Simulation of surface work-hardening process during controlled inertial impact treatment of parts made of high strength cast iron

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Abstract. The paper deals with the results of simulation of elastoplastic impact of the deforming ball with the surface during inertial impact treatment. The deforming ball is made of hardened steel ShKh15 (GOST 801-78), and special high strength spheroidal graphite cast iron is used as the treated material. The paper provides recommendations on conditions for inertial impact treatment of surfaces.

1. Introduction

At present, a number of different methods are used for finishing and hardening treatment of inner cylindrical surfaces of parts made of high strength cast iron. Apart from reducing roughness, they produce a work-hardened layer, which increases the surface wear resistance. Shot peening is a widely used surface treatment method. Although shot peening is a relatively simple process, it has a number of disadvantages, including poor controllability and the necessity of using the abrasive recovery system and a special chamber. Inertial impact treatment (IIT) can be used as an alternative to shot peening as it is devoid of the above disadvantages. The main advantage of IIT is the ability to provide controllability of the technological process, both by creating a partially regular microrelief of the surface and by obtaining the required hardening properties. The tool used for IIT can be mounted on the most common types of metalworking machinery – lathes, drilling and milling machines.

A schematic representation of the tool used for IIT of cylindrical holes is shown in figure 1 [1]. When the tool is in operation, the rotational motion from the workpiece is transmitted through collet 9 with friction rings 10 to the ball-type reducer comprising drive link 5 and driven link 4, the latter serves as a supporting element for deforming balls 3. The supporting element sets the deforming balls in motion by interacting with disk with radial grooves 2. The balls move in the radial direction perpendicular to the surface and strike it. Concurrently, a change in the frequency of rotation of the workpiece leads to a change in the deforming ball velocity in the direction of the surface being treated at the moment of impact. When the feed motion of the tool changes in the axial direction, the entire surface is covered with dents produced by deforming balls striking the surface. These multiple dents have regular or partially regular characteristics.

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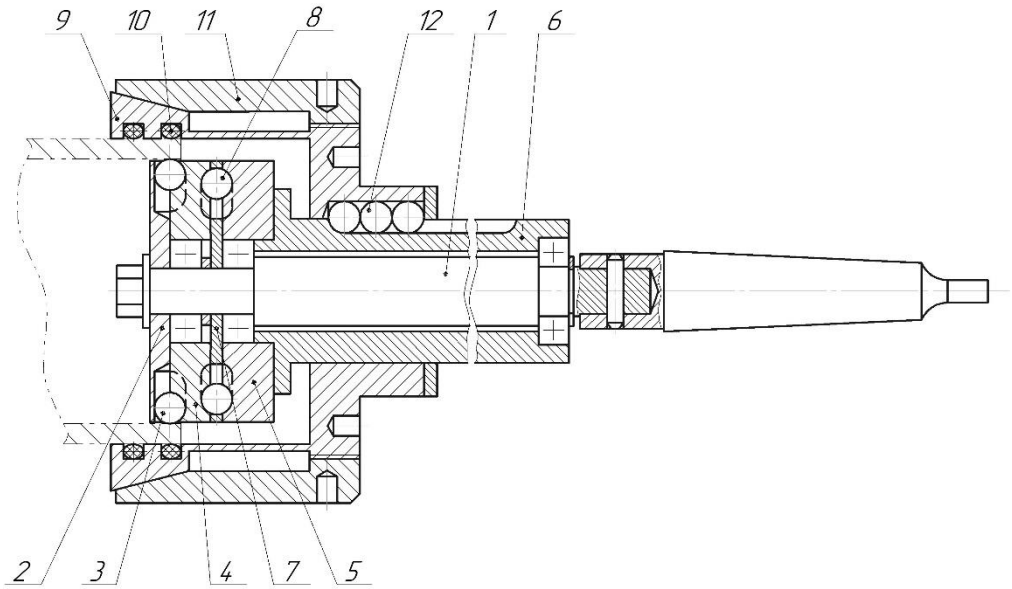

Figure 1. Inertial impact burnishing tool for holes.

To study the IIT process, a computer model simulating the impact of the deforming ball with the surface it strikes has to be created. The present paper is devoted to creating the simulation model and studying the IIT process characteristics.

The paper is aimed at building a computer model and performing numerical analysis of the process of inertial impact treatment of cylindrical holes in products made of high strength cast iron.

The methods used in this study are numerical methods (including the finite element analysis performed within SolidWorks environment) and methods of numerical approximation.

2. Results and discussion

By using the finite element analysis in SolidWorks environment, a model of elastoplastic impact of the deforming ball with the surface was developed.

The simulation of objects made of special high strength cast iron with spheroidal graphite, which has characteristics similar to VCh 60 cast iron (GOST 7293-85), was performed. The deforming balls were made of tempered bearing structural steel ShKh15 (GOST 801-78) with a diameter of 10 mm.

In the model, the velocity of the deforming ball at the moment of impact with the surface was varied.

During the simulation, the displacement of the material of the treated surface and arising residual stresses were studied.

It was assumed that the ball and the surface to be treated were perfectly smooth (no roughness), and shape and location errors did not occur. The impact was produced in the direction strictly perpendicular to the surface being treated; the surface at the point of contact was flat. The surface was subjected to a single impact; possible repeated impacts were not taken into consideration.

Enhanced ten-noded tetrahedral elements were used as finite elements (figure 2).

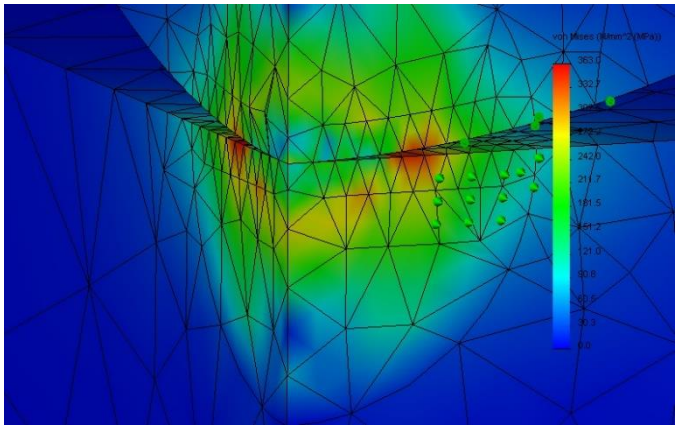

Figure 2. Results of finite element simulation of elastoplastic impact.

Before starting the calculations, the duration of interaction between the deforming ball and the surface was determined numerically (from the moment the ball strikes the surface to the moment the surface returns to its original state and the output parameters of the model are stabilized). For most numerical experiments, this time was assumed to be equal to 6×10^{-6} seconds.

The results obtained from the computer model simulation have shown that the deforming ball leaves a crater-like impression (dent) on the surface (figure 3, 100x magnification along the y-axis), which is in good agreement with the experimental data [2, 3].

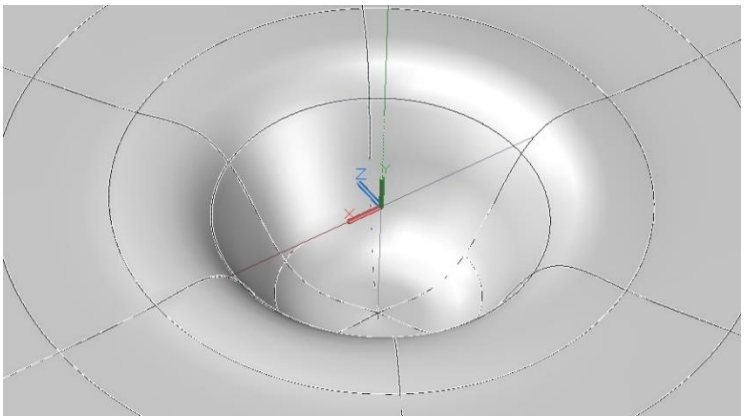

Figure 3. Deforming ball dent.

As can be seen in the figure 3, after the deforming ball strikes the surface, a number of phenomena related to formation of a new microrelief occur.

Firstly, the material in the central region of the ball dent (indentation) starts to flow; the surface tends to return to its original shape and becomes bulged to a greater or lesser extent. The amount of bulging is especially noticeable in ductile materials (steel) and less visible in cast iron (in the latter case, it is relatively larger for weak impacts).

Secondly, the material is squeezed out of the indentations into peripheral areas, which leads to formation of budging in the form of an annular ridge; the outer sides of the ridge asymptotically go down to the level of the initial surface.

Thirdly, under real conditions, when the impact produced by the ball in the radial direction occurs simultaneously with the rotation of the workpiece in the tangential direction, the dent caused by the impact becomes “blurred”, the surface is partially smoothed out, and the shape of the indentation becomes elliptical, elongated.

These three phenomena lead to the formation of the surface microrelief as a combination of crater-like areas [4, 5].

After IIT, the value of residual stresses in the depth of the workpiece is characterized by nonlinear dependence (figure 4), and at a noticeable distance from the treated surface this value tends to zero. For this reason, it is rather difficult to estimate the depth (borders) of the hardened layer.

For practical purposes, the following estimation criterion can be used.

The depth of work-hardening is the depth at which residual stresses exceed their maximum allowable value for the as-received material. For stabilized products made of ductile high strength cast irons, residual stresses should not exceed 20-40% of their yield strength. For example, the yield strength σ_y for VCh 60 cast iron is 370 MPa. For such materials, a magnitude equal to 30% of the yield strength, i.e. 111 MPa, was taken as the maximum allowable value of residual stresses.

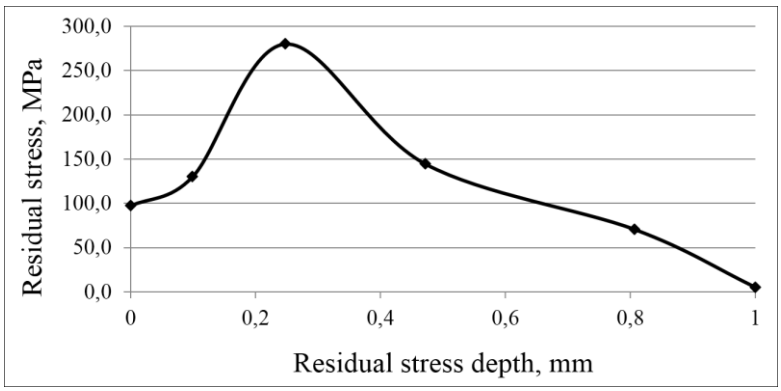

Figure 4. Distribution of residual stresses in the material under the point of impact (deforming ball material - ShKh15; workpiece material – high strength cast iron; ball diameter - 10 mm; ball velocity - 1.5 m/s).

The relationship between the depth of residual stress penetration into the material and the velocity of the deforming ball at the moment it strikes the surface, obtained from the simulation, is shown in figure 5.

The residual stresses of the work-hardened area are located in the subsurface layer both on the sides of the indentation and on the sides of the ridge of the ball dent.

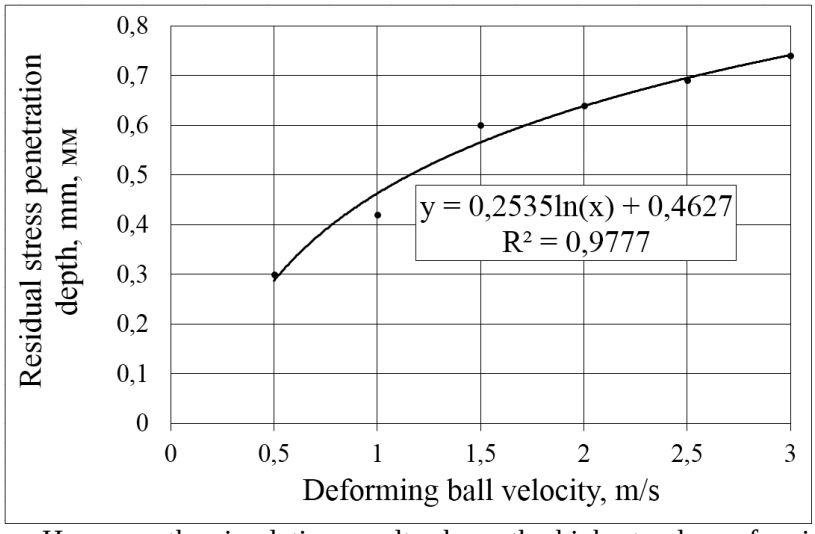

Figure 5. Relationship between residual stress penetration depth and deforming ball velocity.

Hence, as the simulation results show, the highest values of residual stresses are observed both in the central region of the indentation (microrelief below the initial surface) and in the area of the ridge itself (microrelief above the initial surface). Besides, residual stresses are noticeable in areas outside

the dent, below the initial surface of the workpiece adjacent to the ridge, especially in case of high velocity impacts. This result is illustrated by an overlay graph showing the relationship between the location of residual stresses on the surface and the distance from the point of impact (figure 6).

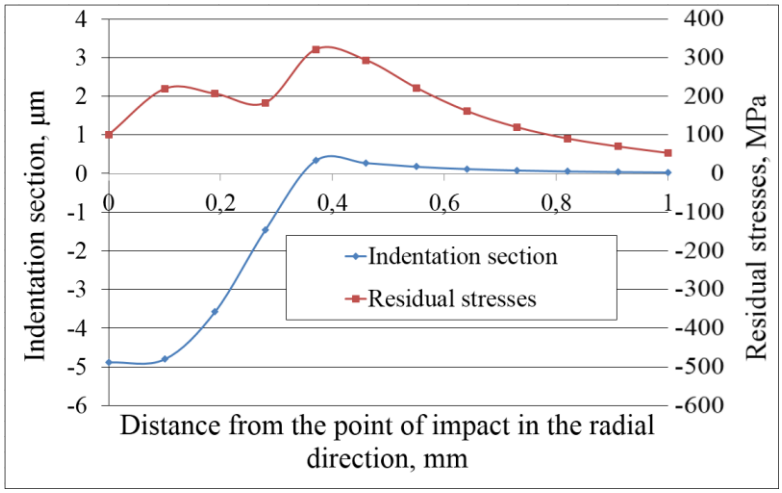

Figure 6. Relationship between location of residual stresses on the surface and distance from the point of impact superimposed on the half-section of the indentation.

As shown in figure 6, the residual stresses on the treated surface vary with distance from the point of impact, and the nature of these variations remains unchanged with different velocities of the deforming ball.

We believe that the diameter of the work-hardened area can be estimated if the formed surface microrelief is considered from the point of view of its future contact with the mating surface. Obviously, this contact will occur mainly in the area of the ridge, and at the beginning of the running-in process it will not affect the area of the indentation. The radius of this area corresponds to transition of the magnitude of residual stresses to values lower than the maximum allowable value for the as-received material (as indicated above, the magnitude of 111 MPa was taken as the maximum allowable value).

It is evident that residual stresses exceeding this value are located in a ring-shaped region. Figure 7 shows the relationship between the width of this region and the deforming ball velocity obtained from the simulation.

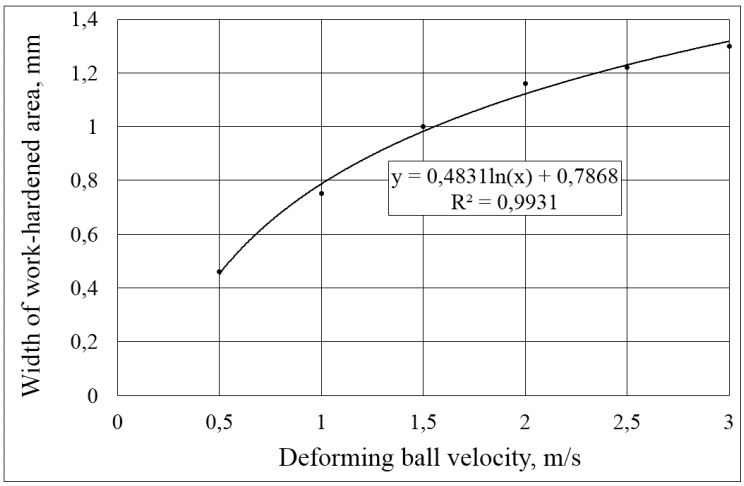

Figure 7. Relationship between width of work-hardened area with residual stresses and deforming ball velocity.

As can be seen from the graph, the relationship is nonlinear and tends to saturate. It is also obvious that a significant increase in the impact velocity does not lead to a noticeable increase in the diameter of the work-hardened area, which allows us to recommend the IIT conditions under which the

deforming ball velocity of 1-3 m/s can be achieved. The results obtained are consistent with the experimental data. However, it should be noted that the above recommendations are valid only in terms of obtaining a specified value of residual stresses and the requirement to reduce surface roughness is not taken into account.

3. Conclusions

The results of the numerical simulation confirmed the hypothesis about the possibility of controlling the IIT-based process of high strength cast iron hardening.

The IIT process can be controlled by changing the frequency of rotation of the workpiece which causes a change in the deforming ball velocity. The density of the surface coverage with ball dents is regulated by changing the tool feed in the axial direction.

To perform IIT, it is recommended to provide conditions under which the deforming ball velocity at the moment of impact is in the range of 1-3 m/s and residual stresses with values of 250-300 MPa at a depth of 0.4-0.75 mm are generated. Residual stresses on the surface of the workpiece are concentrated in areas with a diameter of up to 0.8-1.3 mm.

4. References

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