustic wave is transformed into a surface wave and vice versa. Used SAW with frequencies of 3, 6, 9 MHz. Machine oil was used for acoustic contact between the transducer prisms and the sample. Determined the change in SAW velocity that occurred as a result of shot peening. The magnitude of SAW velocity was determined sequentially on the test sample and the comparison sample.

The sample in the initial state was taken as a reference sample. The difference between the time of passage of the acoustic signal in the test sample and the comparison sample was determined. Based on these data and the size of the measurement base, the change in the SAW velocity was determined.

The accuracy of the measurements was determined by the error in determining the time of passage of the SAW between the receiving and exciting part of the transducer, the error in determining the distance traveled by the acoustic wave and the value of the measurement base L.

The difference between the times of passage of the acoustic wave through the test and reference samples **wa**s with an error of 2 ns.

As noted, the invariance of the distance that the acoustic wave passed through the sample is determined by the invariance of the value of the measurement base.

However, the instability of the path of the acoustic wave is due to the instability of the thickness of the liquid layer, which provides acoustic contact between the prism of the transducer and the sample. During each installation of the converter, the thickness of this layer is uncontrolled. This is the main source of error in determining the distance traveled by an acoustic wave. It should be noted that the accuracy of measurements increases with the growth of the measurement base The measurement base was 30 mm. The measurement error in our measurements is 0.05%.

3. RESULTS AND DISCUSSION

The measurement results are shown in Fig. 2. The velocity in the reference sample was taken as the zero velocity level. As seen from Fig. 2 shot peening will reduce the SAW velocity. In samples subjected to a longer treatment (due to the greater number of nozzle passes), the velocity decreases by a greater amount.

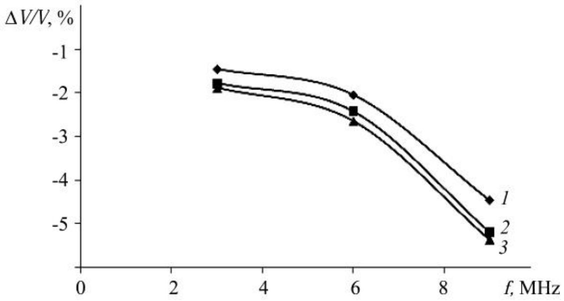

Fig. 2. Dependence of SAW velocity on its frequency for samples with different number of nozzle passes: 1 - one pass of the nozzle, 2 - two passes of the nozzle, 3 - three passes of the nozzle

For all samples, an increase in the frequency of the acoustic wave is accompanied by a change in the SAW velocity by a large value. For SAW with a frequency of 3 MHz, a decrease in velocity is observed for various samples in the range of 1.45-1.9%, for waves with a frequency of 6 MHz, the decrease in velocity is 2.05-2.6%, and for waves with a frequency of 9 MHz, this value lies in the interval 4 , 45-5.5%.

Since the roughness of the surface of the samples increases during shot peening, to assess its effect on the change in the SAW velocity, the velocity measurements were carried out in the process of gradual grinding of the surface layers of the sample (Fig.2).

Also, these studies make it possible to assess changes in the properties of the treated metal in depth. The change in the thickness of the sample was determined using a clock-type indicator with a division price of 2 μm. The measurement results are shown in Fig. 3.

There is a decrease in change of velocity with increasing thickness of the sanded layer.

A particularly strong decrease is observed at the initial stage of grinding the sample within 20 µm.

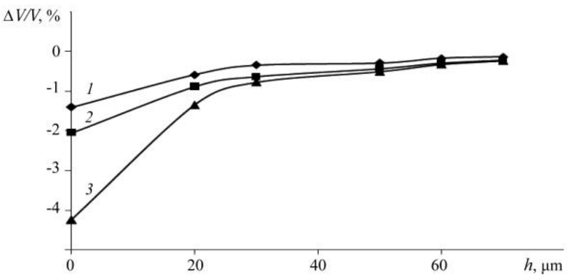

Fig.3. The distribution of the change in the SAW velocity of different frequencies depending on the thickness of the ground surface layer of metal *h*, for the sample with one pass of the nozzle: 1 - *f* = 3 MHz, 2 - *f* = 6 MHz, 3 - *f* = 9 MHz

In this area, there is a decrease in the change in the velocity of SAW with a frequency of 9 MHz by 2.9%, for waves with a frequency of 6 MHz by 1.2% and for waves with a frequency of 3 MHz by 0.8%. With further grinding of the metal layers, the reduction in velocity is much slower.

In the process of grinding metal layers in the range of thicknesses of 20 -70 µm, the velocity reduction occurred for SAW with a frequency of 9 MHz by 1.1%, and by 0.7% and 0.45% for waves with a frequency of 6 MHz and 3 MHz, respectively. Thus, the dependence of the SAW velocity on the thickness of the grinding layer is characterized by two sections: 0-20 µm and 20-70 µm, which differ in the different slope of the curve of the velocity change from the thickness of the grind layer.

Measurements of surface roughness characteristics were also performed using a profilometer. To determine the roughness and waviness of the materials, a profilograph-profilometer "Caliber S-265" was used, in which the diamond needle contacts the surface of the material, and its oscillations are converted into a voltage change by the inductive method. The characteristics of the surface roughness were assessed by the profilogram within the base length which was chosen so that other types of irregularities (waviness and macrodeviations) did not appear on it.

As a result of the research, it was found that the value of R_{max}, which is equal to the distance between the line of protrusions and the line of depressions within the base length, is 3 µm for the sample in the initial state, for the sample after one pass of the nozzle - 34 µm, after two passes - 48 µm, after three - 52 µm . The Rp value was also determined, characterizing the roughness and is defined as the distance from the line of protrusions in the center line within the base length. In the samples without treatment, it was 1 µm, and in the sample subjected to abrasive-blasting from one pass it was 16 µm, two passes - 18 µm, three passes - 30 µm. Thus, as a result of abrasive blasting, the surface roughness increases.

To assess the effect of shot peening on the near-surface layers of metal, the distribution of residual mechanical stresses along the metal depth by the method described in [1] was investigated. In this work, the residual stresses were determined on prismatic samples of rectangular cross-section, successively removing the thin surface layers of the sample, the surface of which was subjected to shot peening. To determine it, resistance tensometers are used, which are glued along the axis. The research results are shown in Fig.4.

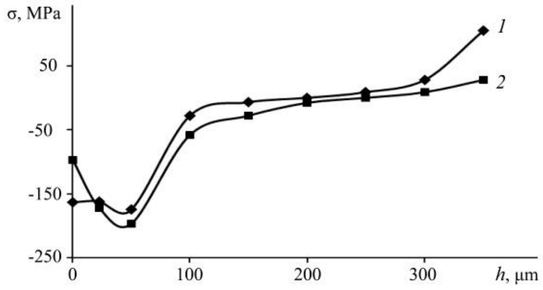

Fig.4. Distribution of stresses along the depth h in specimens from low-carbon steel after shot peening different number of nozzle passes: 1 - one nozzle pass, 2 - five nozzle passes

As can be seen from the graph, significant compressive stresses are formed in the surface layer of the sample; on the surface of the sample, their value is ~ -150 MPa and grows at a depth of 50 µm to a value of ~ -180 MPa. With increasing depth, the value of residual compressive stresses decreases and at a depth of 100 µm is -30 MPa for a surface with one nozzle pass and a value of -60 MPa for a surface with five nozzle passes. With a further increase in depth, the residual compressive stress gradually decreases and reaches zero at a depth of 200-250 µm. Mechanical tensile stresses are observed in the deeper layers of the metal.

4. ANALYSIS OF THE RESULTS OBTAINED

As can be seen from Fig.2, the SAW velocity changes significantly as a result of shot peening and depends on the duration of its action. To assess the mechanisms that cause this change in velocity, its dependence on the thickness of the abraded layer of the sample, which is shown in Fig. 3, is important. The presence of two areas on these graphs with different slopes indicates that the nature of changes in the surfactant velocity at a depth of 0-20 µm and a depth of 20-70 µm is different. The conducted studies of the surface roughness make it possible to estimate the characteristic dimensions of the irregularities and, accordingly, the size of the metal layer, in which there is a significant effect of roughness. As noted, the thickness of this layer is tens of micrometers and thus the decrease in the change in velocity in the layer with a thickness of 0-20 μm can be associated with the surface roughness resulting from shot peening. The SAW velocity and its dispersion are determined by the characteristics of the surface roughness. The amount of surface roughness relative to the SAW length will be different for waves of different frequencies. Therefore, a frequency dependence of the change in the SAW velocity is observed. The velocity of the SAW of a higher frequency changes by a large value, since the relative roughness of the surface for it is greater.

A quantitative assessment of the effect of surface roughness on the surfactant velocity can be made on the basis of the results of [21]. It is assumed that there is a certain layer of material bounded by the boundary, in which surface irregularities caused by roughness are concentrated. The acoustic wave does not propagate in this layer. The effect of roughness on the SAW velocity is carried out as a result of the appearance of an additional mass attached to the surface of the material in which the surface wave propagates. To characterize the surface roughness, an effective thickness d is introduced, which is defined as the ratio of the density of the material ρ to the surface density of the material ρ_r:

$$d = \frac{\rho}{\rho_r} \quad (1)$$

The surface density of the material is given by the expression

$$\rho_r = \frac{\rho}{S} \int \xi(r) d^2(r), \quad (2)$$

where S is the area, ξ (r) is a function that sets the height of surface irregularities caused by roughness. On the basis of the performed analysis in this work, an expression was obtained for the velocity of the SAW, which propagates over a sample with a rough surface [21]:

$$v = v_r(1 - Rkd), \quad (3)$$

where v – surface wave velocity, v_r – Rayleigh wave velocity, $k = 2\pi/\Lambda$, Λ – acoustic wavelength, $R = R(v_l, v_t, v_r) > 0$, v_l – velocity of longitudinal wave,
v_t – velocity of transverse wave. Thus, according to expression (3), the roughness reduces the velocity of the surface acoustic wave. Since the value of $k \sim f$ then with increasing frequency of the acoustic wave, the effect of roughness increases.

The experimental results shown in Fig.3 qualitatively correspond to expression (3). At the depths of the sample 0 - 20 μm, the velocity of the surface wave changes due to the surface roughness, as well as a result of the presence of a plastically deformed layer at depths of 20 - 70 μm.

Assume that the contributions of these mechanisms to the change in velocity are independent. After grinding the sample to a thickness greater than 20 μm, the effect of roughness on the SAW velocity is absent, and the SAW velocity is determined by the influence of the plastically deformed layer.

The change in SAW velocity caused by roughness can be estimated as the difference between the total change in velocity on the initial surface of the sample and the change in velocity that occurred after grinding a layer of material with a thickness of 20 μm.

Based on the data shown in Fig. 3 it can be assumed that the contribution to the change in the SAW velocity caused by the plastically deformed layer is: for a wave with a frequency of 9 MHz - 1.35%, for a wave with a frequency of 6 MHz - 0.9%, and with a frequency of 3 MHz - 0.6%.

Based on these estimates, the initial roughness in the sample leads to a change in velocity by -2.9% for a wave with a frequency of 9 MHz, and for waves with a frequency of 6 MHz and 3 MHz by -1.2% and - 0.8%, respectively.

Thus, there is a qualitative correspondence of the obtained results with expression (3).

However, expression (3) assumes a linear dependence of the change in velocity on the frequency of the acoustic wave, which does not agree with the results obtained. A possible reason for this is the discrepancy of this theoretical approach to describe the propagation of surface acoustic waves in the frequency range greater than 9 MHz. After all, the analysis carried out in [21] is based on the assumption that the acoustic wavelength is greater than the characteristic size of the surface inhomogeneity caused by roughness.

Based on expression (3) and the obtained values of changes in the SAW velocity caused by roughness, we can estimate the thickness of the effective layer d. The corresponding value for waves of different frequencies is in the range of 12-19 μm.

Its value is qualitatively consistent with the characteristic values of roughness obtained by measuring R_{max} profilometer. The thickness of the layer d is equal to the thickness of the solid layer of metal whose mass is equal to the mass of the rough layer of metal. Since there are regions of voids in the rough layer, the condition $d < R_{max}$ is valid, which is observed in our case.

Another part of the dependence (Fig.3) within 20-70 μm is associated with the influence of the plastically deformed layer on the SAW velocity. It is known that plastic deformation leads to a decrease in the velocity of acoustic waves due to the appearance of texture and porosity of the work-hardened layer [14, 18]. Also, a change in the SAW velocity occurs due to the effect of mechanical stresses. Therefore, this part of the dependence is important for evaluating the state of the metal.

As can be seen from the graphs in Fig.3, for high-frequency SAW a greater change in velocity is observed under the action of shot peening. This suggests that large changes in material characteristics occur in thin layers of metal. From the obtained dependences of mechanical stresses (Fig.4) and the dependences of the change in the

SAW velocity (Fig. 3), it can be concluded that the thickness of the work-hardened layer is about 100 μm. Considering that the SAW velocity for low-carbon steel is about 3000 m / s, the corresponding wavelength in the frequency range 3-9 MHz will be 1-0.3 mm. Thus, only some part of the wave propagates in a plastically deformed metal layer in which changes in elastic moduli and density have occurred.

It can be assumed that the magnitude of the change in the velocity is proportional to the thickness of the plastically deformed layer normalized with respect to the surfactant wavelength. This effect can explain the dependence of the change in speed on frequency.

It can be assumed that the magnitude of the change in the SAW velocity is proportional to the thickness of the plastically deformed layer normalized with respect to the SAW wavelength. This effect can explain the dependence of the change in velocity on frequency.

The mechanisms that lead to a change in velocity can be estimated by the magnitude of this change. The influence of residual mechanical stresses on the change in the SAW velocity is set by the magnitude of the acoustoelastic coefficients. For steel, this coefficient is 0.01% / 100 MPa [14]. Thus, the maximum value of mechanical stresses equal to -180 MPa will lead to a change in the surfactant velocity by 0.018%. This value is much less than the value of the change in the speed obtained in the experiment. Therefore, it can be concluded that the dominant influence of the mechanisms associated with a change in the texture and porosity of the surface layer of the metal.

As can be seen from the analysis performed, the maximum contribution to the change in the surfactant velocity is made by the surface roughness, which arises as a result of shot peening. At the same time, the purpose of studying the dispersion of the surfactant velocity is to determine the characteristics of the plastically deformed layer, the effect of which on the change in velocity is less than the effect of roughness. Therefore, it can be recommended to grind off the surface layers to reduce the roughness. This will make it possible to determine the change in the surfactant velocity caused by the appearance of a plastically deformed metal layer.

Therefore, it can be concluded that the dominant influence of other mechanisms associated with plastic deformation in a layer with a thickness of 20 - 70 μm, which includes changes in the texture and porosity of the material.

Thus, the change in the velocity of the surface acoustic wave after shot peening is mainly caused by the change in surface roughness, as well as due to the appearance of a surface plastically deformed layer. The velocity of surface acoustic waves can be used as an effective tool for evaluating the results of shot peening.

5. CONCLUSION

A comprehensive study of the characteristics of the surface layer of the metal subjected to shot peening has been carried out. Based on studies of the speed of SAW with a frequency in the range of 3-9 MHz, it can be argued that the main changes in the properties of the metal after abrasive-jet processing took place in a layer about 100 μm thick. This conclusion is confirmed by the study of the distribution of residual mechanical stresses in metal depth. The maximum value of mechanical stresses was observed at a depth of 50 μm from the surface. It was found that the characteristic dimensions of the surface roughness caused by shot peening are several tens of micrometers. A monotonic frequency dependence of the surface acoustic waves (SAW) velocity in the frequency range 3 - 9 MHz was revealed. The maximum change in velocity, which arose as a result of shot peening, is observed for a SAW with a frequency of 9 MHz. It is shown that the appearance of roughness can lead to a decrease in the velocity of the surface acoustic wave by several percent. It was found that the magnitude of the change in the SAW velocity which occurred due to residual mechanical stresses is insignificant compared to the contribution of other factors. Shown that the velocity of SAW can be used as an effective tool for evaluating the results of shot peening.

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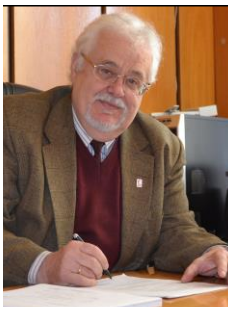

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