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AN INTELLIGENT SENSOR BASED SUPERVISION SYSTEM FOR CYLINDRICAL GRINDING PROCESSES

The paper presents a sensor based supervisory control system for cylindrical grinding processes which ensures reliable process monitoring and control in the presence of process disturbances. The system makes use of different processing techniques and process models to reliably detect incipient and abrupt symptoms of undesired process states and tool wear. As a result the supervisory system manages different actions to keep the process within the optimal working region. The system consists of two levels which act in parallel. The objective of the first optimisation level is to maximize the material removal rate, simultaneously satisfying restrictions on surface roughness, out-of-roundness and waviness errors and on grinding temperature. At the same time the second, geometrical control level is responsible for the removal of the initial shape error by stabilising the motion trajectory of the grinding wheel in relation to the part being ground. The concept of the supervision system was evaluated by a preliminary experiments to prove its effectiveness.

1. INTRODUCTION

Cylindrical grinding processes such as plunge or traverse grinding are important manufacturing techniques frequently used in industry. From the parts being ground it is required to be of very fine tolerances and small shape errors in any direction. Unfortunately, due to mechanical deflections, variable allowance distribution and grinding wheel wear the achievement of high accuracy according to a predefined run of machining is hardly ever possible [5]. Consequently, many spark-out workpiece rotations or traverse passes may be needed to meet these requirements, at the expense of increased machining time. Apart from the problems outlined above the objective of cylindrical grinding processes is to produce parts of desired surface finish and surface integrity. To satisfy these requirements some reliable models are essential to select proper set-up parameters. Besides, the grinding wheel properties change during the course of grinding process and may cause increased heat generation and increase of chatter vibrations [2,7].

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To counteract these process abnormalities a few selected features of process variables have to be continually monitored and chosen kinematic parameters need to be corrected to keep the process in the optimal working region. Therefore, to effectively supervise the grinding processes these relations have to be precisely recognized and described by an appropriate models [6]. In consequence, a synthesis of a supervision system was begun from preliminary experiments.

2. PRELIMINARY EXPERIMENTS

Experimental investigations were carried out on a common cylindrical grinding machines equipped with adequate control and measurement units. During the traverse grinding the rollers were ground which were 550 mm long and had a 70 mm diameter. A 38A80KVBE aluminum oxide grinding wheel of 495 mm diameter was used. The wheel was equipped with a preliminarily dressed oblique segment 20 mm wide and of 0.3° angle. During the experiments the nominal depth of cut a_0, traverse feed f_a and peripheral workpiece speed v_w were changed on three levels: a_0 [μm] $\in$ (20, 50, 100); f_a [mm/rev] $\in$ (2, 4, 8); v_w [mm/s] $\in$ (108, 216, 433). In the case of plunge grinding an influence of workpiece peripheral speed on grinding results was mainly investigated. A vitrified 38A60 grinding wheel was used. The workpiece speed was changed on three levels: n_w [rev/s] $\in$ (0.5, 1.5, 2.5). The infeed velocity of grinding wheel v_f was the same for all tests, equal to about 15 μm/s, so as to keep the material removal rate at constant level. Tests were continued until the end of wheel life. Limits on surface roughness R_a, workpiece roundness and waviness errors were assumed as initial criteria of process performance. To characterize process state the grinding force components, RMS acoustic emission and vibration signals were measured. Moreover, in plunge grinding process raw acoustic emission signal was measured using the sensor attached to the tailstock centre.

3. CHARACTERIZATION OF PLUNGE GRINDING PROCESS BY ACOUSTIC EMISSION PRELIMINARY EXPERIMENTS

In literature it is often suggested that acoustic emission signal is a good source of information about phenomena occurring in grinding processes, such as friction, grain impacts or grain and bond cracking [6]. However, since these sources of different phenomena emit interfering waves of variable frequency it is very difficult to recognize the nature of AE signal changes. Recently, time-frequency analysis techniques, mainly wavelet transform have been extensively investigated for the purpose of feature extraction from nonstationary, transient signals such as acoustic emission or vibration signals. However when using wavelet transform the results relies to a great extent on the parent wavelet employed, basic wavelet function and the discretization of scales. Improper selection of these parameters may produce results that approach a traditional Fourier method.

From among the many frequency analysis techniques the Huang-Hilbert transform HHT seems to be the most promising. This nonlinear technique was developed by the need to analyse nonlinear and nonstationary signals changing even within one oscillation cycle [1]. The HHT transform uses two processing techniques, i.e. empirical mode decomposition EMD and Hilbert transform HT. The EMD method decomposes time-series into a set of intrinsic mode functions IMFs which represent a simple oscillatory modes, but unlike the simple harmonic functions they can have variable amplitude and frequency along the time. Next, for each IMFs the Hilbert transform is used to find changes of amplitude and frequency over the time. The HHT method was used to find a symptoms of grinding wheel wear and workpiece burn in plunge grinding process on the basis of a raw acoustic emission signal measurements. In Fig. 1 a few, first IMF components are shown for sharp and worn grinding wheel for the case when workpiece rotational speed was equal to 2.5 rev/s.

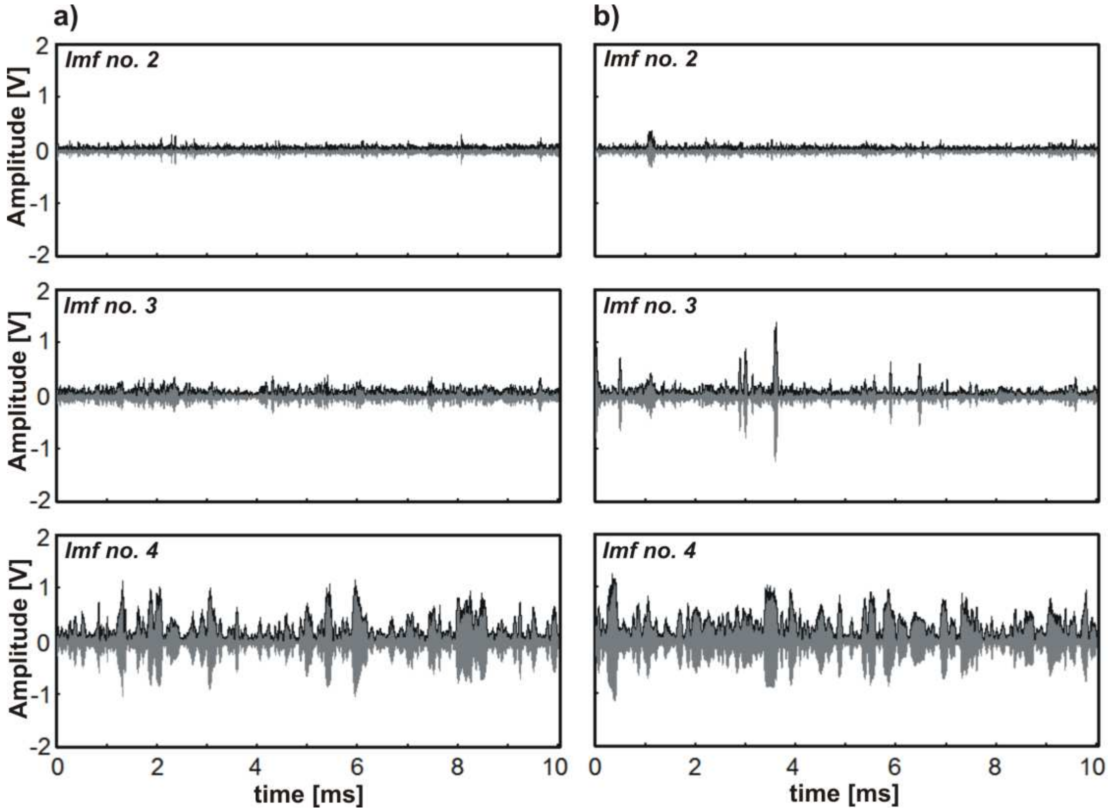

Fig. 1. Changes in the AE IMF signals for the sharp a) and worn b) grinding wheel (n_w=2.5rev/s; black line is the amplitude of Hilbert transform)

Since the first IMF component was connected with measurement noise it wasn't shown. The second IMF component is responsible for the waves of frequencies in the range from 170 to 250 kHz, while the third and fourth IMF components correspond to frequencies of about 80 and 56 kHz respectively. From this figure it may be seen that instantaneous level of IMFs amplitude increases for the worn grinding wheel. Also the increase in number of sudden changes of IMFs amplitude is clearly observed, especially for the third IMF component. Visible changes in the course of IMFs amplitudes may be connected with the increase of intensity of grinding wheel grains or vitrified bond fracture. The fourth and a few next IMF components are rather connected with cutting mechanism and friction.

The previous results were compared with the results of grinding where the workpiece rotational speed was low, equal to 0.5 rev/s, see Fig. 2. During these tests a visual symptoms of workpiece thermal damage were observed. The infeed velocity of grinding wheel was the same so as to keep the material removal rate at the same level. Just like in the previous example an increase of instantaneous amplitude for all IMF components as a measure of wheel wear is visible, but the occurrence of rapid jumps of amplitude for the third IMF component may be observed as early as for the sharp grinding wheel. Such changes in the course of this IMF component may be caused presumably by reduced strength of grinding wheel grains and bonds due to the higher grinding temperature.

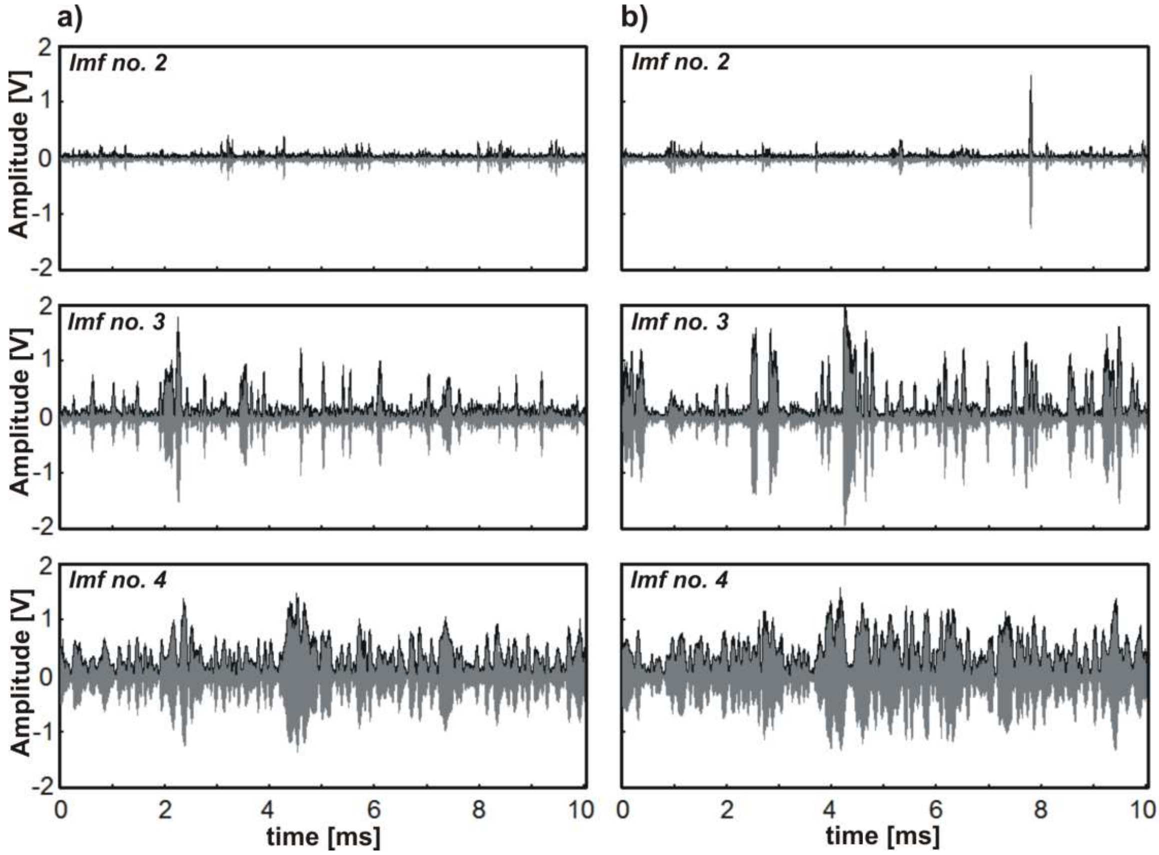

Fig. 2. Changes in the AE IMF signals for the sharp a) and worn b) grinding wheel (n_w=0.5rev/s)

Additionally, jumps of amplitude could be observed for the second IMF component. It must be noted that, in general, these occurrences of amplitude jumps for this component were not found in the case of tests for high workpiece rotational speeds, even when coolant was switched off. Therefore it may be responsible for material microcracks. Nevertheless, explanation of this amplitude increases needs further research. Moreover, it was found that mean frequency of the first few IMF components decreases significantly along with the tool wear, what may be connected with the decrease of active grains of the grinding wheel. The drawback of the presented method is high dimensionality of features that could be extracted from the IMF components. To reduce the number of these features the principal component analysis PCA will be used.

4. GRINDING DATA MODELLING AND ANALYSIS

The received data of grinding processes relations were analysed with the use of neural network modelling techniques [3,5]. In order to obtain high ability of extrapolation and generalization an efficient training program has been developed based on the Wolf-Broyden-Davidon variable metric optimization algorithm. Its efficiency has proved to be vastly superior to the conventional back-propagation learning scheme. Using the developed program, correlations between input and output data in traverse and plunge grinding were found. An exemplified relations for traverse grinding process are shown in Fig. 3, where the influence of axial feed f_a and workpiece peripheral speed v_w on surface finish and roundness errors $\mathbf{A_{1\text{-}9}}$ (from one to nine waves on circumference) are presented.

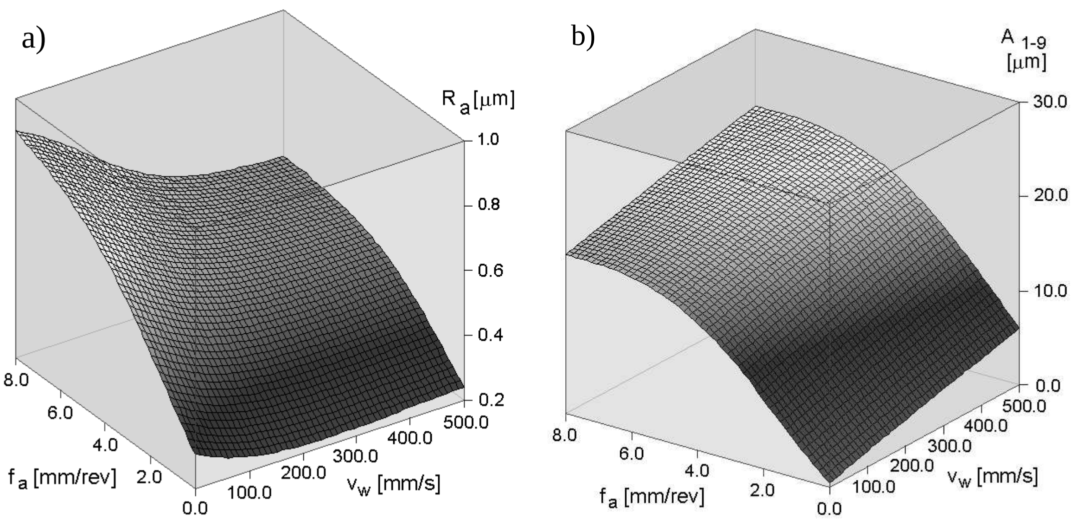

Fig. 3. An influence of traverse feed f_a and workpiece peripheral speed v_w on: a) surface roughness R_a; b) roundness errors $A_{1\text{-}9}$; a_0=50μm

As may be seen the surface roughness increases when too low workpiece peripheral speeds are applied. Also in plunge grinding process such symptoms were observed when the workpiece peripheral speed was too low. On the other hand, in both, plunge and traverse grinding processes an increase of workpiece peripheral speed causes the increase of out-of-roundness errors. In the case of traverse grinding process it follows that in the domain of traverse feed and workpiece peripheral speed there exists a region of optimal working conditions with respect to grinding quality constraints. In plunge grinding process the same optimal region exist in the domain of workpiece peripheral speed and depth of cut. Therefore, the workpiece peripheral speed, depth of cut and traverse feed in the case of traverse grinding should be optimised as an effect of the modifications of process constraints and variables in the following grinding phases.

5. CONCEPT OF THE SUPERVISION SYSTEM

Based on the above analysis it was established that in spite of the presence of process disturbances repeatable grinding results may be assured by designing the hierarchical supervision system as shown in Fig. 4.

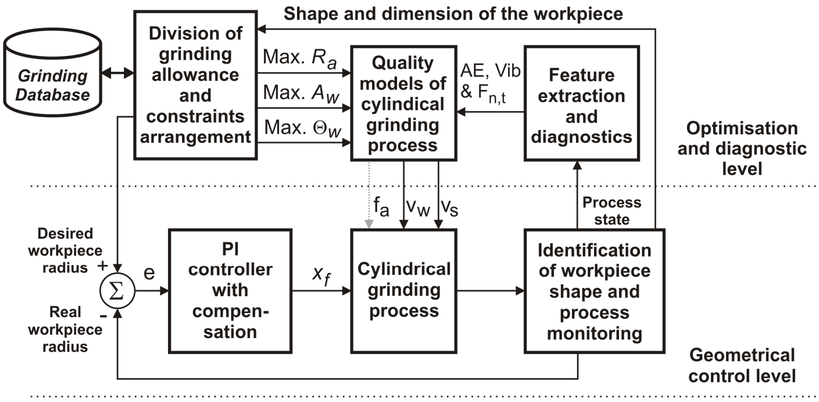

Fig. 4. Structure of the supervision system

The upper level of the system should consist diagnostic and optimization subsystems. Its task is to setup the initial kinematic parameters and next to modify them as a result of change of grinding conditions and tool wear. The diagnostic subsystem should detect the occurrence of chatter vibrations, grinding wheel wear and grinding burn on the basis of measurements of selected features of vibration and acoustic emission signals. As a result of chatter development the system may decide on change of basic kinematic parameters and whether to modulate grinding wheel or workpiece peripheral speed. The primary element of this subsystem is a neural network quality model, which for instance in the case of traverse grinding estimates the grinding results, i.e. surface roughness R_a, roundness errors A_w and grinding temperature Θ_w on the basis of measurements of temporary values of traverse feed f_a, workpiece peripheral speed v_w, estimates of maximum depth of cut a_e, grinding wheel cutting ability K_z and process vibrations A_{vib} [4]. The optimisation scheme is identical to the standard error backpropagation algorithm, with the inputs of the quality model being treated as weights. Firstly, if quality restrictions are exceeded the differences between permissible and actual grinding results are calculated and next are propagated all the way back to the input layer of the neural network quality model. As the result of the backpropagation procedure the errors δ_{fa} and δ_{vw} in the input layer are found, at inputs of f_a

and v_w. These errors with the addition of small increments responsible for productivity maximisation form the desired corrections of input variables being optimised. The task of the lower geometrical control level is to remove the initial shape error and generate the required shape of the workpiece. The strategy of geometrical control applied here is based on such corrections of the grinding wheel edge x_f which would compensate for the workpiece elastic deflections, calculated on the basis of the finite element compliance model and measurement of the grinding force [4]. A workpiece radius outcoming from the grinding area was taken as a variable being controlled.

6. CONCEPT OF THE SUPERVISION SYSTEM

Initial verification of the proposed concept of supervision system was carried out on the basis of traverse grinding process. For this purpose the rollers with large preliminary shape error, equal to ±25 μm, were ground, being made up of barreling, conicity and small flexure. Firstly, the efficiency of the geometrical control subsystem was verified for relatively difficult grinding conditions, i.e. high workpiece peripheral speed and traverse feed. Fig. 5 demonstrates the results of grinding without and with the use of the geometrical control subsystem.

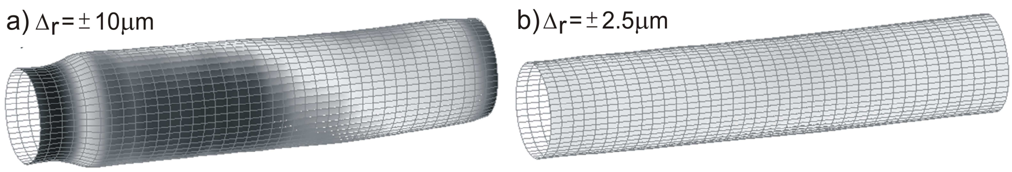

Fig. 5. The shape error of the roller middle step: a) error without and b) with the use of the geometrical control subsystem

It may be seen that the preliminary out-of-cylindricity error of approximately ±25 μm was reduced to within ±2.5 μm, whereas in the case of grinding without the control, cf. Fig. 5a, the error remained very large and equal to ±10 μm. The final part of the experimental results demonstrate the abilities of the optimisation subsystem. Fig. 6 illustrates the estimated changes of maximum depth of cut, Fig. 6a, grinding wheel cutting ability and process vibrations, Fig. 6b.

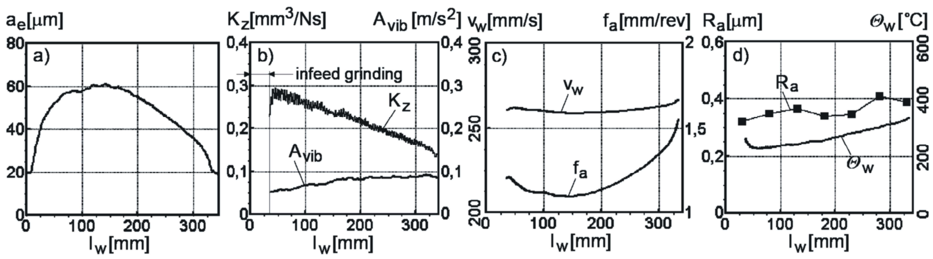

Fig. 6. The courses of process state estimates, kinematic parameters and resultant surface roughness

These changes are followed by courses of remaining kinematic parameters to keep the grinding results in the required limits, i.e. surface roughness R_a<0.4 μm, shape errors A_w<6 μm and grinding temperature Θ_w<400°C. As may be seen from Fig. 6c the optimisation procedure was able to keep the process in the optimal working region by continuous changes of traverse feed and the workpiece peripheral speed. In Fig. 6d the resultant surface roughness measured along the roller and grinding temperature estimated by the quality model are presented.

7. CONCLUSIONS

A concept of supervision system for optimization and control of cylindrical grinding processes was presented. The experiments showed that the application of the newly developed system makes it possible to remove shape error very quickly, keeping the remaining quality parameters within the required limits. The experimental evaluation of the system was done on the basis of traverse grinding process, however a basic intention is to build a system that could be also applicable to plunge grinding process. With this end in view a preliminary investigations were done to recognize plunge grinding process relations and constraints. The additional problem that should be taken into account is to find adequate strategies for chatter suppression. The application of active dampers mounted e.g. in the centres will be considered.

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