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Application of Pulsations of Oscillating Gas Flow Pressure for Processing the Heat-Strengthened Samples of Steel

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Abstract

Subject of study. The experience of using the advanced technology of aeroacoustic materials processing for increasing the impact toughness of 40X (Russian classification) structural steel samples is presented. The basis for this method is the sample being affected by a pulsating airflow that contains oscillating shock-wave structures. As a result, the so-called Maxwell waves arise in the sample, which can lead to a favorable change in its micro- and substructure, as well as in the phase structure, in particular, in hardened steels. The obtained changes may be sufficient to increase the impact toughness and to reduce the dangerous level of residual stresses arising in the course of previous processing. This helps to reduce the deformation of the parts and the likelihood of their destruction during further processing or operation. The advantage of the technology lies in the elimination of additional thermal treatment, such as relaxation annealing, which serves to reduce residual stresses. This can be useful, in particular, for maintaining high hardness and wear resistance obtained during quenching and low tempering (~ 200 °C), since relaxation annealing, which usually has a higher temperature, will lead to their decrease. An increase in impact toughness of the samples is assumed as an indicator for positive effect of the processing under consideration. *Main results*. The characteristics and regimes of experimental acoustic radiator performing the aeroacoustic processing are determined. Experiments have been carried out to evaluate the influence of aeroacoustic effect on the toughness of widely used structural 40X steel. The obtained results suggest that applying the aeroacoustic processing to heat-strengthened samples leads to an increase in toughness of the studied material. At the same time, the increased hardness value obtained after thermal treatment remains. *Practical significance*. The results of the work supplement the previously obtained experimental data on aeroacoustic processing of metallic materials. They can be used (after increasing the statistical reliability of the data) in the development of technology for processing parts, for which it is important to have a high hardness and wear resistance along with sufficient impact toughness.

Keywords: thermal treatment of steel, hardening, tempering, aeroacoustic processing, resonator, acoustic radiation generator, Maxwell waves, impact toughness.

INTRODUCTION

Brief description of the problem. One of the tasks of ensuring the operability of heat-strengthened steels in products can be attributed to a reduction in the risk of deformation and destruction of products during processing or operation while maintaining high hardness and wear resistance. Promising in this case may be the method of aeroacoustic processing (AAO), based on the periodic impact of shock wave structures containing oscillations of discrete tone due to the occurrence of Maxwell waves in the material [1, 2]. Such treatment, as shown earlier [3, 4], allows to influence the parameters of the micro- and substructure of metallic materials, as well as to cause phase changes in them. As a result, relaxation processes should occur that increase the dimensional stability of the parts by reducing the level of residual stresses and the accompanying increase in toughness (KCU) [5, 6]. It is important here that the relaxation proceeds sufficiently locally, in the regions of the greatest concentration of stresses. This will preserve the high values of hardness and wear resistance, obtained with the previous heat treatment. In some cases [7, 8], hardness was observed on samples that had been quenched with high tempering and then subjected to AAO. The relevance of research. A high level of residual stresses, arising, in particular, in the process of hardening heat treatment can lead to unacceptable deformation of parts, as well as their destruction during further processing or operation. The AAO is intended to be one of the solutions to the problem, since, as previous studies have shown, it leads to an increase in the toughness, which is largely due to a decrease in the level of undesirable residual stresses. This is apparently facilitated by the phase-structural evolution in materials that occurs during AAO. The purpose of the study was to assess the degree of impact of AAO on the toughness of 40X steel samples preliminarily subjected to hardening heat treatment.

THE SUBJECT AND THE METHOD OF RESEARCH

The subject of the research is the following:

– Determining the possibilities of controlling the parameters of the acoustic radiator in use for obtaining the optimal regimes of AAP;

– Evaluating the effects of selected AAP regime on the impact toughness and hardness of 40X steel samples, preliminarily subjected to hardening thermal treatment.

To implement the AAP, an acoustic radiator was used. It consisted of a special resonator and a Gavreau generator, which uses the effect of oscillation generation during the flow of subsonic stream (which has a velocity lesser that the speed of sound) onto the sharp edge ("knife"). By changing the geometric parameters of the radiator, it is possible to adjust the generation of wide spectrum acoustic oscillations (noise), having a discrete tone of a certain frequency.

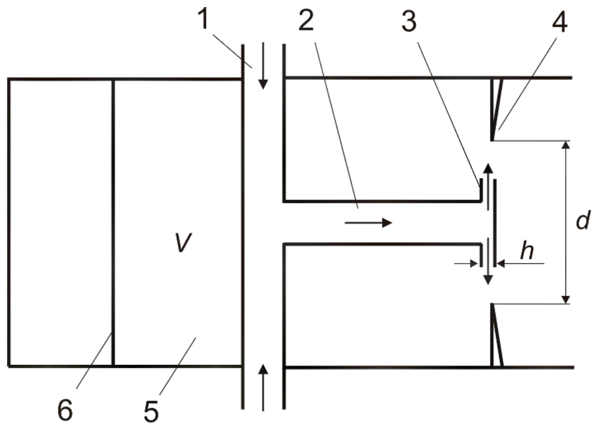


Figure 1: Acoustic radiator. 1 - the main line entrance, 2 - the central canal, 3 - the radial nozzle, 4 - the circular diaphragm, 5 - the resonator, 6 - the resonator wall (d - diameter of the circular diaphragm, h - width of the slot nozzle gap, V - resonator volume).

The principle of radiator's operation (Fig. 1) is based on the transforming the energy of compressed air into the energy of the pulsating flow with radiation of the acoustic waves into the space. The air pressure P0, supplied from the main line 1 into the central canal 2 passes through the slit radial nozzle 3. The flat radial fan jet emanating from the nozzle flows onto the sharp edge of the circular diaphragm 4. The pulsating flow is formed inside the adjustable volume of the resonator 5. The selection of radiation's amplitude-frequency characteristics is done by changing the width of the gap h, the diameter of the diaphragm d, and volume of the resonator V by moving the wall 6. The resonator for the acoustic radiator is designed and manufactured on the basis of a patent [9].

During acoustic processing, the sample is subjected to a combined effect of gas flow fluctuations and pressure pulsations, which should contribute to a change in the phase-structural parameters of the material.

An acoustic sensor with a noise level meter and a frequency spectrum analyzer record the acoustic emission characteristics. The sensor signals are fed into the data logging system through the RS-232 channel.

TECHNOLOGICAL REGIMES OF AEROACOUSTIC PROCESSING

Since in this work the samples were subjected to acoustic effects at room temperature only, then, in contrast to previous experiments, the concept of aeroacoustic (AAP) rather than aerothermoacoustic (ATAP) processing was used.

To adjust the AAP regime, a connection between the parameters of the radiator and the characteristics of acoustic radiation was established. To assess the effect of the resonator and the diaphragm on the characteristics, experiments with and without using a diaphragm and a resonator were carried out. During the optimization of the AAP regime, the integral noise level of the fan jet was measured. It was found that the presence of a resonator increases the noise level by more than 40%. Installing the diaphragm, on the sharp edge of which a fan jet flows, made it possible to achieve oscillatory processes with stable values of frequency and amplitude. This allowed to regulate the frequency H of the discrete tone of acoustic radiation in the interval from 500 to 2200 Hz. When tuning the radiator, the parameters optimal for this experiment were obtained: h = 2 mm, d = 100 mm, P_0 = 2 atm, V = 1428 cm^3. These parameters corresponded to the highest sound pressure of acoustic radiation L = 131 dB near the selected frequency H = 630 Hz (Fig. 2).

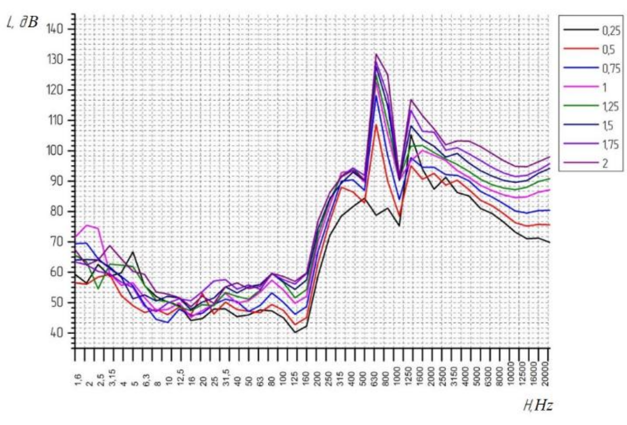


Figure 2: The acoustic emission spectrum L = f(H) formed at pressure P_0 from 0.25 to 2 atm (h = 2 mm, d_n = 100 mm, V = 1428 cm^3).

Such characteristics of acoustic radiation were applied in this work for AAO samples of steel 40X. However, in the spectrum, in addition, there are high-energy oscillations (broadband shock-wave noise) with a pressure of about 100 dB and frequencies close to the ultrasonic range, which also cause oscillations in the sample that accelerate the relaxation processes [10-13].

STUDY MATERIAL

The structural grade 40X steel was chosen as a research material. This choice is due to the wide use of this low-alloy steel. Hardening and low tempering of this steel provide high values of hardness and wear resistance, but low impact toughness. Hardening and high tempering make it possible to obtain a combination of strength, ductility and toughness that is optimal for many applications with reduced hardness and wear resistance [14]. Low tempering (~ 200 °C) does not lead to a decrease in the residual stresses, sufficient for an acceptable increase in impact toughness. At high tempering (~ 600 °C), the stresses decrease completely, which causes an increase in impact toughness, but with a significant decrease in hardness [15].

An experiment on studying the effect of AAP on the impact toughness of a sample was carried out in the following sequence:

1. Samples with a U-shaped stress concentrator having standard geometric parameters for impact bending tests were hardened, which includes heating to 850 °C, holding for 30 minutes and cooling in the water.
2. Low tempering of the samples (200 °C), 30 minutes hold and air cooling was performed for half of hardened samples.
3. Heat-treated samples were affected with a wide range pulsating subsonic air flow with a discrete tone frequency of H ~ 630 Hz and a sound pressure level of L ~ 130 dB over the course of 15-20 minutes at room temperature.
4. Tests for impact bending with pendulum coppers in accordance with GOST 9454-78 were preformed using 3 samples per processing option.
5. Fractographic analysis of the surfaces of obtained samples fractures using a scanning electron microscope Quanta Inspect at the NTM Chair of ITMO University was carried out.

THE OBTAINED RESULTS AND THEIR ANALYSIS

Fig. 3. Presents the effect of various thermal processing regimes, as well as of a thermal processing, supplemented by AAP on the impact toughness of 40 X steel samples.

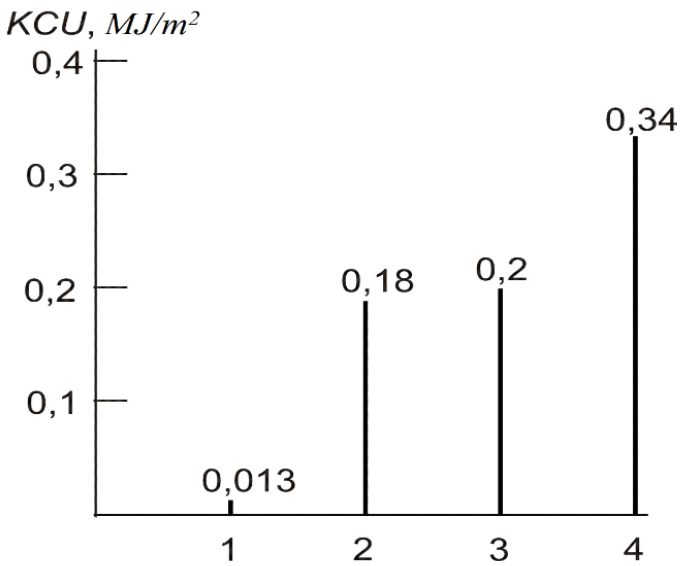
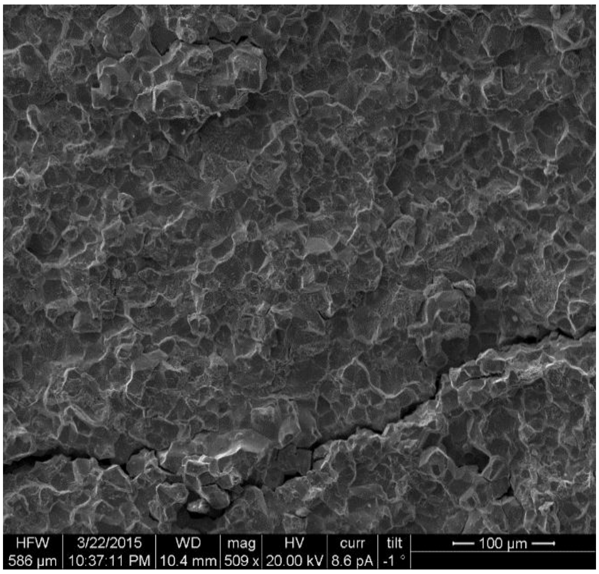


Figure 3: Test results of impact toughness (KCU) for various types of processing: 1 - hardening, 2 - hardening + AAP, 3 - hardening + low tempering, 4 - hardening + low tempering + AAP.

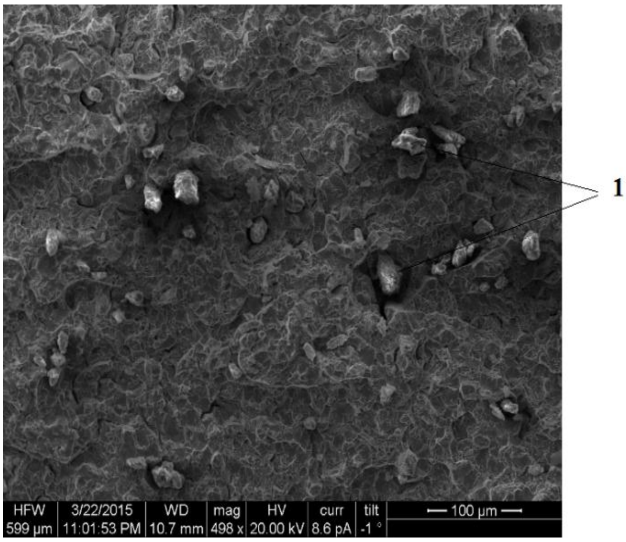
The obtained results show an increase in impact toughness on account of additional AAP both after quenching, and after hardening and low tempering. However, the impact toughness remains lower than the KCU recommended for structural steel (≥ 0.4 MJ/m^2). For example, for 40X steel this value, after quenching and high tempering, should be at least 0.59 MJ/m^2.

Fractograph investigations was carried out based on comparing the fractures of samples that were destroyed after the impact bend test with the data from the guide-atlas "Defects in metals" [16].

Analysis of the Fractographs of quenched sample’s fracture shows that AAP has led to the escape of small particles of the carbide phase (position 1, Fig. 4b), which are absent in the fracture of the hardened sample that has not undergone AAP (Fig. 4a). It is known that, the appearance of carbides in the 40X grade steel, which is associated with the carbon emission from the martensite is only noticeable after tempering at a temperature of about 200 °C. AAP, apparently, accelerates the processes of carbon escape and carbide particles formation. The level of tensile residual (hardening) stresses is reduced, which is associated with a decrease in tetragonal distortions of martensite due to the presence of an excessive concentration of carbon atoms in the lattice.



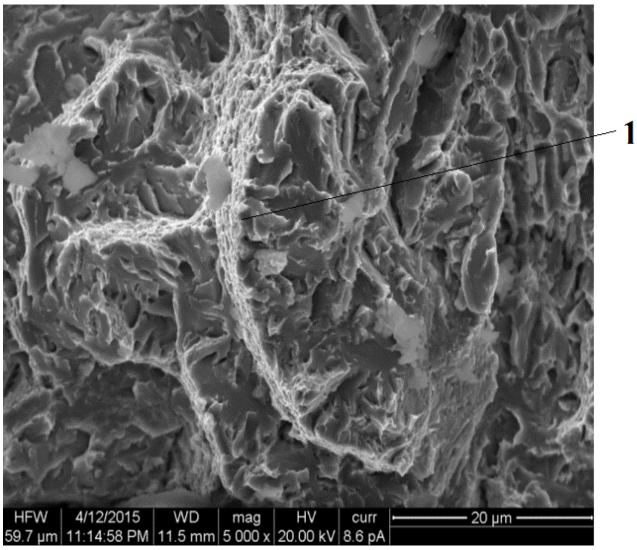
(a)



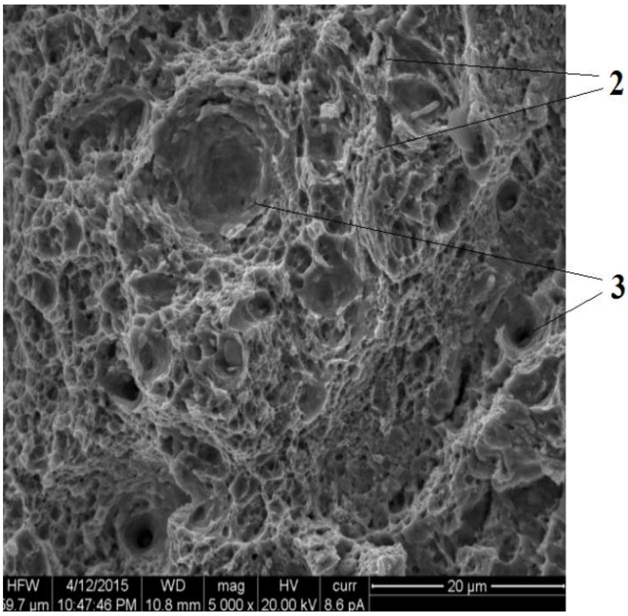
(b)

Figure 4: Fractural structure of the sample with an increase to x500 after the hardening (a) and hardening + AAO (b).

It is known that traditional thermal treatment, designed to obtain high hardness of the parts comparable in size to Menage's samples, includes low tempering for 1.5-2 hours after quenching. Such a long tempering is required for reducing the level of hardening stresses and for a certain stabilization of material's energy state [15]. At the same time, the impact toughness is significantly increased, but after the subsequent AAP, the impact strength has increased by additional 1.5 times during 15 min. This, apparently, is associated with a further decrease of hardening stresses due to a more uniform escape of excess carbon from the lattice.



(a)



(b)

Figure 5: Fractural structure of the sample with an increase to x5000 after the hardening and low tempering (a) and after hardening, low tempering and AAP (b).

This is confirmed in photographs of samples fractures (Fig. 5). Electron-microscopic examination revealed the river-lined structure of fractures after hardening and low tempering of the sample (position 1 in Fig. 5a), which is typical for brittle fracture. After additional AAP of thermal-treated samples, the fracture can be characterized as shallow-holed (position 2 of Fig. 5b) with the presence of separate larger holes (position 3 in Fig.5b). This indicates a quasi-brittle fracture, which is already preceded by a noticeable plastic deformation.

CONCLUSION

The acoustic radiator used in the work made it possible to control the radiation characteristics in sufficient ranges for the studies in order to optimize the regimes of aeroacoustic processing (AAP). For carrying out the AAP of 40X steel samples, acoustic radiation of a wide spectrum was used with a maximum sound pressure of about 130 dB at a discrete tone frequency about 630 Hz. In addition, a broadband shock-wave noise with a significant sound pressure (~ 100 dB) and with a frequency comparable to ultrasound was present in the spectrum, which should also contribute to relaxation processes in the material of the samples being processed.

The obtained results showed that the method of aeroacoustic processing might prove promising for thermally processed products of structural 40X grade steel when it is necessary to increase its impact toughness without reducing the hardness and wear resistance. The results are preliminary in nature, since the measurement of impact toughness of samples in a brittle state usually results in a large scatter of obtained values . In addition, in order to quantify the changes in phase-structural parameters of the processed samples material, more thorough and comprehensive fractographic analysis of the fractures is required.

ACKNOWLEDGMENT

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