Integral criterion of the state of physical parameters of the surface layer of machine parts

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Abstract. Exoelectronic emission, which is used as a non-destructive method for monitoring the parameters of the surface layer of parts, and the level of exoemission current from the machined surface, that is a complex criterion for the physical and chemical state of the metal have been studied. Correlations between the main parameters of the surface layer and exoemission are found.

1. Introduction

The reliability of technical systems is proved by the trouble-free performance of their parts that undergo the most significant loads of various types during operation. Achievement of a target product life requires a science-based approach to the design of route and operational technological processes ensuring an optimality state of physical parameters of the surface layer for the specified operating conditions.

In the function of the integral criterion for parameter estimation of the surface layer (PESL) it is desirable to use a non-destructive evaluation method that objectively describes the physics of the surface of the part after technological attacking. As such, the method of exoelectronic emission (EEE) can be used.

The term "exoelectronic emission" defines the phenomenon of non-stationary electron emission from the surface of a solid body in an excited state, under external thermal or light stimulating action with the energy below the threshold for the occurrence of stationary emission effects. By now the fact of relationship of emission parameters and unsoundness of materials is considered the proof of it. Technological methods of attacking the surface, accompanied by deformation and thermal phenomena cause complex physical and chemical processes that cause some imbalance in the electronic system of materials [1 – 4]. Despite the difference in the physical nature of the transformations that occur in the surface layer as a result of external influences, the emission reaction is reduced to a decrease in the energy threshold. It is also established that the EEE method is not sensitive to the type of surface defect, but only serves as its indicator. Therefore, its use for monitoring the state of the surface layer should be accompanied by studies of the relationship between EEE parameters and the regularities of the defect formation process in the surface layer. Wide practical use of the method is caused by a number of features:

– no restrictions related to the nature, structure and properties of materials;
– the ability of acquisition of information both in integral form from the entire controlled surface, and locally, from its individual sections;
– rapid response to surface defects, which makes possible to use it in dynamic testing;
– measurements can be carried out in a variety of medium, a wide temperature range, and after various external energy depositions on the surface.

As is commonly known, the real surface of a solid body is always covered with layers of adsorbates, an oxide film, that results in a modification of the energy spectrum of existing electron states. Due to the structural imperfection the surface is a source of dislocation generation, which inevitably affects its mechanical properties. Many researchers associate this phenomenon with the presence of grain boundaries and crystal twins, oxide films, cracks, etc.

In applied technical problems, there are mainly two types of EEE:
1) photon stimulated electronic emission (PSEE) – emission recorded during lighting at a constant temperature;
2) thermostimulated electronic emission (TSE) is an emission recorded when a controlled object is heated.

2. Results
The technological system (TS) of diamond burnishing (DB) of flat surfaces of gray cast iron (SCh20) parts, used in the manufacture of basic elements of equipment and technological equipment, after preliminary face milling (or flat grinding) was considered as an object of research.

In this paper, the PSEE was used to estimate the physical and chemical state of surfaces.

To avoid high-energy effects on the surface, an ultraviolet visible radiation probe is used in the measurement process. Photostimulation results in delocalization of electrons from traps, which take place due to defects in the surface layer of the material. Light with quantum energy \( h \nu > E_{\text{opt}} \), where \( E_{\text{opt}} \) – optical ionization energy of trapping center causes either ionization of center with further trap depletion or electron excitation. Although metals have a sufficient number of free electrons, EEE requires excitation and stimulation. For most metals and alloys, the work of electron liberation is 4–5 eV, so that the EEE of metals should occur if the excitation and stimulation reduce the surface potential barrier. In thin oxide layers on the surface of metals, there are structural defects, which, as a rule, are the centers of electron localization. Such traps can recapture electrons, which found themselves in carrier band of oxide. But under the conditions of photostimulation they are immediately emptied in accordance with the PSEE mechanism.

The energy state of the surface layer, measured by the level of ecoemissions current depending on methods of processing, types of material parts, tool materials and machining modes, was investigated in an experimental apparatus of the Moscow aviation Institute construction.

The vacuum system of the unit ensures stable pressure in the chamber \( 10^{-7} \) Pa, which after replacement of the next sample is achieved within approximately 30 minutes. For photostimulation of EEE a monochromator of spectrophotometer SPh-26 was used, that allows controlling the parameters of luminous flux. The quartz optical system provides an adjustable diameter UV probe. The ion counter served as the register system IC-04, the range of detected currents – from \( 1 \cdot 10^{-13} \) to \( 2 \cdot 10^{-18} \) A.

The segments, exsected from cylindrical test-pieces by means of electroerosion method, served as a model. Scanning was performed along the cylinder's generatrix along a 12 – 16 mm long track. Before exoemission analysis, the samples were thoroughly washed with ethanol.

Scanned images taken from the sample surfaces made the obtaining of the average value of the EEE level from one surface possible, as well as identifying areas with an increased degree of deformation besides analyzing the heterogeneity of the energy properties of the surfaces.

Thus fig. 1 shows scans from the surfaces of samples made of harden steel 45, turned on a lathe and processed by circular grinding and diamond burnishing.

Analysis of the scans shows that in absolute terms, the instability of the energy properties of the studied surfaces is more typical for grinding and less for turning. In addition, there is a significant difference in the average level of exoemission flow \( I \) for these processing methods: for turning it is approximately 160 sec\(^{-1}\), for grinding – 500 sec\(^{-1}\), for diamond burnishing – 930 sec\(^{-1}\). These data
indicate a significant difference in the physical state of the sample surfaces due to the excellent conditions of plastic deformation in the surface layer expressed by individual force, speed, and heat factors for each processing method.

![Graph](image1.png)

**Figure 1.** Standard scans of the treated surfaces of harden steel 45: 1 – fine turning with composite 10, $t = 0.3$ mm, $S = 0.06$ mm/rev, $V = 180$ m/min; 2 – plunge-cut cylindrical grinding (white electrocorundum) $t = 0.005$ mm, $S_{\text{пр}} = 800$ mm/rev, $V = 28$ m/min; 3 – diamond burnishing (synthetic polycrystalline diamond), $r = 1.5$ mm, $S = 0.05$ mm/rev, $V = 120$ m/min

To study the stability of energy properties over the area of the machined surface, the end surface of a cylindrical sample made of harden steel 65G was taken (fig. 2). The decision to investigate the end surface was due to the need to exclude possible energy losses when a section of the cylindrical surface is excited consequent on various conditions owing to the reflections of the absorption of the light stream from the scanning spot.

![Graph](image2.png)

**Figure 2.** Exoemission topogram of the end surface section of a sample made of harden steel 65G, turned with a composite 10: $t = 0.45$ mm, $S = 0.08$ mm/rev, $V = 210$ m/min

The presented graphs of the dependence of the exoemission flow $I$ on the section of the route $(x, y)$, made every 1 mm of the surface area of 30 mm$^2$ indicate a high degree of uniformity of the exoemission currents, which is expressed in close average values of the fixed parameter (162, 170,
167, 174 sec\(^{-1}\)). This allowed concluding that the energy properties of the entire sample were adequately evaluated for the level of EEE taken from a single track of a section of the cylindrical surface. Experimental dependences of the differentiated influence of the main elements of the modes of the studied processing methods on EEE are shown in fig. 3 (the research was conducted in partnership with V. V. Shorin).

During the process of turning the depth, feed and the cutting speed have bearing on the volume of exoemmision current. With their increase the parameter \(I\) rises and in the studied ranges of changes in processing modes, these dependencies are monotonous. The growth of exoemission current with increasing cutting depth and feed is associated with an increase in deformation effects on the metal of the surface layer and, consequently, with an increase in the number of defects in the grains of the material. A cutting speed step-up is accompanied by the increase in the deformation temperature, which contributes to a more intensive process of localization of free electrons at the surfaces of newly formed grains and causes a decrease in the work function during further photostimulation. In terms of quality the effect of the depth and speed of plunge-cut cylindrical grinding on the EEE remains the same as during the process of turning.

The effect of longitudinal flow is reversed, i.e. by increasing it the value of exocurrent decreases and that is connected with a reduced probability of multieffect on one and the same microscopic volume of metal surface layer of the grains of the circle.

![Figure 3. Influence of technological factors on the level of EEE in various methods of processing of harden steel 45: a – turning with composite 10); b – circular grinding (white electrocorundum); c – diamond burnishing](image)

A similar effect of the line feed on the exoemission can be seen in the case of diamond burnishing. It is obvious that the effectiveness of the deformation affection on the metal of the surface layer decreases with increasing of line feed.

An increase in the smoothing force and speed in the studied ranges contributes to an increase in EEE. Planned experiments were carried out to identify the complex influence of machining factors for obtaining corresponding empirical dependencies. Steel 45 was used as a feedstock. This method extends the effect of the obtained empirical dependences on other materials by experimental refinement of \(b_0\) coefficient of the standard model of the corresponding treatment process.

Table 1 shows the average EEE values for the studied processing methods.

As a result of processing the experimental results, the following dependencies were obtained:

- turning:
  \[ I = b_0t^{0.18}S^{0.16}V^{0.28}r^{0.12}, \]  
  \[ (1) \]

- circular grinding:
  \[ I = b_0t^{0.21}S^{0.18}V^{0.32}, \]  
  \[ (2) \]

- plunge-cut cylindrical grinding:
  \[ I = b_0S_pV^{0.25}Z^{0.12}, \]  
  \[ (3) \]
– diamond burnishing:

\[ I = b_0 P^{0.21} S^{0.13} V^{0.14}. \]  

Only statistically significant factors are included in dependencies (1) – (4). The values of the coefficients \( b_0 \) taking into account the processed material are given in table 2.

Table 1. Average values of exoelectronic emission depending on the processing method

| № experiment | Turning | Circular grinding | Plunge-cut cylindrical grinding | Diamond burnishing |
|--------------|---------|-------------------|--------------------------------|-------------------|
| 1            | 110.6   | 529.6             | 466.0                          | 575.6             |
| 2            | 185.2   | 651.4             | 688.9                          | 874.3             |
| 3            | 180.7   | 416.3             | 536.5                          | 503.3             |
| 4            | 175.2   | 511.8             | 801.4                          | 762.4             |
| 5            | 201.8   | 658.3             | 509.4                          | 670.2             |
| 6            | 196.3   | 812.4             | 761.3                          | 1021.3            |
| 7            | 190.5   | 520.3             | 586.3                          | 584.6             |
| 8            | 320.6   | 638.7             | 868.7                          | 889.6             |

Table 2. The values of the coefficients \( b_0 \)

| Processing methods | Material                  | Normalized steel 45 | Harden steel 45 | Harden steel 65G | High-grade cast iron |
|--------------------|---------------------------|----------------------|-----------------|-------------------|---------------------|
| turning            |                           | 80.8                 | 98.6            | 116.3             | 73.8                |
| circular grinding  |                           | 1.15-103             | 1.58-103        | 1.92-103          | 1.45-103            |
| plunge-cut cylindrical grinding |                   | 362.6                | 471.6           | 546.4             | 395.5               |
| diamond smoothing  |                           | 54.8                 | 94.5            | 86.8              | 69.7                |

The rank diagram obtained for turning shows that the critical factor in this process is cutting speed, which primarily affects the temperature and rate of plastic deformation. Factors mainly shaping the force pattern in the facing layer (\( r \) and \( t \)) are approximately 1.5 times lower if the degree of influence over EEE is meant. During the circular grinding the line feed designating the time of effect of the circular on the machinable surface comes first. By way of illustration, the rank of the "average grain size" factor is shown, which was not statistically significant.

As the plunge-cut cylindrical grinding rank chart shows, the greatest influence over EEE is made by radial feed (actually depth of cut) and speed, with the \( S_p \) factor in the first place. This suggests that with this method, which is accompanied by abundant cooling, the main factor designating the strength of the exocurrent from the surface is the deformation one.

Expectedly the indenter force factor came out on top in case of diamond burnishing. Correlation analysis was used to establish statistical relationships between the EEE intensity and the parameters of the surface layer state.

The following parameters were preferred:
- \( R_a \), \( \mu m \) – arithmetic mean deviation of the profile,
- \( H_k \), kg/mm\(^2\) – surface microhardness,
- \( U_n \) – coefficient of the degree of cold work,
- \( \sigma_0 \), MPa – technological tangential macrostresses on the sample surface,
- \( d \) – the number of grains of the metal surface layer,
- \( \rho \), cm\(^2\) – dislocation density.

The initial data for correlation analysis were the results of both single-factor and multi-factor experiments. The coefficients of pair correlation between all analyzed parameters were obtained (table 3).
Table 3. Coefficients of pair correlation between parameters of the surface layer state

| Parameters | $Ra$ | $H_\mu$ | $U_\mathrm{n}$ | $\sigma_0$ | $d$ | $\rho$ | $I$ |
|------------|------|---------|--------------|-----------|-----|-------|-----|
| $Ra$       |     | 0.17*   | -0.22        | -0.31     | -0.17| -0.86 | 0.17|
| $H_\mu$    | -0.22| 1.00    | 0.92         | -0.16     | 0.91 | 0.86  |     |
| $U_\mathrm{n}$ | -0.19| 0.84    | -0.19        | -0.33     | 0.27 | 0.84  | 0.88|
| $\sigma_0$ | 0.21 | 0.92    | -0.33        | -0.19     | 0.87 | 0.91  |     |
| $d$        | -0.11| 0.96    | 0.16         | 0.96      | 0.89 | 0.87  |     |
| $\rho$     | 0.34 | 0.16    | 0.84         | 0.86      | 0.78 | 0.77  | 0.37|
| $I$        | 0.29 | 0.22    | -0.11        | 0.27      | 0.31 | 0.17  |     |

* – the top line shows the correlation coefficient for turning, the second line – for circular grinding, and the third line-for diamond smoothing.

3. Discussion of results

Considering the strength of the relationship of each parameter separately with the intensity of the exocurrent, first of all, it should be noted that for all three studied processing methods, there is a fairly good convergence of the values of the pair correlation coefficients.

If we conveniently classify microgeometric and physical parameters included into correlation analysis into two groups we can definitely say that surface microhardness, coefficient of the degree of cold work, the number of grains and dislocation density are allied to EEE, while arithmetic mean deviation of the profile and technological tangential macrostresses are loosely correlated with the studied parameter. At another point, if you look at the coefficients of pair correlation between $H_\mu$, $U_\mathrm{n}$, $d$ and $\rho$, they all fall into the range of values $0.74 – 0.96$, which indicates their strong mutual influence. Therefore, the relationship of the first group of parameters with EEE should be considered as a whole. Thus, with an increase in the surface microhardness and, consequently, coefficient of the degree of cold work, there is a decrease in the grain size (an increase in its number) and an increase in the dislocation density. This statistical analysis does not contradict the physics of the surface layer. Since an increase in hardness is nothing more than an increase in the metal’s resistance to plastic deformation, in the vast majority of cases this is due to a decrease in the size of the metal grains of the surface layer and the barrier effect of grain boundaries [4, 8]. These last two factors significantly inhibit the movement of dislocations in the real crystal lattice of polycrystals, which is explained by the barrier effect of grain boundaries (the smaller the grain, the larger the boundaries) and the “locking” property of dislocation planes. This close correlation of all four factors and the amount of exoelectron emission is explained by the sensitive reaction of this method to the material defect, the increase of which is accompanied by a significant increase in the number of exoelectrons in the surface.

The effect of the roughness parameter $Ra$ on the EEE is rated by correlation coefficients from 0.47 for diamond burnishing to 0.36 for grinding, which can be considered rather weak from the point of
view of mathematical statistics. From the point of view of physics phenomena theoretically it is difficult to say what will affect the growth of exoemission current mostly – the increase of surface area due to increasing $Ra$ and thus there is higher probability of electron exit into the vacuum during the process of stimulating or power reduction of excitant light probe as a result of large losses when scanning the surface with orange-peel defect. Besides, depending on the methods and modes of fine machining and strengthening treatment the micromicrelief can be formed under the influence of relatively minor force influences (grinding with fine grain circles having small cutting depths), and at high specific loads (diamond burnishing). Such a situation can form a combination of low roughness in some cases with a relatively large surface grain and a small density of dislocations, and in others a similar micromicrelief will be on the surface with a smaller grain and a higher density of dislocations. It would be safe to assume that this physical model explains weak correlation between the heigh parameter of roughness and the value of EEE.

As for the coefficients of pair correlation between surface macrostresses and the energy characteristic of the surface, in table 3 they are bottom in absolute terms.

The statistical relationship between the grain size $d$ (number) and the dislocation density $\rho$ with EEE is of practical interest. Using data for correlation analysis, we obtain equations of the form:

$$d = C_d + a_d,$$  \hspace{1em} (5)

$$\rho = c_\rho (I - a_\rho).$$  \hspace{1em} (6)

The values of the coefficients in dependencies (5) and (6) are shown in table 4.

| Coefficient | Material |
|-------------|----------|
| $C_d$       | Steel 45 (normalized) | 0.019 |
|             | Steel 45 (harden)     | 0.024 |
|             | Steel 65G (harden)    | 0.029 |
| $a_d$       | 6.5       | 6.9  |
|             | 7.2       |
| $C_\rho$    | $2.2\cdot10^6$       | $1.9\cdot10^7$ |
|             | $2.9\cdot10^7$       |
| $a_\rho$    | 22        | 15   |
|             | 84        |

4. Conclusion
According to the results of conducted research and obtained experimental data it can be concluded:

1. The level of exoemission current from the treated surface can serve as a complex criterion for the physical and chemical state of the metal of the surface layer.

2. EEE can be used as a non-destructive method for monitoring the quality indicators of parts surface, which allows providing the specified parameters of the surface layer state.

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