Application of multi-sensor measurement system for machining process monitoring – a case study for sequential turning and burnishing processes

Zastosowanie wielosensorowego systemu pomiarowego do monitorowania procesu skrawania – przypadek sekwencyjnych procesów toczenia i nagniatania

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In this paper, the structure and operational functions of a measurement system, which was installed on a 3-axis CNC lathe for monitoring and optimization of the cutting process are presented. In general, the system records signals of the components of the resultant cutting force, acceleration signals (cutting vibrations) and EFM force signals generated for various machining conditions employed. As a result, the total power consumed was determined. The generated data were archived in the expert system which supports the optimization of the cutting process in terms of various optimization criteria including power/energy consumption.
KEYWORDS: machining process, measurement system, signal processing, monitoring, process optimization

Introduction

It can be easily noticed that that the technological progress in the leading manufacturing sectors is growing continuously year by year. Machining technology, although it does not meet stringent requirements concerning material and energy savings, is still one of fundamental processes for shaping machine parts. On the other hand, a visible progress in the intensification of machining process due to more applications of the difficult-to-machine materials such as nickel and titanium superalloys is observed [1, 2].

Moreover, a strong economic and ecological pressure is present on the market. As a result, the maximum production profits should correspond to the minimum environmental pollution. This strategy causes that lower production costs and better utilization of production inventories are achieved from the wider applications of innovative production/manufacturing processes and technologies [1, 3]. As indicated by production practice, some optimal sets of manufacturing conditions, which combine all demanded criteria, are selected. It should be noticed that the decision process can be effectively supported by SCADA programs which collect and visualize current production data [4, 5].

Unfortunately, industry is now at the learning stage in a wider application/utilization of programs which rationalize the production management. For instance, a world leading producer of CNC machine tools, DMG MORI (Germany/Japan) promotes now a CELOS APP programming system as a type of the specific CAE system. Its monitoring abilities cover current exploitation state of the machine tool, data visualization and observation of effective utilization of its machining capabilities. In general, CELOS does not support the optimization procedures of machining processes performed. However, it makes the decision process itself more effective [5, 6].

Objectively, it can be stated that the technological progress of materials, sensors, and data processing systems will be crucial for future development of "intelligent" machine tools [1, 4, 7, 8]. However, the way to intelligent management of machining/manufacturing processes will be based on the stream data which are transferred in an on-line mode and reliable decisive models based on the dynamic adaptive algorithms [9]. Moreover, in the case of machining processes a crucial role will be played by the practical possibility of process simulation and more advanced option termed process virtualization [1, 10, 11, 12].

The stream of machining data includes such process quantities as the cutting temperature, values of cutting forces, machining power consumed, vibrations generated during unstable machining process and surface finish/surface roughness. The literature survey indicates that monitoring and optimization of machining/manufacturing processes are not elaborated comprehensively. For instance, it is noticed based on the detailed characterization of force sensors that the most important is the structure of complete measurement circuit [7, 10, 11]. On the other hand, both force and temperature signals can be useful in an effective optimization of the machining process but this approach is also not completed.

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In this analysis information on the cutting edge geometry and the surface roughness produced are necessary and the optimization process can be based on a Grey relational analysis [1, 9]. As a result, optimal conditions of the machining process can be determined in terms of a maximum process effectivity/productivity keeping also the demanded surface roughness. On the other hand, the cutting tool state can be monitored based on AE signals and the values of cutting forces [1, 10, 11]. For instance, a strong correlation between AE signals and the formation of BUE (built-up edge) is observed. The tool wear and corresponding changes in the tool-work material pair can also be related to appropriate fluctuations of the power consumption [7, 10, 11]. In addition, a correlation between MRR (machining removal rate) and the power consumption exists [1, 13]. As a result, a rational selection of machining conditions can result in performing more effective process in terms of energy consumption, which also result in notable financial profits and ecological effects.

Authors of this paper did not find, after analysis of many measurement/monitoring systems dedicated to machining processes, a comprehensive solution for data collection directly from production in on-line mode, which can be subsequently analyzed according to the algorithm and generate optimal machining conditions regarding the demanded criteria. It was an impulse to undertake own research activities towards the design of a new complex multi-sensor measurement system with broader abilities to the acquisition of data generated during turning processes on a 3-axis CNC lathe, their on-line transfer and processing with a final task to select optimal process conditions which satisfy the defined technological criteria.

Structure and capability of the measurement system

General description of the system

Measurement system for the monitoring of a cutting process developed in this study was installed on a 3-axis CNC lathe, model OKUMA GENOS 200 E-M. Its functions cover the values of force components, *emf* signals and power consumption in in-process mode. The surface roughness and tool wear indexes were measured in post-process mode. A scheme of information flow in the DAQ system tested in this study is illustrated in Fig. 1*b*.

The general concept of a diagnostic system with the application of AI is shown in Fig. 1*a*. The core element is the information tool termed the Intelligent Designer of Diagnostic Systems (IDDSs). The information elements of the measurement system tested in this study were based on the measurement and data processing devices produced by National Instruments. A scheme of the experimental setup is shown in Fig. 2.

The data gathered during and after the cutting process were stored in a new data base. Both the gathered data and new data generated were used for process optimization. In the study, the process optimization in terms of process parameters covered a range of metallic materials during different turning operations and hybrid processes which combine turning and ball burnishing operations.

Process data were processed and archived using a laptop and a custom LabView operation program. As mentioned above the National Instruments instrumentation was used to build the control and measurement system. It should be noted that the vibrations were measured at a frequency of sampling 5 kHz, components of the total cutting force – at a frequency of 1 kHz, and the *emf* (temperature) – at a frequency of 100 Hz. In order to determine the values of the cutting temperature, the value of *emf* signal is multiplied by the calibration constant based on the calibration data for the pair consisting of cutting insert material and workpiece material. For example, the calibration equation obtained for H10F carbide and AISI 321 steel is: (t = 66.633 × *emf* + 198.281 °C) with the regression coefficient of 0.845 (see Fig. 10).

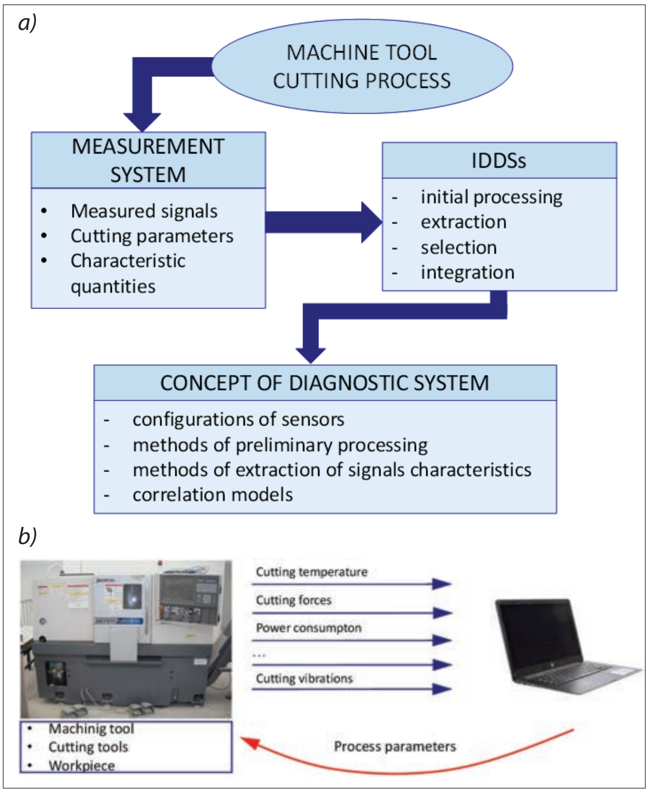

Fig. 1. General concept of a diagnostic system [8, 10] (*a*) and scheme of information flow in the measurement system of cutting process characteristics (*b*)

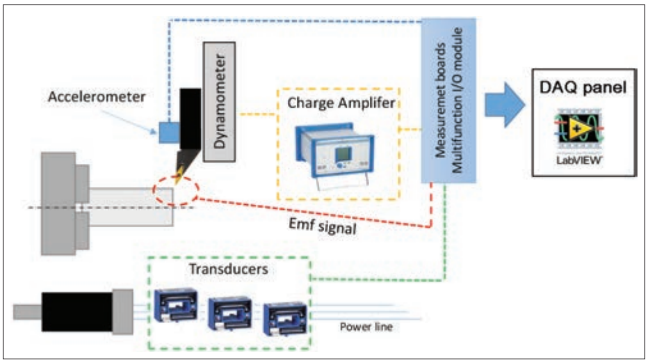

Fig. 2. Scheme of measurement system for characteristics of the turning process installed on a CNC lathe, model OKUMA GENOS L200 E-M

Measurement circuit for power consumption monitoring

It is obviously known that power consumed by driving and controlling elements of the machine tool is a valuable information source on the process performance, tribological interactions between the tool and the workpiece and tool wear evolution. As mentioned above they can be utilized for assessing the energetic effectiveness of the machining process as a major component of the whole manufacturing process. The measurement strategy used was that the power consumption was recorded continuously based on the signals generated by current and voltage sensors, respectively LEM LV25-P and HAS50-S series, which were positioned directly on the conductors and behind all active elements of the machine tool, such as axis drivers, hydraulic pumps, etc. Localization of the sensors in the control cubicle is shown in Fig. 3. The generated signals were acquired and processed using a NI 9215 A/D board.

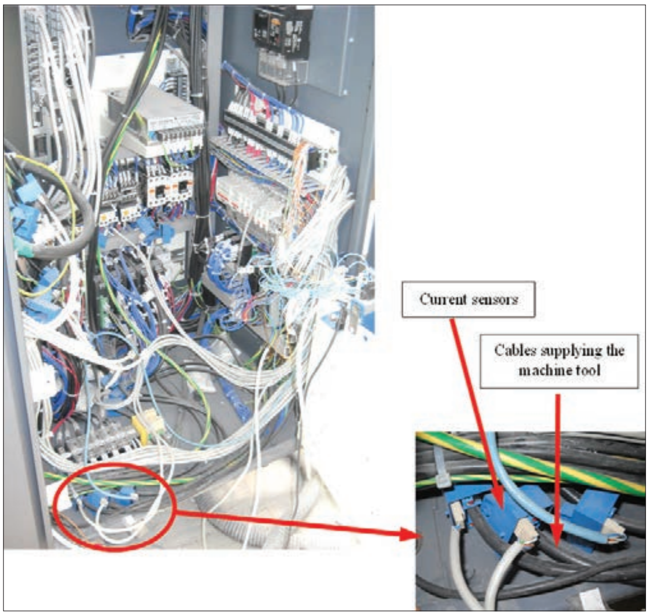

Fig. 3. A view of control cubicle showing the terminals of current and voltage sensors

As mentioned in the previous section, process monitoring was performed based on a custom DAQ program. One of its operation functions is that the continuously generated data are archived and the power consumption can be observed for all individual power supply phases in an on-line mode. Figure 4 shows an exemplary box for power consumption monitoring during the turning process. It can be easily seen how the total energy consumption changes during the subsequent stages of machine tool's running. Moreover, it is possible to measure not only the total power consumed but also the active and wattless power components.

For instance, Fig. 5 presents the total power consumption recorded for sequential (hybrid) machining including turning and subsequent ball burnishing of an alloyed DIN 41Cr4 steel. The following machining parameters (cutting speed/feed rate, depth of cut) were used:

- turning: v_c = 200 mm/min, f = 0.1 mm/rev, a_p = 0.2 mm,
- burnishing: v_b = 50 mm/min, f_b = 0.1 mm/rev, normal load of F_n = 200 N.

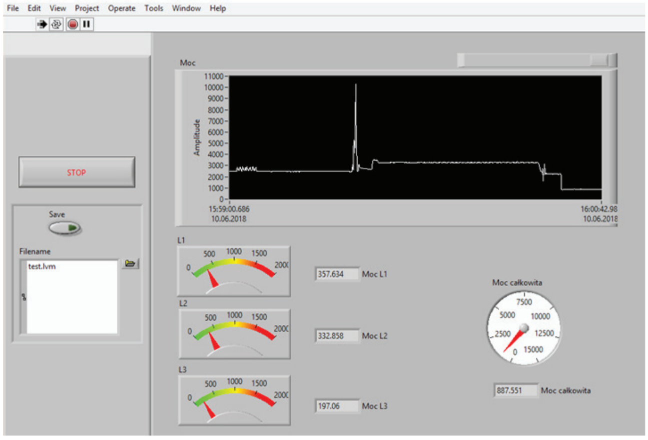

Fig. 4. Exemplary box of the control-measurement system showing a recorded power chart

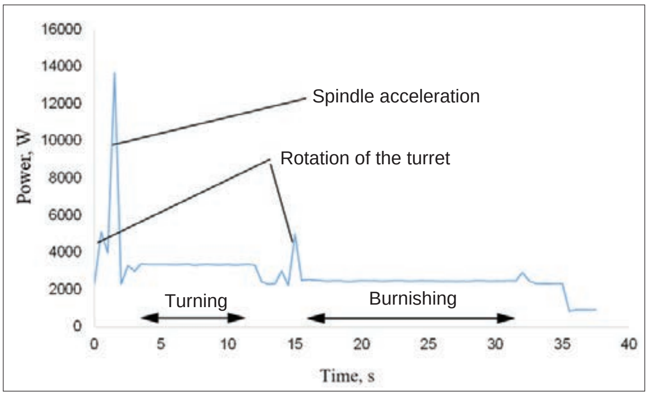

Fig. 5. Exemplary power consumption record obtained for sequential machining of 41Cr4 steel

Measurement circuit for monitoring of cutting forces

This measurement circuit was set-up using commercial force piezoelectric-based measurement devices and DAQ system by a leading world producer Kistler

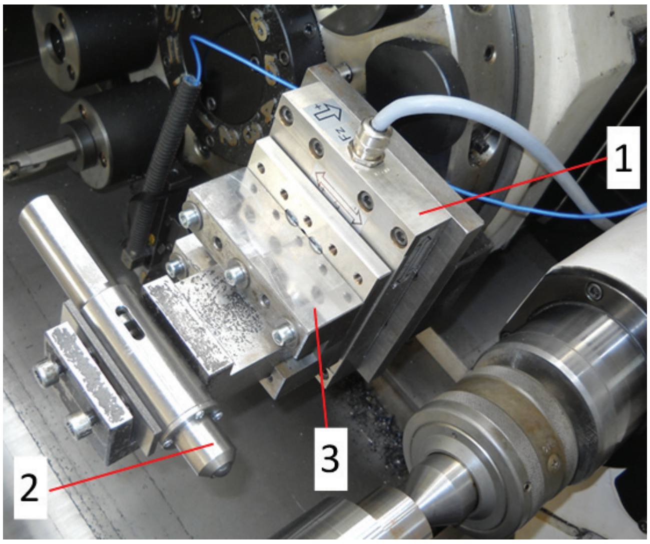

Fig. 6. View of a 3-component piezoelectric dynamometer (*1*) with fixed burnishing tool (*2*) using a special adapter (*3*)

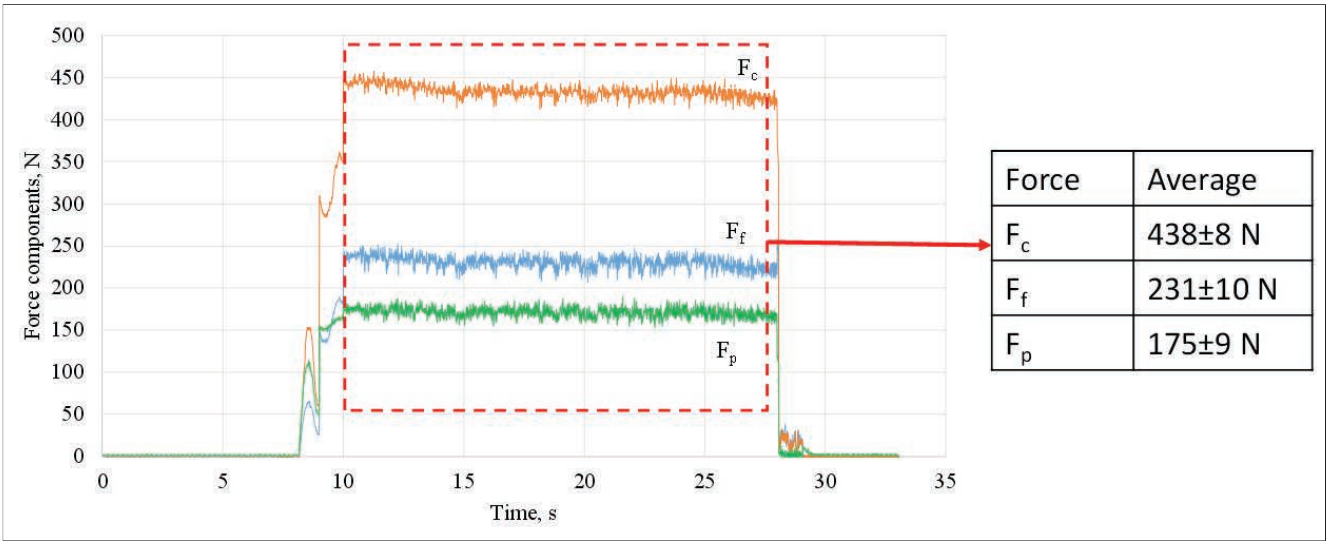

Fig. 7. Records of the components (F_c – cutting force, F_f – feed force and F_p – passive force) of the resultant cutting force for turning of a steel

(Switzerland). In this case a three-component piezoelectric dynamometer, model KISTLER 9129A with charge amplifier, model KISTLER 5070 were used. The generated force signals were processed in a A/D board, model NI 9215 and archived in the computer memory. It should be noted that such a DAQ system is a universal system which can be used for investigating/monitoring of various machining processes.

As an example, Fig. 6 shows the burnishing tool fixed in the measuring plate using special adapter, which is finally fixed in the turret and can be controlled by a CNC control system as all tools positioned in the turret. As a result, Fig. 7 presents the changes of three forces recorded during turning operation performed for an alloyed 41Cr4 steel with the cutting speed of v_c = 150 mm/min, the feed rate of f = 0.1 mm/rev and the depth of cut of a_p = 0.2 mm.

Measurement circuit for monitoring of cutting vibrations

According to the metal cutting fundamentals, vibrations generated in the machine tool–fixture–workpiece–cutting tool result from the changes in

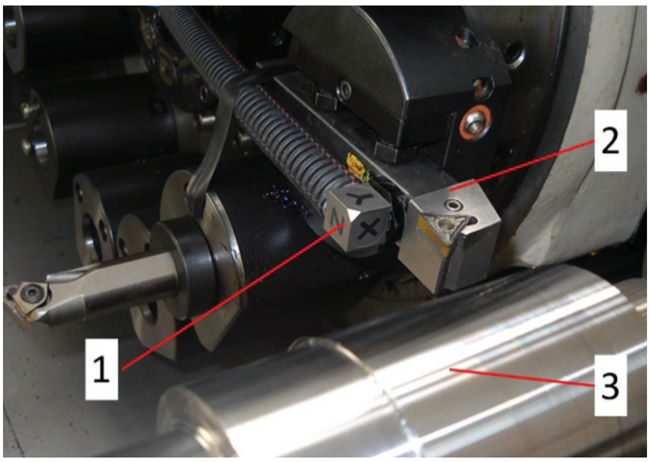

Fig. 8. View of three-component accelerometer model PIEZOTRONICS 356A01 (*1*) fixed to the tool shank (*2*) in a working space of the machine tool; (*3*) workpiece

friction conditions at the contact between the tool and the workpiece. Friction is intensified due to the tool wear evolution and changes in the resolution of force components [14]. As a result, monitoring of cutting vibrations provide a useful information on the cutting tool state. Moreover, it can be correlated with power consumption and corresponding changes of the components of the resultant cutting force or the deterioration of surface finish. The detection of all these negative symptoms can be used for correction of machining parameters. In the measurement system tested cutting vibrations were detected by means of a PIEZOTRONICS 356A01 accelerometer which was fixed to the tool shank in the vicinity of the cutting tool insert. The localization of the vibration sensor in the working space of the CNC lathe is presented in Fig. 8.

Acceleration signals generated in the 3-component vibration sensor were amplified in the measurement board NI 9234 using a custom Lab View program. An example of acceleration signals recorded during the turning of a 41Cr4 steel (v_c = 200 m/min, f = 0.05 mm/rev, a_p = 0.1 mm) for about 5 sec is shown in Fig. 9. In this case study, vibrations were measured in the three orthogonal directions corresponding to the x, y and z directions of the measured forces F_z (F_c), F_y (F_p) and F_x (F_f) [6].

Measurement circuit for average cutting temperature

The measurement system is equipped with the temperature sensor and the average values of the tool–chip contact temperature were measured and stored along with forces and cutting vibrations. The natural thermocouple method is typically applied but the application of the IR technique is also possible [1]. The measurement circuit is described in Ref. [16]. The thermo-electromotive forces (EMF) were measured using a A/D NI 9214 board and they were subsequently converted into temperature (t) values taking into account the calibration data in the form of a *emf* vs. *t* function.

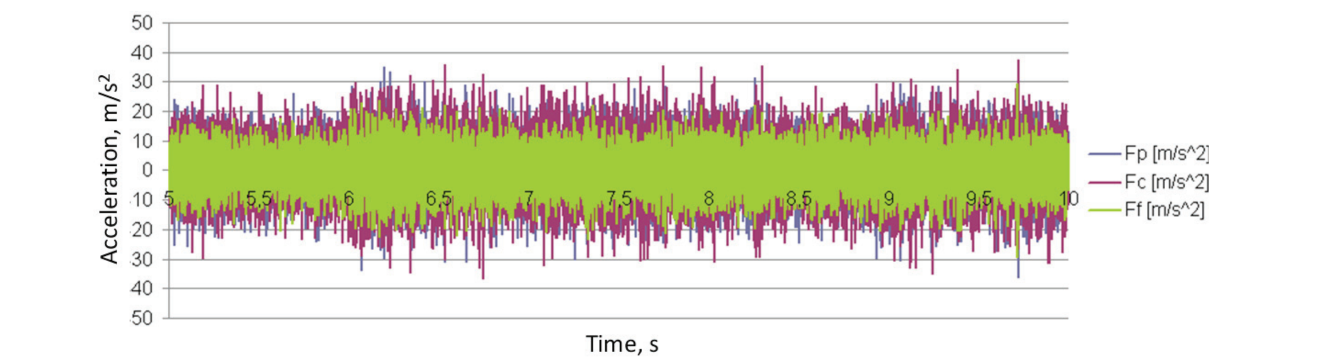

Fig. 9. Accelerations recorded for the turning of 41Cr4 steel with the cutting speed of v_c = 200 m/min, feed rate of f = 0.05 mm/rev and depth of cut of a_p = 0.1 mm

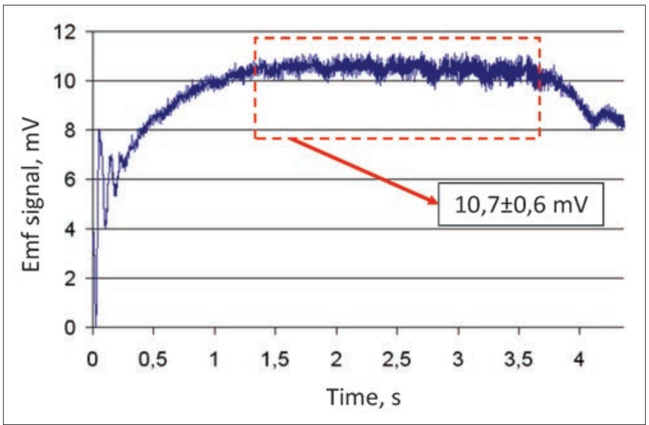

Fig. 10. A course of average cutting temperature versus time for TiCN-coated tool, process parameters: v_c = 100 m/min, f = 0.2 mm/rev, a_p = 2 mm [19]

Figure 10 shows the recorded *emf* signal during machining time of about 4 sec. The machining test was performed for an AISI 321 stainless steel and Ti(C,N) coated H10F carbide cutting tool. It can be recognized in Fig. 10 that the *emf* signal increases during the tool engagement period and then it stabilizes when cutting with a constant depth of cut. In this case the influence of tool wear can be neglected.

Measurement circuit for surface roughness

As mentioned in Section 2.1 surface roughness was measured after machining using a MAHR PS-10 hand-portable profilometer. The measured values of the selected roughness parameters, for instance the average roughness R_a and the maximum roughness height R_z

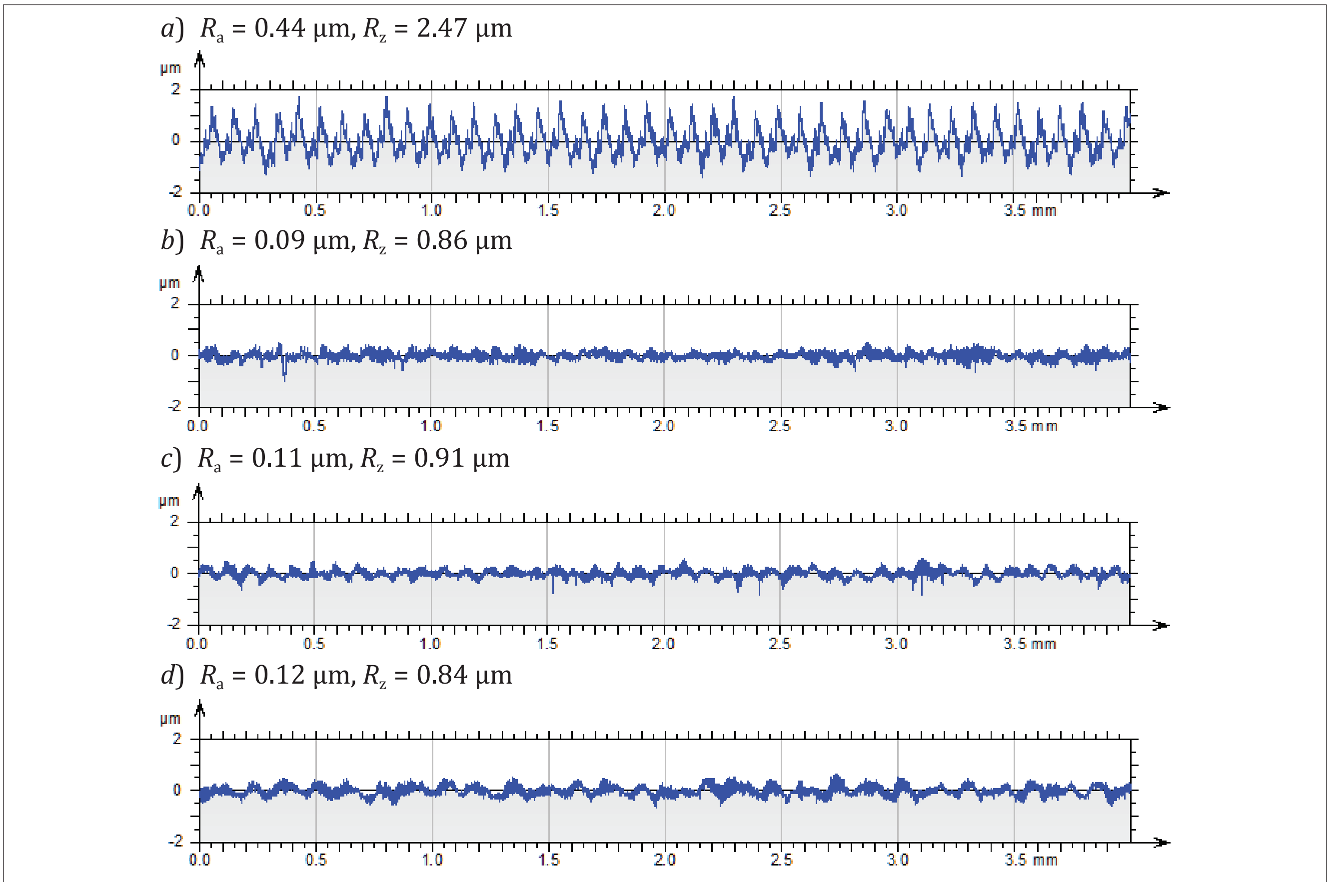

Fig. 11. Selected roughness profiles recorded for steel of 20 HRC hardness: *a)* after turning with v_c = 200 m/min, f = 0.1 mm/rev and a_p = 0.2 mm; after one-pass burnishing with v_b = 60 m/min and variable feed rate: *b)* f_b = 0.05 mm/rev, *c)* f_b = 0.1 mm/rev, *d)* f_b = 0.15 mm/rev [17]

were introduced as input data to the operational program [16, 17]. They were also considered during process diagnostics and optimization procedure. Figure 11 presents a set of surface roughness profiles recorded after finish turning (*a*) and one-pass burnishing performed with a variable burnishing feed of 0.05, 0.1 and 0.15 mm/rev (appropriately cases: *b*, *c* and *d*) operations.

System for optimization of machining parameters

The optimization of machining process is a very complex engineering task which needs a number of measured process characteristics transferred in on-line mode to the diagnostic system [10, 16]. In general, adaptive decisive models or artificial intelligence (AI) should be applied in order to make the decision process acceptably reliable [1, 9]. The concept of process optimization based on the own optimization strategy is shown in Fig. 12.

In particular, apart from obviously considered output data such as machining parameters, also initial surface state of the blank, cutting tool material and cutting tool angles (geometry) were additionally covered in this system. Such approach makes the optimization process more effective and complete.

As an example, Fig. 13 shows the power consumption spectrum recorded during a turning operation with defined machining conditions and workpiece material properties. The value of the total machining power (TMP) (equivalently total machining energy – TME) determined from this diagram was used as the optimization criterion in the selection of machining parameters.

The model showing the dependence of the TME on the cutting speed and feed rate is presented in Fig. 14. This model was determined based on the surface response methodology (SRM).

For the machining conditions used the model can be presented as the following multi-factorial function:

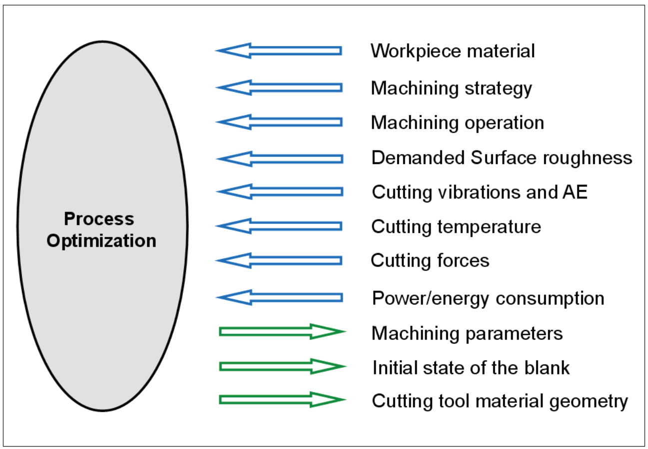

Fig. 12. General concept of optimization strategy employed in this study

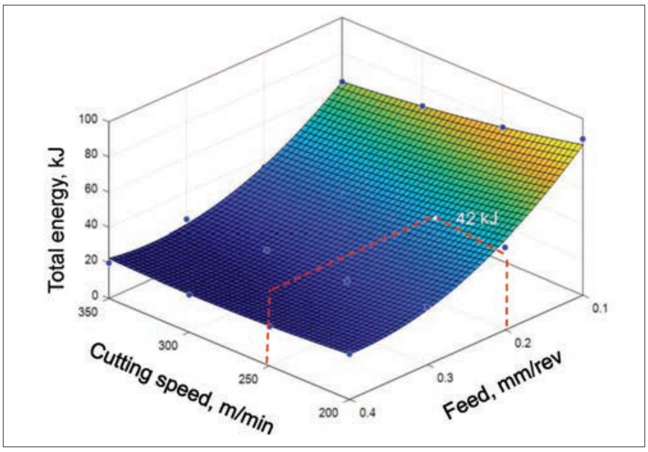

Fig. 14. Influence of cutting parameters on total machining energy of 41Cr4 steel of 20 HRC hardness; depth of cut a_p = 0.2 mm [17]

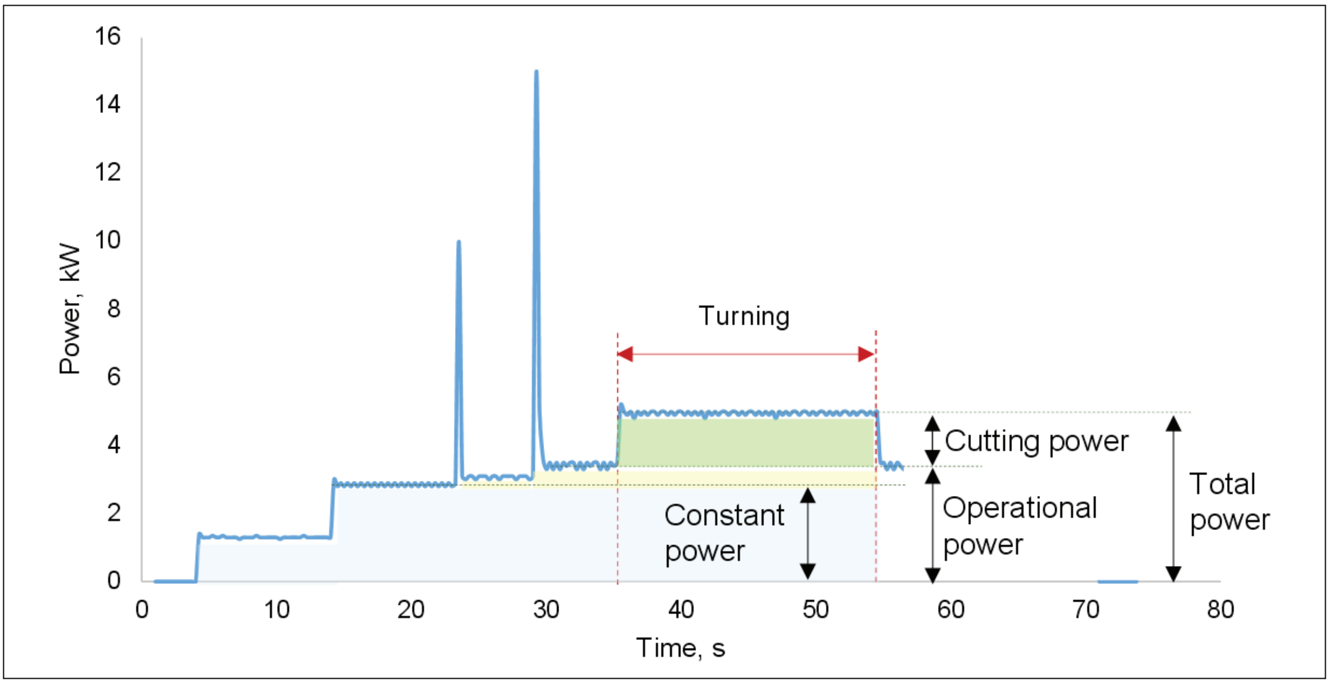

Fig. 13. Exemplary power consumption spectrum recorded for turning operation of 41Cr4; cutting parameters: v_c = 300 m/min, f = 0.1 mm/rev, a_p = 0.5 mm

$$E_t = 198.1 - 0.403v_c - 635.9f + 0.0004v_c^2 + 0.4069v_c \times f - 714.3f^2$$

The optimization procedure is based on the minimum energy consumption with additional consideration of the demanded surface finish [13, 16]. Of course, other optimization criteria such as minimum costs, maximum productivity, demanded tool life can be included as well.

Conclusions

This paper overviews problems concerning diagnostics and multi-criteria optimization of machining processes including a sequence of cutting and burnishing operations. A prototype measurement system consisting of current, voltage, force, acceleration and temperature sensors with further extensions to surface roughness and tool wear measurements is presented. The generated signals are processed and integrated into a decisive system for process diagnostics. For this purpose, a special database is developed.

The optimization strategy developed is based on the registration of power consumption spectrum which allows determination of the machining power, total power and operational power components. The first optimization criterion which minimized power consumption was used for selection of machining parameters. The second factor which considers the demanded surface finish can also be concurrently included into the optimization algorithm.

Process data recorded in this DAC system are subsequently processed and archived using a custom LabView operation program.

The monitoring system due to its open architecture can be developed and extended as a module supporting virtual machining models used in digital manufacturing. At present, the software applied in the system, especially in the domain of signal processing and integrating, is developed. The future extensions will be focused on the integration of the system within the concept of an intelligent machine tool.

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