# ON-LINE VIBRATION-BASED DIAGNOSTICS OF THE PRODUCTION PROCESS

KOZOCHKIN M.P., GRIGORIEV S.N. (MSTU STANKIN, Moscow, Russia)

The automatic working capacity maintaining of the machine-tool equipment by minimal manual intervention ("untended manufacturing") cannot be done without wide use of the built-in diagnostic tools, which are collecting data about the quality of the production process. The functions of the on-line diagnostics are not only evaluation of the mechanisms and working process condition, detection of the faulty operation's place and its causes, but also the decision-making function to eliminate the failure effect. To the problems solving by the on-line diagnostics can be refered: 1) diagnostics of the cutting tool condition; 2) diagnostics of the cutting process and its optimization; 3) control of the functioning and condition diagnostics of the machine tool units; 4) size control; 5) additional problems appearing under certain circumstances, for example operation mode adaptation to the changeable situation in the cutting area, correction of the actuating elements position to compensate the temperature deformation. The tool (sensors) selection for the on-line diagnostics of the cutting process is generally determined by two factors: the informativity, which is adequate to the investigated situation appearing in the cutting area, and the simplicity and reliability of the integration into the machine tool. Following this criterion the selection will generally depend on the force parameters and vibration parameters control in the wide frequency range. It seems that the control of the cutting force, torque moment or cutting power solves the problem. But it is so at first sight. In the production conditions the cutting force monitoring requires such built-in diagnostic tools, which are not reducing the machine tool omnitude by conditions of the gang-tooled machining by the automatic tool change. By these conditions the most universal diagnostic parameter remains the control of the drive cutting power. This the most widespread method is not void of essential defects. Point is that the automation industry, where are needed the built-in tools of the on-line diagnostics, is mainly based on the multifunction machine tool, which make possible to become a finished piece by the one set-in. That is at one machine tool is used the cutting tool for the primary machining, cutting tool for finishing process inclusive the small end-cutting tool. By its working the consumed power is significantly lower than the variation of no-load power even of the modern drive. The failures of this cutting tool make the basic part of the common quantity of the cutting tool failure. The experience shows that the failure of such cutting tool by means of the control of the drive power either cannot be detected, or are identified but with a significant delay, while the further broken tool advance leads to significant plastic deformations of the work piece and tool.

The vibrations in the range of 30-40 kHz are measured by serially manufactured accelerometers, which can be safely installed on the elastic system of the machine tool at a considerable distance from the cutting area, where the sensor is protected from chips and accidental damage. This setup does usually not require the machine-tool retrofit, although it should be given attention to protect the sensor cable against damage. The problems appear by having swing joints between the accelerometer and the cutting area, i.e. when are rotating both the cutting tool and the work piece. However, at high cutting speeds, for example, at the circular grinding machines, it does not cause difficulties. But if machine tables are periodically rotating the machine tool must be additionally tooled up by the mechanism, which extracts and presses the accelerometer during rotation of the table. This makes relevant to equip the measuring channel by the wireless signal transmission system, which would help to install accelerometers onto the rotating elements freely and would make unnecessary the cable laying through the machine tool to the sensor. Sometimes the accelerometer can be replaced by a microphone. In the published articles can be seen such solutions, although in this case the correlation of the useful signal and the interference becomes much worse.

By cutting and friction the nature of the vibroacoustic signal has a complicated structure in a wide frequency range, which does not coincide with the nature of the forces during cutting. For

example, by increasing the contact area during friction the oscillation amplitude may increase sharply by some stages and at some stages it can fall or doesn't change at all. The complex nature of the vibroacoustic signal is compensated by its sensitivity to changes of the contact processes during cutting and friction, but also by "long-range action" of the vibroacoustic signals. For example, the sensitivity shows by the fact, that when the cutting tool approaches with the rotating work piece, the moment of their contact significantly changes the vibroacoustic signal as early as at the stage of elastic interaction of the cutting tool with the microrelief of the work piece. The "long-range action" of the signal becomes apparent in the fact, that the signal representing the processes in the cutting area communicates this information to the remote locations of the elastic system. The variety of manufacturing operations and cutting conditions have an impact on the parameters of the vibroacoustic signals. If you are currently interested in information, for example, on the wear of the cutting tool, the influence of other factors will be the source of interference, which reduces the reliability of the diagnostic procedures. Conversely, by finishing operations the information about the parameters of vibrations in the cutting area affecting the condition of the surface and the surface layer may become a priority.

The proper assessment of the cutting process condition finds difficulty because of the complexity of the process itself, which hasn't so far any unified theory, as well as because of the complex structure of its dynamics. The dynamics of the contact interaction during cutting is determined, on the one hand, by the impact interaction of the microrelief, on the other and – by the intense formation of adhesive bonds, seeking to turn the cutting tool and the work piece into a coherent whole. There are grounds for the allegations, that the process of plastic materials cutting is, in principle, self-oscillating. Thus, the vibroacoustic signal is generated by the complex nonlinear system and its self-oscillating process adjusts to the processing conditions. In this situation the search of the parameters of the vibroacoustic signals, which give reliable information about the tool wear and the surface quality is a complex and multivariate problem. It is further complicated by the fact that the update of the tool and construction materials takes place much faster than the research in the area of the cutting process diagnostics.

As the vibroacoustic signal carries information directly from the cutting area, we lay our hopes on it by the adoption and adjusting of new technologies of the materials processing. The problem is urgent, because the high-speed processes cannot be directly watched and after the cutting was stopped, it becomes impossible to restore an adequate picture of what took place during the cutting. This is related to the thermic and structural changes in the machined material. The typical example of the use of the vibroacoustic diagnostics in this area is to study the process of "hard turning". The operational principle of the solid turning is the heating of the material, for example, hardened steel in the contact zone with the cutting edge to the temperature of 1400-1600 ˚C. The correctly designed tool geometry and cutting conditions allow to heat the machined material through the heat generated during plastic deformation, what leads to its local tempering to the supposed hardness ca. 25 HRC. Maximum temperatures occur in the primary zones of plastic deformations. The main heat is derived by chips and the machined surface and the tool are heated slightly. After the separation of the chips the material becomes rapid cool, what reduces the final hardness of not more than 2 units. These features of hard turning define the requirements to the geometry of the cutting tool, the stiffness of the mechanic system of the machine tool and cutting parameters etc. However, more detailed descriptions of hard turning studies are difficult to find in the literature. The greatest interest is the development of the tempering process of the machined material during the incision of the cutting tool. Because the incision is going on into the hardened material, and the wholeness of the cutting edge and surface smoothness depends on the tempering speed. The parameters of the tempering in the cutting zone can be assessed only by indirect means by the average temperature in the cutting zone, which varies both in time and in the volume of deformed material. The temperature in the zone of plastic deformations may depend on processed and tool materials, on the cutting parameters, on the geometry of the cutting edge, on the substrate material, on the rigidity of the elastic system of the machine tool and on its dynamic characteristics. You can find a number of other factors, which influence is difficult to assess.

In the process of ongoing studies of hard turning [2] was applied the control of the vibroacoustic signals, accompanying the process of hard turning from the moment of the incision and till the tool will go out the cutting area. As is known, by cutting and friction the vibroacoustic signals (especially its high-frequency components) are mainly determined by the relative speed in the contact point and by the lowest value of hardness in the contact pair. In relation to the hard turning this is the hardness of the workpiece surface. Relying on the monotonic increase in amplitude of the vibroacoustic signal by increasing of hardness the unsteady processes can be observed during the incision into the workpiece and evaluated the tempering process of the surface. To organize these observations accelerometers were located at different points of the elastic system, including the cutting tool itself. Thereby the cutting parameters, tool wear and the substrate material under the cutting plates were varied. Figure 1 shows the picture of the cutting area with three-component accelerometer mounted on the cutting tool. On the right hand an example of vibration acceleration signals is shown, recorded on each coordinate axis. Table 1 shows the effective (root mean square - RMS) and maximum values of the vibroacoustic signals at different frequency ranges for different cutting speeds, by the incision into the workpiece and by cutting itself. Previously, it was found that the amplitude of the high-frequency components of the vibroacoustic signals by friction is in the first approximation proportional to the relative velocity in the contact point and to the minimum hardness in the pair. As shown in Table 1 the highest frequency range is above 5.6 kHz. The speed in the contact point is known, but the hardness of the workpiece material changes under the influence of the cutting temperature. The hardness can be estimated, if the data in the table 1 will be brought to the same speed-value.

Table 1. The maximum and effective values of the vibroacoustic signal by different cutting speeds, in different frequency ranges, m/s$^2$ (steel 40X (Russian marking) - BOK 60 (ceramics – Russian marking), feed 0.24 mm / rev, cutting depth 0.15 mm).

| Frequency range, kHz | | Lower than 1 kHz | | | 1.0 – 1.4 kHz | | | 1.4 – 2.8 kHz | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cutting speed, m/min | | 125 | 250 | 500 | 125 | 250 | 500 | 125 | 250 | 500 |
| By incision | RMS | 11.2 | 6.6 | 3.6 | 4.6 | 0.5 | 0.5 | 4.5 | 7.7 | 3.5 |
| | Max | 18 | 27.5 | 8.5 | 16.7 | 1.5 | 1.5 | 18 | 30 | 12 |
| By cutting | RMS | 7.3 | 7.2 | 8.6 | 1.6 | 0.5 | 0.5 | 1.3 | 1.6 | 3.9 |
| | Max | 10.2 | 15.7 | 22 | 10.7 | 1.2 | 2.2 | 8.8 | 15.8 | 22 |

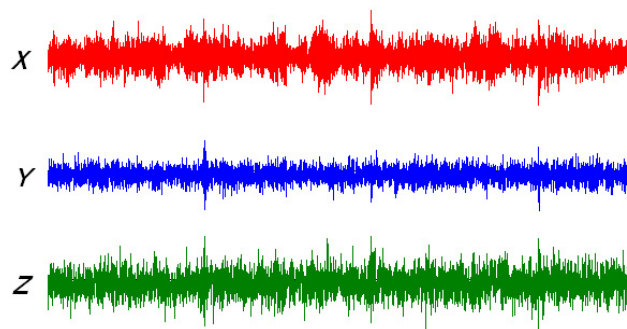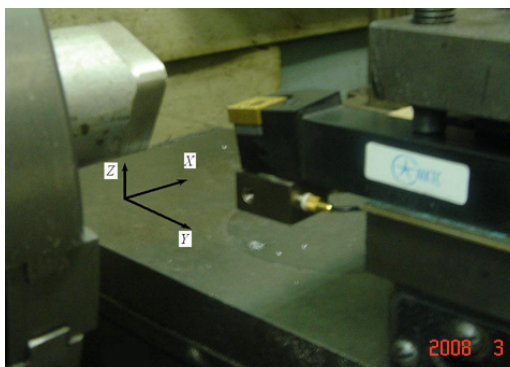| Frequency range, kHz | | 2.8 – 5.6 kHz | | | More than 5.6 kHz | | |
|---|---|---|---|---|---|---|---|
| Cutting speed, m/min | | 125 | 250 | 500 | 125 | 250 | 500 |
| By incision | RMS | 6.1 | 7.4 | 4.2 | 11.7 | 27.4 | 12.3 |
| | Max | 20 | 29 | 15 | | | |
| By cutting | RMS | 1.8 | 1.5 | 3.1 | 3.8 | 5.2 | 6.8 |
| | Max | 12.5 | 16 | 17.2 | | | |



Fig. 1. Installing of the three-component accelerometer mounted on the tool and an example of signals received by hard turning.

To bring all speeds to the same value, for example, to 250 m/min, we need to reduce the indications by higher speed in so many times, in how many times was the speed higher compared with 250 m/min. After such an operation was done, we have got the following result: by the speed of 500 m/min the surface hardness of the workpiece was by one third lower than it was by the speed of 250 m/min. By 125 m/min the hardness is by 46 percent higher than by speed of 250 m/min. By speed 500 m/min the unsteady process develops significantly faster. The average surface hardness for the incision period is almost 4 times lower than by the incision by the speed of 250 m/min. Fig. 2 shows the spectrum of vibration acceleration in the X-direction by the incision of the new tool by speed of 250 m/min into hardened workpiece up to 55 HRC. The dotted line in the figure shows the contour of the spectrum, obtained after the unsteady process has finished and the stable cutting occurs. On the upper part of the figure 2 the type of the vibroacoustic signal by incision into the workpiece is shown. The unsteady process is continuing in this case for 0.12 s, but the workpiece rotates more than one turnover. It can be enough to cause the microchipping of the cutting edge (or formation of additional microcracks) and to reduce the quality of the surface area, what is unacceptable. The unsteady process and the amplitude of the accompanying vibroacoustic signal depend on the stiffness of the machine tool, including the workpiece and the tool [2]. Watching the vibroacoustic signal we can assess the quality of the equipment, its suitability to the hard turning, what is especially important by interrupted cutting, where during the machining the tool has to incise the hardened surface repeatedly, for example by milling. In this regard the lifetime tests must be carried out taking into account the frequency of incision into the hardened surface. Increasing the cutting speed to obtain an additional reduction of the hardness of the workpiece surface can be efficient only if the lifetime of cutting plates and the surface hardness after machining remain by an acceptable level.
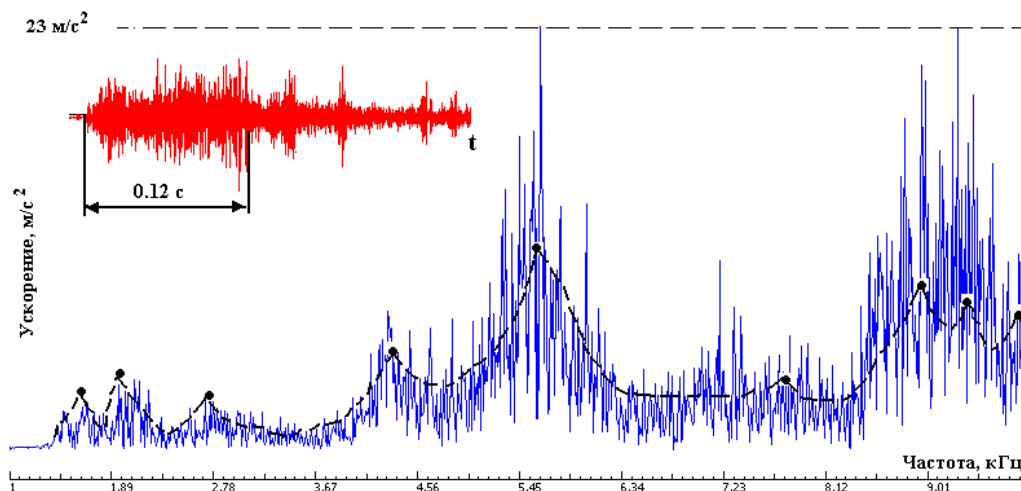


Fig. 2. The spectrum of the vibroacoustic signal by the incision of the sharp cutting tool into the hardened surface. The dotted line shows the contours of the same spectrum, but after the unsteady process has finished. The upper part shows the recording of the vibroacoustic signal in the X-direction by incision.

The wear and microchipping of the cutting plate by hard turning is not a small problem, because the changed geometry of the cutting edge affects the temperature of the zone of plastic deformation, and the latter changes the hardness of the workpiece. Amount of heat while the cutting edge is wearing increases, but its distribution by increasing the contact area on the front and back surfaces of the instrument can vary irregularly. In this case, on the contact area can occur areas with higher hardness compared with a sharp tool. First of all this refers to the flank surface of the cutting tool, where the contact speed is higher and the depth of warmed surface layer is shallow compared with the chip size. The blunting of the cutting edge increases the penetration depth of the tool point into the machined surface and further increase of the contact area. The volume growth of the

deformed material by the flank surface and its distance from the zone of the primary plastic deformations can cause by tool wear the hardness increasing in the contact area on the peripheral areas of the flank surface of the cutting tool.

Figure 3 shows the block diagrams of the vector distribution of the vibration of the cutting tool point in the cutting zone [3]. Dark squares designate the directions (distribution center), where the time of the vector presence is not less than 60% of the maximum distribution. The small points designate other areas. Fig. 3a shows a diagram for the new tool, and Fig. 3b shows a diagram for the same conditions, but for a blunt tool. The numbers in conditional units designate distribution limits along the axes. It is evident that the dispersion in X-direction is much greater on the both diagrams than the dispersion in Y-direction. With the wear increasing the dispersion is increasing mainly in the X-direction and the distribution center is close to the surface of the workpiece. It means that the vibrational displacement inside the workpiece are growing more slowly with the wear increasing. Perhaps this is related to the decrease of the pyroplastic layer depth. The contact area is increasing, but the heat flow is not enough to warm up in the sufficient depth throughout the whole area. It can be seen on the Fig. 4, where the the spectra of the vibration acceleration in the X-direction are shown. The figure shows the spectrum in the range above 1 kHz for cutting by a blunt cutting tool, and the dotted line shows the contour of the spectrum for cutting by a sharp cutting tool. It is seen that the amplitude of almost all spectral components are grown up. The growth of the amplitudes at the highest frequencies speaks in favor of the hypothesis of the hardness increasing of the machined surface by the wear increase. It can be added, that the signal that accompanies the turning by a worn cutting tool, characterized by uneven over time, it contains numerous peaks that are not characteristic of a sharp tool. The level of these peaks is not lower than the amplitudes which occur during the incision into the workpiece. The quality of the surface by cutting with the worn cutting tool can significantly deteriorate, it becomes obvious even by a simple touch. Table 2 for example shows how the diagrams of the vector vibrations distribution has evolved in the octave of 4 kHz for individual coordinate planes. The distributions are shown by the lines of the equal level. In the top row of the table the distributions for the new tool are shown, on the bottom – for the blunt tool. It is seen that the greatest evolution proceeds along the X axes (growth in 2.6 times) and along the Z axes (growth in 2.2 times). Along the Y axis the growth is relatively small, only 35 percent. Thus, to install the accelerometer those positions on an elastic system of the machine tool have the greatest interest, where the reaction near 4 kHz on the top of tool vibration in the direction of XZ will be the greatest.

Since heat flows determine the hardness of the surface layer of the machined workpiece, affecting these flows we can in some way manage the hardness change. We can manage the change of the cutting speed by changing the geometry of the cutting edge, as well as by changing of the conductivity of the substrate material, on which the cutting plate is based [2]. During research the material of the substrates was varied. In addition to standard substrates of steel the substrate of granite, of chlorite slate, of polymictic sandstone and of the composition of the steel with synthetical granite were tested. The tests have shown that under identical conditions of the machining of the surfaces with the hardness of 55 HRC the surface roughness was Ra = 0,6 micron, when using a standard substrate. The use of the substrates with a mineral component allowed to obtain a surface with Ra = 0,3 micron.
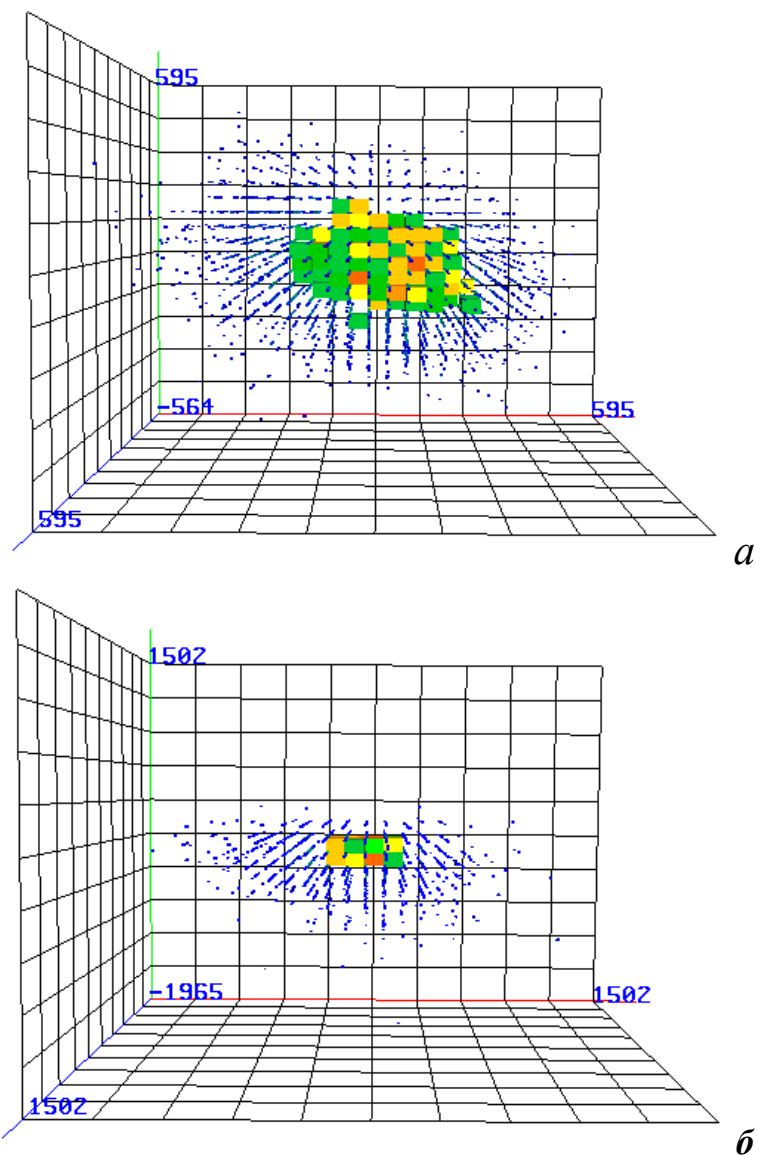
Fig. 3. The three-dimensional diagrams of the vibration vector distribution of the tool center point in different directions of the cutting area: *a* – fort he sharp tool, *b* – fort he blunt tool.
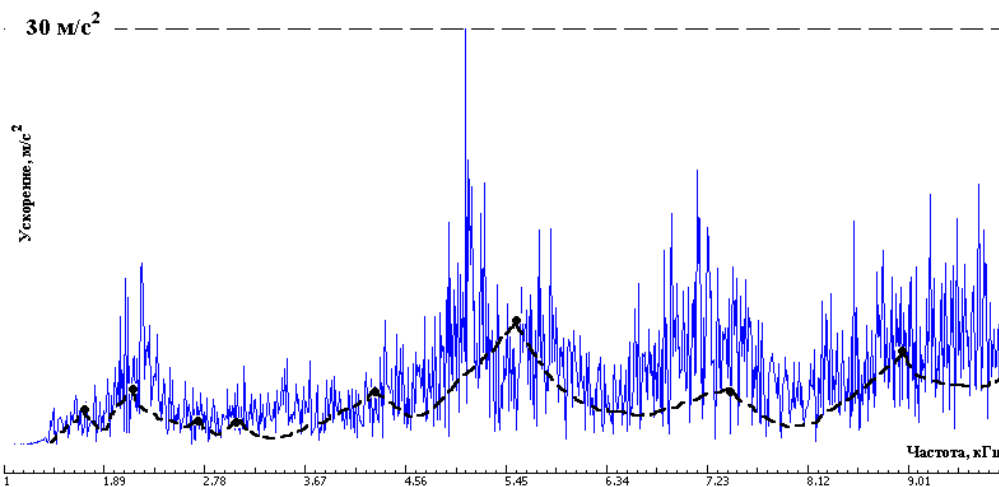


Fig. 4. The spectrum of the vibroacoustic signal by hard turning with the blunt cutting tool. The dotted line shows the contours of the spectrum, for turning in similar conditions, but with a sharp cutting tool.

Fig. 5 shows an example of the spectrum in the range of 1-10 kHz in the X-direction, which occurs by the stable cutting of the surface with the hardness of 55 HRC when using a standard substrate. On the background of the dotted line the contours of the spectrum are shown, which occur under similar conditions, but using the substrate of chlorite slate. It is seen that the spectral components, especially in the range of 5 to 10 kHz, are significantly larger by working with the standard substrate. This speaks in favor of the hypothesis that the thermal conductivity of the substrate influences the changing of the heat flow and its direction toward the surface layer, what enhances the tempering of the latter.
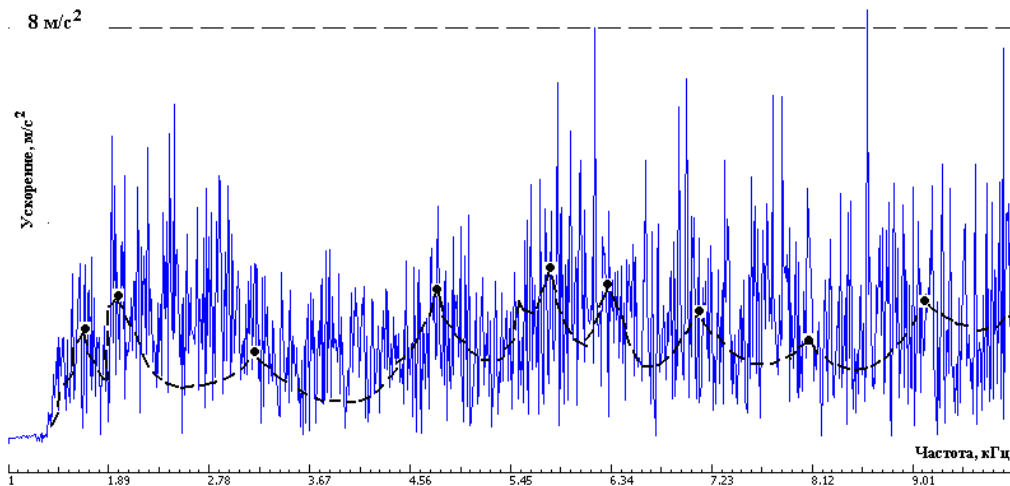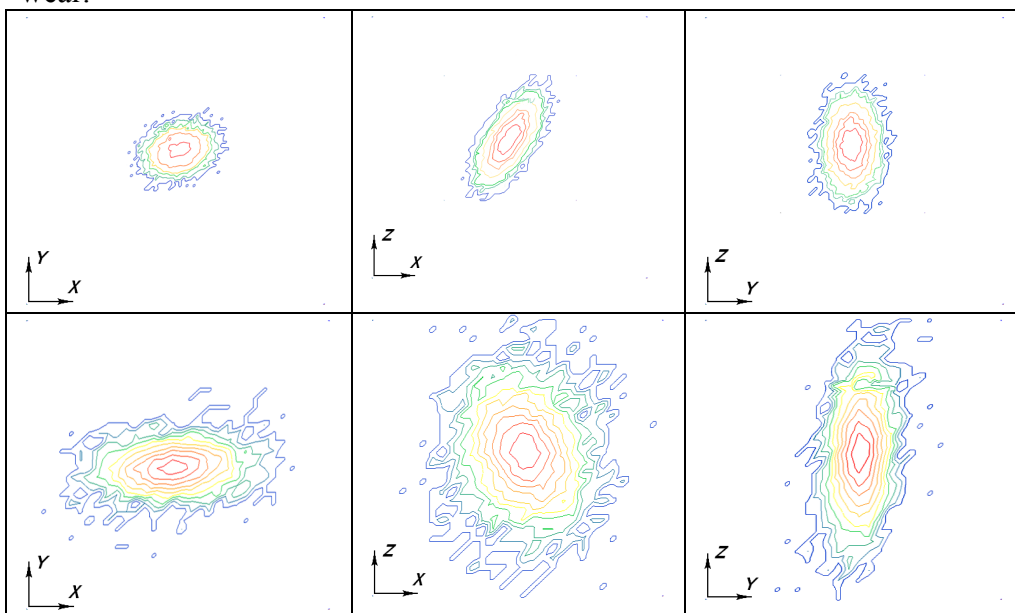


Fig. 5. The spectrum of the vibroacoustic signal by hard turning using the standard substrate. The dotted line shows the contours of the spectrum by turning in similar conditions, but using the substrate of chlorite slate.

Table 2. The evolution of the distribution diagrams of the vibration vector with the cutting tool wear.



Thus, control of high-frequency components of the vibroacoustic signal can monitor the speed of the surface layer tempering by hard turning. This gives a possibility to reasonably choose the cutting conditions, to evaluate the degree of the equipment fitness and design options of the cutting tool for the implementation of the stable process of hard turning.

Speaking about the construction of the cutting tool it must be noted that there is in the literature, which is about the relative vibrations in the cutting zone, attention is usually given to the

vibrations in the Y-direction (normally to the machined surface). It is believed that exactly they determine the surface roughness and intense self-oscillations by cutting. The studies of the three-dimensional vibrations have shown that in cases of intense self-oscillations in the cutting zone the position of the vibration vector closes to the normal direction to the cutting surface, which often coincides or is close to the X-axis of the workpiece by the modern geometry of the cutting tool. Fig. 6 shows an example of the three-dimensional distribution of the vibration vector by occurring of the intense self-oscillations by hard cutting. It is seen that the main direction of oscillation expansion is closing to the X axis. In this case there are traces on the surface, affecting the quality of the surface layer and roughness.
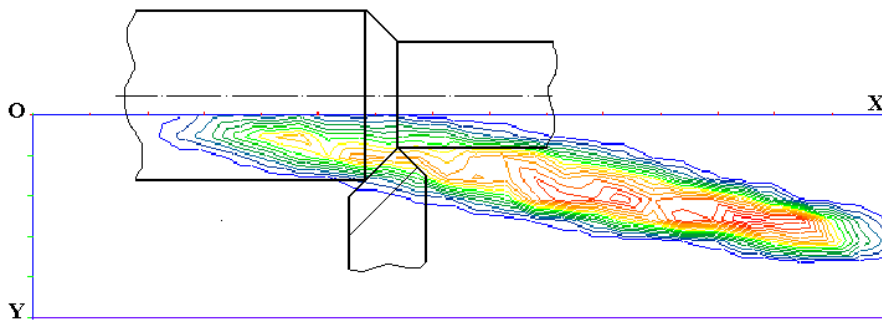


Fig. 6. The distribution diagram of the vibration vector of the tool center point of the cutting tool in the XOY-plane by intense self-oscillations occurring during hard turning.

Based on analysis of the vibroacoustic signals by self-oscillation during the cutting process it was concluded that the stability of the cutting process depends not only on the dynamic properties of the elastic system along the Y-axis, but also along the X-axis. This fact should be considered when designing the cutting tool and the whole tool unit.

The observations of the cutting process using the vibroacoustic signals have shown that the self-oscillations of the cutting tool are always present. Their trajectory is determined by the displacement of cutting tool center point in the tangential (along the cutting speed, the Z axis) and in the radial directions. By normal cutting the trajectory is elongated in the Z-direction, by intense self-oscillations the trajectory is elongated along the normal (see Fig. 6) to the cutting surface [1]. By such vibrations the movement of the cutting tool along the cutting speed is proceeding closer to the cutting surface than by the movement against the speed. This oscillation cycle happens by one of the natural frequencies of the cutting tool. It was assumed that part of the trajectory of the cutting tool lays along the cutting speed, storing potential energy. This movement takes place until the shear of the chip element. However, the studies of the vibroacoustic signals registering from the cutting tool center point have shown that by the cutting process the vibration speed does not exceed a few percent of the cutting speed. During the cutting process the cutting tool vibrations by its natural frequencies along all axes are presented in the form of the significantly modulated sinusoid. However, the sinusoid distortion does not allow to understand it as collisions that could occur by the contact abruption during cutting. Only by low cutting speeds the distortion of the sinusoidal vibration of the cutting tool center point can be interpreted as possible collisions. These data support the hypothesis of the existence of the pyroplastic layer by certain cutting speeds near the cutting tool center point. In this layer the top is moving unseparated even by relatively intense self-oscillations. Only by the big depth of cutting, by large amounts of shifted chip elements the top may come beyond this layer, causing a drastic distortion of the workpiece surface and other negative consequences. Fig. 7 shows the picture of the workpiece surface area obtained by occurring of the intense self-oscillations. The traces of the cutting tool are seen. They have periodic displacements along the axis of the workpiece. At the moment of the shift of the chip element along the normal to the cutting surface was so powerful that the continuity of the machining traces was broken
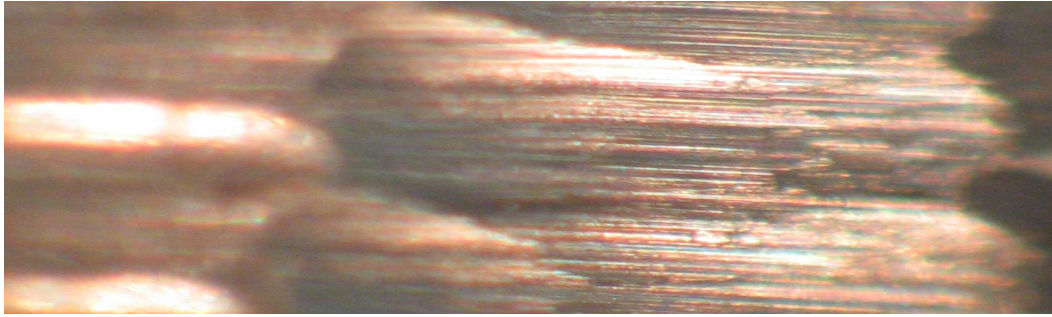
Fig. 7. The photo of the surface area by turning of the roller with intense self-oscillations. The size of the surface area in vertical direction is 0.5 mm.

To the problems of diagnostics of the cutting process the problem of the diagnostics of the most important units of technological equipment is added. This problem is responsible for the accuracy of the machining and can cause an emergency situation or a failure in the technological cycle. First we need to consider the work of the spindle units, which in modern machine tools are mechatronic modules having high accuracy and speed of rotation. Slight deviations in the stage of assembling of these units or breaking of the usage conditions cause unexpected failures during machining, what leads to costly repairs and downtime. The traditional areas of diagnostics, including the vibroacoustic methods at the stage of running of such units do not always reveal inconspicuous faults, what at the stage of intensive use leads to their rapid development and the instantaneous destruction of the bearing. In this regard such units must be equipped with not only temperature sensors but also with accelerometers tracking the vibration anomalies by presence of multiple interferences, which are present when the equipment is functioning. For a detailed assessment of the readiness of spindle units for use in multifunction machines we have to search for new diagnostic algorithms, including the analysis of the three-dimensional distribution of the vibration vectors and vibration acceleration (similar to those shown in Fig. 3 and Table 2), of the dynamic testing of spindles with variable directions of the dynamic effects and variations of spindle loading by its run-in [4]. It has long been known various methods for diagnostics of bearings, which are widely used in industry. But the spindle units can not be represented as an additive system of several bearings. Distortion of the races by mounting of one bearing will have a complex impact on the work of the others. It should be noted that the spindle units contain two and three bearers, each of which may contain multiple bearings. Increase in temperature during running of the unit is having an impact on the tightness and strain in the bearings, providing an additional impact on the picture created by the vibroacoustic signals. Unfortunately, there occur often the situations, where we can say that the picture of the functioning of the unit is not good, but the exact reasons cannot be fully enumerated. There are claims to the depth of the diagnosis. An industrial company needs to know the diagnosis, expressed in constructive and technological parameters for the implementation of corrective actions to remove the main reasons, which are reducing the functioning quality of the object. All this requires the conditions for more thorough review of the objects of the diagnostics and the development of new methodologies for diagnostic procedures. To implement the algorithms on-line diagnostics, which is implemented during the operation of equipment, is necessary to implement more subtle methods of the preoperational diagnosis. They define the algorithms of making the decisions by systems for operational diagnostics, which must clearly decide when to stop work and when to change modes of operation and determine the extent of these changes.

Fig. 8a shows the photo of the spindle unit of the turning machine, where the workpiece is fixed in a holder, which is getting blows of the dynamometric hammer. At the holder two accelerometers are mounted, recording the dynamic effects. Fig. 8b shows the amplitude-frequency characteristics (AFC), obtained after processing of information in the special program [5]. AFC were drawn for two machine tools, one of them was vibration active by cutting.
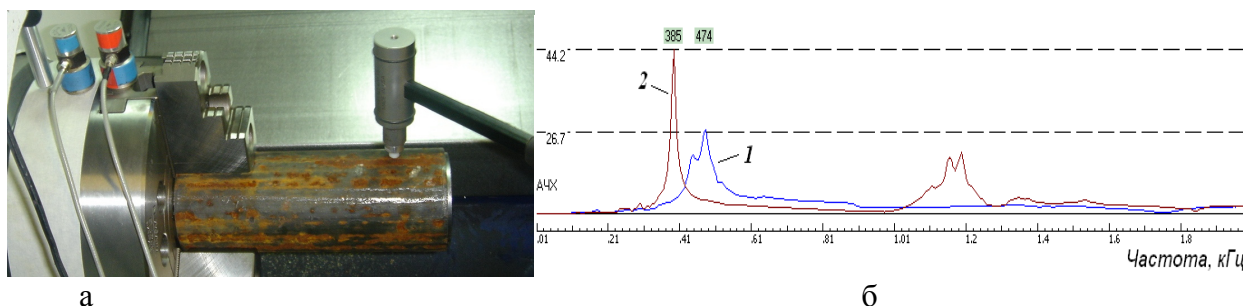
Fig. 8. Experimental AFC of the spindle units of two turning machines with CNC model TNL-100AL: a - picture of the experiment, b - AFC obtained for the two machines; *1* − the machine tool with the usual vibrations; *2* – the machine which is vibration active

It is clearly seen (characteristic 2) that the machine spindle, which is vibration active, has a lower natural frequency and high Q factor, which led to intense self-oscillations by some operations. The subsequent computer simulation has shown that the cause of the anomaly is the bad quality of the assembling of the 2nd spindle, resulting the reduction of the radial stiffness of one of the bearing in the front bearer fivefold.

The foregoing speaks in favor of the right direction, being developed at the MSTU STANKIN. It is the creation of operational diagnostics that can be integrated in the CNC machine tools and creation of preoperational diagnostics, allowing to work with more exact diagnoses.

In conclusion, we can say that, despite the fact that a number of the vibroacoustic methods for diagnostics is sensitive to changes in conditions and cutting process, and spindle units, the development of criteria by which a decision can be taken requires the accumulation of statistical material. Such material can appear only with the large-scale implementation of the methods of pre-operational and operational diagnostics by the manufacturers and users of machine tools.

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