THE GENERAL REGULARITY OF SURFACE LAYER WORK HARDENING IN THE HONING OPERATION OF MEDIUM CARBON STEELS

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Abstract

This paper discusses the general issues of controlling the formation of work hardening in the internal cylindrical surfaces during the honing process using technological methods. Based on the general characteristics of the honing operation of medium carbon steel materials, and considering surface quality and productivity, the technological regularity of work hardening has been identified. Experimental research results on the influence of the main processing parameters-such as the forward-backward (Vb-f) and rotational (Vr) speeds of the honing head, specific pressure (Ps.p), abrasive grit size (Z), and processing time (T) on the degree of work hardening are presented. The functional dependencies of the main input parameters of the process on work hardening, which is taken as the main output parameter for surface quality, have been graphically determined. As a result, the technological foundations for selecting optimal processing regimes have been established.

Keywords: abrasive grain, work hardening, honing process, hardness, special pressure, surface roughness, accuracy.

I. Introduction

The application of the honing operation in the production of machine parts, as in other machining methods, is accompanied by plastic deformation -work hardening of the material's surface layer. The degree of work hardening (H) and the thickness of the hardening layer (a) are primarily proportional to the external force and processing time. The heat generated in the cutting zone increases the value of plastic deformation on the working surface of the material, which results in a change in the frictional force and also leads to structural transformations of the metal. During the honing process of the internal cylindrical surfaces of parts made of medium carbon steel materials, which operate under high pressure-temperature conditions, it becomes necessary to study the dependence of the degree and depth of work hardening on cutting regime parameters. Experimental research results show that, during surface plastic deformation of steels, in addition to the crushing of blocks, the hardening effect plays a crucial role in the dispersion hardening, changes in dislocation density, and phase transformations [1, 2]. An increase in dislocation density and an increase in the dispersion of carbides, which restrict movement on the slip plane, are also observed to lead to an increase in hardness. A similar situation is observed when the amount of martensite deformation and the transformed residual austenite increases.

The formation of work hardening in the surface layer during honing is a sufficiently complex technological issue, as a number of input parameters of the process, as well as the influence of external factors, can cause significant changes, all of which have a substantial effect on the degree of surface work hardening.

The effect of various factors on the honing process was investigated using the method of planning multifactorial experiments. As the research object, medium carbon steels used in the production of high-precision parts in the special machine engineering and instrument-making industries were selected. Based on the calculations, a mathematical model of the honing process was developed, characterizing the dependence of the surface layer work hardening (H) on the factors such as specific pressure ($P_{s.p}$), abrasive grit size (Z), processing time (T), forward-backward ($V_{b\text{-}f}$) and rotational (V_r) speeds of the honing head, for both the coded and natural values of these factors. Relevant checks were performed for the necessary criteria for second-order orthogonal planning. The obtained models are fully applicable for calculating the values of the work hardening degree (H) depending on the factors $P_{s\text{-}p}$, Z, T, $V_{b\text{-}f}$, and V_r at the α = 0.05 significance level.

Let's write the equation characterizing the effect of the coded values of the factors $P_{s.p}$, Z, T, $V_{b\text{-}f}$, and V_r:

$$\begin{gathered}\hat{y}_H = 7343{,}23 - 164{,}56x_1 - 321{,}23x_2 + 191x_3 - 167{,}23x_4 + \\ +134{,}14x_5 - 74{,}26x_1x_2 - 61{,}95x_1x_3 - 62{,}38x_1x_4 + 81{,}12x_1x_5 - \\ -58{,}87x_2x_3 - 73{,}67x_2x_4 + 85{,}45x_2x_5 - 73{,}14x_3x_4 + 83{,}21x_3x_5 + \\ +81{,}37x_4x_5 + 32{,}79x_1^2 - 187{,}23x_2^2 + 53{,}51x_3^2 + 54{,}52x_4^2 + 51{,}57x_5^2\end{gathered} \tag{1}$$

For the natural values of the factors, after the appropriate transformations, equation (1) takes the following form:

$$\begin{gathered}H = 8121{,}22 - 951{,}73V_{b-f} - 71V_r - 4{,}14P_{s.p} - 0{,}782Z - \\ -12{,}42T - 8517{,}67V_{b-f}\!:V_r - 28{,}51V_{b-f}\!:P_{s.p} - 134{,}41V_{b-f}\cdot Z + \\ +23{,}24V_{b-f}T - 10{,}91V_r\cdot P_{s.p} - 52{,}32V_r\cdot Z + 58{,}45V_r\cdot T - \\ -0{,}31P_{s.p}\cdot Z + 0{,}4P_{s.p}\cdot T + 0{,}32ZT + 998{,}63V_{b-f}^2 - \\ 8723{,}45V_r^2 + 0{,}11P_{s.p}^2 + 0{,}62Z^2 + 0{,}03T^2\end{gathered} \tag{2}$$

By applying equation (2) to the optimization, the following values of the friction process parameters, which ensure the maximum surface layer work hardening, are obtained: - $V_{b\text{-}f}$=0.22 m/sec, V_r=0.41 m/sec, $P_{s.p}$=71 kPa, Z=160/125 μm, T=95 sec. Using the obtained equations, the surface layer work hardening degree (H) has been calculated based on the input parameters of the honing process ($P_{s.p}$, Z, T, $V_{b\text{-}f}$ and V_r), and the corresponding functional dependencies have been established in the following graph.

Technological factors that cause an increase in temperature in the honing zone lead to a rise in temperature and cause a decrease in the hardness of the surface layer material. Examples of such factors include the forward-backward ($V_{b\text{-}f}$) and rotational (V_r) speeds of the honing head. With an increase in the values of these parameters, the temperature in the cutting zone rises proportionally, and the degree of work hardening in the surface layer starts to decrease (Fig. 1). The results of the studies [3 and 4] show that if the plastic deformation process occurs at relatively high temperatures (where atomic displacements increase and the elimination of distortions in the crystalline lattice becomes easier), then both relaxation and hardness reduction occur more rapidly.

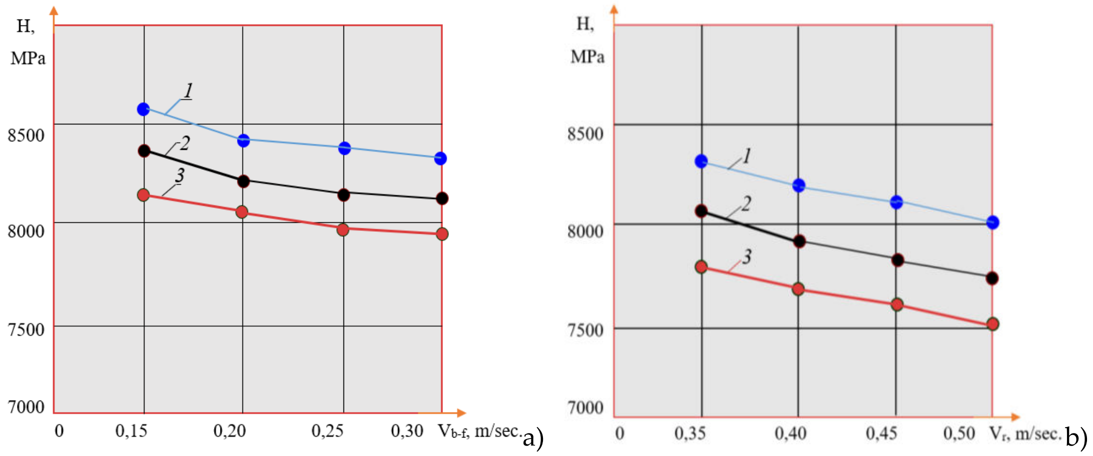

Figure 1: *Dependence of work hardening (H) on forward-backward $V_{b\text{-}f}$ (a) and rotational $V_{r\,(b)}$ speeds: 1, 2, 3 - corresponding to abrasive grit sizes: Z=125/100Z,160/125, and 230/200 µm*

As seen in Fig. 2a, an increase in specific pressure ($P_{s.p}$) reduces the surface layer work hardening degree. As is known from [5, 6], the work hardening of the metal caused by plastic deformation leads to a state of tension and structural instability. Consequently, upon the completion of the plastic deformation process, relaxation occurs directly in the metal, which results in the metal attempting to return to its initial, stable state. Even under normal processing conditions, i.e., with low and medium values of specific pressure, atomic displacements can alter the structure of the atomic crystal lattice and reduce the work hardening of the surface layer.

With an increase in the abrasive grit size (Z), the work hardening value decreases (Fig. 2b). This regularity can be explained by the fact that, under a certain balance of abrasive action, the absolute value of plastic deformation increases with the increase in grit size. Therefore, alongside the removal of material, a decrease in the surface layer work hardening degree also occurs.

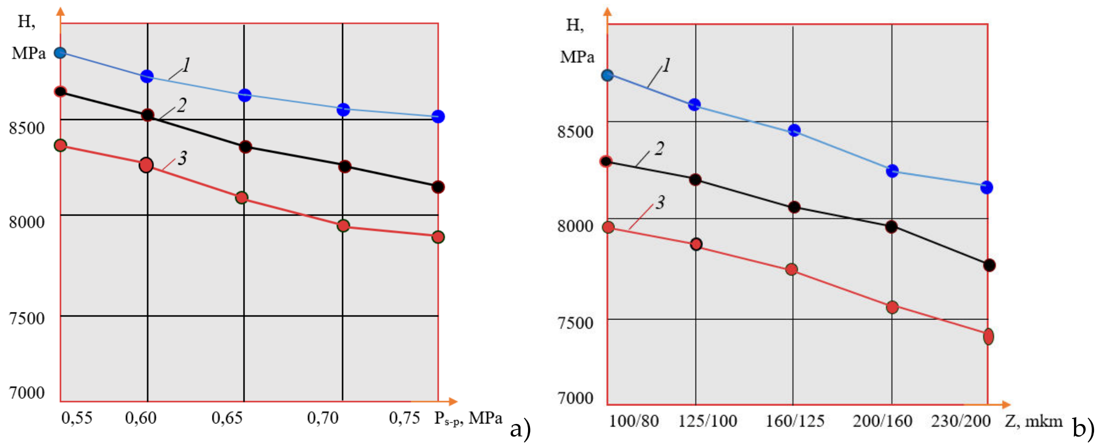

Figure 2: *Dependence of work hardening (H) on specific pressure ($P_{s.p}$) and abrasive granularity size (Z): 1, 2, 3 - corresponding to V_r=0.40, 0.45 and 0,50 m/s.*

The graphical dependencies obtained through experimental research show that with an increase in processing time (T), the surface layer work hardening degree (H) increases proportionally (Fig. 3). This can be explained by the increase in the duration of abrasive action on the processed surface [7, 8]. However, during the course of the processing, the number of cutting grains decreases, and due to the clustering of the main cutting edges of the abrasive grains, more favorable conditions for surface layer work hardening are created, which also leads to an intensive increase in the work hardening depth (a).

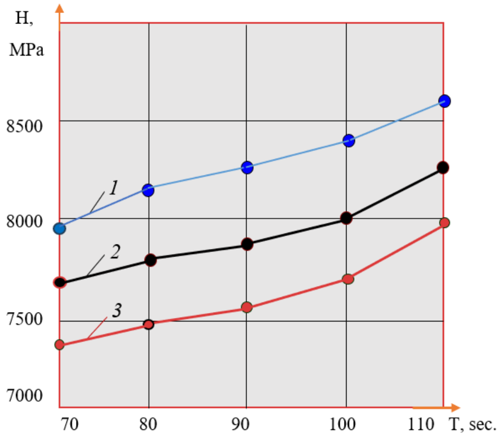

Figure 3: *Dependence of work hardening (H) on processing time (T): 1, 2, 3 – corresponding to abrasive granularity sizes: Z=125/100, 160/125 and 230/200 μm*

It is well known that the machining process of metal materials by any cutting method is accompanied by plastic deformation of the surface layer. Although in abrasive machining methods, especially in the honing process, this is observed at relatively small values compared to traditional cutting methods, it is not negligible. During the honing of medium-carbon steel materials, the work hardening degree (D) of the surface layer can increase by 35-40% within a depth range of 4-24 μm. It is particularly important to note that, as with other machining methods, in the internal cylindrical honing process, the values of work hardening degree and work hardening depth can be controlled (regulated) by changing the main input parameters of the process.

The graphical dependence of the work hardening degree (H) on the depth (a) of the hardening surface layer during the honing process is shown in Fig. 4. Here, the results obtained from experiments for three different values of the rotational speed of the honing head (V_{r1}=35, $Vr2$=40, V_{r3}=45 m/sec) under the same processing conditions are presented.

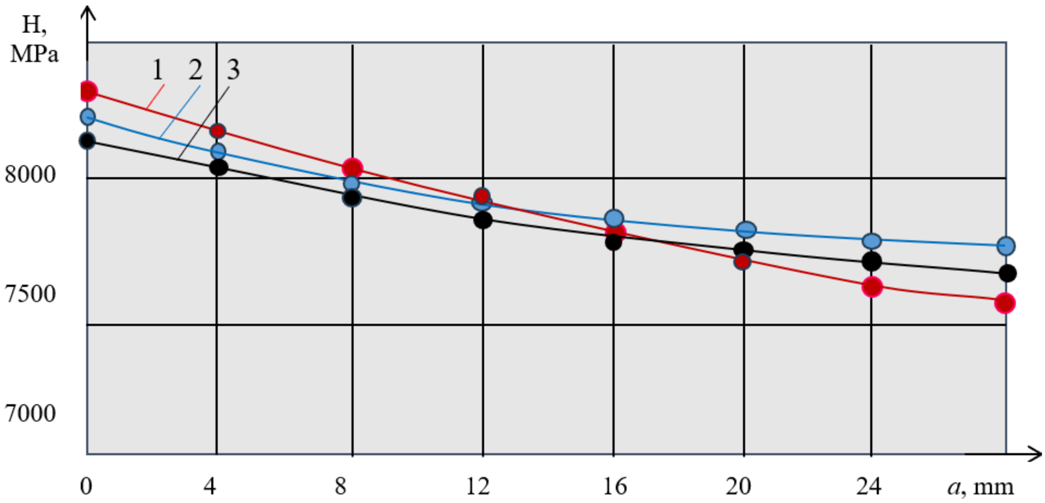

Figure 4: *Distribution of work hardening (H) on the depth (a) of the surface layer during the honing process (1-V_r=35, 2-V_r=40 and 3-V_r=45 m/sec)*

When considering the general regularity of the influence of each parameter of the honing process on the surface layer work hardening, it becomes clear that any technological process involving cutting is accompanied by plastic deformation- work hardening of the surface layer, which significantly changes in depth direction from the metal surface. Therefore, depending on the values of processing parameters ($V_{b.f}$, V_r, $P_{s.p}$, Z, T) in the friction process, it is possible to achieve a wide range of work hardening values in the surface layer. Based on the purpose of the machine parts and the technological requirements set for the main working surface, the optimal values of work hardening degree and depth are determined.

In the honing operation, an increase in grit size is accompanied by a proportional decrease in the work hardening degree. This regularity can be related to the ability of abrasive particles to cause plastic deformation on the surface. The combined rotary and forward-backward motion of the honing head leaves fine tracks of the abrasive particles on the machined surface. The photograph and topography of the honed surface are shown in Fig. 5a and b, respectively. The plateaus of the honed surface constitute a large apparent contact area, which results in higher load-carrying capacity. The cross-hatch patterns retain the lubricant, which helps reduce the friction coefficient and running-in wear [9].

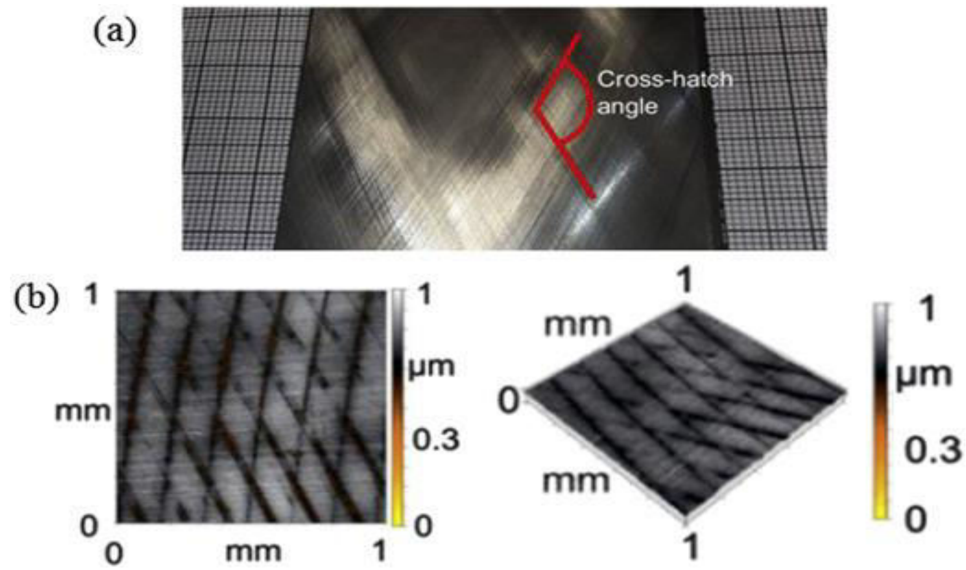

Figure 5: *Photograph (a) and 3D topography (b) of honed surface*

With an increase in the forward-backward and rotational motion speeds, the work hardening of the surface layer decreases. This can be related to the rise in temperature in the contact zone, which results in the softening of the material. In this regard, under specific processing conditions, the work hardening of the surface layer can only decrease to a certain minimum value. Based on the results of experimental studies, it can be stated that during the honing operation, a temperature field is generated in the surface layer that exceeds the initial value, which leads to a reduction in the plasticity and work hardening.

Increasing the specific pressure ($P_{s.p}$) from 0,55 MPa to 0,73 MPa results in a decrease in the surface layer work hardening (H) from 8500 MPa to 7700 MPa. Increasing the value of Ps.p enhances the material removal from the surface layer, and the honing process transitions from diamond polishing to micro-cutting. A decrease in the value of $P_{s.p}$ reduces the value of plastic deformation, and the abrasive grains only participate in cutting the tips of the protrusions on the surface. After that, the intensity of the cutting process sharply decreases, the apparent surface area increases, and the value of specific pressure becomes insufficient to generate plastic deformation in the surface layer.

When the granularity size is increased from Z_{min}=100/80Z to Z_{max}=230/220Z, the initial state of the surface continuously changes from a highly hardened layer to a less hardening one, and this difference can sometimes reach 35-40%. This trend can be explained by the fact that, at the beginning of the process, the cutting grains come into contact with the tips of individual protrusions on the surface's micro-relief. As the grit size increases, the abraded surface smoothens, the number of engaged grains increases, and the intensity of material removal from the surface layer rises, which leads to a decrease in the work hardening degree of the surface layer.

The abrasive grains of the honing wheel, in their cutting area, are irregular in shape and size, with an arbitrary arrangement and varying cutting angles, thus creating micro-cutting. In this regard, each abrasive grain penetrates the surface to a different depth-larger grains are more loaded, while smaller grains are less loaded [10]. Some abrasive grains are unable to perform cutting work; they only cause plastic deformation of the surface, while very small grains generally do not make contact at all. Microscopic observation of the chips obtained from honing shows that their size and shape are also varied.

The formation of different processing conditions for each grain individually naturally leads to the creation of varying cutting temperatures in the contact zone. Therefore, it is completely logical that different levels of work hardening appear on the individual micro-areas of the surface. When designing the technological process, processing conditions should be created in such a way that the process can transition from micro-cutting to the polishing process without the need for additional conditions [11, 12]. At this point, the optimal value of processing time plays a significant role. Specifically, the maximum (T_{max} = 110 sec) and minimum (T_{min} = 70 sec) values of processing time do not provide the required surface quality, and are also considered economically inefficient. However, when the processing time is in the range of T =90-95 sec, the surface layer's work hardening degree increases intensively, while at longer times, it increases gradually. This progressive increase in work hardening with increasing processing time is considered normal. This is because, as processing time increases, the honing head's contact time with the surface also increases, resulting in additional deformation and strengthening of the surface layer.

II. Conclusion

In order to achieve high surface quality during the honing operation of internal cylindrical surfaces of high-precision parts, and especially to control the surface layer’s work hardening in a systematic way, the following key technological issues must be addressed:

- the optimal processing conditions should be selected, taking into account the main characteristics of the honing process, which is the final technological operation, in order to enhance the product quality and durability;
- the mechanism of the effect of the main honing parameters on the work hardening degree should be investigated through both theoretical and experimental research, considering the production efficiency and quality;
- the characteristics of the work hardening formed on the surface layer, as well as the influence of these characteristics on the friction and wear processes during operation, should be considered as a key factor, with particular regard to the physical-mechanical properties of medium-carbon steel, especially its hardness.

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