Revealing the technological modes range for ultrasonic surface hardening of cast iron

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Abstract. Prospects of using the ultrasonic surface hardening of different materials as a way of achieving a simultaneous strengthening and finishing effects are presented. It is shown that this method is applicable for non-rigid and brittle parts. Thus, it allows processing gray cast iron. Therefore, the paper is devoted to establishing technologically significant parameters of ultrasonic surface hardening of particular gray cast iron. Research was conducted using mathematical modeling of the process. According to the calculations, the application of the modes revealed makes it possible to achieve the depth of the hardened layer up to 2 mm. Moreover, the parameters of the hardened layer, such as the diameter of a single imprint and the maximum intensity of deformation for specified processing conditions are calculated.

1 Introduction

One of the urgent problems of modern machine production is the formation of specific properties of the surface which differ from the properties of the basic material. The analysis of methods for modifying the surface layer has shown the prospects of using surface plastic deformation methods in the technological processes of manufacturing machine parts. The ultrasonic surface hardening plays a significant role among other methods of surface hardening. This method can be described as a method of surface layer deforming by instrument vibrating with the ultrasonic frequency. In different works it can also be named as "ultrasonic impact treatment" [1], "nanocrystal surface modification" [2], "ultrasonic surface rolling processing" [3, 4], "ultrasonic impact peening" [5] "ultrasonic hardening" [6], ultrasonic deformation [7], diamond-ultrasonical treatment [8] etc. This method is widely used in technology to modify the surface layer due to the simultaneous strengthening and finishing effect. It is shown in [9, 10] that ultrasonic surface hardening allows forming a hardened surface layer with increased mechanical characteristics: microhardness and stress-strain state. In addition, the imprints of the deforming element create a regular microrelief on the surface. All this combined allows increasing the wear resistance and durability of machine parts. As shown in [2, 9], due to the low static force, the ultrasonic surface hardening can also be used for non-rigid, thin-walled parts, as well as parts made of brittle materials. However, it should be noted that the brittle materials have

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low ductility. Therefore they are difficult to plastic deformation. That is why it requires a certain approach to the choice of the technological mode. Under the technological mode we understand a set of the following processing parameters: the amplitude and frequency of ultrasonic vibration of the instrument, the frequency of vibrating, the static force of pressing the tool against the surface being machined, the diameter of the deforming element, and the kinematic parameters (feed and speed) that ensure the tool movement over the surface.

This work is aimed at revealing the region of the regime parameters of ultrasonic surface hardening of gray cast iron. In order to reveal the regularities in formatting the characteristics of the surface layer in the process of ultrasonic hardening, theoretical studies were carried out. During studies the interrelationships of the regime parameters with changes in the microgeometry of the processed surface as well as the mechanical properties of the surface layer were revealed. The investigations were based on the known model of ultrasonic plastic deformation described in [11-12].

2 Theoretical framework

To describe the motion of the deformer the equation of free oscillations of the rod (1) in the model of ultrasonic plastic deformation the, was used [11]:

$$\frac{\partial A(t)}{\partial t} = V_{K0}(x,t) + \frac{\partial A_0(x,t)}{\partial t} + \frac{F_D(t)}{\rho \cdot c \cdot S} \tag{1}$$

where $A(t) = A(0, t)$ – displacement of the deformer, $V_{K0} = \partial A(x,t_0)/\partial t$, $A_0(x,t) = A(x,t_0)$ – distribution of the vibration velocity and displacements along the length of the waveguide at the time t_0 (before impact), $F_D(t)$ – acting force, ρ- density of the waveguide material, c – spreading speed of longitudinal sound waves in the waveguide, S- square of the waveguide cross section.

It is necessary for ultrasonic surface hardening, to provide a combination of finishing and hardening effects with minimal time and energy costs when the required parameters are achieved. A generalizing characteristic of the hardening and finishing effect can be considered by the diameter of a single imprint (d_{otp}) made by the impact of an ultrasonic instrument. In [11-12], a relation between the value (d_{otp}) and the processing parameters is established:

$$d_{otp} = \int 2\sqrt{D_c \cdot h(t)} dt \tag{2}$$

where D_c – diameter of the deforming element, $h(t)$ – depth of tool indentation at time point t.

The depth of the tool indentation $h(t)$ changes during the deformation in two different dependencies corresponding to the indentation period of the tool (3) during the time t0 - t1 and the reverse phase (4) in the time period t1 - t2.

$$h_1(t) = A_{max}\left[\sin(\omega t + \varphi_1) - e^{-q\omega t}\sin\varphi_1\right], \tag{3}$$

$$h_2(t) = A_{max}\left\{\left[\sin(\omega t + \varphi_2) - (\sin\omega t_1 + \varphi_2)e^{\frac{q\omega(t-t_1)}{R}}\right] + Rh_{max}\right\}, \tag{4}$$

where A_{max} – amplitude of ultrasonic vibrations, ω – circular oscillation frequency, $\varphi_1 = \varphi_0$ +arctg q, φ_0 – the tool trajectory angle corresponding to the time of starting deformation (t_0), q=πHB· D_c / $\omega\rho$cS, ρ – density of the waveguide material, HB – hardness of the material, Dc – diameter of the deforming element, c – spreading speed of longitudinal sound waves in the waveguide, S – square of the waveguide cross section, $\varphi_2=$ φ_1+arctg(q/R), $R = \left(\dfrac{D_c \cdot 10^{-3}}{2h_{max}}\right)^{1/3}\left[\dfrac{3\pi(1-\mu^2)HD}{E}\right]^{2/3}$ - coefficient of elastic recovery, here μ – Poisson's ratio, E – Young's modulus of the processed material; h_{max} – maximum penetration depth of the deformer; HD – dynamic hardness of the processed material, HD=HB·k (k=1,5÷2,25 [13]).

The time t_0 is determined by the equation characterizing the change in the deformation indentation depth in the period t_0 - t_1 when the left part of equation (2) reaches zero after determining the value of ϕ_1. The value of ϕ_1 is determined by solving the equation (5) taking into consideration the known static force.

The time moments t_1 and t_2 are determined by solving of the equations (6) and (7), respectively [11].

Integrating the equation (2) with equations (3) and (4), which describe the change in the indentation depth of the deformer at different stages of deformation, an expression for determining the diameter of the plastic imprint (d_{otp}) can be obtained as (8).

$$F_{cr} = \frac{\pi \cdot HD \cdot D_c \cdot A_{max}}{T}\left(\begin{array}{l} K_c\left\{\dfrac{\sin\varphi_1}{q\omega}\left(e^{-q\omega t_1}-1\right)-\dfrac{1}{\omega}\left[\cos(\omega t_1+\varphi)-\cos\varphi_1\right]\right\}+ \\[3mm] +\dfrac{K_c}{R}\left\{\dfrac{\sin(\omega t_1+\varphi_2)R\cdot e^{\frac{q\omega t_1}{R}}}{q\omega}\right\}\left[e^{-\frac{q\omega t_2}{R}}-e^{-\frac{q\omega t_1}{R}}\right]- \\[3mm] \dfrac{1}{\omega}\left[\cos(\omega t_2+\varphi_2)-\cos(\omega t_1+\varphi_2)\right]+\dfrac{R\cdot h_{max}}{A_{max}}\left(t_2-t_1\right) \end{array}\right) \quad (5)$$

$$\cos(\omega t_1+\omega_1)+qe^{-q\omega t_1}\cdot\sin\varphi_1=0 \quad (6)$$

$$A_{max}\left[\sin(\omega t_2+\varphi_2)-\sin(\omega t_1+\varphi_2)\cdot e^{-\frac{q\omega((t_2-t_1))}{R}}\right]+Rh_{max}=0, \quad (7)$$

$$d_{otp} = 2\left[Dc\cdot A_{max}\cdot\left(\begin{array}{l}\sin(\omega t)\cdot\cos(\varphi)\cdot e^{q\omega t}+ \\ +\cos(\omega t)\cdot\sin(\varphi)\cdot e^{q\omega t}- \\ -\sin(\varphi)\end{array}\right)\cdot e^{-q\omega t}\right]^{\frac{1}{2}}\Bigg|_{t_0}^{t_1} \quad (8)$$

3 Discussion

Modelling showed that the value of the diameter of the imprint could be obtained by a various combination of the technological parameters. Fig. 1 shows that each combination of fixed values of the indenter diameter D) and the amplitude (Amax) corresponds to a single value of the static force Fst, which is the maximum under the given processing conditions.

When moving along the line d = const, it is possible to obtain a combination of mode parameters that ensure the same diameters of single imprints. It should be noted that each point belonging to this family of lines corresponds to the maximum achievable print size for a particular combination of fixed values (D), (Amax), (Fst).

The diameter of the imprint (d_{imp}) does not exceed 0.2 mm when D = 1. Considering the dimensions of the machined surfaces of gray cast iron parts, further reduction of the imprint diameter is not advisable. Otherwise the processing time of the entire surface is increased by decreasing the feed and speed. In this case, the condition D ≤ 1 mm can be one of the limitations for the processing mode parameters. When the indenter diameter (D) equals 20 mm, the value of the ultimate static force reaches 1107 N, which ensures the strain intensity in the surface layer not more than $\varepsilon_{i,0} = 0.02$. Further increase in D is not advisable, since a less deformation effect does not provide the required strengthening effect. Thus, the second restriction of the mode parameters is the condition: D≥20 mm.

Since the inclusions of graphite in gray cast iron can reach sizes up to 0.15 mm, one more restriction can be revealed for the parameters of the ultrasonic surface hardening: the diameter of the imprint d=0.2 mm. It should be noted that the different deformation intensity values ($\varepsilon_i, 0$) can be achieved. Fig.2 shows the combinations of ultrasonic surface hardening parameters, which ensure identical values of the plastic deformation intensity ($\varepsilon_i, 0$) at the center of the imprint. Since for each material there is a limiting value of the intensity of deformation, the excess of which can lead to desreasing the hardeness of the material, one more restriction must be established. For gray iron $\varepsilon_i, 0 = 0.2$ will be the restriction, that limits the value of the intensity of plastic deformation, which determines the maximum possible strengthening effect. The minimum strengthening effect, as shown above, is determined by the restriction $\varepsilon_i, 0 = 0.02$.
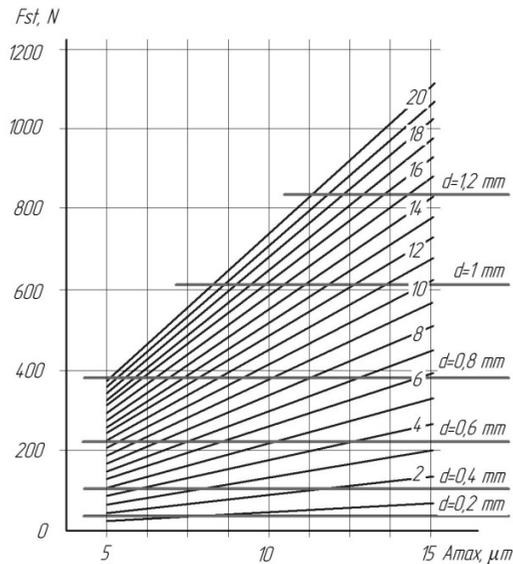

Fig. 1. Distribution of lines of equal imprint diameters (d_{imp}) for different diameters of the deformer (D).

The calculated zone of the mode parameters for frequency f = 18 kHz is shown in Fig. 3. In accordance with the constraints described above, this zone is limited by curves 1 and 2 corresponding to the largest and smallest deformer diameters. Curves 3 and 4 determine the minimum and maximum values of the oscillation amplitude. The minimum and maximum strain rates are determined by curves 5 and 6. Finally, curve 7 determines the minimum allowable diameter of the print.
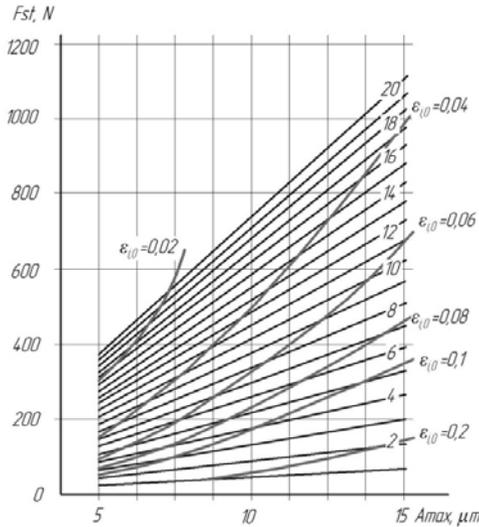
Fig. 2. Distribution of lines of equal strain intensities ($\varepsilon_{i,0}$).
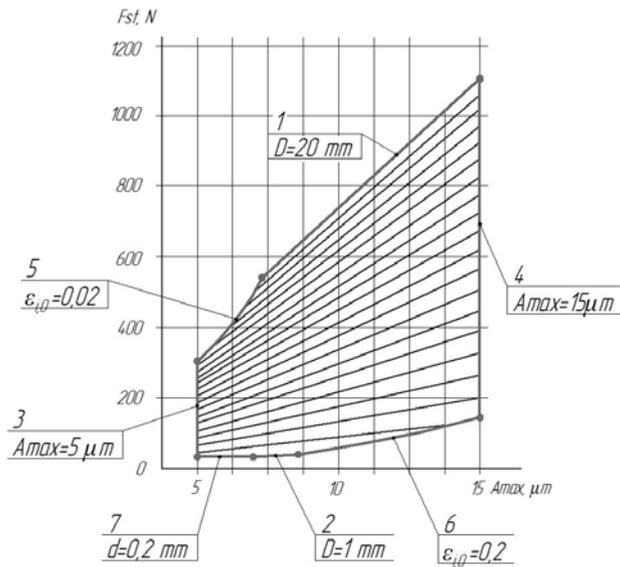
Fig. 3. Calculated range of the mode parameters for ultrasonic surface hardening of cast iron.

4 Conclusions

Realization of processing at the established zone of technological mode allows forming the deformed layer with a depth of up to 2 mm, and reaching the maximum intensity of deformation up to 0.2, with obtaining imprint diameters up to 1.3 mm

As the frequency increases, the calculated zone shifts upward, to higher values of the static force. At the maximum displacement (f = 66 kHz, D = 20 mm, Amax = 15 μm), the static force reaches a value of 1500 N.

Mathematical modeling of the deformation process allowed establishing a calculated range of technologically grounded processing parameters providing the necessary deformation effect in the processing of gray cast iron.

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