Integrated Processing: Quality Assurance Procedure of the Surface Layer of Machine Parts during the Manufacturing Step "Diamond Smoothing"

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Abstract. The present study has found that during the integrated processing after the diamond smoothing, in the surface-hardened sample a cold-worked layer 0.01 ... 0.02 mm in thickness, the microhardness value of which reaches 868 HV, is formed. The intensity of compressive stresses on the part surface increases to $\sigma_t = -678$ MPa. The analysis of the experimental data has shown the relationship between the parameter $Ra$ and the processing modes that can be used during diamond smoothing, based on the high performance and the desired surface roughness. It has been found that the minimum value of roughness $Ra = 0.18 \pm 0.08 \mu$m is reliably achieved by smoothing processing when the smoothing force $P_y$ ranges from 100 N to 150 N.

1. Introduction
Production of competitive and high-quality products is the main direction for the development of modern engineering. In this regard, in the machine tool industry close attention is focused on developing a new type of processing equipment – hybrid manufacturing systems processing multifunctional capabilities [1 - 7]. Integration of different processes in one machine: laser surface hardening combined with mechanical treatment [8, 9], the abrasive grinding - surface hardening [10 - 12], cutting - hardening [13], turning - quenching - grinding, is caused by the desire of developers to expand technological capabilities of machines and to ensure their autonomy in a flexible mechanical production [14, 15]. This method allows not only to achieve high levels of resource and energy saving, but also to provide the appropriate level of processing performance and quality of the items [16]: the accuracy of the shape, size and arrangement of the surface, roughness and the specified physical and mechanical properties of the surface layers and the material.

The object of this research is the process of manufacturing machine parts, consisting of the following operations: pre-machining (rough turning), surface hardening (high-energy high-frequency heating) and finish machining (finish turning and diamond smoothing).

Since it is the finishing operations which form in the surface layer of parts optimal combination of quality parameters (surface roughness, size and distribution of microhardness and residual stress, microstructure of the surface layer, and others.), determining the performance of products [17 - 21],
the aim is to study the quality of the surface layer, achieved during the diamond smoothing in the integrated processing environment.

2. Materials and methods

A cylindrical rod (diameter \(d = 50\) mm, length \(l = 70\) mm), made of steel 45, is used as a test sample. The feed material was checked by the optical emission spectrometer ARL 3460. The results are shown in Table 1.

For the integration of mechanical and surface heat treatments a screw-cutting lathe model UT16PM has been upgraded, i.e. it has been equipped with additional concentrated source of energy, for which an external quenching circuit implementing high-energy heating by high frequency currents (HEH HFC) and characterized by high thermal coefficient of efficiency, has been used. As an energy source generator HFG 6 - 60 / 0.44 with the current operating frequency \(\omega = 440\) kHz has been used.

When turning, HEH HFC hardening and diamond smoothing, the sample was fixed in a three-jaw gripper with the center in abutting relation to the screw-cutting tailstock.

**Table 1. Chemical compositions of steel 45**

| Elements | C  | Si  | Mn  | S   | P   | Cr  | Ni  | Cu  |
|----------|----|-----|-----|-----|-----|-----|-----|-----|
| Weight, [%] | 0.44 | 0.23 | 0.61 | 0.013 | 0.019 | 0.11 | 0.15 | 0.17 |

Rough turning was carried out with a replaceable insert straight turning tool (the material of the insert T15K6) under the following conditions: cutting speed \(V_d \approx 92\) m min\(^{-1}\) (work rotational speed \(n_w = 588\) min\(^{-1}\)); feed per revolution \(S_{rev} = 0.35\) mm; cutting depth \(t = 1\) mm.

When surface hardening, the loop-type inductor, equipped with brand ferrite N87, was used. The heating process was carried out on a progressive feed method (the thickness of the hardened layer did not exceed the depth of penetration of the current into the hot metal - 0.6 ... 0.8 mm) [22, 23]. The studies were conducted using heavy water spray cooling of the surface within the following range of processing modes: the specific source power \(q_s = (1.5 - 4.0) \times 10^8\) W m\(^{-2}\), the travelling speed of the parts under the inductor \(V_p = (0.05 - 0.1)\) m s\(^{-1}\) (corresponding to \(n_d = 19.9 - 39.8\) min\(^{-1}\)). The width of the active conductor of the inductor \(B_i\) was 2 mm, the processing was carried out with a gap \(\Delta = 0.1 - 0.2\) mm.

Finish turning was carried out with an indexable-insert straight turning tool (the material of the insert - oxycarbide ceramic insert based on the composition \(\alpha\)-Al\(_2\)O\(_3\)-TiC). Cutting modes: cutting speed \(V_d \approx 133\) m min\(^{-1}\) (work rotational speed \(n_w = 882\) min\(^{-1}\)); feed per revolution \(S_{rev} = 0.025\) mm; cutting depth \(t = 0.01 \div 0.015\) mm. When rough and finish turning, a cooling lubricant was sulphonated mineral oil "Sulfofrezol".

Diamond smoothing was based on the two-pass scheme using designed and manufactured insert holder with elastic fixing of the diamond indentor (Technical Regulations 2-037-631-88) with the radius \(R = 1\) mm. The radial component of the smoothing force \(P_y\) considering the stiffness of the processing equipment, the surface layer hardness of the processed part after the HEH HFC surface hardening (HV = 700 ... 800) and the radius of the diamond areas, respectively, was equal to 50, 100, 150, 200 N. In this the surface meters per minute of the processed part was \(V_{ds} = 25.3; 33.2; 41.9\) m min\(^{-1}\) (work rotational speed \(n_d = 168; 220; 278\) min\(^{-1}\)); and the feed per revolution - \(S_{ds} = 0.018 \div 0.08\) mm. A cooling lubricant for the diamond smoothing was industrial oil I-20A.

Structural studies of the samples were performed on an optical microscope Carl Zeiss Axio Observer Z1m and on a scanning electron microscope Carl Zeiss EVO 50 XVP, equipped with energy dispersive analyzer INCA X-ACT (Oxford Instruments). The microstructure of the samples was revealed by etching with a 5% ethanolic solution of nitric acid and a saturated solution of picric acid in ethanol with surfactants [24].

Microhardness of the hardened surface layer of parts was evaluated on the instrument Wolpert Group 402MVD. Residual stress research was carried out with application of the X-ray method on
the high-resolution diffractometer ARL X’TRA and the mechanical destructive method: the layered electrolytic etching of the sample [25, 26]. For the detection of defects in the surface layer in each manufacturing operation we used: visual and optical method using a microscope Carl Zeiss Axio Observer A1m, capillary method, eddy current method using eddy current flaw detector VD - 70. In the study for the simultaneous measurement of form deviations, waviness and roughness of the surface we used profilograf - profilometer Form Talysurf Series 2 of Taylor Hobson Company. The evaluation of the surface topography was carried out on a laser profilograph-profilometer Zygo New View 7300.

Statistical analysis of the experimental studies results was performed in software products Statistica, Table Curve 2D and Table Curve 3D.

3. Results and discussion

Studies of surface quality after the first manufacturing operation of the integrated processing showed that in the process of rough turning we get a defect-free surface the roughness value of which according to the parameter Ra is 3.3±0.7 µm.

At the second manufacturing operation we carry out HEH HFC surface hardening, maintaining the required depth of hardening h = 0.6 mm and rational nature of the residual stresses distribution; the specific power (q_s [W m^{-2}]), and the speed of parts movement (V_p [m s^{-1}]) was carried out by solving the equations system h(q_s, V_p) and \( \Psi(q_s, V_p) \) [27, 28]:

\[
\begin{align*}
\frac{h(q_s, V_p)}{V_p} &= a + bV_p + cV_p^2 + dV_p^3 + eV_p^4 + gV_p^5 + hV_p^6 + jV_p^7 + q_s^8 + q_s^9, \\
\Psi(q_s, V_p) &= k + nV_p + mV_p^2 + oV_p^3 + pV_p^4 + qV_p^5 + sV_p^6 + tV_p^7 + uV_p^8 + V_p^9, \\
0.25 &\leq \Psi(q_s, V_p) \leq 0.35.
\end{align*}
\]

where \( a = 0.426008, b = 2.827121, c = 3.025072 \times 10^{-9}, d = -301.591960, e = -4.694423 \times 10^{-18}, f = 3.600666 \times 10^{-8}, g = 1953.668810, h = 3.216427 \times 10^{-27}, i = 1.375401 \times 10^{-17}, j = -3.779401 \times 10^{-7}, k = 0.087564, l = -7.429933, m = 1.062284 \times 10^{-8}, n = 235.19293, o = -3.42486 \times 10^{-17}, p = -8.850919 \times 10^{-8}, q = -1309.3045, r = 2.9423 \times 10^{-26}, s = 1.403793 \times 10^{-16}, t = 1.010925 \times 10^{-7} - \text{coefficients of functional dependencies for 45 steel.}

Figure 1 is a graphical solution of this problem. When hardening Steel 45 to a depth of 0.6 mm the range of the recommended conditions is limited within the points A and B on the curve (black solid line): while \( q_s = (3.0 \ldots 3.4) \times 10^8 \text{ W m}^{-2}, V_p = (0.072 \ldots 0.081) \text{ m s}^{-1} \). The determined processing modes (shaded area) guarantee a required depth of hardening and rational value of the transition zone.

![Figure 1](image-url)

**Figure 1.** The dependence of the source specific power on its travelling speed during the HEH HFC hardening of Steel 45 to a depth h_{45} = 0.6 mm
The job setting was carried out in the following modes: \( q_s = 3.2 \times 10^8 \ \text{W m}^{-2} \) and \( V_p = 0.078 \ \text{m s}^{-1} \), (work rotational speed \( n_d \approx 31 \ \text{min}^{-1} \)). To ensure the required spindle rotational speed the main drive has been upgraded, that is equipped with the frequency converter \textit{HF Inverter model F1500-G0015S2B}.

Microhardness pattern of samples in the cross section is shown in Figure 2. The mean level of the hardened after HEH HFC layer microhardness was 739 HV, wherein the base material microhardness was 204 HV.

The maximum level of the surface compressive residual stress (RS) was \( \sigma_s = -560 \pm 20 \ \text{MPa} \). The peak tensile stress reached \( \sigma_t = 75 \pm 45 \ \text{MPa} \) and is at a depth of \(~0.8 \ \text{mm}\).

Finish turning was carried out in the part size \( d = 48 \ \text{mm} \), the surface roughness value of the parameter \( Ra \) was \( 1.2 \pm 0.2 \ \mu\text{m} \). Surface microhardness and residual stress were at the level achieved in the transition zone HEH HFC.

The process of diamond smoothing forms a plastically deformed surface, topography of which is characterized by a rounded shape of the microrelief without scoring and snatching.

Figure 3 shows the dependence of the effect of speed \( V_{ds} \) and feed \( S_{ds} \) on roughness parameter \( Ra \) for different values of the smoothing force \( P_y \). As it can be seen from the figures, the increase in \( V_{ds} \) and \( S_{ds} \) in the studied ranges of mode parameters results in the increase of the surface roughness. To a greater extent it is the change of the feed \( S_{ds} \) that influences the surface pattern.

Figure 2. Microhardness distribution in the surface layer of Steel 45 after HEH HFC hardening: the mode \( q_s = 3.2 \cdot 10^8 \ \text{W m}^{-2} \), \( V_p = 0.078 \ \text{m s}^{-1} \), \( B_i = 2 \ \text{mm} \)
In the study of the smoothing effect it was revealed that in the section from 50N to 100N we observed a high reduction of the roughness parameter Ra (Figure 4). In the interval [100N; 150N] the value of the Ra stabilized at the level of 0.18±0.08 µm: initial surface pattern was almost completely leveled, and the surface roughness depends on the parameters V_{ds} and S_{ds}. For values P_y = 100N and P_y =150N the functional relationship Ra(V_{ds}, S_{ds}) was determined:

\[ Ra(V_{ds}, S_{ds}) = a + bV_{ds} + cS_{ds} + dV_{ds}^2 + eS_{ds}^2 + fV_{ds}S_{ds} + gV_{ds}^3 + hS_{ds}^3 + iV_{ds}S_{ds}^2 + jV_{ds}^2S_{ds}, \]  

where

for P_y = 100 N:  
\[ a = 0.098931, \ b = -0.00422, \ c = 2.512088, \ d = 0.000135, \ e = -23.857743, \ f = 0.020124, \ g = -1.326322 \times 10^{-6}, \ h = 105.49039, \ i = -0.028432, \ j = -0.000193; \]

for P_y = 150 N:  
\[ a = 0.070639, \ b = -0.002061, \ c = 2.729073, \ d = 7.897542 \times 10^{-5}, \ e = -23.406582, \ f = 0.005446, \ g = -8.396753 \times 10^{-7}, \ h = 92.631383, \ i = -0.001955, \ j = -1.421271 \times 10^{-5}. \]

A further increase in the values of P_y enhances the parameter Ra. These results are coherent with the materials presented in [29 - 32].

The minimum value of the roughness parameter Ra, which had been recorded while processing in the modes V_{ds} = 25.3 m min^{-1}, S_{ds} = 0.08 mm; 2 - V_{ds} = 33.2 m min^{-1}, S_{ds} = 0.06 mm; 3 - V_{ds} = 33.2 m min^{-1}, S_{ds} = 0.04 mm; 4 - V_{ds} = 25.3 m min^{-1}, S_{ds} = 0.018 mm.

A structural study carried out on a scanning electron microscope showed that in the process of diamond smoothing in a surface hardened sample a hardened (cold-worked) layer with a thickness of 0.01 ... 0.02 mm was formed (Figure 6). Thus, microhardness and compressive stress in the surface layer increase to the values of 868 HV and \( \sigma_c = -678 \pm 20 \) MPa, respectively (Figure 7).

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**Figure 4.** The dependence of the roughness parameter Ra on smoothing force P_y: 1 - V_{ds} = 25.3 m min^{-1}, S_{ds} = 0.08 mm; 2 - V_{ds} = 33.2 m min^{-1}, S_{ds} = 0.06 mm; 3 - V_{ds} = 33.2 m min^{-1}, S_{ds} = 0.04 mm; 4 - V_{ds} = 25.3 m min^{-1}, S_{ds} = 0.018 mm.

**Figure 5.** Surface profilogram and topography of the part after diamond smoothing: V_{ds} = 25.3 m min^{-1}; S_{ds} = 0.018 mm; P_y = 150 N; R = 1 mm; Ra_{initial} = 1.2±0.2 µm; HV_{initial} = 739.
4. Conclusions
Studies have shown that diamond smoothing performed as part of an integrated processing can significantly improve the quality of the surface layer of machine parts. It was established experimentally that when completing the final transition with respect to the HEH HFC transition it becomes possible to increase the surface microhardness and the level of residual compressive stresses in the surface layer of the product by ~15...20%. It was revealed that after diamond smoothing in the surface hardened sample a cold-worked layer with a thickness of 0.01...0.02 mm, the microhardness of which is ~868 HV, is formed, while the level of compressive stress in the surface layer increases to $\sigma_r = -678 \pm 20$ MPa. The rational range of the smoothing force $P_y \in [100N; 150N]$ has been determined, wherein the minimum value of the roughness parameter $Ra = 0.18 \pm 0.08 \mu m$ is guaranteed. The resulting functional relationship $R_a(V_A, S_A)$ allows determining the modes of diamond smoothing, based on the high performance and the desired surface roughness.

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