Hybrid Processing: the Impact of Mechanical and Surface Thermal Treatment Integration onto the Machine Parts Quality

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Abstract. The comparative analysis of the two hybrid process technologies, which are based on the integration of mechanical treatment (abrasive grinding or turning) and a surface heat strengthening by high frequency current on the same processing equipment, is given in the paper. The acquired results demonstrate that the suggested integrating approach allows carrying out the processing on the one technological base, which leads to the increase in the quality of the machine parts surface layer. The conducted experimental research proves that a minor stock allowance value for the final mechanical processing (sparkout or diamond smoothing) ensures the absence of defects such as local abatement zones and provides strain hardening of the work piece surface. This leads to the formation of the work-hardened layer of 0.01 - 0.03 mm, increase in microhardness value by 12 - 17% and the level of residual compressive stress in the surface layer by 10 - 21 % respectively.

1. Introduction

The most promising direction of modern metalworking equipment development is to combine on a single machine multiple processing steps, and even processes of various types and sequences [1 – 7]. This idea implements a number of combined processing methods: electromechanical, friction, laser and ultrasound, plasma-ultrasonic, hardening grinding and others [8 – 15]. The use of combined treatment allows achieving some additional effect that is not characteristic of each of the merged operations separately.

The main characteristics of the parts surface layer quality are known to be formed on the final stage of their manufacturing process [16 – 19]. Therefore, this paper considers two realization schemes of integrated processing on the same production equipment. The first scheme is implemented on the basis of a lathe: rough turning, surface hardening by high frequency currents, finish turning and diamond smoothing. The second scheme is implemented on the basis of grinding machine: grinding, surface hardening, sparking.

The aim of the research is to study the impact of the integrated mechanical and surface thermal treatments operations on the hardness and residual stress of the steel machine parts surface layer.
2. Materials and methods

Plates with dimensions 100x10x5 mm and cylindrical bars with diameter d = 50 mm and length l = 70 mm made of 45 grade steel were used as specimens. The composition of the base material was defined on the optical emission spectrometer ARL 3460. The analysis results are given in Table 1.

The retrofit of 3G71 surface-grinding machine and UT16PM screw-cutting lathe by equipping the machine systems with additional concentrated energy source was carried out to integrate the processes of mechanical and surface thermal treatment. As the energy source we used a detachable hardening contour providing high-energy heating by high frequency currents (HEH HFC) powered by HFG 6-60/0.44 generator with current operating frequency $\omega = 440 \cdot 10^3$ Hz.

Table 1. Chemical compositions of 45 grade steel

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

In the process of surface heat strengthening we used the loop inductor equipped with grade N87 ferrite (Figure 1). The heating was executed in accordance with deep-lying scheme by continuous step-by-step method. The thickness of the hardened layer did not exceed the depth of current penetration into the heated metal – 0.6…0.8 mm. The machining conditions are: the source power density $q_s = (1.5 - 4.0) \cdot 10^8$ W m$^{-2}$; the speed of the specimen movement under the inductor influence $V_s = (0.05…0.1) \text{ m s}^{-1}$. The breadth of the active inductor cord was $B_s = 2 \text{ mm}$, the processing was executed with clearance $\Delta = 0.1…0.2 \text{ mm}$. The intensive water (shower) surface cooling was used [20, 21].

Abrasive grinding of the hardened and nonhardened steel was carried out taking into account the recommendations in [22] by the abrasive wheel in accordance with the State Standard “GOST P 52781-2007: 1 250x32x76 25A F60 L 6 V 35 m/s 2cl.; 1 250x32x76 25A F46 L 6 V 35 m/s 2cl.”. The machining conditions are: wheel speed (cutting speed) of $V_{cs} = 35 \text{ m/s}$, line feed was varied in the range of $V_{lf} = 5 \ldots 20 \text{ m/min}$. Since the height of the wheel is greater than the breadth of the workpiece (10 mm) the scheme used plunge grinding. In this case, the cross-feed $S_{cf}$ was not used, and the infeed grinding at the depth $t$ was performed discretely per each table stroke.

Rough turning was performed by a straight cutting tool with indexable-insert, the material of the insert being T15K6, at the following modes: the cutting speed $V_{cs} \approx 92 \text{ m min}^{-1} \ (n_d = 588 \text{ min}^{-1})$; feed per revolution $S_{rev} = 0.35 \text{ mm}$; the cutting depth $t = 1 \text{ mm}$.

At the stage of finish turning we used a straight cutting tool with indexable-insert, the material of the insert being $\text{Al}_2\text{O}_3$-TiC. The cutting modes were: the cutting speed $V_{cs} \approx 133 \text{ m min}^{-1} \ (n_d = 882$
min$^{-1}$); feed per revolution $S_{rev} = 0.025$ mm; the cutting depth $t = 0.01 \div 0.015$ mm. Sulfurized mineral oil Sulfofrezol was used as lubricant and coolant at the stages of rough and finish turning.

At the stage of diamond smoothing we used a toolholder with elastic nose with a settled diamond nosepiece manufactured in accordance with Standard Specifications “TU2-037-631-88”. The sphere radius was $R = 1$ mm. Taking into account the rigidity of the lathe, surface layer rigidity of the processed workpiece after the surface hardening by HEH HFC (HV = 700…800) and the diamond sphere radius the radial component of the smoothing force $P_y$ was 50, 100, 150, 200 N correspondingly. The circumferential speed of the workpiece was $V_{cs} = 25.3; 33.2; 41.9$ m min$^{-1}$ ($n_d = 168; 220; 278$ min$^{-1}$); feed values were $S_{rev} = 0.018 \ldots 0.08$ mm. Industrial oil of I - 20A grade was used as a lubricant and coolant during the process of diamond smoothing.

Structural investigation was conducted on the optic microscope Carl Zeiss Axio Observer Z1m and scanning electron microscope Carl Zeiss EVO 50 XVP, which was equipped by a energy dispersive detector INCA X-ACT (Oxford Instruments). To reveal the specimen microstructure we used a 5% ethanol solution of nitric acid and a saturated solution of picric acid in ethanol with surfactants [23].

To assess microhardness of the specimen hardened surface layer we used the instrument Wolpert Group 402MVD. A mechanic destructive method (layerwise electrolytic specimen etching) was employed to investigate the residual stress as well as X-ray technique, executed on the high definition diffractometer ARL X’TRA [24, 25]. The surface layer defects detection was performed on each technological stage by: visual optical method using microscope Carl Zeiss Axio Observer A1m; capillary method; eddy-current testing employing eddy-current flaw detector VD-70. Surface topography assessment was executed on the laser profilograph-profilometer Zygo New View 7300. The surface deviation in form, undulation and asperity was measured by Taylor Hobson profilograph-profilometer Form Talysurf Series 2.

3. Results and discussion
The assignment of rational mode for each stage of the mentioned hybrid treatment was based on the recommendations in papers [26, 27] and conditioned by the maximum production capacity and the desired quality of the final product. For example, while choosing the second stage modes - surface hardening by HEH HFC limited by the required hardening depth $h = 0.6$ mm and a rational character of residual stress distribution - the power density ($q_s [W \cdot m^{-2}]$) and the source traverse speed ($V_s [m \cdot s^{-1}]$) were defined via a set of equations solution, namely functional dependence of the hardened layer depth on the HEH HFC modes $h(q_s, V_s)$ and functional dependence of the transition layer relative value $\Psi(q_s, V_s)$ [28]:

$$\begin{align*}
\begin{cases}
h(q_s, V_s) = a + bV_s + cV_s^2 + dV_s^3 + eV_s + fV_s^3 + gH_s + iV_s^2 + jV_s^2 q_s,
\Psi(q_s, V_s) = k + lV_s + mV_s^2 + nV_s^2 + oV_s^2 + pV_s^3 + qV_s^3 + rV_s^3 + sV_s^3 + tV_s^2 + uV_s^2 q_s,
\end{cases}
\end{align*}$$

with $a = 0.426008$, $b = 2.827121$, $c = 3.025072 \cdot 10^9$, $d = -301.591960$, $e = -4.694423 \cdot 10^{-18}$, $f = 3.600066 \cdot 10^{-8}$, $g = 1953.668810$, $h = 3.216427 \cdot 10^{-27}$, $i = 1.375401 \cdot 10^{-17}$, $j = -3.779403 \cdot 10^{-7}$, $k = 0.087564$, $l = -7.429933$, $m = -1.062284 \cdot 10^{-8}$, $n = 235.19293$, $o = -3.424286 \cdot 10^{-18}$, $p = -8.850919 \cdot 10^{-8}$, $r = -130.93045$, $s = 2.9423 \cdot 10^{-26}$, $t = 1.403793 \cdot 10^{-16}$, $u = 1.010925 \cdot 10^{-7}$ - being the values of functional dependency ratios for the 45 grade steel. The relative breadth of the transition layer $\Psi$ equals the ratio of the transition zone (i.e. the zone between pure martensite structure layer and a layer with the original structure) to the depth of the hardened layer.

In the process of hardening the grade 45 steel at the depth of 0.6 mm the range of the recommended modes is limited by the source power density intervals $q_s = (3.0 \ldots 3.4) \cdot 10^9 \ W \cdot m^{-2}$ and speed $V_s = (0.072 \ldots 0.081) \ m \cdot s^{-1}$. The calculated combination of the treatment modes ensures the required results in the hardening depth and a rational transition zone value.
The machines were adjusted for the following modes: 1) for the surface grinding machine 3G71 - \( q_s = 3.2 \times 10^8 \, \text{W m}^{-2} \) and \( V_s = 0.078 \, \text{m s}^{-1} \); 2) for the screw-cutting lathe UT16PM - \( q_s = 3.2 \times 10^8 \, \text{W m}^{-2} \) and \( n_d \approx 31 \, \text{min}^{-1} \) (the reequipment of the main motion drive by adding the HF Inverter model F1500-G0015S2B frequency converted to the electric circuit was executed to provide the required rotation speed of the spindle).

Figure 2 illustrates the pattern of microhardness and the surface layer residual stress distribution in the specimen. The maximum level of compressive residual stress on the surface was \( \sigma = -560 \pm 20 \, \text{MPa} \). The peak of the tensile stress was situated at the depth of \( \sim 0.8 \, \text{mm} \) and comprised \( \sigma = 75 \pm 45 \, \text{MPa} \).

Figure 3a. shows the hardened grade 45 steel layer microstructure. It is made of martensite with insignificant additions of minor ferritic grains of less than 10 µm. The average microhardness level of the hardened by HEH HFC layer is 739 HV in comparison with initial material microhardness of 204 HV. The microstructure of the transition zone near the base material consists of ferritic grains of 20-30 µm and low-carbon steel (Figure 3b). The breadth of this zone is \( \sim 0.17 \, \text{mm} \). The presence of ferrite and its lineage structure (the same as in the base material) indicates that this zone was heated between \( \text{Ac}_1-\text{Ac}_3 \).

The integral processing on 3G71 machine presupposes the removal of the stock allowance occurred due to volume expansion of the hardened layer (not more than 0.015 mm) to be performed at finish grinding. Considering the types of the used abrasive disks, the average abrasive grain rounded radius is: for the wheel - 1 250x32x76 25A F60 L 6 V 35 - 19 \( \pm 4 \, \mu \text{m} \); for the wheel - 1 250x32x76 25A F46 L 6 V 35 - 32 \( \pm 5 \, \mu \text{m} \).

Hence, the stock allowance for the finish grinding is significantly smaller than the abrasive grain average radius, which in fact excludes the possibility of mechanical metal removal and predetermines its plastic deformation.

Figure 2. The distribution of microhardness and residual stress in the specimen surface layer after the hardening by HEH HFC.

Figure 3. The microstructure of the grade 45 steel after HEHHFC surface hardening:

a) hardened layer area; b) transition zone area.
The next stage was sparking, which was performed during $\tau = 15\ldots20$ s at the following modes: wheel speed (cutting speed) $V_{cs} = 35$ $\text{v s}^{-1}$, line feed $V_{lf} = 20$ $\text{m min}^{-1}$, cross feed $S_{cf} = 0.2$ $\text{mm per double pass}$. In the course of experimenting, we registered the increase in surface microhardness to the level of HV $830\pm15$ (Figure 4), i.e. the increase was by $\sim 12\%$. At the same time, there was an increase in the surface compressive residual stresses: $\sigma = -620\pm10$ $\text{MPa}$. The increase in the level of the residual stresses in comparison with the stage of HEH HFC hardening was by $\sim 10\%$. The surface undulation was about $R_a = 0.15\pm0.05$ $\mu\text{m}$ (Figure 5).

![Figure 4](image1.png) ![Figure 5](image2.png)

**Figure 4.** The distribution of microhardness and residual stresses in the surface layer after sparking $\tau = 15$ s.

**Figure 5.** 3D model of surface topography after the stage of sparking. Surface undulation $R_a = 0.143$ $\mu\text{m}$. Sparking time $\tau = 15$ s.

In the course of conducting experiments on work station based on UT16PM lathe the finish turning was performed to the size of the workpiece $d = 48$ mm, the surface undulation in Ra value was $1.2\pm0.2$ $\mu\text{m}$. The surface microhardness and residual stresses were at the level of the HEHHFC stage.

In the process of diamond smoothing there forms a surface with plastic deformation and a rounded microrelief without tears and pits (Figure 6).

![Figure 6](image3.png)

**Figure 6** 3D model of workpiece surface topography after the diamond smoothing stage: the initial surface undulation before the diamond smoothing $R_a = 0.18\pm0.08$ $\mu\text{m}$. Processing modes: cutting speed $V_{cs} = 25.3$ $\text{m/min}$; feed $S_{rev} = 0.018$ $\text{mm}$; smoothing force $P_y = 150$ $\text{H}$; $R = 1$ $\text{mm}$. 
The structural research revealed that in the process of diamond smoothing there forms a work-hardened layer of 0.01…0.03 mm in the surface hardened specimen (Figure 7). The empirical data shows that the surface microhardness of the workpiece rises to 868 HV (the increase by ~ 17%), and the level of compressive stresses in the surface layer rises to $\sigma = -678 \pm 20$ MPa (the increase by 21%).

**Figure 7.** The distribution of microhardness and residual stresses in the workpiece surface layer after diamond smoothing.

▲ - residual stresses value acquired by X-ray technique.

### 4. Conclusions

It has been found experimentally that the suggested integration principle allows to perform workpiece processing on the same equipment thus ensuring minor values of stock allowance for the final stage of hybrid processing. This in turn ensures a significant decrease in the possible defects formation on the workpiece surface and contributes to the additional hardening of the workpiece. In the course of research it was registered that the integral processing leads to the surface microhardness increase by 12…17%, and the level of compressive residual stresses in the surface layer increase by 10…21% respectively.

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