Problem formulation of analytical characterization of part surface layer hardened by a moving elastic indenter

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Abstract. The development of manufacturing engineering leads to the bill of goods expansion that work in extreme conditions and are made of new steels and alloys. Unfortunately, the traditional technological methods are not able to ensure the necessary performance characteristics of parts surfaces. Diamond smoothening is a well-behaved technological method that allows to finely controlling the quality parameters of the layer surface. However, we consider that the physical processes that occur in the interface between the indenter and the hardened surface are not well understood. A deeper understanding of the physical processes occurring in the contact zone will expand the scope of surface hardening by smoothening. In our work, we tasking the physical boundary conditions in the contact zone between the hardening tool and part surface.

1. Relevance

The process of parts surface hardening by deforming it with a moving indenter differs from other methods of surface plastic deformation by:

- decrease in statistical variability of the qualitative parameters of the surface layer;
- increased supporting capability due to formation of microroughness of round shape;
- surface layer hardening.

To control the surface layer quality of parts hardened by an indenter (of various shapes), the most frequently used control and measurement of the following quality parameters of the surface layer:

- roughness;
- residual stresses;
- the distribution of microhardness in the surface layer after hardening;
- the formation of the crystallographic texture of the surface layer, characterized by a decrease in grain size and an increase in the density of dislocations.
The ability to control the qualitative parameters of the surface layer by changing the modes of surface plastic deformation (SPD) allows in many cases to increase the operational properties of parts with hardened surfaces or to stabilize their properties.

When a metal with increased hardness (HRC of at least 52 units) is used as hardening element (indenter), the characteristics of the part surface layer are affected not only by surface deformation, but also by deformation of the indenter. Taking into account the mutual deformations of the contacting parts during SPD will allow more accurate control of the formed residual stresses, as well as the nature of microhardness distribution along the depth of the part surface layer \( h_H \). In addition, the formed deformation pattern in the contact zone between the elastic surface and the elastic reinforcing element will allow a deeper study of the physics of the hardening process by smoothing the surface layer of parts. Note that an experimental study of the mutual deformations of contacting bodies is associated with significant technical difficulties. This is evidenced by the lack of domestic and foreign publications on this topic (they are not known to the authors).

For these reasons, the development of a non-destructive technique (method) for determining the nature of deformations of the hardened part surface and indenter surface is an urgent technological task. The results of solving this problem are undoubtedly in demand for the choice of hardening modes for surfaces that work on wear or under cyclic loads. In this regard, a technique was developed for the analytical calculation of the elastic mutual deformations of the contacting parts: a long cylinder \((l \gg 15\text{mm})\) with a diameter of \(\varnothing \leq 5\text{ mm}\) of the elastic half-plane. Note that the hardened surface may have a curvature.

2. Methodology

The strain hardening (microhardness \( H_H \)) diagram was measured on the surface of inclined polished specimen. The surface of the samples from which the sections were made was pretreated with an indenter. In this case, the axis of symmetry of the indenter was parallel to the axis of rotation of the cylindrical sample, from which fragments under thin sections were subsequently cut using the electroerosion method. Microhardness was measured by the reconstructed imprint formed by indentation of the Vickers diamond point. The indentation force was 2 N in accordance with the national standard GOST 9450 - 76 “Measurement microhardness by indentation of diamond point”. To measure the diagonal of the print, the PMT-3 microhardness meter manufactured by LOMO (St. Petersburg) Russia was used.

The average values of the qualitative parameters of the surface layer were estimated using the Student t-test. Reliability of the results corresponded to a significance level of \( p < 0.05 \). Each test of the device was duplicated at least 10 times.

3. Statement of the problem.

The roughness of the hardened surface, the depth and degree of hardening of the surface, as well as the nature of the residual stresses during SPD, depend on the processing conditions: specific pressure \((P_y)\), speed \((V)\), radius of the cylindrical surface of the indenter \((R_{ind})\). The physical and technical parameters of the hardened surface (elastic modulus \((E)\) and Poisson's ratio \((\nu)\) [1, 2, 3]) also affect the parameters of the hardened surface layer.

For engineering production, it is of interest to study the deformation pattern of the hardened surface in the contact zone with an elastic indenter.

The curvature of the surface of a cylindrical indenter is much less than the curvature of the hardened surface, therefore, we assume that the reinforcing element moves along the plane (surface of the part).

Figure 1 shows a 3D image of the contact problem under consideration. Figure 1 shows the hardened surface \(I\), which has two bulges of deformed metal before and after the moving hardening element \(2\). The bulge in front of the moving indenter \(2\) is bigger.

From this point on, we assume that the indenter \(2\) is not limited along its axis of symmetry, the radius of its cylindrical surface is known.
A moving indenter is embedded in the metal of the machined surface with a normal force $P$, the value of which is known and predefined. In the zone of the hardening element and the work surface two multidirectional friction forces $F_{fr1}$ and $F_{fr2}$ are acting. In addition, between the zones with friction there is a fragment of the contact zone with adhesive bonds. In figure 2a shows a 3D model of the workpiece with a surface that includes a fragment of the contact surface.

Figure 1. Contacting bodies: a - 3D model of contacting bodies; b - contour image of contacting bodies. The following notation is used in the figure: 1 - hardened body, 2 - hardening element (indenter).

Figure 2. Contact zone on the treated surface: a – 3D model of the workpiece; b – normal section (figure 2a); c – diagram of the surface deformation of a cylindrical indenter.

Figure 2 b shows the normal section of a fragment of the contact zone on the treated surface. In figure 2c shows a loading diagram of the contact line of the treated surface with the cylindrical surface of the indenter.

Friction forces $F_{fr1}$ and $F_{fr2}$ are acting in sections $A_1A_2$ and $A_3A_4$, respectively and they are differently directed. Friction in section $A_1A_2$ is due to the formation of a bulge in front of the moving indenter. Friction in section $A_3A_4$ is due to the elastic unloading of the material of the hardened surface behind the moving indenter. In $A_2A_3$, there is adhesion bond between the surfaces of the indenter and the hardened surface.

4. The plane elastic problem of introducing a sphere into an elastic half-plane
The cylindrical surface of the hardening element moves along the hardened surface with a constant speed $V$, the value of which is known in advance and is set by the modes of technological influence on the part.

The value of the indenter penetration into the hardenable half-plane can be measured by the static imprint of pressing the hardening element into the hardenable surface with a given force $P_y$.

The scheme of the effect of the cylindrical indenter on the hardened surface (figure 1) suggests that the deformation pattern of the surface layer of the part in the contact zone is the same in each plane of
the normal section (in the plane perpendicular to the axis of symmetry of the cylinder of the reinforcing element). For this reason, we chose the model of a plane elastic contact problem as a theoretical model.

A feature of the considered contact problem is the presence on one part of the surface of the elastic body of one or another contact with another elastic body. In this case, surface forces are the result of the interaction of the treated surface with a moving indenter adjacent to it. The boundary conditions in the contact zone are complicated by the fact that the stresses in the contact zone are not known and the separation points of the various interactions of the contacting bodies are unknown. Such contact problems are called boundary value problems with mixed boundary conditions.

We assumed that the contact area increases with an increase of force $P_y$ (figure 2c). In this case, tangential forces of interaction (adhesive contact or bonding of the contacting bodies) take place on part of the contact zone, the magnitude of which is less than the product of normal pressures by the coefficient of friction ($f$); and on the rest of the contact zone - (slippage) the presence of tangential friction forces equal to the product of normal pressure by the coefficient of friction ($f$).

Many researchers believe: the sliding speed of bodies is much less than the speed of sound propagation in them. In their opinion, this gives reason to neglect the dynamic effects in the formulation of contact problems [4, 5, 6]. Along with this series of experimental studies [7, 8, 9] proved that the resistance to relative displacement of surfaces under sliding conditions to one degree or another always depends on speed, which is often a manifestation of imperfect elasticity not of interacting bodies themselves, but of thin surface layers. For this reason, we consider a dynamic contact problem.

To simulate elastic deformations in the contact zone and in the surface layer of the hardened part, we chose the theory of functions of a complex variables, which allows us to obtain an analytical solution to the contact problem. Conformal representation [10, 11, 12] allows to display the boundaries of the contacting bodies on the canonical region (unit circle or half-plane), as a result of which the curvature of the contacting bodies can be taken into account in solving the contact problem. The latter circumstance is important for working out the hardening regimes for mechanical engineering parts. In this regard, the consideration in figure 1 the introduction of a moving cylinder indenter elastic half-plane is not a restrictive condition. The hardened surface may be in the form of a cross section of the turbine airfoil, ellipse, etc.

![Figure 3. Possible physical models of diamond treatment: a – not considering the bulge of deformed metal formed in front of the moving stamp; b - considering the bulge formed in front of the moving stamp.](image-url)
Figure 4. Possible physical models of diamond treatment: c - considering the magnitude of the irreversible plastic deformations of the hardened surface; d - considering the magnitude of irreversible plastic deformations of the hardened surface and the bulge formed in front of the moving stamp.

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Conclusions
The following task is posed.

- Using the terminology of Galin L.A. [13-16] we will call the indenter (hardening element) hereinafter a stamp, and the hardened surface of the part - an elastic half-plane.
- The stamp has elastic characteristics and moves at a constant speed along the boundary of the elastic half-plane.
- The speed of movement of the stamp is less than the speed of propagation of sound in the material of the elastic half-plane. In this case, we can neglect the dynamic phenomena.
- The zone of contact of the stamp with the elastic half-plane is divided into three sections: the central section corresponds to adhesive adhesion, and to the others, friction. In figure 3 shows possible physical models of diamond treatment.

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