Pawel LEZANSKI
Jan RAFALOWICZ
The Institute of Machine Tools and Production Engineering
Technical University of Lodz, Lodz, Poland

AN INTELLIGENT MONITORING SYSTEM FOR CYLINDRICAL GRINDING

Summary. A sensor based system for process state monitoring during the cylindrical grinding is described. A modular and hierarchical structure with a multiple-sensor approach (cutting forces, vibration, acoustic emission, and both diameter and out-of-roundness of the workpiece) for process monitoring has been proposed for the system. Features are extracted from the sensor readings by signal processing. They form a set of data which makes it possible to evaluate the grinding process in every respect.

1. Introduction

Present manufacturing systems have to be flexible and have to run automatically and free of errors. Furthermore, to ensure economical use, the effective machining time of a machine tool has to be increased. These conditions lead to utilization of monitoring and diagnosis of the manufacturing systems with advanced computer control [8].

Such systems should be provided with the functions which have been performed by operators till now: inspecting the work quality, monitoring the cutting state, taking the proper action if any trouble would happen, as well as optimizing the cutting conditions. The abilities of the operator to perform such tasks are cultivated through his long experiences and learning. A monitoring and control system which could replace the human operator can be qualified as an intelligent system. The system must be so constructed as to possess the functions of pattern recognition and decision making whose algorithms can be improved by any learning process in accordance with the empirical data accumulated [7].

Grinding is a quality-defining finishing machining process. However, it is a very complex process affected by so many factors that a reproducible result is rarely obtained. The most important one is that the cutting ability of the grinding wheel changes considerably during the grinding time. In practice the grinding processes are carried out with cutting parameters which are "safe" but not optimal. The workpiece quality depends to a great extent on the experience of the operator. All these difficulties with a control of the grinding processes are related mainly to the lack of reliable process models. Thus, the idea of collecting the maximum amount of information about the state of a process from a number of different sensors seems to be a very reasonable solution of control problems during grinding.

An intelligent, sensor based system for process state monitoring during the cylindrical grinding is being developed at the Lodz Technical University. It has been assumed that the system has to be provided with two basic functions: the recognition of machining situation and the decision making of the control action to be taken. It also has to be able to learn and adjust itself according to knowledge gained during the learning process.

2. Functions and structure of the monitoring system

Malkin and Koren [6] proved that the time optimal cylindrical plunge grinding cycle should consist of two basic stages: a roughing stage with a controlled infeed velocity limited only by surface integrity and grinding wheel overloading, and a stage of fast elastic deflection recovery with a negative infeed velocity. The first stage should be preceded by a rapid approach with detection of the first cut. To satisfy the surface quality requirement around the whole circumference, after the second stage, a spark-out has to be added for a time of at least one revolution of the workpiece, followed by a rapid retraction.

Functions of any monitoring system for cylindrical grinding would be different in the succeeding stages of the process as well as limitations.

During the rapid advance of the grinding wheel to the workpiece, the main task of the monitoring system is to switch the infeed velocity from rapid to roughing infeed velocity at the point of contact of the wheel with the workpiece. A workpiece or a grinding wheel failure which could not be compensated during grinding is a limitation for this stage.

During the stage of rough grinding, a quick transformation to steady grinding conditions has to be carried out and the high metal removal rate has to be secured. Therefore, the identification of the cutting abilities of grinding wheel and the identification of the type of wheel wear are of paramount importance. It would enable to make a proper selection of the wheel to the work material and to make a decision about the dressing action. Damages to the surface integrity developed during this stage have to be possible to remove during the next stages.

The stage of elastic deflection recovery with a negative infeed velocity can be implemented to accelerate the spark-out and to secure a reproducible deflection at the begining of finishing and spark-out stage. During this negative infeed, the grinding wheel must not lose contact with the workpiece. An allowance remaining for the finishing and spark-out stage should be as small as is needed to achieve the required standard of geometry and surface topography of the work. For this reason the spark-out has to last for a period of at least one revolution of the work.

Moreover, the monitoring system has to take the proper action during each stage of the machining if any trouble would happen.

The monitoring system recognizes the machining state by means of sensors mounted on the grinder. In order to perform the functions considered above, different kind of data about the grinding process is needed. The in-process sensors have to give signals from which the data can be obtained by using different methods of signal processing, feature extraction and modelling. In grinding, there are several combinations of sensors and models for monitoring of every stage of the process.

The first contact between the grinding wheel and the workpiece can be detected with a force, power or acoustic emission (AE) sensor but the sensitivity of the AE signal exeeds those of force and power measurements [4,5]. Signals representing the cutting forces, power, chatter and acoustic emission are useful in measurement of the grinding wheel wear. A more effective method for this measurement from the viewpoint of quality results are measurements of the surface integrity parameters such as out-of-roundness and roughness. Monitoring of the workpiece quality requires also measurement of the workpiece diameter which combined with the measurement of the real position of the wheel (neglecting

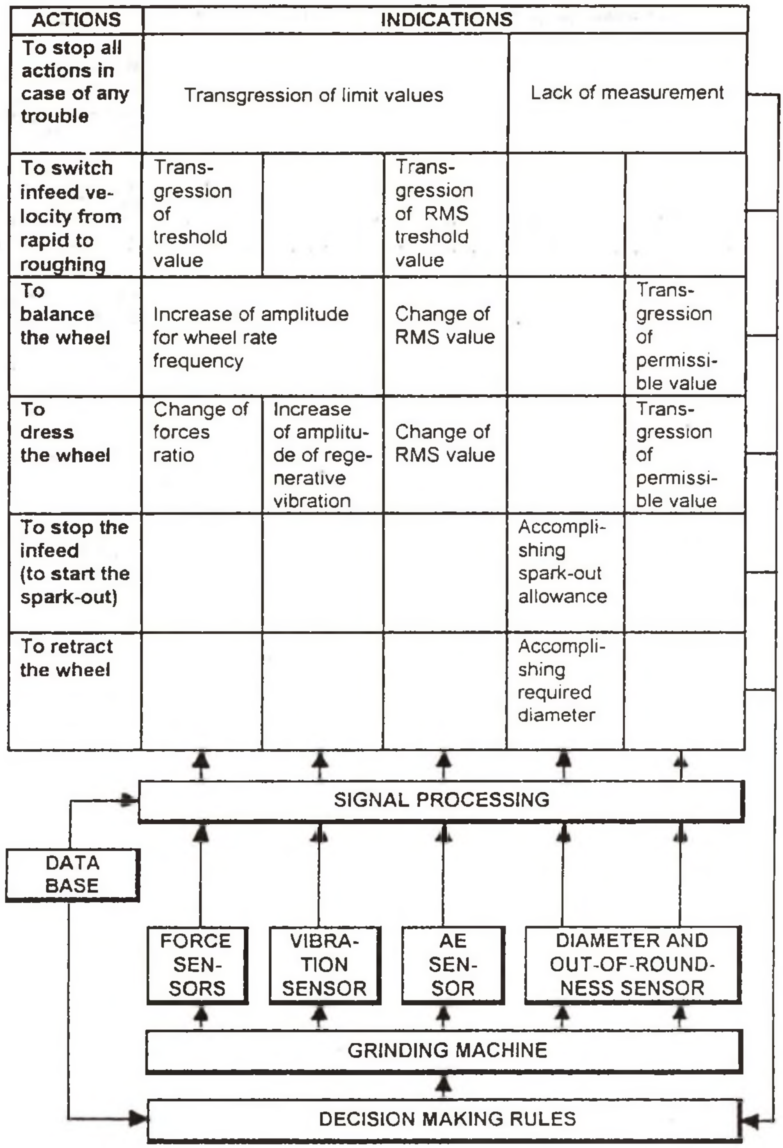

Fig.1. The functional structure of the monitoring system for cylindrical grinding

wheel wear) detects the elastic deflection in the grinding system and the metal removal rate. The use of more sensors and models results in a more reliable and more flexible supervising process and increases the feasibility of better control [1,4,13].

Taking into account the above analysis and hardware limitations, the discussed monitoring system has been equipped with in-process sensors of the normal and tangential cutting force, vibration, acoustic emission, and both diameter and out-of-roundness of the workpiece. The grinding power, the grinding wheel displacement and the rotational speeds of the work and wheel can also be measured. They form a set of signals which is able to evaluate the grinding process in every respect because the signals represent different groups of process features.

Intelligent control of machining processes can, in general, be treated as a decision making problem [2,3,13]. This method has been adapted for the monitoring system discussed here. Figure 1 illustrates the functional structure of the system.

The core of the system is a decision matrix. The columns represent the sensor signals applied for process evaluation. The rows represent the control actions which can be undertaken to keep the process in a desirable state. The matrix elements are indications of process state expressed in the different values of features extracted from the sensor readings by signal processing, related to the given actions.

In the decision process the following actions are assumed:

- to stop all actions in case of any trouble,
- to switch the infeed velocity from rapid to roughing,
- to balance the wheel,
- to dress the wheel,
- to stop the infeed (to start the spark-out),
- to retract the wheel.

The values of the features related to the particular sensor signal for each of the proposed actions have to be estimated in advance by off-line learning based on process related knowledge and experiments. When estimating the features, an appropriate criterion for process quality evaluation must be considered. For instance, the minimum total cycle time for a given workpiece quality would be a commonly used criterion.

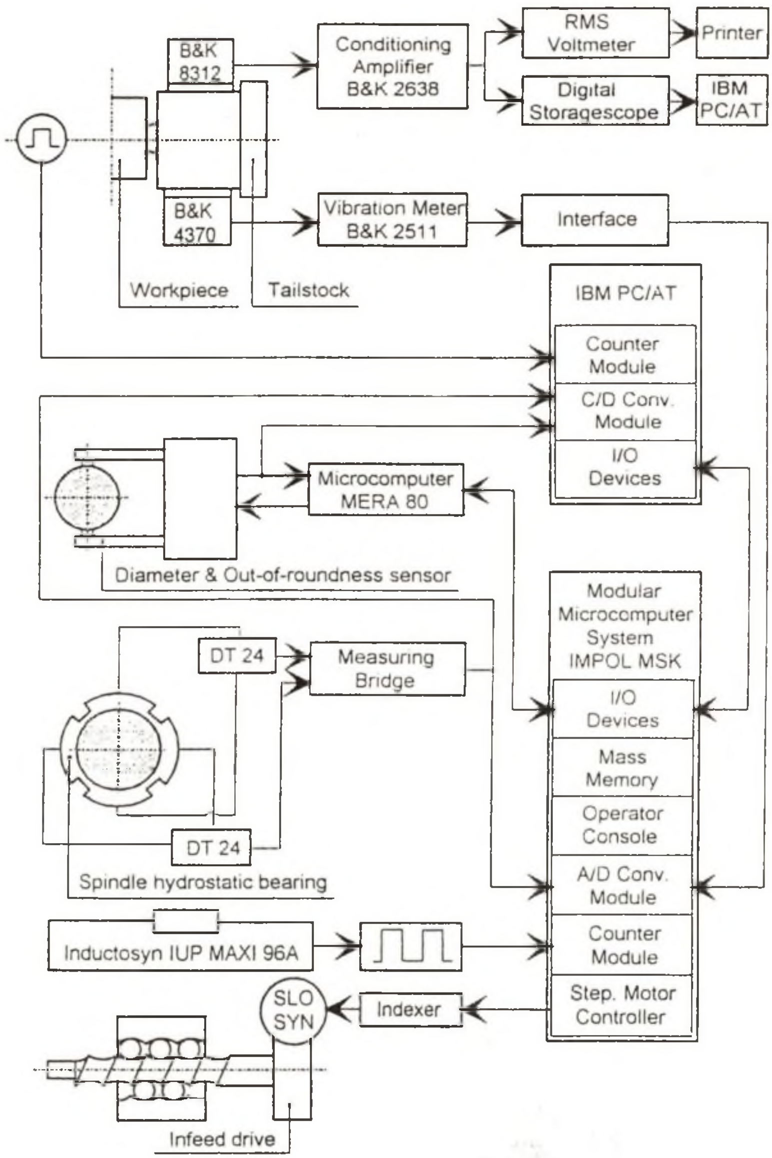

Fig. 2. The equipment setup

3. System implementation

The system setup was based on a PONAR-JOTES SWF25 modified cylindrical grinder. A conventional fluid drive in the infeed mechanism has been replaced with a stepping motor, a worm gear and a ball leadscrew. It allows of the infeed elementary displacement of 0.25-0.5 μm. Hydrostatic bearings in the grinding wheel spindle head and hydrostatic slides have been applied and the grinding wheel power has been increased up to 10 kW.

As mentioned earlier, the monitoring system consists of in-process sensors giving the signals representing as follows:

- the tangential and the normal grinding force (the difference in pressures inside the pockets of the spindle hydrostatic bearings is utilized for the measurement),
- the vibration (the FFT procedure is used),
- the acoustic emission (the actual and the RMS value of the amplitude signal is analysed),
- the workpiece diameter and out-of-roundness (a special sensor which measures both diameter and out-of-roundness has been developed).

A modular microcomputer system (MSK) and an IBM PC compatible computer are used for data processing and control. The modular microcomputer system MSK is used as a recorder of the sensor signals and as a controller of the infeed drive. The IBM PC/AT microcomputer is used for the signal processing.

The equipment setup is shown in Figure 2.

Developed software incorporates and integrates tasks shown in Figure 1. This is a collection of software routines for signal processing, data storage and extraction, data presentation, and grinding cycle control. The software structure is modular and extensible to facilitate future expansion.

4. System testing

The discussed monitoring system for cylindrical grinding was evaluated using a set of experiments during grinding. The experiments was conducted to examine the fundamental characteristics of the measured signals. First of all, their usefulness in measurement of the grinding wheel wear was tested. The effectiveness of used hardware and developed software was also examined.

5. Conclusions

A monitoring system for cylindrical grinding has been developed and discussed in this study. A modular and hierarchical structure with a multiple-sensor approach for process monitoring has been proposed for the system. The in-process sensors give signals representing the normal and tangential cutting force, vibration, acoustic emission, and both diameter and out-of-roundness of the workpiece. They form a set of signals which is able to evaluate the grinding process in every respect because the signals represent different groups of process features. The proposed decision-making approach allows for integration of information from different sensors.

The results of this study confirm the effectiveness of the proposed forces, vibration, acoustic emission and workpiece geometry sensing techniques for monitoring of the grinding process but further investigations are necessary to find appropriate learning and pattern recognition algorithms which could be incorporated into the monitoring system. In particular, futher works should be focused on the effectiveness of acoustic emission sensing methodologies for grinding process monitoring and analysis.

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