Improving the efficiency of planing operations when processing large parts based on gas analysis

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Abstract. The paper presents a comprehensive study of the process of diffusion of impurities, the formation of gases and their mass transfer in the gas-air space of the treatment zone. In addition, the author discusses changes in the state of the cutting process, including the state of the cutting tool and the surfaces of the processed products. Accordingly, the main scientific result is the development of methods and means of controlling the processes of mechanical processing based on mathematical models. The use of such systems in automated production allows you to increase productivity and reduce processing costs by increasing the reliability of processing at higher cutting conditions, timely change of substandard tools, reducing product scrap and tool consumption. In addition, to increase the reliability of the processing systems by timely replacement of extremely worn or broken tools on a backup tool.

1. Introduction

The growth in the automation of production processes in mechanical engineering places high demands on the means of diagnosis, which are used for the operational control of the condition of equipment, the detection and localization of faults. For metalworking equipment, one of the urgent issues of increasing its reliability and improving the quality of products is the diagnosis of the condition of the cutting tool and the rapid detection of the initial stage of critical wear, chips or breakage.

Known methods for evaluating machining processes, based on measuring cutting forces, vibroacoustic emission, thermoEMF and others, do not provide complete information about ongoing processes or do not fully reveal their potential capabilities, so their use in automated control and monitoring systems is limited. An analysis of the works [1, 2, 3, 4] devoted to methods of control of machining processes, as well as information-measuring systems, shows that much attention is paid to the issues of ensuring a given or optimal reliability of monitoring the state of the cutting tool, as well as the accuracy of measurements. The smallest group consists of works in which the quality of the surfaces of the processed products is controlled, although this parameter is one of the main ones. Thus, the scientific problem discussed in this paper is very topical. The paper is devoted to the establishment of interconnections between physicochemical and thermal deformation processes, as well as the condition of the cutting tool and the quality of the processed material with gas formation parameters.
2. Results and discussion
The occurrence of high temperatures in the cutting zone contributes to the diffusion of gas impurities from the removed chips and the formation of volatile compounds upon contact of the processed material with atmospheric air. The temperature field arising in a solid under the action of a moving or motionless heat source of any shape acting temporarily or continuously can be obtained as a result of one or another combination of temperature fields arising under the action of a point system of instant heat sources. The main foci of heat during cutting are, as you know, the plane of shear in the sheared deformable layer of material and the friction zone of the front and rear surfaces of the tool with descending chips and the workpiece, respectively.

![Diagram](image)

**Figure 1.** The main processes of burnout of impurities with the formation of volatile compounds.

Figure 1 shows the main processes that lead to the mass transfer of diffusing elements in the material with the formation of volatile compounds in a gaseous medium. The theory of thermal processes in technological systems during cutting is only part of the general theory of heat conduction and physical processes, which presents expressions for determining various quantities, including cutting forces:

\[ P_X = C_{p_X} \cdot t^{1.2} \cdot S^{0.55} \]  
\[ P_Y = C_{p_Y} \cdot t^{0.9} \cdot S^{0.75} \]  
\[ P_Z = C_{p_Z} \cdot t^1 \cdot S^{0.75} \]  

The value of the normal component of the cutting force \( P_N \) is determined by the formula.
\[ P_N = \sqrt{P_X^2 + P_Y^2}, \]  

where \( P_x \) and \( P_y \) are the constituent cutting forces, determined by reference data, by the conditions of the experiment, or from literature, for example, [1]:

The values of the coefficients \( C_{px}, C_{py} \) and \( C_pz \) are also determined by reference data or by formulas. For example, for cast iron

\[ C_{pz} = \text{const} \cdot HB^{0.55}, \]

where \( C_{pz} \) is a constant component; 
\( HB \) – Brinell hardness.

Based on this, the mathematical expressions are presented below, which reflects the diffusion processes of impurity atoms without taking into account their interaction with the cooling medium under various metal processing conditions.

\[ N(s,t)_D = N_0 \cdot \text{erfc} \left( \frac{s \cdot \sin \phi}{2 \cdot \sqrt{\frac{t \cdot \eta}{v \cdot \sin \phi} \cdot D_0 \cdot \exp \left( \frac{E_D}{RT_D} \right)}} \right), \]

where \( t \) is the diffusion time, sec;  
\( t \) is the cutting depth, mm;  
\( v \) is the cutting speed, m / min;  
\( \eta \) is the coefficient of longitudinal shrinkage of chips;  
\( N_0 \) is the initial concentration of impurities in the metal;  
\( \text{erfc} \) is an additional function of Gaussian errors;  
\( D_0 \) is the diffusion constant;  
\( E_D \) is the thermal energy of deformation;  
\( R = 8.314 \text{ J} / \text{mol} \cdot \text{K} \) is the gas constant.

Figure 2 shows the heat distribution during chip formation, described by expression (5).

![Figure 2](image)

**Figure 2.** Heat distribution during chip formation: 1 – elementary volume before deformation, 2 – elementary volume after deformation.

Thus, the obtained mathematical model allows us to determine the concentration of diffusing impurities under any processing conditions of various materials. The developed technique allows to determine the areas of the processed surface with deviations from the specified hardness. This technique is based on the analysis of the physicochemical properties of the specific gases generated in
the cutting zone during processing of materials. Three main groups are identified as controlled gases: those formed by combining the air components with impurities burnt out from the processed material (carbon oxides, sulfur oxide, hydrocarbons), as well as compounds formed by combining atmospheric oxygen and atmospheric oxygen. The results obtained during the experiments revealed a change in the concentration of a number of controlled gases in the treatment zone, reflecting a change in hardness and confirming the presence of abnormal areas in the surface layer of the processed material. When planing with a cutting speed $v = 0.07 \ldots 0.4 \text{ m/s}$, feed $S = 10 \ldots 20 \text{ mm/dv.x}$, cutting depth $t = 0.5 \ldots 2 \text{ mm}$, a different concentration level is noted formed nitrogen oxides in the processing zone of various materials.

Table 1 presents data on the concentration of nitric oxide in the processing of materials with various physicochemical properties.

### Table 1. Change in the concentration of nitric oxide in the processing of materials with various physicochemical properties.

| №  | Material         | Concentration of nitrogen oxides |
|----|-----------------|----------------------------------|
| 1  | Stainless steel | 15                               |
| 2  | Steel 40H       | 3                                |
| 3  | Steel 18 HGT    | 13                               |
| 4  | Steel 38H2MUA   | 15                               |
| 5  | Grey cast iron  | 26                               |
| 6  | Aluminum alloy  | 3                                |

The hardness of the material can be estimated when there is a dependence of the concentration level of a gas on a diagnostic parameter. During the research, a large-sized part made of gray cast iron was processed with a surface area of approximately $5 \text{ m}^2$, the hardness of which should not be lower than $HB 170 \ldots 180$. Objective control of the surface hardness of a workpiece with a large processing area is difficult or impossible. A change in the concentration of gases formed during the cutting process is a consequence of the scatter in the physicochemical parameters of the workpiece, including the presence of hardness anomalies. The concentrations of released gases measured during the planing indicate the presence of anomalies in the hardness of the surface of the workpiece, which is confirmed by the results of hardness measurements by standard methods. The calculation of the linear correlation coefficient between the concentration of carbon monoxide CO in the treatment zone and the hardness of cast iron according to the results of planing a large cast iron table of a machine on a planing machine is presented below.

### Table 2. Calculation of linear correlation coefficients between the concentration of carbon monoxide CO and the hardness of cast iron.

| $HB$ | ppm | $X^2$ | $Y^2$ | $X \cdot Y$ |
|------|-----|-------|-------|------------|
| 163  | 5.6 | 20.8  | 31.4  | 25.5       |
| 165.2| 5.2 | 45.3  | 27.04 | 35.0       |
| 162.7| 6.2 | 17.9  | 38.4  | 26.2       |
| 160.5| 2.8 | 4.2   | 7.8   | 5.8        |
| 162.7| 3.8 | 17.9  | 14.4  | 16.1       |
| 165.8| 3.4 | 54.6  | 11.6  | 25.1       |
| 165.8| 5.2 | 40.8  | 27.04 | 33.2       |
| 167.2| 6.6 | 76.2  | 43.6  | 57.6       |
| $\Sigma$ | 47.8 | 354.0 | 282.3 | 303.1     |
where $X$ is the average value of the measured Brinell hardness, $HB$;

$Y$ – averaged over two histograms, the value of the level of CO emission during planing finish processing of the table, ppm;

$X_i, Y_j$ are the arithmetic mean of hardness and concentration, respectively.

Based on the data given in table 2, we determine the value of the variances: $S_X = 2.84$, $S_Y = 2.45$. The correlation coefficient according to the results of measurements of hardness and concentration level in the processing zone of carbon monoxide is: $R_{XY} = 0.63$.

The value of the sample function $T = 3.69$, i.e., $T > t$. From this we can conclude that the measured values of the hardness of cast iron and the concentration of gases formed in the treatment zone (i.e., $X$ and $Y$) are connected by a linear dependence. The dependence of the concentration of carbon monoxide on the hardness of the processed material is presented in table 3.

**Table 3.** The dependence of the concentration of carbon monoxide on the hardness of the processed material.

| Material     | Hardness, HB | N / N₀  |
|--------------|--------------|---------|
| Steel 10     | 97           | 0.74    |
| Steel 20     | 126          | 0.67    |
| Steel 20H    | 134          | 0.66    |
| Steel 40     | 179          | 0.62    |
| Steel 45     | 180          | 0.61    |
| Steel 50     | 191          | 0.60    |
| U8           | 210          | 0.56    |
| 08H18N10T    | 165          | 0.56    |

Thus, the experiment to determine the concentration of carbon oxides in the cutting zone when machining a large part and measuring the hardness of the surface of the material confirmed the fundamental possibility of diagnosing the processed material (in this case, gray cast iron), based on the analysis of the gas-air medium during the machining of metals (in this case in the process of cutting metals by planing).

In this case, restrictions on the cutting force and power were taken depending on the parameters $t$ (cutting depth), $v$ (cutting speed) and $h$ (tool wear), determined from experimental studies based on gas analysis. The most optimal when using this method, as experiments show, are speeds from 0.33 to 0.42 m/sec. The use of recommended cutting speeds depending on the type of processing prevents the acceleration of wear of the cutting tool and reduces the auxiliary time when processing the workpiece itself.

When processing large table blanks, the gas-air medium was continuously monitored in the processing zone with registration of anomalous zones on the surface at each pass of the planing cutter. After processing and recording the anomalous zones, the table surface hardness was monitored and a conclusion was drawn on the suitability of this product for use, further or repeated processing, which made it possible to increase the monitoring efficiency in the manufacture of products. Theoretical studies and practical results obtained show that the greatest and most reliable information about the state of the cutting process of materials is obtained when using equipment for a comprehensive analysis of the gas-air environment. A study of the influence of the state of the material on the gas formation process with the implementation of this method was carried out when machining large-sized tables of heavy machines, which are a large casting with an area of about 5 m², on a planing machine. Based on the overall dimensions of the workpiece, when monitoring the entire machined surface, it is necessary to carry out about 2000 hardness measurements. This is due to the fact that with one measurement, an area of 2500 mm² is required. The proposed method allowed to reduce the number of measurements from 100 to 200 (in the anomalous zones detected by gas analysis). The proposed
method was also used in the control of large-sized bushings of compressor cylinders during processing on boring machines in mechanical repair work.

3. Conclusion
The interrelations of cutting conditions and the quality of the processed material with the parameters of gas generation during planing are determined. The main physicochemical processes during mechanical processing are investigated and identified, which allow to effectively monitor the condition of the workpiece material, based on gas analysis in the chip formation zone. The mathematical dependence of the diffusion of impurities on the processing parameters is established, which allows controlling the planing process and ensuring the quality of the surface layer of the processed products. In the process of research it was found that the concentration of formed gases generated during machining increases with increasing surface hardness of the processed products. Recommendations are developed for controlling the surfaces of products in planing operations, based on the analysis of gas formation in the cutting zone, which made it possible to increase labor productivity and processing quality by evaluating the working capacity of the cutting tool and the characteristics of the processed material.

References
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