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Practical Aspects of Ensuring Accuracy of Machining on CNC Machine Tools within Framework of "Smart Manufacturing"

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***Abstract*—The paper presents practical aspects of insuring the accuracy of manufacturing parts on CNC machine tools operating in "Smart manufacturing". A model is described that reflects quantitative and logical relationships between variables that characterize the state of controlled parameters of technological operations. The concept of preventive maintenance of machine tools based on operational monitoring of their condition is presented. This allows, on the one hand, to avoid unexpected downtime of equipment because of breakdowns. On the other hand, it means a more reasonable approach to planning preventive maintenance of equipment operability. The concept of the information system for the predicted maintenance of process equipment is based on the model of correspondence between the characteristics obtained from external measuring instruments (fixed at the commissioning stage) and measurements obtained from the equipment diagnostics tools, integrated into the control system, during its operation.**

***Keywords*—digital manufacturing; smart factory; CNC machining; on-line monitoring of the machine tools; the circle-test**

I. Introduction

The creation of the basic digital economy infrastructure requires the introduction of modern high-tech means of production founded on the paradigm of "smart manufacturing".

"Smart manufacturing" is linked to concept of industrial Internet of things, which entails a continuous stream of data. In "smart manufacturing" the real equipment and the virtual reality interact in a single model called "digital manufacturing".

The model of digital manufacturing combines the data model, the objects interaction model, the dynamic model and the model of control object functioning [1]. The last one is the most complicated, because it describes the objects operating in real time, such as CNC machine tools, programmable logic controllers, motion controllers, programmable automation controllers, etc. [2]. The main task of the functional model of the object is to obtain the reliable information about the real parameters of the technological processes. The model establishes the quantitative and logical relationships between the variables, characterizing the state of controlled parameters of the technological operations. The stability of the technological equipment operation and, as a consequence, the timely release of the quality products is substantially determined by the strategy of the maintenance and the monitoring of the state of the equipment [3].

Currently, substantial MDC systems (Machine Data Collection) are gaining growing popularity. MDC system automatically records the time and the duration of the work/downtime/failure states of the machine tool; the advanced version allows to collect data on technological parameters (the feed, the cutting speed, capacity) and on the control program, the error codes, and the cause of downtime [4]. However, in practice the users face many problems provoked by the lack of concordance between the CNC and the systems of information collecting, whose interaction should be ensured by the standardized hardware and software interfaces [5, 6]. This could be solved by connecting additional hardware solutions; however, this requires coordination with the equipment manufacturers. Furthermore, the information received from the equipment is limited [7]. In addition, the CNC system does not always allow free exchange of system data, and the manufacturers of CNC systems do not adhere to the single standard for the exchange of information with the MDC system, which becomes an obstacle for building monitoring systems [8–9]. The use of MDC could facilitate the machine tool operation process controlling, thereby increasing the efficiency of its using. The article puts forward the concept of the information system of forecasted maintenance of the processing equipment, where the necessary information is retrieved from the NC racks and transmitted over a wired or wireless network to the server where it is centrally stored and processed, forming the accrued history of the equipment [10–11].

The commissioning of equipment includes the setting and the saving of machine tool parameters, the carrying out the reference measurement, the test processing of the workpiece. Subsequently, during the exploitation machine tools undergo maintenance between planned and unplanned repairs. The routine maintenance of CNC machine tools includes operations such as: checking of the bearing clearances of the spindle, checking of the backlash on the axes and testing the geometric accuracy of the machine tool, etc. [12]. This often requires partial disassembling of the machine tool or opening of the individual nodes. In case of maintenance, primarily the technological and geometric accuracy of machine tools is checked:

- checking the geometric accuracy of the moves of working mechanisms in relation to the base elements and their dynamic performance (according to ISO 230-4);
- verification of correspondence between the geometric dimensions and the technical parameters of the obtained parts and the assessment of the capacity to manufacture quality products.

II. Model of Matching External and Internal Measurement Data in the Course of Online Monitoring

The proposed concept of the preventive maintenance of the technological equipment for "smart manufacturing" is based on building the models of correspondence between the reference parameters of technological equipment, obtained at the stage of commissioning, and the parameters obtained during the online monitoring of this equipment in operation. The implementation of the idea allow one to avoid the scheduled maintenance of the process equipment according to the regulations defined by machine tool manufacturers (that leads to the forced downtimes) and to replace it with preventive assessment of technological systems and the maintenance of the technological equipment when necessary (Fig. 1).

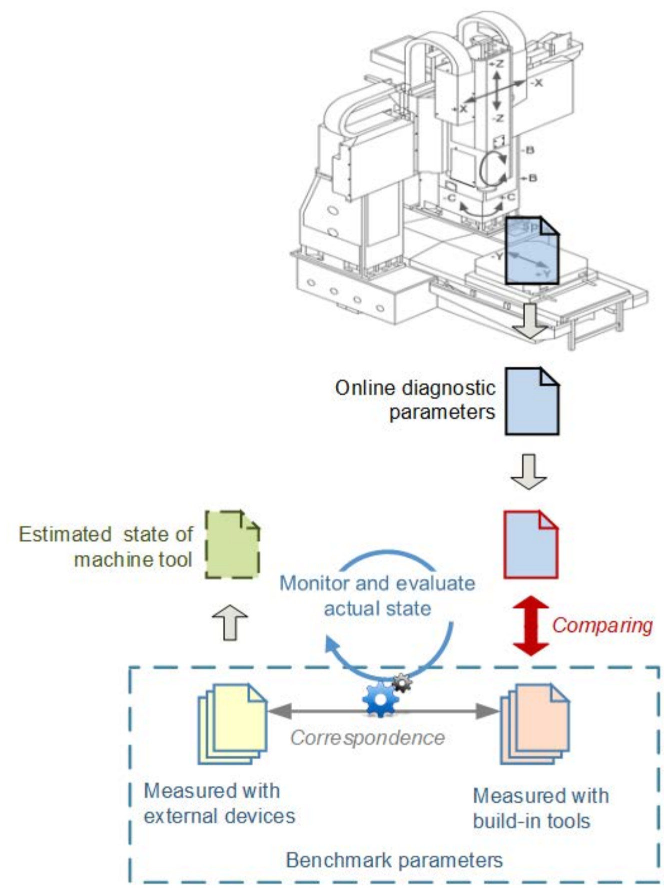

Fig. 1. Model of data collection and processing within online monitoring

Making measurements using the built-in control system instrumentation (logic analyzer, digital oscilloscope, etc.) usually does not require long shutdowns of the treatment process and the results can usually be obtained within a few minutes. The accuracy of the data depends on whether the machine tool is equipped with additional measurement encoders (linear or angular) or information is obtained from actuating motor encoders. Measurement data from motor encoders does not allow the direct examination of the mechanical errors of the machine tool's moving parts, such as a backslash or uneven pitch of the ball-screw. These errors can be taken into account only indirectly, by comparing the results of the measurements made by internal CNC system tools with the results obtained by using external measurement devices.

Control system manufacturers sometimes supply internal software tools for diagnostics and configuration of servo drives and remote input/output devices [13]. In addition, the industry produces a wide range of standalone measurement devices (oscilloscopes, ballbars, laser interferometers, motion trackers, etc.), allowing the quick and efficient estimation of the technological system individual components parameters for the purpose of making decisions on their further exploitation.

The CNC system core has all the required information about the state and motion characteristics of the servo drives for the purposes of diagnosis and configuration of the control loop parameters [14, 15]. If the analysis requires additional data from the drive, which are not related to motion control routine, there is a possibility to add them to the list of parameters that are cyclically exchanged between the drive controller and the CNC system core. High-speed industrial fieldbus protocols, such as SERCOS III and EtherCAT, have special mechanisms for transferring values of the additional lists of parameters in the cyclic data [16, 17]. They can be added "on the fly" during operation without having to switch the drive controller into parameterization mode.

However, despite the common tasks served by built-in CNC system measurement tools and external devices, they are too heterogeneous in terms of parameters such as the data exchange format, the form of results representation, etc. This, for example, makes it impossible to correlate the measurement data with the internal data of the CNC system, while it is critically important for the development of control algorithms [18, 19].

It should also be noted that measurements made using external devices require at least one hour of preparation time on the machine tool and the presence of a qualified metrologist.

A. The method of creating and using reference measurement

Below is a more complex case when the machine tool is not equipped with additional measuring encoders and uses only servo motor position sensors. In this case, the mechanical error can be estimated only indirectly. The methodology of creating and using reference measurements is presented in the form of an algorithm (Pic. 2). The initial data, in this case, is the measurements of the circular deviation, obtained during the commissioning of the machine tool. Measurements made according to ISO 230-4 standard by means of using external and internal tools, and are used as the reference values.

The machine tool state monitoring implies performing at a certain interval (once in a few working shifts) the internal measurement of the circle test. This takes only a couple of minutes and makes no significant impact on the production process. These measurements allow the estimation of the real accuracy of the machine tool only if they have been obtained from external measuring devices. However, having the sets of reference measurements, made by both external and internal tools, on the basis of revealed correlations between them it is possible to estimate, with a certain degree of error, the actual accuracy characteristics of the machine tool. If during the operation of the machine tool the indicators are going outside the acceptable boundaries, a number of steps associated with adjustments of the machine tool settings should be performed (Fig. 2).

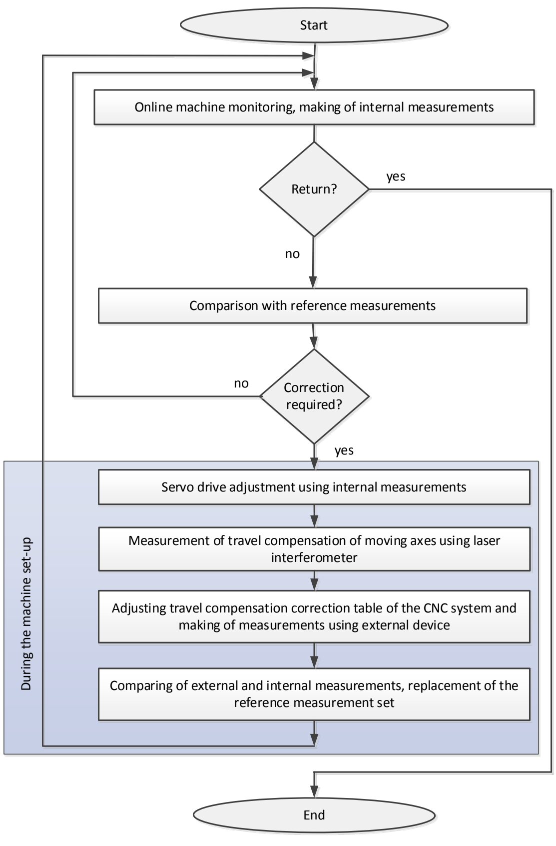

Fig. 2. Generalized fragment of the algorithm of the creation and usage of reference measuremen

III. Practical Aspects of Application of the Accuracy Comparison Model for a Planer-Milling Machine Tool

The planing and milling machining center (Fig. 3) is designed for multi-axis machining of complex profile parts such as dies and molds, by the methods of four-axis milling and volumetric 5-axis power planing. Parts from thermally hardened steels, cast iron and aluminum alloys are processed [15]. The machine tool implements three linear motions (along the axes X, Y, Z), which provide movement with a speed of at least 40 m / min and acceleration of 2g. The milling head is equipped with a hydraulic clamp to fix and support the backlashes and rotary axes during the machining process. The machine tool is controlled by a specialized Russian CNC system, built on the basic control platform "AxiOMA Control"[20].

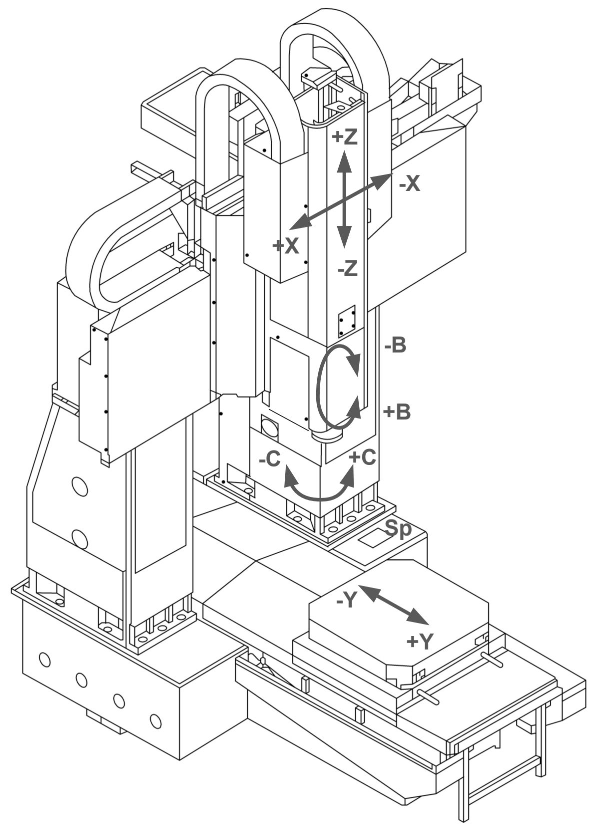

Fig. 3. The planing and milling machining center

A. Performing standard measurements when the machine tool is put into operation

One of the main parameters, which is measured as accuracy indicator of the machine tool in accordance with the standard, is bi-directional circular deviation G(b). This indicator is defined as the minimum radial distance between two concentric circles representing the actual trajectories of motion along and against the clockwise direction. Bi-directional circular deviation G(b) can be estimated as the range of the maximum radial deviations from the RMS circle contour and is calculated by using the clockwise and counterclockwise trajectories.

At the stage of machine tool commissioning, the deviation of the reproduction of the reference trajectory was measured by means of a special tool for estimating the accuracy of the Grid Encoder KGM machine tool (Figure 4), its accuracy class corresponding to ± 2 μm.

The bi-directional circular deviation is 20 μm (Fig. 5). The backslash along the X axis in the positive and negative directions is, respectively, (X+) 4.3 μm (X-) 3.7 μm. For the Y axis, the backslash is (Y+) 10.1 μm and (Y-) 9.5 μm. Reversal spikes are (X+) 1.5 μm, (X-) 1.9 μm, (Y+) 2.7 μm and (Y-) 2.5 μm.

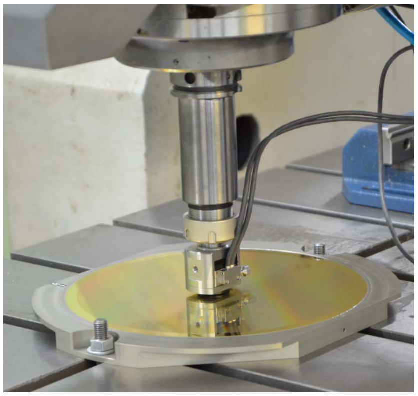

Fig. 4. Performing circle test according to ISO 230-4 standard on the planing and milling machining center Э7106МФ4 using the Grid Encoder KGM

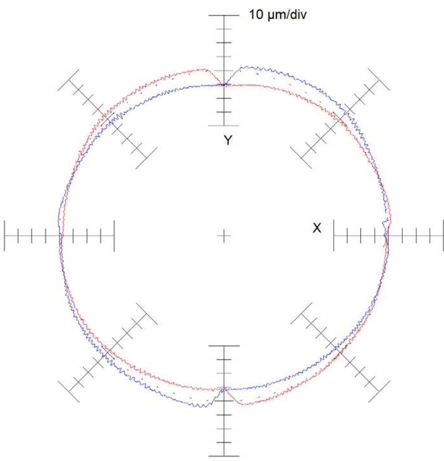

Fig. 5. The result of bi-directional circular deviation measurement by the Grid Encoder KGM device

The corresponding internal measurement made by the motor sensors (Fig. 6) showed deviations in the range of 3 µm, since it does not take into account the mechanical errors of the machine tool.

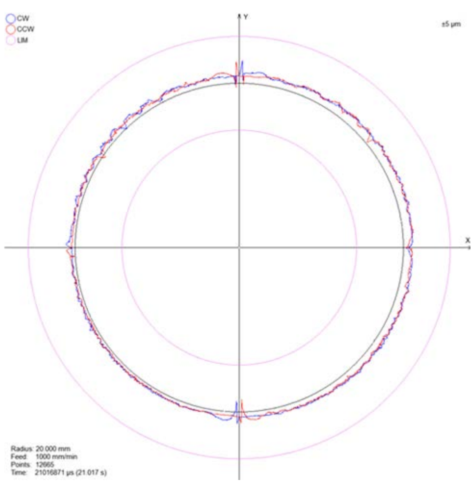

Fig. 6. The result of an internal measurement of bi-directional circular deviation (measured by motor sensors)

The performed external measurements showed a bi-directional circular deviation of 46.3 µm (Fig. 8).

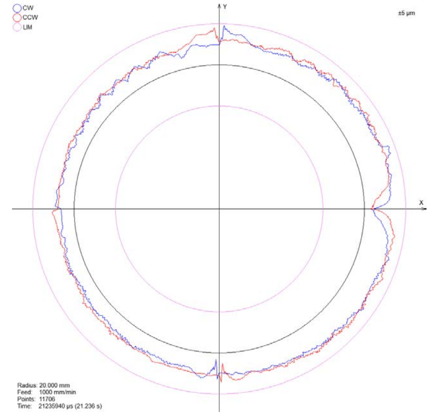

Fig. 7. Out-of-tolerance errors, revealed during online monitoring with internal measurements

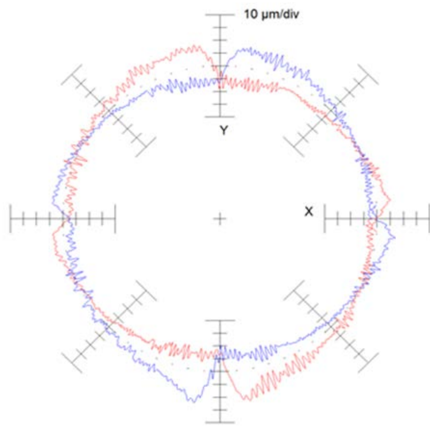

Fig. 8. The result of external measurements

According to the algorithm presented above, the gain factors in the servo drives circuits were corrected and the acceleration feed forward link was switched on. After that, measurements of the positional error in the axes according to ISO 230-4 using a laser interferometer were carried out again. Based on the measurement results, the compensation table in the CNC system is updated and the backlash compensation algorithm is switched on. Measurements of the circle test after the introduced changes showed a bi-directional circular deviation of 16.4 µm (Fig. 9).

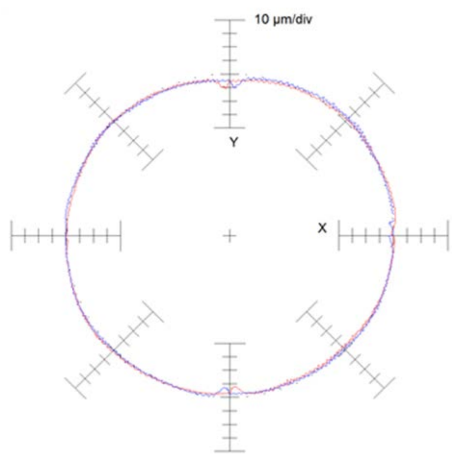

Fig. 9. Measurements after enabling compensation algorithms

IV. Conclusion

The concept of the information system for the predicted maintenance of process equipment is based on the construction of a model of correspondence between the characteristics obtained from external measuring instruments (fixed at the commissioning stage) and measurements obtained from the equipment diagnostics tool integrated into the control system during its operation. Such a solution will allow the quick and reliably monitoring and evaluation of the information on the state of technological equipment in order to exclude the possibility of equipment failure during the process operations and avoid the procedure of routine maintenance of machine tools (which is often unnecessary and leads to their forced downtime).

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