

Residual Stress, Structure and Other Properties Formation by Combined Thermo-Hardening Processing of Surface Layer of Gray Cast Iron Parts

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Abstract. The proposed combined thermo-hardening processing of gray cast iron enables to control the surface layer structure and mechanical properties formation. The processing includes high-speed heating by low-temperature plasma source and ultrasonic surface plastic deformation. The algorithm of calculation the stress-strain state of a surface layer at combined processing of gray cast iron is developed. This algorithm is based on method of sections. The ultrasonic surface deformation contribution is determined during formation of residual stresses. It is established that the combination of the thermal and deformation effects on the material provides an additional increment of microhardness and increase of surface layer thickness. Experimental results shows that the features of structural and phase transformations in a surface layer are revealed without a surface melting by energy of low-temperature plasma. The top of a layer does not contain inclusions of graphite that testifies to change of structural transformations in conditions of combined processing.

1. Introduction

The durability of machine parts working in conditions of alternating load, fatigue wear, high dynamic load is determined by mechanical properties and structure of the material. The gray cast iron has the rather low strength characteristics, so the formation of favorable stress-strain state condition of a surface layer of machine parts is important.

Improving performance properties of the surface layer can be achieved using thermal and deformation hardening methods. Efficiency of laser and plasma hardening methods are shown by authors [1, 2]. Results of hardening by deformation, including ultrasonic methods are presented in papers [3, 4, 5]. However, combined technologies based on a combination of high thermal and deformation effects represent significant opportunities to provide high-strength state of the surface layer [6].

The surface layer properties during combined thermo-hardening processing are formed in two stages: ultrasonic surface plastic deformation and high-speed heating by energy of low-temperature plasma. Each of this stage changes the structural and stress-strain state of the material.

The ultrasonic surface plastic deformation is carried out by the instrument oscillating with an amplitude $2A$ at static load P (Figure 1). Thermal and structural changes caused by high-speed heating by a source of density of power q with a concentration factor k (Figure 1). For effective control of processing the study of structural and stress-strain state forming is necessary.



However mechanical and X-Ray methods of residual stresses determination allows studying only final condition. Mechanical methods as a rule have destructive testing character. They are not applicable for working machine parts and requires manufacturing of special pattern. Furthermore the X-ray method allows to determine stress only in the limited surface layer. Thus mathematical modeling which aimed at simulation of stresses and deformations forming process at combined effect is of interest.

Structural and phase transformations were investigated by metallographic analysis. The microhardness was accepted as a characteristic of mechanical properties of a surface layer.

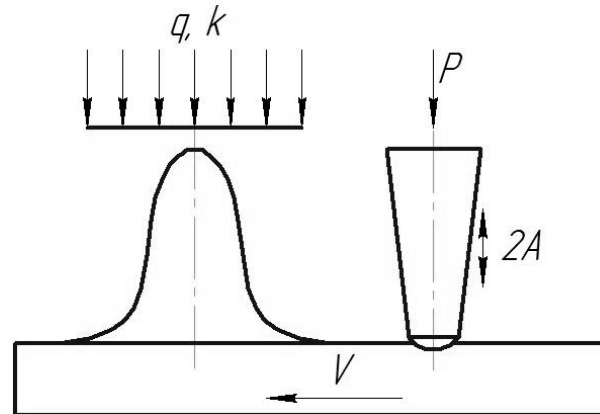


Figure 1. Scheme of the combined processing.

2. Materials and methods

A well-known method of sections was applied to calculate the stress-strain state [6]. In this paper the earlier moment of calculation for combined processing when the ultrasonic deformation precedes high-speed heating is not shown. In this research processing presented as combination of two stages - deformation and thermal effects. At a both stages the scheme of interaction of material with a source of effect can be approximated by the scheme of an equivalent rod system. According to a method of sections we can split a part on computational layers. There is condition that within the limits of each layer it is possible to consider deformations, stresses and temperatures constant for current step of calculations.

The rod approximation allows to determine stresses in computational layers from one layer to another though the method of series tests and iterations under the formula:

$$\sigma_{zi} = [-\delta_i + e_z + \Theta_x y_i] E_i \quad (1)$$

where δ_i - a total strain of a calculated layer; e_z - relative axial strain; Θ_x - relative angle of rotation of transversal sections; y_i - the ordinate of a computational layer center; E_i - coefficient of elasticity.

At the first stage of processing the surface layer is formed by imposing impressions from separate imprints of ultrasonic tool. The intensity of deformation in each imprint within the limits of depth h_s is determined by expression:

$$\varepsilon_i = \varepsilon_{i,0} \exp \left[-C \cdot \frac{y_i}{h_s} \right] \quad (2)$$

Depth of distribution of plastic deformation (h_s) and it's intensity in center of an imprint ($\varepsilon_{i,0}$) can be expressed through parameters of elastic-plastic contact of the tool with a surface:

$$\varepsilon_{i,0} = 2.4 \cdot \sqrt[3]{\left(\frac{2hk_d^{-2}}{D_p} \right)^2 \cdot \left(\frac{B}{A} \right)^{0.2}}; \quad (3)$$

$$h_s = k_d \sqrt{9.81 D_p h_{\max} - 1.42 ab}, \quad (4)$$

where k_d , D_p , A , B , a , b - the geometric parameters of a contact. This parameters are determined by the solution of differential equation of the tool motion with allowance for dynamic properties of gray cast iron [6]; h_{\max} - maximum depth of the ultrasonic tool indentation and h - depth of residual the plastic imprints.

Out the plastically deformed zone we accept the linear law of distribution of intensity of deformation:

$$\varepsilon_i = k_\varepsilon y_i \quad (5)$$

where k_ε - constant of proportionality, defined of the equilibrium condition of internal forces.

Applying rod approximation we consider, that the intensity of deformation is numerically equal to the biggest deformation. Receiving in (1) $|\delta_i| = |\varepsilon_i|$ we can define stresses in computational layers.

Summarizing values of deformations and stresses from a step to step during process of deformation we can obtain the characteristics of the stress-strain state to the end of the first stage of processing:

$$\delta_{R,i} = \sum_k \delta_{i,k}; \quad \sigma_{R,i} = \sum_k \sigma_{i,k}; \quad e_{Z,i} = \sum_k e_{Z,k}; \quad \Theta_{x,R} = \sum_k e_{x,k} \quad (6)$$

where k - number of a step of calculation.

At the second stage of processing the computational layers will be determined by the sum of thermal expansions of graphite inclusions (δ_G) with temperature and structural extensions of a metal matrix of gray cast iron ($\delta_{MT} + \delta_{MS}$):

$$\delta_i = \alpha \delta_G + \beta (\delta_{MT} + \delta_{MS}) \quad (7)$$

where α and β - volumetric share of graphite inclusions and metal matrix (for gray cast iron $\alpha=0.025$, $\beta=0.975$).

The matrix strains were defined through changes of volumes of phases, which are included in it's structure:

$$(\delta_{MT} + \delta_{MS}) = \frac{V_T - V_{T_0}}{3V_{T_0}} \quad (8)$$

where V_T and V_{T_0} - volumes of a matrix at initial (T_0) and current (T) temperature.

In it's turn volume of a matrix at current temperature can be calculated as the sum of volumes of separate phases (V_{JT}):

$$V_T = \sum_j \alpha_j V_{\alpha_j T} \quad (9)$$

where α_j - volumetric contents of j^{th} phase in metal matrix.

According to the diagram of volumetric condition of phases the temperature relations of volumes of possible phases included in the matrix of the gray cast iron (ferrite (V_α), cementite (V_c), austenite (V_γ), martensite (V_M)) can be calculated by expressions:

$$\left. \begin{aligned} V_\alpha(T) &= 0.12708 + 5.528 \cdot 10^{-6} T; & V_\gamma(T, C) &= 0.12282 + 8.56 \cdot 10^{-6} T + 2.15 \cdot 10^{-3} C; \\ V_c(T) &= 0.13023 + 4.884 \cdot 10^{-6} T; & V_M(T, C) &= 0.12708 + 4.448 \cdot 10^{-6} T + 2.79 \cdot 10^{-3} C \end{aligned} \right\}, \quad (10)$$

where C - percentage of carbon in a phase.

Volume of matrix (V_T) is determined pursuant to regularities of structural transformations at heating and cooling for gray cast iron (Table 1). In Table 1 the following labels are adopted:

A_{c1} - temperature of the beginning of austenite transformation determined with allowance for influence of silicon, included in cast iron a structure, and high-speed character of heating;

V_p - volume of a perlite matrix of gray cast iron:

$$V_T = V_p = 0.88 \cdot V_\alpha(T) + 0.12 \cdot V_c(T) \quad T \in [T_0; A_{c1}] \quad (11)$$

where 0.88 and 0.12 - volumetric shares of ferrite and cementite respectively;

A_γ - volumetric share of austenite, generated to a moment, when temperature increase up to current value T . The research on a kinetics of α - γ transformation at continuous high speed heating and data

obtained from the solution of a diffusion problem, show that duration of transformation medium laminated perlite in austenite has exponential character. It can be calculated by expression:

$$\tau_{\alpha-\gamma} = 0.1 \cdot \exp(-0.00051 \cdot (V_H - 10^3)) \quad V_H \in [10^3; 10^4] \quad (12)$$

At known values of heating speed (V_H) and time $\tau_{\alpha-\gamma}$ the temperature T_k at which the transformation will be finished, can be determined by expression:

$$T_k = A_{C1} + V_H \cdot \tau_{\alpha-\gamma} \quad (13)$$

Accepting the exponential law of change A_γ , and taking to account that $T=T_k$ and $A_\gamma=1$, we can present change A_γ during heating by expression:

$$A_\gamma = \left(1 - \exp \left[-6.9 \frac{T - A_{C1}}{T_K - A_{C1}} \right] \right) \quad T \in [A_{C1}; 911^\circ\text{C}] \quad (14)$$

$$M = \left(\frac{0.05(M_H - T)}{M_H - 20} \right)^{0.2} \quad M_K \leq T \leq M_H \quad (15)$$

where M_H and M_K - temperature of a beginning and the end of martensite transformation.

M - the volumetric share of martensite, generated to a moment, when temperature downturn up to current value T . Taking into account, that austenite is transformed in martensite, near to temperature M_H and that at surface quenching of gray cast iron in a structure of a hardened layer remains from 40 up to 60% residual austenite, we can obtain M by expression:

Table 1. Values of specific volume of matrix (V_T) of gray cast iron

	$T_{\max} < A_{C1}$	$A_{C1} \leq T_{\max} < 911^\circ\text{C}$	$T_{\max} \geq 911^\circ\text{C}$
Heating	$T < A_{C1}$	$A_{C1} \leq T < 911^\circ\text{C}$	$T \geq 911^\circ\text{C}$
	V_P	$(1 - A_\gamma)V_P + A_\gamma V_\gamma$	V_γ
Cooling	$M_H < T \leq T_{\max}$		
	V_P	$(1 - A_{\gamma\max})V_P + A_{\gamma\max}V_\gamma$	V_γ
		$M_K \leq T \leq M_H$	
		$(1 - A_{\gamma\max})V_P + A_{\gamma\max}[(1 - M)V_\gamma + MV_M]$	$(1 - M)V_\gamma + MV_M$

To unit calculations of stresses and deformations at two stages in process of combined processing simulation the fulfillment of the following requirements is necessary:

1. At both stages the calculations should be executed for the same computational layers;
2. Resultant values of the characteristics of the stress-strain state obtained on expression (6) after ultrasonic deformation should be introduced as initial values in the beginning of second stage of calculation.

At the experimental part of research the samples with sizes 25x25x100 mm of gray cast iron, containing C-3.3%, Si-2.3%, Mn-0.46%, Cr-0.092%, Ni-0.12% are used. Ultrasonic deformation execute by the tool with spherical working part (indenter) with radius 4mm. Oscillation amplitude accepted 15 μm and oscillation frequency 20 kHz. For plasma heating the plasma generator with a tungsten electrode and fixation of arc length was used.

The modes of ultrasonic deformation and plasma heating were set from condition of obtaining of hardened layer with maximum thickness and absence of surface melting.

3. Results and discussion

The simulation of the first stage of processing has shown, that the ultrasonic deformation on all investigated modes (amplitude from $A=5$ up to $A=15\mu\text{m}$, static effort from $P=50$ up to $P=1500$ N, the ultrasonic frequency from $f=18$ up to $f=66$ kHz) forms in a surface layer compressing residual stresses. Distribution of residual stresses on a thickness of detail is shown on Figure 2.

The experimental data shows that the ultrasonic plastic deformation creates a surface layer by a thickness up to $300\mu\text{m}$ with microhardness up to 3560 MPa for gray cast iron with initial structure containing up to 95% of perlite and inclusions of flaked graphite and with microhardness $1850\text{--}2100\text{ MPa}$ (Figure 3, curve 1).

The analysis of the deformed layer structure has shown that such increase of microhardness is stipulated first of all by deformation of a matrix. The ultrasonic processing results to increases of dispersibility of matrix structural components - splitting, deforming of cementite plates in perlite (Figure 4). The surface roughness after ultrasonic deformation reduced from $Ra\ 2.5\mu\text{m}$ to $Ra\ 0.66\mu\text{m}$. The completely new regular microrelief was generated.

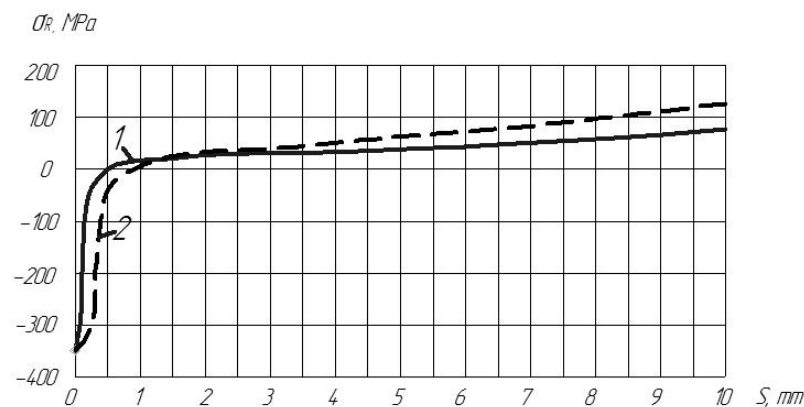


Figure 2. Distribution of residual stresses on a thickness of detail ($f=18$ kHz, $D=8$ mm, 1 - $P=185$ N, $A=5\mu\text{m}$, 2 - $P=420$ N, $A=15\mu\text{m}$)

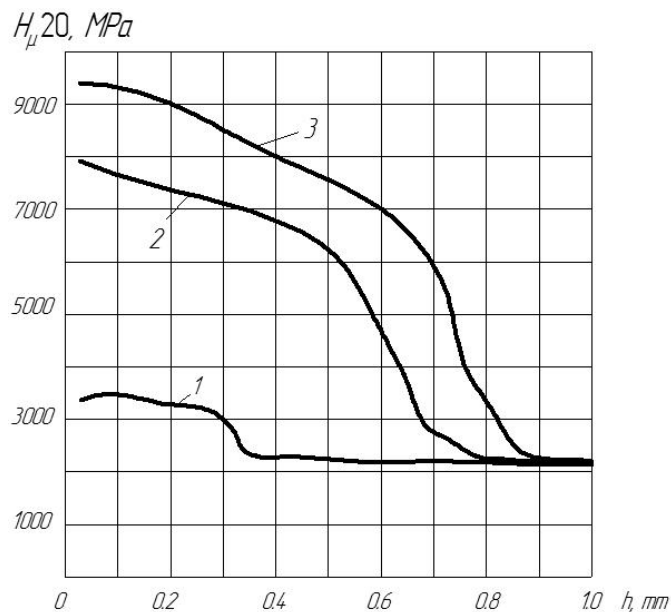


Figure 3. Distribution of microhardness on depth of a surface layer: 1 - ultrasonic deformation; 2 - plasma hardening; 3 - combined processing

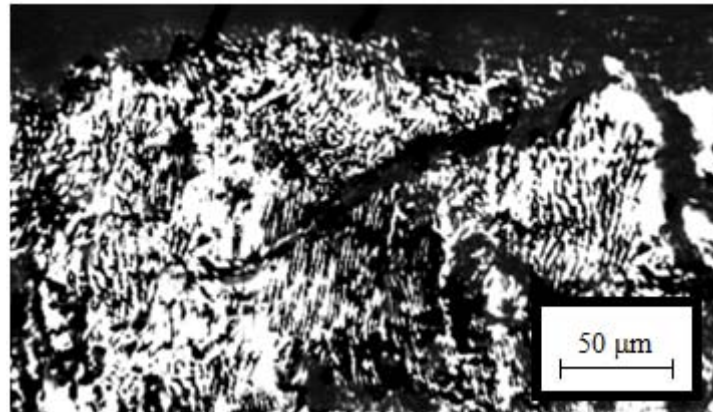


Figure 4. Structure of a surface layer after ultrasonic deformation ($P=250$ N, $V=50$ m/min)

At simulation of the second stage of processing it is established that in computational layers testing phase transformations at a stage of heating stresses reach a yield point. Therefore stresses changes only in layers, in which phase transformations does not happen. Change of modes of thermal effect (q , k , V) reducing depth of the phase transformation penetration and increase influence of ultrasonic deformation on a state of material at combined processing. Thus, changes of a combination of ultrasonic deformation modes with modes of high-speed heating allow to control process of stresses and deformations forming.

The high-speed surface heating by energy of low-temperature plasma without surface melting allowed to get a surface layer with thickness of $600\text{ }\mu\text{m}$ and microhardness up to 7500 MPa (Figure 3, curve 2).

For determination of graphite inclusions behavior during thermal processing the following experiment was conducted. Two samples enclosed in metal holders with microsections were prepared and microphotos of initial structure made at increase $\times 500$. Then in a special device the surfaces of microsections were densely pressed to each other. In such position the outside surfaces of samples were thermally treated. Then the microphotos of face surfaces were again made at the same increase. The comparison of the shape and sizes of graphite inclusions before and after heat treatment has not revealed essential changes. Apparently it is possible to explain this fact by a narrow time-temperature interval of austenite transformation in gray cast iron, because it is insufficient for dissolution of large graphite inclusions.

The analysis of a structure after etching by a 4% alcoholic solution of nitric acid has shown that it is possible to select different zones in it (Figure 5). At all zones there are graphite inclusions. The metal matrix in a zone 1 ($40\text{ }\mu\text{m}$ in depth) is formed by structures of a ledeburite. In a zone 2 (about $80\text{ }\mu\text{m}$) the matrix has a structure of a short-acicular martensite. The zone 3 represents a transient layer ($60\text{--}80\text{ }\mu\text{m}$) consisting from short-acicular and unstructured martensite. The zone 4 has the greatest expansion ($300\text{ }\mu\text{m}$) and the fine structure, which can be classified on a level of hardness as an unstructured martensite.

The zone 5 ($100\text{ }\mu\text{m}$) is formed by a sorbitic layer which hardness is gradually reduced and on a distance $600\text{ }\mu\text{m}$ from a surface reached values of initial structure characteristics.

The combined processing allowed to increase hardness (up to 9300 MPa) and thickness of surface layer (up to $750\text{ }\mu\text{m}$) (Figure 3, curve 3). The analysis of microstructure has shown that the zone 1 with a ledeburite structure has the larger sizes than at simple plasma heating and does not contain graphite inclusions (Figure 6). As the modes of thermal effect did not vary, it can be assumed that such difference in a structure of zones caused by change of a thing structure of graphite and metal matrix during ultrasonic deformation, that probably is reflected on kinetics of phase transformations.

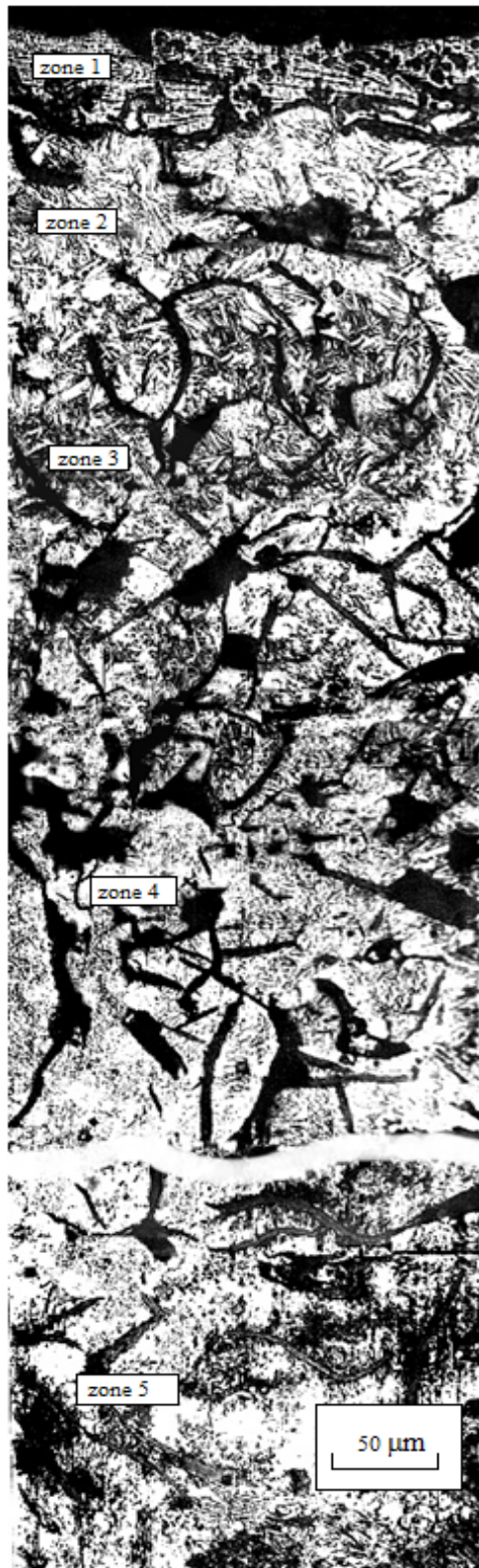


Figure 5. Structure of hardened layer after plasma hardening ($q=3300 \text{ W/cm}^2$, $k=10 \text{ cm}^{-2}$, $V=1.06 \text{ cm/s}$)

The sizes of underlying zones (2-5) at combined processing were increased on the average at 10% and their structure corresponds to structures obtained at plasma heating. The measurement of a surface roughness has shown immutability it at a level created by ultrasonic plastic deformation ($R_a 0.66 \mu\text{m}$)

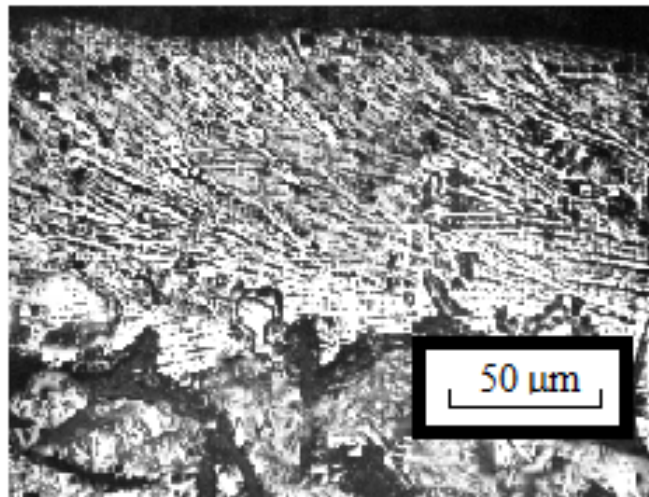


Figure 6. Structure of a hardened layer after combined processing ($P=250 \text{ N}$, $q=3300 \text{ W/cm}^2$, $k=10 \text{ cm}^{-2}$, $V=1.06 \text{ cm/s}$)

4. Conclusions

The application of rod approximation for the description of processes of loading at ultrasonic deformation and high-speed heating in combination allowed to execute simulation of process of residual stresses formation. Setting the optimum modes ensures required ratio of residual deformation of a surface with the residual stresses.

The combined hardening-finishing processing of gray cast iron on the base of deformation and thermal effects combination allows to change a kinetics of phase transformation to increase homogeneity of a structure. It makes it possible to get surface layers of an increased thickness with increased hardness without surface melting.

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