Effective combined surface hardening processes of structural steels using ultrasound

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Abstract. The effectiveness of hardening of the surface layer of machine parts is evaluated by the operational properties of the surface layer and depends on many conditions that characterize the specific features of the technological process in which this method of hardening is carried out. The surface plastic deformation of structural steels with the use of ultrasound is studied. Four variants of hardening are considered: ultrasonic treatment with continuous supply of ultrasonic energy, pulse ultrasonic treatment, combination of ultrasonic treatment with subsequent pulse treatment, ultrasonic treatment after hardening with induction heating. It is shown that ultrasonic treatment increases microhardness of surface layer of structural steels by 1.5 times, HF hardening by more than 2 times, HF hardening + UZO combination by 3 times and HF hardening + IUZO combination by 3.2 times. Ultrasonic treatment increases compression stresses occurring in steel surface hardened by HFI hardening. The compressive stresses increase especially strongly after pulse ultrasonic treatment with five passes and reach the value of 1200 Pa.

1 Introduction

The range of materials subjected to various methods of surface hardening is expanding; their composition is becoming more complex. The effectiveness of hardening of the surface layer of machine parts is evaluated by the operational properties of the surface layer and depends on many conditions that characterize the specific features of the technological process in which this method of hardening is carried out. The combination of features of various technological methods of hardening opens up the prospect of further development of metal hardening methods and increasing their efficiency. Thanks to the research of Soviet and Russian scientists, surface hardening methods have been created and are being successfully introduced into production, which allow controlling the surface quality within wide limits. The complex conditions in which modern machines operate have led to the creation of a large number of such methods and often require their combined application.

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The most complete assessment of the acceptability of the hardening method for given conditions is possible when the most important parameters determining the quality of the surface layer, such as geometric characteristics, the physical state of the surface and its stress state, are taken into account.

Table 1 shows the classification of parameters determining the quality of the surface layer [2]. This classification establishes uniform parameters for assessing the impact of numerous technological treatment options on the operational properties of parts.

Management of these parameters, taking into account the specifics of operation, is the most important task of mechanical engineering technology, the solution of which is possible with the use of hardening and finishing treatment, by technological combinations of various electrophysical hardening methods.

The aim of the work is to study the effect of HF hardening and ultrasonic treatment on the main parameters determining the quality of the surface layer, such as microhardness, residual stresses, and roughness.

### Table 1. Classification of parameters determining the quality of the surface layer

<table>
<thead>
<tr>
<th>Group</th>
<th>Subgroup</th>
<th>Features</th>
<th>Designations</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric characteristics</td>
<td>Roughness</td>
<td>Maximum height of profile irregularities</td>
<td>$R_{MAX}$</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Height of profile irregularities</td>
<td>$R_Z$</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average arithmetic mean deviation of the profile</td>
<td>$R_A$</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average pitch of profile irregularities</td>
<td>$S_M$</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average pitch of local profile protrusions</td>
<td>$S_t$</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative reference length of the profile</td>
<td>$L$</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waviness</td>
<td>$H_b$</td>
<td>µm</td>
</tr>
<tr>
<td>Physical condition of the surface layer</td>
<td>Crystal structure</td>
<td>Lattice parameter</td>
<td>$a$</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dislocation density</td>
<td>$\rho$</td>
<td>cm$^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vacancy concentration</td>
<td>$c$</td>
<td>-</td>
</tr>
<tr>
<td>Deformation hardening</td>
<td>Layer depth</td>
<td></td>
<td>$h_N$</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td>Degree of build-up</td>
<td></td>
<td>$H_N$</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>The gradient of the sticking</td>
<td></td>
<td>$N_U$</td>
<td>kg/µm$^3$</td>
</tr>
</tbody>
</table>
2 Materials and methods of research

Studies of the effect of HF hardening and various ultrasonic treatment (UHT) methods on the structure and hardness were carried out for medium carbon steel 45 (0.45% C). HFI hardening was carried out in an induction furnace with an inductor output voltage of 40 V and an operating current frequency of 50 kHz.

Ultrasonic treatment was carried out according to the following schemes: ultrasonic treatment with continuous transmission of energy (CT); pulsed ultrasonic treatment (PUT); combination of ultrasonic treatment with pulsed treatment (CT + PUT). The treatment was performed with the ultrasonic frequency \( f = 18 \text{ kHz} \) and oscillatory displacement amplitude \( \xi = 10 \mu \text{m} \). During the ultrasonic blasting the tool - the ball vibrating with ultrasonic frequency was pressed to the processed surface with the static force \( P_{st} \) equal to 50 H and 100 H so that continuous contact between them was provided, and during the ultrasonic blasting a gap was created between the ultrasonic tool and the processed surface.

Microstructure was studied with an optical microscope "Neophot-21", microhardness was measured with a PMT-3 microhardness meter. Residual stresses were determined on the installation "DRON-3" by the method of multiple oblique surveys "\( \sin^2 \Theta \)".

3 Research results and discussion

Quenching by induction heating with high frequency currents is one of the most common methods of treatment of medium-carbon steels used for heavily loaded machine parts in order to improve their strength and fatigue characteristics by creating significant compressive stresses on the surface [3].

Surface plastic deformation (SPD) is widely used in the production of products and is of significant practical interest in shaping the performance properties of products. PPA, as a method of metal finishing, is used to increase surface hardness, strength, wear resistance and reduce roughness.

Ultrasonic treatment of metals is also widespread nowadays. Because of such an exposure, scallops from previous treatments are compressed on the surface, a riveted layer is formed, and residual compression stresses arise, which also contribute to the fatigue strength of products [4]. Compared to other methods of surface plastic deformation, ultrasonic treatment is characterized by better indicators of surface layer quality, such as microhardness, roughness and distribution of residual stresses [5].

Metallographic studies of the microstructure of steel 45 showed that, compared to the original sample after ultrasonic treatment (UHT) in the surface layer, the treated sample...
grains acquire an elongated shape and are oriented in the direction of deformation (Fig. 1). The thickness of the deformed layer is 150 µm. In the process of processing the value of deforming stresses decreases with distance from the surface, so the processes of dislocation multiplication, fragmentation of crystals into blocks and other accompanying phenomena that accompany hardening are of damping nature and the top part of the plastic deformed layer is the most hardened [6]. Ultrasonic exposure leads to a significant increase in the density of dislocations in the near-surface layers of the treated metals. If in non-deformed metals the average dislocation density is 10⁶...10⁸ cm⁻², after ultrasonic treatment the dislocation density increases to 3×10¹¹ cm⁻² that significantly increases the microhardness of the hardened layer [7-8].

The microhardness of the surface layer of steel 45 after such treatment is 3800 Pa...4200 Pa and depends on the clamping force of the ultrasonic tool to the machined surface (Fig. 2).

After quenching by induction heating with high frequency currents, a hardened layer up to 2 mm thick is formed, which has three characteristic zones. The first is a structure of martensite with residual austenite; the boundaries of martensite laths are weakly revealed, indicating that there are no precipitates on them. The second zone is transitional and has the structure of troostite and ferrite, and the third zone is the initial structure after normalization, consisting of lamellar sorbitol and ferrite. The microhardness of the hardened layer is 5600 Pa.

Subsequent ultrasonic (UZO) and impulse treatment (IPT) increases the surface hardness to 7600 Pa and 8000 Pa, respectively. The distribution of microhardness over the layer depth is shown in Fig. 3.
Fig. 2. Distribution of microhardness on depth of the hardened layer of steel 45 after ultrasonic processing on an axis of ordinates - microhardness, on an axis of abscissa - distance from a surface at:
1 - Pst = 50 H, 2 - Pst = 100 H

Fig. 3. Distribution of microhardness on depth of the hardened layer of steel 45 after various types of hardening processing on axis of ordinates - microhardness, on axis of abscissa - distance from surface: 1 - hardening HF; 2 - hardening HF + RCD; 3 - hardening HF + RCD

Fig. 4 shows the microstructures of steel 45 after hardening by HFI with subsequent ultrasonic treatment and pulse ultrasonic treatment. It can be seen that ultrasonic exposure leads to crushing of martensite crystals and their orientation in the direction of deformation, a block structure is formed, and the sizes of laths and blocks are significantly reduced.
In this work, the distribution of residual stresses arising in the near-surface layer during surface plastic deformation by ultrasonic and SPD methods was investigated. To increase the efficiency of ultrasonic influence the processing was carried out by increasing the number of passes with the ultrasonic tool on the surface of the sample.

Studies have shown that all samples have compression residual stresses on the surface, the value of which increases with the number of passes of the ultrasonic tool on the machined surface (Fig. 5 and 6).

Fig. 4. Microstructures of steel 45: a - hardened HFC; b - hardened HFC+CFC; c - hardened HFC+CFC, x500.

Fig. 5. Distribution of residual stresses on the depth of the hardened layer in steel 45 after various types of treatment, on the abscissa axis - distance from the surface: 1) HF; 2) HF + RCD (1 pass); 3) HF + RCD (3 passes); 4) HF + RCD (5 passes).
Fig. 6. Distribution of residual stresses on the depth of the hardened layer in steel 45 after various types of treatment, abscissa axis - distance from the surface: 1) HF; 2) HF + SPT (1 pass); 3) HF + SPT (3 passes); 4) HF + SPT (5 passes).

Fig. It can be seen that ultrasonic treatment increases the residual compressive stresses arising in the surface layer of a sample of steel 45 after HF hardening treatment. Moreover, the compressive stresses increase especially strongly after HF treatment with five passes and reach the value of 1200 Pa. In this case, the depth of the layer in which significant compressive stresses are observed reaches 1.5 mm.

In ultrasonic machining, as in any method of surface plastic deformation, the average height of surface irregularities is reduced. However, unlike other methods of surface plastic deformation, ultrasonic treatment is characterized by multiple deformations. Therefore, the average height of irregularities is several times lower than in conventional hardening or grinding. The surface acquires a regular relief, and the average height of protrusions and depressions is significantly reduced. Roughness as well as hardness and level of residual stresses at ultrasonic processing depend on the clamping force $F_N$ and amplitude of oscillatory displacements $\xi$ and after processing according to the suggested modes decreases from $Ra = 0.63 \mu m$ to $Ra = 0.16 \mu m$.

4 Conclusions

1. The use of combined methods of surface hardening of structural steels makes it possible to increase the efficiency of each of the methods used and to obtain higher quality indicators of the surface layer compared to their use separately. So, UZO raises microhardness of a surface layer of structural steels in 1.5 times, HF hardening - more than in 2 times, a combination of HF hardening + UZO - in 3 times and HF hardening + UZO - in 3.2 times.

2. The microhardness increase after HFI hardening is explained by formation of martensite structure, and after ultrasonic influence, the microhardness additionally increases at the expense of increase in dislocation density, crushing of structure fragments, and the microstresses arising at distortion of a crystal lattice.

3. Ultrasonic treatment increases residual compressive stresses arising in the surface layer of samples of steel 45 hardened by HF hardening. Compressive stresses increase especially strongly after SPMT with five passes and reach the value of 1200 Pa. The depth of the layer, in which significant compressive stresses are observed, reaches 1.5 mm.
4. Ultrasonic treatment has a positive effect on the surface quality, significantly reducing its roughness from Ra = 0.63 μm to Ra = 0.16 μm.

5 Acknowledgements

References

1. O. V. Chudina, Hybrid Technology for Surface Hardening of Structural Steel, Russian Engineering Research, 42(11), 1192–1194 (2022)


