SELF-PRESENTATION
for the application for the initiation of a Doctor of Science qualification

1. Applicant: **Paweł Leżański**

2. Possessed diplomas and university degrees:

Master of mechanical engineering in the field of machine tools, cutting tools and production engineering from Politechnika Łódzka, Faculty of Mechanical Engineering, 1974.
Ph.D., Politechnika Łódzka, Faculty of Mechanical Engineering, 1983 on the basis of the doctoral thesis entitled “Model of face grinding carried out on a grinding machine with a rotary table from the aspect of an adaptive control application”.

3. Course of employment in scientific institutions:

1974 – 1983	assistant, senior assistant, Politechnika Łódzka, Faculty of Mechanical Engineering, Institute of Machine Tools and Production Engineering, Research Group of Machine Tool Automation.
1984 –	adjunct, Politechnika Łódzka, Faculty of Mechanical Engineering, Institute of Machine Tools and Production Engineering, till IX.2004 Research Group of Machine Tool Automation, from X.2004 Research Group of Robotics and Automation.
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4. As a scientific achievement I submit the monograph entitled:

”Automatic Supervision of External Cylindrical Plunge Grinding”
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Description of the scientific purpose and accomplished results of the submitted scientific achievement

The automation of manufacturing processes that bring the elimination of the human being from direct participation in the supervision process is currently one of the most important factors stimulating research in the field of production engineering. It creates the necessity for the development of automatic supervision systems which would include slowly-changing and rare occurrences such as tool wear or cooling system failure respectively into their operation scope. In taking these occurrences into consideration, the supervision system would ensure the acceptable state of the machining process, the overriding purpose of which is to obtain the required level of workpiece quality and machining capacity. Under these criteria, a study of the general rules and recommendations for an automatic intelligent supervision system of the external cylindrical plunge grinding process was adopted as the general purpose of the monograph entitled, “Automatic Supervision of External Cylindrical Plunge Grinding”. A strategy of process state identification in such a system should be based on measuring signals from sensors monitoring features characterizing the state of the machining process and its results.

The external cylindrical plunge grinding process was chosen as the object of the monograph because it is one of the most commonly used types of grinding and it is characterized by a number of specific features resulting from its kinematic and geometric conditions. The workpiece, as well as the tool, performs rotary motions in this type of grinding and the accompanying phenomenon of chip formation under these conditions is a reason for the fast development of chatter, which has a crucial influence on the workpiece geometrical quality and the wear of the grinding wheel. Because of the high randomness of the development of the phenomenon as described, the application of an automatic supervision system seems to be the most effective method for the effective functioning of the process. The kinematic conditions of this type of grinding also create some critical problems related to the measurements of the process quantities and the methods for their processing.

The purpose of the monograph and the tasks resulting from it were formulated to prove the following thesis.

Data characterizing the process with respect to its limitations and results is required for reliable grinding process supervision. This data is obtainable from measuring signals characterizing the process and its results in all possible aspects. However, because of the process randomness and the difficulties resulting from industry conditions, this data can be contaminated, unclear and even inconsistent. Thus, reliable grinding process supervision is a multi-criteria decision making (MCDM) problem under uncertain conditions and its automation is possible with the application of computer aided data mining methods.

The monograph begins with the meanings of the basic concepts of monitoring, diagnostics and supervision as adopted. According to these meanings, an automatic supervision system includes diagnostics which detect process malfunctions through process monitoring and establishes the causes of these malfunctions and uses the diagnostics as a base for process control and optimization.

The grinding wheel dressing is an important element of any grinding process and it determines the wheel working surface geometry and topography, which in turn influence the grinding results. Because of this, a monitoring of the wheel dressing should ideally be included in the grinding process supervision. However, in the monograph, problems related to dressing are not discussed because there are already many studies devoted to these problems. Moreover, the influence of dressing on the grinding process in cylindrical plunge grinding is limited only to the first part of the grinding wheel life period.

Additionally, it can be said that the following issues are also important for grinding process supervision:

- Detection of the first contact between the wheel and the workpiece,
- Detection of collisions,
- Monitoring of the correctness of the workpiece fixing, coolant supply etc.

These issues are important, but, at present, most of them have been technically solved and because of this they are also not discussed in the monograph.

Following the establishing of definitions, a review of the state of knowledge in the field of grinding process supervision is given. The general structure of measuring units, examples of measurements of the grinding power, force components, vibration, acoustic emission (AE) and other process quantities, with an analysis of their effectiveness, is considered. A review of the applied methods of signal processing, as well as modeling and the classification of the process state, is also given and the idea of an intelligent grinding system is discussed. About 150 references were taken into consideration in the review.

It was established that to identify the incorrect states of the process, an acceptable working area, delimited by process limitations, has to be known. This area is delimited by a dynamic stability limit for small values of specific material removal rate and by the possibility of burn and other thermal damage appearing in the workpiece surface layer for higher values of specific material removal rates. Additionally, this area is narrowed down by a restriction resulting from the required surface roughness, the allowable normal force and the allowable work speed. Any point inside these limits determines the process input parameters which meet all the limitations. However, the constraints of the acceptable working area change their locations during the single wheel life period because of the continuous change of the wheel cutting ability and other process disturbances. Under such circumstances, the problem of grinding process diagnosis should be based on the monitoring of the grinding wheel wear and all phenomena related to the process limitations. This also determines the process and workpiece quality parameters to be supervised. The macro-wear and micro-wear of the grinding wheel, chatter, thermal damage to the workpiece surface layer and the roughness of the workpiece surface were included in the supervised parameters and, in this case, an analysis of phenomena and processes related to these parameters was carried out and allowed for the conditions for the cylindrical plunge grinding process supervision to be established.

A reliable description of the changes in the cutting ability of the grinding wheel, as a result of wheel wear during grinding, has a crucial meaning. The wheel micro-geometry is related to the state of individual abrasive grains and their vicinity (air gaps and bonding bridges). Changes in micro-geometry are connected with the flat wear of grains, their breakage and pullout, as well as the grinding wheel cutting surface (WCS) loading. All these phenomena influence the workpiece surface layer quality, the grinding capacity and the cost. They form the wheel micro-wear. The wheel macro-geometry concerns the wheel shape and directly influences errors in the workpiece geometry and dimension. The sum of the micro-geometry changes forms the wheel macro-wear. Both types of wear occur simultaneously during grinding.

The wheel macro-geometry can be described with the aid of many indexes connected with the volume and radial wear of the wheel. The volume wear has a bearing on grinding cost. The radial wear has a bearing on the workpiece geometry and dimension as well as on process stability. The development of waviness on the WCS is a special form of radial wear and has an important influence on process stability. The waviness of the grinding wheel, as well as the waviness of the workpiece, is a fundamental reason for chatter regeneration in cylindrical grinding. The development of chatter can cause a loss of process stability and damage to the wheel or workpiece. Because of this, an assessment of the grinding wheel wear should be a basic criterion. An analysis of the cylindrical plunge grinding dynamics is used to consider this issue because the wheel macro-wear is strictly connected to process stability. The analysis is based on a closed loop representation of the plunge grinding operation as proposed by R. Snoeys and D. Brown. The grinding stiffness, the wheel wear stiffness, the stiffness of the contact area and the dynamics of the machine are taken into account in this representation. The wheel and the workpiece chatter regeneration are also taken into consideration, but they are modulated by the geometrical interference of the waves developed on the wheel and the workpiece surface. However I modified the waviness interference functions for the grinding wheel and workpiece.

The adopted closed loop representation of the plunge grinding operation allows for a stability criterion formula to be established. From the formula, it can be concluded that a higher static stiffness of the machine is conducive to process stability, whereas a higher grinding stiffness, wheel wear stiffness, stiffness of contact area and width of grinding bring the process to an unstable state. The grinding stiffness and the wheel wear stiffness are of a great priority for grinding supervision because their influence is modulated by the phenomenon of wave geometrical interference which can result in the cut down of waves on the wheel and the workpiece, The degree of this cut down is expressed by a coefficient which is equal to the ratio between the height of the wave remaining correspondingly on the wheel and the workpiece surface and the amplitude of chatter generating this wave. The threshold frequency for a workpiece above which the cut down of the waves begins in conventional grinding is lower than 500 Hz, whereas this frequency for the wheel, because of a much higher grinding ratio, is at least 100 times higher. This explains why nearly all cylindrical grinding processes run under instability, taking into account the wheel regenerative chatter. Chatter frequencies in cylindrical grinding, which are close to the natural frequency of the mechanical system, are usually higher than the workpiece chatter frequency, but much lower than the wheel chatter frequency. This means that wheel waviness can develop to a very high amplitude. Thus, the state of chatter should be supervised because it is an important symptom of the grinding wheel state, whereas chatter is not an important symptom of the workpiece waviness because waves on the workpiece are, as a rule, cut down by the wheel.

Waviness on the grinding wheel develops much slower than on the workpiece. Because of this, the development of chatter as a criterion of the grinding wheel life becomes significant as the time from the last dressing elapses. Additionally, this depends on the combination of applied grinding and dressing parameters. Workpiece thermal damage or higher than acceptable workpiece roughness are much more likely for higher values of the specific material removal rates. The chatter level determines the wheel usefulness for the lower values of the specific material removal rates.

The micro-geometry of the WCS is described by many parameters with the aid of different measuring methods. Generally, these methods can be divided into direct and indirect. The direct methods are based on a measurement of the WCS profile and its geometrical parameter determination or their density distribution description. The usefulness of these methods for grinding automatic supervision is narrowed by the number of imperfections resulting from the nature of these methods. However, the lack of an explicit relationship between these parameters and the grinding results and the very limited possibilities of the measurement execution in industry conditions are the main drawbacks of these methods. In spite of this, a profilogram of the WCS is the most extensive source of information about the WCS micro-geometry and can be used for comparative purposes in laboratory conditions. Such an approach to the measurements of the WCS profile is used in the monograph..

Because of the drawbacks of the direct methods, indirect methods have to be used. They are based on measurements of process quantities correlated with the cutting ability of the grinding wheel. Such an approach requires the relationships between them to be established.

Grinding force and all quantities related to it are important process quantities commonly considered as correlated with the cutting ability of the grinding wheel. A grinding force model as proposed by L. Lichun and F. Jizai was used to consider the relationship between the force and the parameters of the WCS micro-geometry. The carried out analysis shows that the WCS micro-geometry parameters influence the values of the grinding force components but it does mean that grinding force monitoring secures a reliable diagnosis of the grinding wheel cutting ability. This is because of two reasons. Firstly, it results from the recurring changes of the grinding wheel wear type in the wheel life period. For example, an initial domination of a flat wear can change into a grain breakage and pullout. Each type of wheel wear has a different influence on the grinding force. Flat wear causes, of course, an increase in this force. In the case of grain breakage and pullout, the total flat area of grains decreases and new, sharp grains become active and this results in a decrease in force. Secondly, a number of disturbances related to process dynamics, heat and chemical phenomena influence the value of the grinding force.

The features related to the grinding force can be useful in grinding process automatic supervision but in connection with other type of process state symptoms. According to the rapper approach in feature selection, taking into consideration relationships between different features can reveal the true usefulness of individual features.

The results of many empirical investigations show that apart from grinding force, selected features of the acoustic emission signal are also correlated with wheel micro-geometry. However, there is a lack of findings regarding the contribution of individual sources for the AE signal during grinding making up the total energy of this signal. The AE signal is nonperiodic, consists of many, frequently short-lived, frequency components and cannot be described with an explicit mathematical function. Thus, its usefulness for wheel micro-geometry supervision can be recognized only experimentally.

The parameters of the workpiece surface layer and the geometrical structure of the ground surface are other process results which depend on the grinding WCS micro-geometry. The type of these dependences can be described with a general rule which says that a higher cross-section area of chips and a lower active grain count causes a growth in the workpiece roughness and a fall in the residual stress of the workpiece surface layer. As in the case of grinding force and acoustic emission, these dependences are indirect and they are determined empirically. The parameters of the workpiece surface layer and, in practice, its roughness cannot be measured in on-line mode.

The possibility of burn and the appearance of other thermal damage in the workpiece surface layer is the next important limitation for the grinding process. Heat penetrating the workpiece through the contact area with the wheel causes a local increase in temperature in the workpiece surface layer. This is a reason for plastic deformation, phase transformations, microcracks, and other mechanical and chemical changes in this layer. As a result, changes in residual stress and the microhardness of the surface layer, as well its burning, can appear. Of course, all of these are undesirable phenomena but, unfortunately, the direct identification of them in an on-line mode or even just after grinding is very difficult. The use of destructive measuring methods is certainly excluded whereas accessible nondestructive methods are not accurate enough and cannot be used in industrial conditions. In practice, all that is left is the application of different indexes correlated with the workpiece surface integrity state, possibly to be determined on the basis of input process parameters and measured process quantities.

As it results from the carried out consideration in the monograph, the properties of the workpiece surface layer can be represented by an index which is a product of specific grinding power and the length of the period contact of the wheel with a point on the workpiece surface during one revolution. B_p usually represents this index. The B_p index is easy to be determined during grinding and only requires the tangential force to be measured. The other quantities represent input grinding parameters and they are constant.

The acoustic emission measurement is also used for thermal damage detection. It is based on the finding that an AE signal is generated by phenomena related to workpiece and wheel material structure deformation and to friction at the contact area.

The roughness of the workpiece surface after grinding is one of the most important process results and very frequently used as an indicator of the process correctness. It should be noted that the relationship between the workpiece roughness and the grinding force, as well as the AE value, is revealed in many references. However, the experimentally obtained relationships do not show a good correlation between the investigated process quantities and roughness and they cannot be generalized. Depending on the applied grinding parameters, a positive or negative sign of the correlation coefficient can be obtained. The correlation between roughness and AE seems to be a little better which is a result of the direct connection between the AE signal and the activity of individual grains on the WCS. In spite of this, an assessment of roughness only on the basis of one feature of the AE signal is hazardous. In practice, roughness nearly always increases during the grinding wheel life. This is mainly because of vibration development which causes a fall in the active grain count and thereby a growth in the cross-section area of chips. In the face of the inevitable development of chatter as the wheel life elapses, this mechanism begins to dominate in the creation of the workpiece surface roughness.

The analysis of the processes and phenomena influencing the state and results of the cylindrical plunge grinding process shows that the automatic supervision of this process should be based on measurements of process quantities which are able to be accomplished on-line along with measurements of the workpiece dimension and shape. Measurements of grinding power, force components, vibration and acoustic emission are most frequently used. The process monitoring system consists of one or more sensors generating signals and allowing a set of features to be extracted from them. These signal features constitute symptoms of process and grinding wheel state.

Each of the discussed process quantities possesses a large potential for plunge grinding process supervision. However, the use of simple features of the measured signals, directly obtained from the measurement quantity (e.g. a mean value) does not usually provide satisfactory results. This large potential of the individual measuring signals is included in their dynamic features. The application of advanced signal processing methods is required to reveal these features. It follows that the selection of suitable sensors and data processing methods is of crucial importance in obtaining a representative set of features describing the supervised process phenomena.

Process state classification based on more than one feature requires a model of relationship between the supervised process outputs and the recognized signal features to be used. Empirical models, most frequently based on artificial intelligence methods, are used nearly exclusively for this purpose. Primarily, the required labour intensity, as well as the ability of generalization and updating, determine the choice of the model type.

Conclusions followed from the presented literature survey and the theoretical analysis were experimentally verified.

The grinding tests were carried out on a modified cylindrical grinding machine equipped with adequate control and measurement units. The monitoring equipment consisted of units for the measurements of all grinding force components, vibration, and acoustic emission signal. Moreover, three special measuring units were used for the process state assessment. The first of them was an on-line workpiece diameter and out-of-roundness sensor. The second one was for measurements of macro-geometry (waviness) of the grinding wheel cutting surface and the third one was a unit for measurements of the WCS profile (topography).

A qualitative assessment of the usefulness of selected process quantities for cylindrical plunge grinding supervision was the purpose of the grinding tests. With this end in view, and based on the accomplished measurements, the effective methods of signal processing allowing a determination of a set of features for a reliable multicriteria assessment of the process state and results were searched for. The features were compared with the results of measurements of quantities directly characterizing the following process results; parameters of the grinding WCS profile, roughness and waviness of the workpiece. The last measurements were performed in an off-line mode. As a result of this, the determination and verification of the relationships between those two groups of quantities and a qualitative assessment of the usefulness of the selected features for process supervision were possible. Feature selection and the quantitative assessment of the selected features were performed simultaneously with process state and results classification.

An AE sensor with a wireless transmission of the signal was mounted on the face of the grinding wheel spindle. This sensor allowed measurements of the AE signal with a frequency up to 1MHz to be recorded in the form of a raw signal or its root mean squared (RMS) value. Measurements of vibration signal in the range up to 10 kHz were carried out with the use of sensors mounted on the tailstock centre. Changes in oil pressure inside pockets of hydrostatic spindle bearings were utilized for the measurements of the grinding force components.

During the tests the workpieces made of 38HMJ steel hardened to 53 HRC were ground using a 38A80KVBE grinding wheel. The range of grinding parameters applied during the tests exceeded the acceptable working area so that the diagnosis of phenomena as process limitations would be possible. To achieve this purpose, a specific material removal rate equal to 1, 2 and 3 mm^3/mms, a speed ratio equal to 60, 100 and 400 and a wheel speed equal to 40 m/s were used. The tests were carried out in series. Each series represented a sequence of grinding cycles completed for a single wheel life period with a given combination of the specific material removal rate and the speed ratio. Depending on the applied parameter combination, the single wheel life period consisted of 8 to 12 grinding cycles that were 400 to 600 mm^3/mm of the specific material removal.

The force components, vibration and the RMS value of the acoustic emission signals were recorded during each grinding cycle. The vibration and AE RMS signals were recorded in segments of 2048 samples every 1 second in a time-sharing mode with the sampling frequency equal to 10 kHz. These segments were linked into 16384 sample packages for analysis. The segments of 16 kB AE raw signal samples were recorded every second grinding cycle with a sampling frequency of 1 MHz. It allowed the raw AE signal to be analyzed in segments of 10000 signal samples. The grinding forces were recorded continuously with a sampling frequency equal to 500 Hz.

After every second grinding cycle, the profile and waviness of the WCS along the wheel circumference were measured with the aid of a specially designed sensor based on the Carl Zeiss Jena ME10 roughness measuring head. An LVDT displacement transducer with a leuco-sapphire crystal tip was adapted for the WCS waviness measurement. The roundness and waviness of workpiece and the workpiece roughness were also measured after every second grinding cycle.

Software prepared by P. Lajmert was used for grinding machine control and data recording in the binary form with the exception of the raw AE signal. The recorded signals were transformed into text files with the aid of the author's own program. Also, the author's own software package DAQSYSTEM prepared in LabVIEW environment, as well as the STATISTICA software package, were used for a spectral and statistical analysis of the signals.

The software package DAQSYSTEM consists of four modules. The module DAQ is designed for data acquisition with the aid of 3 National Instrument DAQ cards: NI6221, NI6040E and NI5120. This module was not used during the presented grinding tests. The module DATA VIEW is designed for preliminary data analysis on the basis of the chart and sample numerical values of the chosen-for-analysis signal. The module FFT is a program for a signal spectral analysis of selected process quantity signals representing the whole grinding wheel life period with the aid of DFT. The module WA is designed for a wavelet packet analysis of the signals.

The measurements of the grinding WCS micro-geometry were performed perpendicularly to its envelope in the parallel direction to the grinding speed vector along one trace on the wheel width. The measurements were repeated three times along the measuring length, equal to at least 25 mm with the radial resolution of 1/15 µm and the peripheral resolution of 0.01 mm. Thus each single measurement consisted of at least 2500 measuring samples. The Abbott's bearing ratio curve (BRC) and its special parameters were used to describe the grinding wheel micro-geometry. The BRC, determined along an assumed measuring length, is replaced by a linear description which divides the whole height of the measured profile into the three characteristic quantities: the core roughness depth R_k, the reduced peak height R_{pk} and the reduced valley depth R_{vk}. The reduced profile height R_{Ges} is equal to the sum of all three parameters. The measurements of the WCS BRC parameters revealed that it is not their absolute values but the trend of their changes which allows the assessment of the WCS micro-geometry state to be better recognized.

The measurements of the WCS waviness were performed in the same manner as its micro-geometry measurements, but along the whole circumference of the wheel and thus ensuring the values of at least 7500 samples every 0.2 mm. A spectral analysis of the measurements allows an assessment of waviness and out-of-roundness of the wheel to be performed. The harmonic components appearing in the measured profiles correspond to different frequencies of waves on the wheel circumference. The highest amplitudes appeared in the range of 10-50 waves per wheel circumference. Thus, the average amplitude of the DFT power spectrum of the wheel circumference profile in this range was used as a measure of the WCS waviness. The FFT analysis shows that the WCS waviness, being a result of the chatter regenerative effect on the wheel, is a good indicator of the WCS macro-geometry state.

The measurements of the workpiece surface roughness and its out-of-roundness and waviness errors were performed for a direct assessment of the workpiece quality after grinding. The roughness measurements show that, in all cases, grinding wheel wear causes an increase of roughness of up to 40%. Much higher values of roughness have been recorded for grinding tests with the occurrence of workpiece thermal damage. As in the case of the wheel profile assessment, the power spectrum average value in the range of 10-500 waves per workpiece circumference of the workpiece peripheral profile DFT has been applied as a measure of workpiece waviness. The DFT analysis confirmed that the change of waviness is not a reliable indicator of the wheel workpiece waviness because the waves on the workpiece are cut down by the wheel. A residual waviness on the workpiece is always lower than the chatter amplitude.

Mechanical vibration and the root mean squared value of the EA signal were recognized as useful process quantities for the grinding wheel macro-geometry supervision.

The development of grinding WCS waviness is strictly related to the development of chatter and therefore it can be supervised with the aid of a spectral analysis of the vibration generated during grinding. The signal of mechanical vibration generated during cylindrical grinding can be considered as linear and stationary so it can be analyzed with the aid of DFT. The DFT analysis showed that vibration growths during the grinding wheel life period were similar for all the used grinding parameters sets. A visible growth of the vibration amplitude occurred for the following two ranges of frequencies: 700–900 Hz and 1500–2000 Hz. Based on the performed frequency-amplitude characteristics, it was established that these are frequency ranges which contain the natural frequencies of the workpiece and the grinding wheel headstock unit and they are related to the chatter because the chatter develops around the natural frequencies of the mechanical system. Moreover, it should be noted that the wheel was rotating with a speed around 24 rev/s so a chatter frequency in the range 700-900 Hz causes 27-36 waves on the wheel circumference. This corresponds to the frequency of the waves with the highest amplitude measured on the WCS. In the considered case, vibration also develops in this higher frequency range. A combination of all conditions such as the workpiece shape, the place of vibration excitation on it and the value of the workpiece and wheel headstock natural frequencies also causes a development of chatter in the frequency which is the second harmonic of the workpiece natural frequency.

The changes of the DFT power spectrum average value during the wheel life period in the frequency range of 600–1000 Hz and 1200–2000 Hz for all grinding tests were discovered. They are very alike in their course. After some material volume removal, the amplitudes of vibration start to increase very quickly and following this, when an inflection point is reached, their increase diminishes, aiming towards a more or less constant level of amplitude. The results confirmed a strong correlation between the development of vibration and the wheel macro-geometry state. Vibration monitoring should include all the natural frequencies of the mechanical system.

The nonlinearity and nonstationarity of the signal has a larger significance in the case of an acoustic emission. This results from the features of the phenomena being the source of this signal. Because of this, a wavelet transform was used for the AE signal analysis and also for the vibration signal analysis. The wavelet analysis allows for the possibility of signal nonlinearity and nonstationarity. A Packet wavelet analysis was used with the Symlet 8 wavelet and the 3rd scale level for both signals. These parameters were determined experimentally. The entropy of a given wavelet decomposition, expressed as $\sum \log(w_i)^2$, where w_i – wavelet coefficients, was adopted as a measure of the energy of decomposition. The obtained results indicate that the supervision of the wheel macro-geometry can also be performed with the aid of wavelet packet analysis. However, a detailed analysis of DFT and wavelet transform application showed their diverse dependence on the removed material volume and input grinding parameters. Thus, it would be more desirable to make a decision on the wheel micro-geometry by taking into consideration all the discussed measures.

To measure the strength of the linear relationship between the grinding WCS waviness and the power spectrum average value of vibration, as well as the energy of the applied wavelet decompositions in the both frequency ranges, the correlation coefficients between these variables as functions of the specific material removal were calculated. In most cases the coefficient values exceeded 0.9. The highest correlations between the amplitudes of grinding WCS waviness and the power spectrum average values of vibration were obtained in the range of 1200–2000 Hz. These results additionally confirmed the high usefulness of the applied measures for the supervision of the WCS micro-geometry.

EA signal and grinding force were recognized as useful process quantities for the grinding wheel micro-geometry supervision.

The changes of the normal and tangential forces, their ratio and the grinding wheel cutting ability coefficient K_z were adopted as measures of the wheel micro-geometry state. The coefficient K_z is defined as the relationship between material removal rate and normal force. The dependence of the chosen process features on specific material removal appeared to some extent to be ambiguous. This confirms the conclusions resulting from the force model analysis. The features related to grinding force can be useful in the grinding wheel micro-geometry supervision but in connection with other types of process state symptoms.

The use of the raw AE signal for the grinding wheel micro-geometry supervision can be summarized as follows:

- The raw AE signal is correlated with the wheel micro-geometry parameters.
- Changes occurring in grain distribution on the WCS can be revealed with the aid of the AE signal kurtosis coefficient.
- The DFT analysis of the AE signal does not give satisfactory results because of the nonlinearity and nonstationarity of the AE signal. Wavelet analysis is more suitable for this.
- The effectiveness of the kurtosis coefficient application can be increased by a determination of its value for the AE signal wavelet decomposition in frequency ranges for which the signal presents the highest power.
- The kurtosis of the AE signal is not a good measure of the grinding wheel wear in the case of the workpiece thermal damage appearance.

The AE signal was also experimentally verified for an assessment of workpiece surface roughness. The arithmetic mean, range and coefficient of the variation of this signal RMS value were adopted as signal features. An analysis of the changes of the mentioned statistical features during the wheel life period and the lack of their correlation with the workpiece roughness indicate a poor usefulness for these features for reliable roughness supervision. However, as in the case of the wheel micro-geometry, they can be useful as input components for roughness model building with the aid of artificial intelligence methods.

An analysis of the B_p index values obtained in the carried out grinding tests confirmed their usefulness for the supervision of thermal phenomena effects during the cylindrical plunge grinding of steels. The relatively fast determination of the B_p value (e.g. during grinding with an adequately small workpiece speed) for which burn will appear on the workpiece surface is possible. Following on, this value, suitably (e.g. twice) lowered, can serve as a limit value in grinding supervision. Because the Bp does not, in practice, depend on the grinding wheel wear, its limit value can be determined as a constant for a given combination of grinding input conditions.

The results of the theoretical and experimental research were used for the development of a classifier for the assessment of the cylindrical plunge grinding process state and results. The choice of a method for the building of the classifier results from the grinding process features. Discrete values, expressed as numbers or symbols belonging to a predefined set e.g. {1, 2, 3} or {good, bad} are used for the assessment of such a process state. Because of this, the multicriteria decision problem in the automatic supervision of the grinding process is reduced to a classification problem of process state and results in predefined classes. It is then possible to include the knowledge of an expert into the assessment procedure through the creation of his/her preferences with regard to the assessment of individual process states. Moreover, if decisions on attributing process state to a specific class are made on the basis of rules which explicitly describe the dependency of the individual states on their symptom values, then the diagnosis of the reasons for this state is possible. A number of requirements related to the type and quality of the input data, as well as the manner and possibility of classification results generation, should also be fulfilled.

It is assumed that all of the mentioned conditions can be fulfilled by a new method of multicriteria decision making based on the modeling of relationships between process individual states and their symptoms using rules which are induced from process data. This new method is called Dominance-based Rough Set Approach (DRSA). The DRSA is an extension of the Rough Sets Theory (RST). The DRSA based models tolerate data inconsistency and ambiguity as well as the artificial neural network (ANN) models but they are not “black box” type models. Unlike fuzzy logic, the DRSA does not require the discretization of the data and any previous assumptions about the data e.g. about their fuzziness distribution, but, like fuzzy systems, a data analysis, with the aid of the DRSA, does provide a search for hidden data features and decision making algorithms with the effective tools. The DRSA can be used for feature clustering and selection, data preselection, the detection of nondeterministic relationships, as well as the optimization of decision making processes related to the supervised object. Thus, The DRSA, at least partly, eliminates the drawbacks of ANN and fuzzy systems while preserving their advantages.

In the classical RST the indiscernibility relation is used to compare objects described by certain attributes. This relation is the basis for the construction of a rough set representing a concept called a decision class (e.g. a class of a product quality) by discriminating its lower and upper approximations. The objects which belong without any ambiguity to the considered decision class constitute its lower approximation, while all the objects whose membership to the class cannot be excluded constitute its upper approximation. Hence, the RST is the tool which enables an analysis of inconsistent and ambiguous data.

The main difference between the DRSA and the classical RST is the substitution of the indiscernibility relation by a dominance relation. Use of the dominance relation allows the DRSA to model the preference orders of attribute domains (a kind of domain knowledge) and semantic correlation existing between attributes. The semantic correlation between condition and decision attributes means that improving the value of the condition attribute should not cause a worsening in the value of the decision attribute, if the values of the remaining attributes stay unchanged. In other words, an object x dominating object y on all considered ordinal attributes (i.e. x having evaluations at least as high (good) as y on all considered attributes) should also dominate y on the decision (i.e. x should be assigned to at least as high (good) a decision class as y). This principle is called the *dominance principle* (or Pareto principle).

The DRSA, like classical RST, classifies objects into some number of separated decision classes but these classes are ordered in such a way that the higher the class number the better the class according to their preference. Thus, the idea of a single class is replaced by the idea of a union of classes. So the decision rules in the DRSA are induced from lower and upper approximations of upward or downward unions of classes representing ordered sets of decision classes (the union of classes of “at least good” includes the classes “good” and “excellent” whereas the union of “at most good” includes the classes “good” and “pure”). Additionally, the condition parts of rules generated from continuous attributes are constructed by means of relations “≥”, “≤” and “=” instead of only “=”, which enables a more compact knowledge representation and does not require the discretization of quantitative attributes.

The first step in the framework of the DRSA to the grinding process diagnosis is the preparation of the process data. For algorithmic reasons, the grinding process data set should be represented in the form of a decision table. The columns of the table are labeled by attributes (grinding process features), whereas the rows are labeled by objects (cases of grinding process running). The attributes are divided into condition attributes (features of process variables) and decision attributes (criteria of process evaluation e.g. the workpiece roughness).

The data obtained during grinding tests was used to develop the decision table. The table consists of 78 grinding process cases diversified in respect of the specific material removal rate Q'_w, the speed ratio q and the wheel cutting ability represented by the specific material removal V''_w since the last wheel dressing. Each grinding case was evaluated with the aid of 17 grinding process features which made up the condition attributes set C. Elements of this set are described in the following table:

Attribute	Attribute description
C_1	specific material removal rate Q'_w
C_2	speed ratio q
C_3	specific material removal V'_w
C_4	normal force F_n
C_5	tangential force F_t
C_6	tangential to normal force ratio μ
C_7	index of heat flux density entering the workpiece B_p
C_8	wheel cutting ability coefficient K_z
C_9	EA signal kurtosis
C_{10}	kurtosis of the AE signal wavelet components in the range of 125-187.5 kHz
C_{11}	vibration signal average power spectrum in the range of 600-1000 Hz
C_{12}	vibration signal average power spectrum in the range 1200-2000 Hz
C_{13}	entropy of the vibration signal wavelet components in the range of 1875-2500 Hz
C_{14}	entropy of the EA_{RMS} signal wavelet components in the range of 625-1250 Hz
C_{15}	average value of EA_{RMS} signal
C_{16}	EA_{RMS} signal range
C_{17}	EA_{RMS} signal coefficient of variation

The decision attributes set *D* consists of 5 quantities belonging to important process results. They are listed in the next table:

Attribute	Attribute description
D_1	type of the grinding wheel wear
D_2	state of the WCS macro-geometry
D_3	state of the WCS micro-geometry
D_4	state of burnings and other thermal damages
D_5	roughness of the workpiece according to the R_a parameter

For each of the decision attributes, the decision classes were established which represented different states of the process. The established classes are presented in the following table:

DA	Classes	Class description
D_1	{T, S}	T = dominance of grain flat wear on WCS, S = dominance of grain breakage and pullout on WCS
D_2	{1, 2}	1 = acceptable state of WCS macro-geometry, 2 = unacceptable state of WCS macro-geometry
D_3	{1, 2}	1= fine state of WCS micro-geometry, 2 = unsatisfactory state of WCS micro-geometry
D_4	{1, 2, 3}	1= no burn on work surface , 2 = risk of burn on work surface, 3 = appearance of burn on work surface,
D_5	{1, 2, 3}	1= low R_a, 2 = middle R_a, 3 = high R_a.

The principles of process results assignment to a class are presented in the next table:

Attribute	Principles
D_1	**T** if R_{Ges} increases for next 100 mm^3/mm ≤ 10 %, **S** if R_{Ges} increases for next 100 mm^3/mm > 10 %
D_2	**1** if WCS average amplitude in range of 10-50 waves/WSC circumference < 0.025 V$_{rms}$, **2** if WCS average amplitude in range of 10-50 waves/WSC circumference ≥ 0.025 V$_{rms}$
D_3	**1** if R_{pk} > R_{pk} after dressing or after 100 mm^3/mm, **2** if R_{pk} ≤ R_{pk} after dressing or after 100 mm^3/mm
D_4	**1**if $B_p \le 0.8$; **2** if $0.8 < B_p \le 1.6$; **3** if $B_p > 1.6$
D_5	**1**if $R_a \le 0.83$ µm, **2** if $0.83 < R_a \le 1.25$ µm, **3** if $R_a > 1.25$ µm

The preference orders of condition and decision attributes were also determined. In the DRSA, continuous attributes do not require discretization. However they have to be criteria i.e. attributes with an increasing (gain type) or a decreasing (cost type) preference with respect to accepted criterion. For example the normal grinding force is an attribute with a decreasing preference for the WCS micro-geometry evaluation (the greater the F_n, the worse the micro-geometry state). The preference orders of condition and decision attributes were determined according to available domain knowledge. They are different for individual attributes. If an attribute is not ordered in its whole domain or its preference scale is unknown, a transformation of this attribute into a criterion is needed. This consists of the doubling of the attribute and assigning the increasing preference to the original and the decreasing preference to the doubled attribute. Then the obtained result of rule induction points to which preference is correct. The preferences for most condition attributes (especially for D_1, D_3 and D_4) were assumed to be unknown. The preferences for all decision attributes, except the type of wheel wear (unknown preference), were assumed to be of the cost type.

The induction of rules was conducted using the VC-DomLEM algorithm which is dedicated to the DRSA and generates a minimal set of rules. A rule removal from such a set means that not every case can be classified. All computations were completed with the aid of jMAF software released by prof. Roman Słowinski's research team in what is now Poznan University of Technology.

The sets of minimal decision rules for all decision criteria can be induced with the use of the full set of condition attributes being in the decision table or only with so-called reducts which are subsets of these full sets, determined for individual decision attributes. A reduct is defined as a minimal subset of all condition attributes required to keep the quality of given classification unchanged. The selection of the reducts should be part of the search for a decision rule set classifying the process state in the best possible way. The process state classification then simultaneously serves for the quantitative assessment of signal features used as the condition attributes in the decision table. A basic criterion for feature selection in such an approach is to minimize the risk of a false decision on process state classification. Such a general criterion takes into consideration the quality of influence of the applied classification algorithm and interrelationships occurring among the features.

The rules induction and the analysis of obtained decision rules were conducted by firstly using all the 17 attributes and then by using the subset of attributes distinguished by a process expert - the so-called expert's subset of attributes (ESA), and then by using reducts of the ESA or supersets of those reducts. The role of the expert was fulfilled by the author of the monograph. The procedure was repeated until the best possible prediction performance was achieved. The obtained decision rules were verified through a determination of the classification accuracy index and the error matrix. To estimate the performance of classification the leave-one-out method was applied. This is a variation of the n-fold cross validation test used for data sets with the number of objects smaller than 100.

Using the DRSA, five minimal sets of decision rules were generated. They allow all the example grinding cases to be classified according to the original classes determined for the 5 different criteria of the process evaluation: the state of form of grinding wheel wear, the macro- and micro-wear of the grinding wheel, thermal damage to the workpiece surface layer and the roughness of the workpiece surface. They can be also used for the classification of new process cases. The rules are in the form of logic expressions which explicitly represent the knowledge of the cylindrical plunge grinding process and they are able to explain the proposed decisions. The rule model for the grinding wheel macro-geometry state is given as an example in the following table.

No	Conditions	Decision
1	(C_{11} ≤ 0.000052003) & (C_{12} ≤ 0.000057067)	at least 1
2	(C_{11} ≤ 0.00006174) & (C_{17} ≤ 7.29041)	at least 1
3	(C_2 = 400) & (C_{13} ≤ -3709.354539)	at least 1
4	(C_1= 2) & (C_2 = 100) & (C_{11} ≤ 0.000212465) & (C_{12} ≤ 0.000278944)	at least 1
5	(C_{12} ≥ 0.000281637)	at most 2
6	(C_{11} ≥ 0.000219779)	at most 2
7	(C_1 = 3) & (C_{11} ≥ 0.000123433)	at most 2
8	(C_2 = 60) & (C_{11} ≥ 0.000083852)	at most 2
9	(C_{12} ≥ 0.000063081) & (C_{17} ≥ 7.67326)	at most 2

The next table summarizes the model building process giving the classification accuracy for the main stages of this process.

Result	**Decision attributes**				
	Type of WCS wear	**State of the WCS macro-geometry**	**State of the WCS micro-geometry**	**State of thermal damages**	**Work roughness R_a**
Cardinality of classes	S – 54 T – 24	1 – 46 2 – 32	1 – 62 2 – 16	1 – 58 2 – 12 3 – 8	1 – 40 2 – 22 3 – 16
CA for all attributes	93.59%	76.92%	58.97%	98.72%	83.33%
Expert subset of attributes	C1, C2, C3, C4, C5, C6, C8, C9, C10, C15, C16, C17	C1, C2, C3, C11, C12, C13, C14, C17	C1, C2, C3, C4, C5, C6, C7, C8, C9, C10, C15, C16, C17	C1, C2, C3, C4, C8, C9, C10, C15, C16, C17	C1, C2, C3, C7, C8, C11, C12, C15, C16, C17
No. of reducts	324	23	643	197	66
CA for ESA	91.03%	80.77%	62.82%	97.44%	75.64%
Final results with the best CA					
Attribute subset	**C1, C2, C3, C8**	**C1, C2, C11, C12, C13, C17**	**C1, C2, C3, C6**	**C1, C3, C15**	**C1, C2, C3, C7**
CA	**98.72%**	**89.74%**	**80.77%**	**92.31%**	**96.15%**
No. of rules	**6**	**9**	**14**	**9**	**14**

CA – classification accuracy, ES – expert subset.

The induced rule model of the process can be used as a knowledge base of an expert system for the external cylindrical plunge grinding process state evaluation and diagnosis. The DRSA automatically generates knowledge about the process from examples gathered in the decision table or examples of an expert's decisions - one of the most difficult problems in expert system building. Such systems can be expressed as intelligent not only because of the used methodology but also because of the nature of their operation.

DRSA also performs the selection of process features which secure the best possible assessment of the process state and results. For all decision criteria, a decision about the process state should be made by taking into account both process inputs: the specific material removal rate Q'_w, and the speed ratio q, as well as the current value of the specific material removal V''_w. Furthermore, the dependence of: the WCS macro-geometry on vibration features, the WCS micro-geometry on the force components, the thermal damage on the value of B_p and the workpiece roughness on the values of AE_{RMS}, vibration and B_p resulting from the literature study and theoretical analysis were confirmed. Many of the features applied, e.g. all of the raw AE signal features, turned out to be useless for the grinding process diagnosis.

Like all artificial intelligence techniques, the DRSA requires special attention to be devoted to some elements of its procedure. Primarily, the proper assignment of the objects in a decision table to a decision class is important. The next crucial step is the determination of the preference direction of attributes. This has a great influence on the permissible condition parts of rules to be induced. Although the doubling of attributes is a solution for a misleading preference determination, it results in a growing number of attributes which makes the analysis, especially the process of attribute selection, more difficult. The attribute selection process also has a great influence on the performance of the final rule classifier. It should be prediction oriented. In the monograph, the selection process was corrected by the process expert. But the participation of an expert can be an obstacle to the full automation of the feature selection. All of this points to the direction of further research on DRSA application. For example, the use of genetic algorithms in attribute selection can appear to be an effective method of feature selection automation.

The monograph gives a practical basis for the automatic supervision of the cylindrical plunge grinding process. Further work should be aimed at an improvement in measuring methods and the search for new algorithms of signal processing for better process description. The process experimental database also has to be expanded by new workpiece materials, new types of grinding wheels, other grinding parameters and so on. This will allow for more universal and practical classifiers of the process state to be developed.

Concluding, it can be stated that the assumed purposes of the work were accomplished and the proposed thesis is proven.

5. Description of other scientific achievements

Immediately following graduation in 1974, I began work as an academic teacher. From the very beginning, the automation of manufacturing processes was the field of my research interest. I firstly worked on topics devoted to the numerical control of machine tools followed by research on the adaptive control of the grinding process. The doctoral thesis, completed in 1983, and devoted to the modeling of face grinding from the aspect of an adaptive control application was a summing-up of this research. It was an empirical model based on the application of a regression analysis of experimental data.

5.1. Research works in Arizona State University and University of California at Berkeley

In 1986, I was awarded the Fulbright scholarship to the United States and in January 1987 I began my work at Arizona State University in prof. M. C. Shaw's research team. During my 15-month stay in ASU I worked on the problem of tool face temperatures in high speed milling.

The purpose of my research was to determine experimentally the truth of the thesis stating the iIn face milling the maximum tool face temperature can decrease with an increase in cutting speed and a constant arc of tool-workpiece contact. Such a thesis had been suggested by the work of previous researchers. Since temperatures generated during the first few tenths of a second in turning correspond to those in an intermittent milling operation, initial turning temperatures simulate those in face milling. Because of this fact, the tests were able to be performed on a lathe using a broad range of turning parameters and a variety of tool and workpiece materials. To perform the tests I built a cutting temperature measuring setup using the so-called tool-chip thermocouple technique in which a mercury contact provides the means for connecting a recorder with the rotating workpiece. The abovementioned thesis was experimentally tested and found to be false. In no case investigated did the temperature at the exit of the cut appear to decrease with increased speed. The results of this research were published in [AZ1] (symbols in accordance with the list of publications).

Simultaneously I was carrying out intensive literature studies and as a result I took an interest in artificial intelligence techniques and their application to manufacturing process monitoring and diagnostics. Prof. D. A. Dornfeld of the University of California at Berkeley was one of the few researches who worked in this field. I established contact with him and he invited me to his laboratory for the last 3 months of my scholarship. The three months turned out to be too short a period of time to build up the facilities needed for experimental research and therefore I used the stay at Berkeley for preliminary laboratory research on the application of acoustic emission measurements and artificial neural networks to manufacturing process monitoring and diagnostics. However this work was too insufficient for publication.

I used the experience earned in both universities in my further research work at Politechnika Łódzka.

5.2. Research works on the supervision of the external cylindrical grinding process – development of facilities for experimental research

In order to meet all the functions of an automated grinding supervision system it is essential to build a proper hardware setup. It was decided to build such a system on the basis of the cylindrical grinding machine JOTES SWF-25. It was a conventional grinding machine with hydrostatic guideways for the table and the grinding wheel headstock as well as hydrostatic bearings for the wheel spindle so it required many modifications. A step motor with a ball screw was used as a drive unit for the infeed of the grinding wheel. An inductosyn was used for the measurement of the headstock position. The hydraulic drive of the table was equipped with a proportional valve. These changes allowed the infeed, as well as the table speed and position, to be controlled digitally. To measure the signals characterizing the state of the grinding process and its results, a monitoring system with multiple sensors was built. The process monitoring system was equipped with in-process sensors for the normal, tangential and axial force components, vibration, acoustic emission and both the diameter and shape error of the workpiece.

The difference in pressures inside the pockets of spindle hydrostatic bearings was utilized for the measurement of the grinding forces with the use of the differential pressure transducers OT-24. The B&K4384 sensor with the B&K2511 amplifier were applied for the vibration measurement and the Hall element for the power measurement and the B&K8312 sensor with B&K2638 conditioning amplifier for the acoustic emission signal measurement. A set consisting of a step motor with harmonic drive, inductosyn and ELKAN measuring heads was used for the diameter and shape error of the workpiece measurement. The MERA-80 microprocessor controller was used to control and process data from the measuring heads and the MSK modular system with the PSPD-90 microcomputer was used as a recorder of the sensor signals and a controller of the infeed drive.

I was a member of the research team which made all the modifications and my role in this work was related to the design and executive supervision of the infeed drive as well as the development of force, acoustic emission and vibration measuring units. These first pieces of research on the facilities needed for experimental research were made and used for the projects [P3, P4, P6] (symbols of projects in accordance with the point 5.9). The results of the research was described and published in [AZ2, AP3, RK2, RK3, RK5, RK6].

The system was rebuilt after 1998. The MSK modular system was firstly replaced with the PSPD-90 microcomputer and a PC computer equipped with UCNC5 motion controller and NI DAQ boards [P7, P8]. The step motor in the infeed drive was replaced with a brushless DC motor and a linear optical encoder for its position measurement. With my participation, the infeed drive reconstruction was created as part of the projects [P7, P8] and on my initiative, the wireless AE Dittel sensor was additionally mounted on the face of the grinding wheel spindle to measure the AE signal [P7]. All these changes are described in [AP9, AP10, RM3, RM6, RM7].

The next modifications were made from 2001-2007. Among other improvements, the grinding machine was equipped with an off-line grinding wheel surface profile measuring unit. The measuring head and the amplifier of the Carl Zeiss Jena ME-10 roughness sensor were used in this unit. The head was mounted on a special slide attached to the shield of the grinding wheel. The slide allowed a precise positioning of the measuring stylus on the wheel profile. During the measurements, the grinding wheel was driven frictionally by the rotating workpiece. I was responsible for devising the hardware aspect of this unit. All of these recent modifications are presented in [AP14].

At the point, the software so far used for data logging and processing required unification and modernization. Thus, the package DAQSYSTEM was developed in the LabVIEW environment, and briefly presented in the monograph submitted as my main scientific achievement, was created under my supervision and participation. It was one of the areas within the project [P9] and is described in detail in the report on this project. DAQSYSTEM is also utilized by me in teaching.

5.3. Research works on supervision of external cylindrical grinding – structure of the supervision system

To develop a reliable supervision system of grinding a suitable structure is required. The structure of the system depends on the assumed functions to be performed and on the methods used for their realization. Thus, I developed and used different system structures for the different systems as proposed by me and they vary with methods used for process modeling and process state classification. Functions to be performed by the system are always the same. Generally it was assumed that it should be an intelligent, flexible, sensor based system which ensures reliable process state monitoring application control in cylindrical grinding and it has to be equipped with reliable and robust sensors. The measured signals have to be the subject of different processing techniques. The monitoring system should possess a feature extraction ability as well as an ability for the automatic selection of their best configuration. It requires the implementation of self-learning strategies from the acquired data to build a model of relationship between the selected features and the observed process state variables. Moreover, the possibility of a representation of the knowledge acquired by the system in a human comprehensible form would be a valuable property**.**

The first proposed approach to the development of such a system structure was presented in [RK1, RK4, RK6, RK7, AP2]. The next was based on the assumption that specific functions of the system would be different during the succeeding stages of the grinding working cycle and they depend on limitations applicable to them. 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. A number of control actions were assumed in the decision process on the process state. The values of the features related to the particular sensor signal for each of the proposed actions have to be estimated by system learning based on domain knowledge and experimental results. When estimating the features, an appropriate criterion for process quality evaluation must to be considered. Such a functional structure of the supervision was first proposed for the systems described in [AP2] and next, after some improvements, in [AP3, AP5, AZ2, RK8, P4]. This type of system structure is most suitable for rule based systems. A modified version was applied in my monograph.

Another approach to the system structure is presented in [AZ3, RM1, RM2, RM3, RM7, RK12, RK13, RK14, P6]. This structure is designed for a system which supervises only a single grinding process disorder - wear of the grinding wheel. In such a case, feature selection, model building and decision making tasks are made automatically by succeeding artificial technique procedures.

The next approach, presented in [AP9, AP11, RM3, RM6, RM7, P7], is an extension of the previous structure to a multilevel system for process monitoring, diagnosis and control, including adaptive control and preliminary optimization. The previous structure can be applied as a part of this one.

In [RM7], I proposed a hybrid system for process optimization. This was devised within the project [P9] which was carried out under my management. The system has four knowledge sources. In a case-based reasoning module a knowledge base selects grinding initial conditions. A neural network performs the optimization of the grinding cycle, taking into account the workpiece quality parameters and grinding time. The next module is an adaptive controller. The user can make a final verification of the selected conditions.

5.4. Research works on supervision of external cylindrical grinding – application of neural networks and fuzzy logic.

Within the project [P6] I developed a neuro-fuzzy system in which a neural network performs feature selection and a neuro-fuzzy module performs a model building procedure as a base for the classification of the grinding wheel wear using fuzzy reasoning algorithm. This consists of a few functional modules.

A data acquisition module collects grinding experimental data obtained during on-line measurements of vibration, acoustic emission and grinding forces.

A feature selection module reduces the number of signal features using a FFBP neural network. The structure of the network was optimized by applying a weight pruning method. From the viewpoint of the further procedure of fuzzy model building, the reduction of the model inputs number has a crucial meaning. The reduced number of inputs allows models with a reasonable number of reliable fuzzy rules which represent knowledge about the process to be built in a more understandable form. Also, the application of fuzzy rule automatic generation and their parameter optimization becomes more effective for the reduced number of inputs to the model. The neural network used for the feature selection task can also be a measure to model the grinding wheel wear.

The next module builds a fuzzy model of the grinding wheel wear in the form of a set of fuzzy production rules with optimized parameters of their linguistic variables. A neuro-fuzzy algorithm for feature integration and model building task was applied. In this algorithm, the fuzzy inference procedure has a neural network structure, which allows the use of the error back propagation to optimize the fuzzy model parameters. The structure and parameters of such a system have a physical meaning so an *a priori* knowledge can be introduced to the system in its initial parameters.

The fuzzy reasoning module performs the function of grinding wheel wear diagnostics. It recognizes the state of grinding wheel wear through firing of the fuzzy model production rules for given crisp inputs.

The NEURALWARE software package was used for the neural network building and optimization, whereas software developed by P. Lajmert on the basis of the algorithm proposed by Wang and Mendel was used for neuro-fuzzy modeling.

The neuro-fuzzy algorithm appeared be an effective application for fuzzy logic based systems with many input variables - as seen in the case of grinding wheel condition monitoring. However, it should be mentioned that the performance of such systems can be lower than the performance of the system based only on a neural network and the potential for knowledge extraction is limited.

The features of the developed neuro-fuzzy system were discussed and presented in [AZ3, RM1, RM3, RK12, RK13].

Working on the supervision systems for grinding process, I was also interested in the usefulness of the acoustic emission signal for grinding process monitoring. The results of this work were published in [AP4, AP7, AP8].

5.5. Research works on rule based supervision systems for external cylindrical grinding

Diagnostics is one of the applications areas of knowledge based expert systems. They are very suitable for diagnostic tasks which can be easily transformed into processing a set of rules of the type: IF (condition) THEN (action). However, a knowledge expressed only in definition, theorems, rules and mathematics formulas often appears not to be sufficient for problem solving on an expert level. In the case of the systems for engineering diagnostics, there is the additional problem of a limited input data. Taking into consideration the above conditions, I developed and presented in [AP6] an expert system for the off-line diagnosis of the results of the cylindrical plunge grinding process. The off-line diagnosis means that the input data does not come from measurements made during the grinding process. Therefore, the aim of the presented expert system was to supplement the sensor-based on-line monitoring systems.

The main source of the expert knowledge for the system was a table of typical workpiece surface defects and their causes. This knowledge can be transformed into a set of rules. Because this type of knowledge is usually incomplete, it is impossible for the system to infer only on a basis of a logical analysis of this type of knowledge. Therefore, the inference engine of the system has to use an approximation procedure in modeling development. In the proposed system, this approximation is realized through the consecutive examination of probable conditions of given defect appearance.

First, the paper presents an idea of knowledge base which is appropriate for an expert system which is developed only with the aid of universal programming languages what gives no limits on the design process but is very time- and labour-consumming. Next, a system developed with the aid of the PC-SHELL shell system is presented. A comparison between the both described approaches is presented.

In the case when the PC-SHELL was used to build the system, the knowledge had to be represented through a set of distinct rules and additional decisive questions could not be put to the user. The effectiveness of the PC-SHELL utilization would be higher if the OR logical operation could be used in the knowledge rules. The number of needed rules would then be much smaller. In both cases, the correctness of the limit values inserted in the tables as a database plays a crucial role for the expert system quality.

As mentioned earlier, from 2004-2007 I was the manager of the project [P9] which was devoted to the development of an artificial intelligence hybrid system for the optimization of cylindrical grinding conditions. Within this project, I worked out a knowledge base for the selection of the grinding wheel characteristic, the initial grinding parameters and the dressing parameters in external cylindrical grinding. The base can be made available to users locally or through the web. For the lack of access to other sources of knowledge, different published catalogs of standards, research reports and grinding wheel producer’s materials were used to build this knowledge base. The user selects the process initial parameters, answering questions from the program. The selection of parameters is made on the basis of many criteria. The grinding wheel is selected according to: workpiece material features, required workpiece quality parameters, size of grinding allowance, type of grinding operation, size of contact area between the workpiece and the wheel, type of cooling, peripheral speed of the wheel and grinding machine features. The algorithm of grinding parameters selection consists of: the determination of workpiece material machinability, determination of allowance size for single stroke, selection of workpiece peripheral speed, selection of infeed and feed velocity, selection of spark-out parameters and selection of wheel dressing parameters. Moreover, the knowledge base contains a guide to an explanation of the different problems related to grinding process execution.

Commonly known and accessible free software APACHE server, PHP language and MySQL system were used for this knowledge base development. The base is described in [RM8].

All my experience in rule based systems building was utilized in my monograph. The application of the DRSA methodology allows a rule model for the 5 different criteria of the plunge grinding process evaluation to be built. The model was automatically induced from examples gathered during experimental tests and can be used as a knowledge base for an expert system for on-line process state evaluation and diagnosis. The DRSA also performs a selection of process features which secure the best possible assessment of process state and results. Thus, it is a new, effective approach to a knowledge based system application in grinding process supervision.

5.6. Other research works on the supervision of external cylindrical grinding

Within the preparation for the monograph, I published results of research on:

- Application of bearing ratio curve parameters to evaluation of grinding wheel wear [AP12].
- Grinding wheel state monitoring through wavelet analysis [RM9].
- Chatter monitoring in grinding wheel macrogeometry supervision [RM10].
- Performance evaluation of the selected process variables in plunge grinding automatic supervision [AP13, RK15].
- The results of the work are discussed in detail in the monograph.

5.7. Research works on the supervision of cylindrical traverse grinding

From 1998-2000, I was the manager of the project [P7] which was devoted to the development of the automatic supervision of cylindrical traverse grinding. I worked out an analysis of Verkerk's model of grinding wheel wear in an axial direction during this type of grinding. The purpose of this analysis was to find out whether it is possible to determine the speed of this wear during grinding through the monitoring of some process quantities, especially grinding force. The results of this analysis were published in [RM4, RM5, RK11].

5.8. Research works on motion planning for mobile robots

From 1994-1995, I participated in the MESSINA (Mobile Execution and Surveillance Systems Intended for Nuclear Application) European project, the scope of which was the motion planning of mobile robots with holonomic and nonholonomic constraints [P5]. The main objective was the development of a method for complex motion planning including the maneuver generation of a complex vehicle in a cluttered environment with an adequate level of autonomy. The results of the work on the project were published in [RK9, RK10]. My contribution to this work included domain literature survey and analysis, the kinematical analysis of robot structures, environment planning and the editing of publications.

5.9. Leadership and participation in international and national research projects

P1 – Applied project for Łódzkie Zakłady Wyrobów Metalowych WIZAMET
„Technical documentation of a prototype and 5 pieces of automatic machine for razor wrapping”
Participant, 1985 -1986.

P2 - Applied project for Fabryka Szlifierek FUM-PABIANICE
“Automation of the slide feed and the grinding wheel infeed for the SP-30 surface grinding machine”
Participant, 1985 -1986.

P3 – Research project CPBP 02.04.
“Diagnostics of the external cylindrical grinding process (including ACO)”
Participant, 1986 – 1991 (with a braek 1987 -1988).

P4 - Research project KBN no. PB 0446/S1/92/03
„Multisignal diagnostics and shape error minimalization in the external cylindrical grinding process”
Participant, 1992 – 1994.

P5 - European Commission research project MESSINA (Mobile Execution and Surveillance Systems Intended for Nuclear Application) nr F12T-CT92-0029/ERBCIPDCT930444
”Complex Motion Generation for Multibody Mobile Robots”
Participant, 1994 -1995.

P6 - Research project KBN No. 7 T07D 047 08
„Application of the fuzzy set theory to the grinding process control and diagnostics”
Participant, 1995 – 1998.

P7 - Research project KBN no. PB 242 T07 98 14,
“Automatic supervision of the cylindrical traverse grinding process”
Supervisor, 1998 - 2000.

P8 - Applied project for KBN - agreement no. 18 I8 187 18 99 B,
„A numerically controled feed drive for grinding machines”
Participant, 1998 – 2000.

P9 - Research project KBN no. PB 4 T07D 014 27
„A hybrid artificial intelligence system for optimization of external cylindrical grinding”
Supervisor, 2004 – 2007.

P10 – Key research project of the Innovative Economy Operational Programme. cofinanced by the European Regional Development Fund „Modern material technologies used in aerospace industry”, Task ZB1.1 „An inteligent system for grinding of difficult for machining aerospace alloys”
Participant, 2009 - 2013 (scheduled completition).

5.10. Participation in international and national scientific conferences

1. International Conference „Adaptive Control in Production Engineering AC’85”, Rydzyna, October 1985, paper RK1.
2. Conference “Advances in tool materials for high speed machining”, Scottsdale, Arizona, USA, March 1987.
3. X Annual Conference on Industry-University Collaboration, College of Engineering, University of California, Berkeley, USA, March 1988.
4. X Workshop on Abrasive Machining, Wrocław, September 1987, paper RK2.
5. XII Workshop on Abrasive Machining, Poznań September 1989, paper RK3, RK4 i RK5.

6. II Workshop on Supervising and Diagnostics of Machining Systems, Karpacz, March 1990, paper AP1.
7. International Conference „Monitoring and Automatic Supervision in Manufacturing - AC’95”, Rydzyna, September 1990, paper RK6.
8. VI Conference “Abrasive Machining, Production Engineering, Machine Tools, Cutting Tools, Measurements”, Łódź, November 1991, paper RK7.
9. Conference „Production Engineering Fundamentals” Wrocław, 1991, paper AP2.
10. III Workshop on Supervising and Diagnostics of Machining Systems, Karpacz, March 1993, paper AP4.
11. CIRP General Assembly, Edynburg, Wielka Brytania, August 1993, paper AZ2.
12. International Conference „Computer Integrated Manufacturing”, Zakopane, May 1994, paper AP5.
13. International Conference „Monitoring and Automatic Supervision in Manufacturing - AC’95”, Warszawa, September 1995.
14. VII Workshop on Supervising and Diagnostics of Machining Systems „Thermal Behaviour, Intelligent Diagnostics and Supervising of Machining Systems”, Karpacz, March 1996, paper AP6.
15. International Conference „Computer Integrated Manufacturing”, Zakopane, May 1996, paper RK9.
16. Project Final Symposium TELEMAN/MESSINA, Karlsruhe, Niemcy, czerwiec 1996, presentation of the final report „Complex Motion Generation for Multibody Mobile Robots” (unpublished).
17. XIX Workshop on Abrasive Machining, Łódź, September 1996, paper RK8.
18. XX Workshop on Abrasive Machining, Poznań – Błażejewko, September 1997.
19. Conference „Production Automation 1997: Innovations in Technology and Management”, Wrocław, December 1997.
20. IX Workshop on Supervising and Diagnostics of Machining Systems „Manufacturing Simulation for Indastrial Use”, Karpacz, March 1998, paper AP7.
21. International Conference “Advances in Production Engineering – APE’98”, Warsaw, June 1998, paper nr RK13.
22. International Conference „Monitoring and Automatic Supervision in Manufacturing - AC’98”, Warsaw, August 1998, paper RM1.
23. XXI Workshop on Abrasive Machining, Warsaw, September 1998, paper RK12.
24. KBN Research Projects Symposium, Radom, December 1998, paper RK11.
25. International Conference ”Computer Integrated Manufacturing CIM’99”, Zakopane, March 1999, paper RM2.
26. XXII Workshop on Abrasive Machining, Gdańsk – Jurata, September 1999.
27. KBN Research Projects Symposium, Warsaw, January 2000.
28. XI Workshop on Supervising and Diagnostics of Machining Systems „Design and Optimization of Intelligent Machine Tools”, Karpacz, March 2000, paper AP9.
29. XXIII Workshop on Abrasive Machining, Rzeszów – Myczkowce, September 2000, paper RM3.
30. Conference „Production Automation 2000: Knowledge – Technology – Progress”, Wrocław, December 2000, paper AP10.
31. XXIV Workshop on Abrasive Machining, Kraków. September 2001, paper RM5.
32. Conference „MANUFACTURING M'01”. Contemporary Problems of Manufacturing. Poznań, November 2001, paper RM4.
33. International Conference „Computer Integrated Manufacturing”, Zakopane, March 2001, paper RM6.
34. European Commission FP6 Workshop on “New Production Processes and Machine Tool Technologies”, Leuven, Belgium, October 2002. Presentation of ”Expression of Interest – An intelligent system for grinding process control and optimization” as a proposal for Integrated Project in FP6 (unpublished).
35. Second International CAMT Conference “Modern Trends in Manufacturing”. Wrocław, February 2003, paper RM7.

36. Conference „Production Automation 2003. Science - Knowledge – Innovations", Wrocław, December 2003, paper AP11.
37. XXVII Workshop on Abrasive Machining, Koszalin, September 2004, paper AP12.
38. XXXI Workshop on Abrasive Machining, Bochnia, September 2008, paper RM8 i RM9.
39. Periodic Conference on the ZB1 task of the Key Project [P10], Warsaw, November 2009, paper "Theoretical and experimental basics for the intelligent grinding process supervision" (unpublished).
40. XXXIII Workshop on Abrasive Machining, Łódź, September 2010, paper RM10.
41. Periodic Conference on the ZB1 task of the Key Project [P10], Lublin, listopad 2010, paper "Chatter monitoring in grinding wheel macrogeometry supervision" (unpublished).
42. 3rd International Conference Manufacturing 2010. Contemporary Problems of Manufacturing and Production Management, Poznań, November 2010, paper RK15.
43. Periodic Conference on the ZB1 task of the Key Project [P10], Łódź, June 2011, paper "Grinding process supervision using the rough set theory" (unpublished).

5.11. Participation in European Programmes

European Commission research project MESSINA (Mobile Execution and Surveillance Systems Intended for Nuclear Application) nr F12T-CT92-0029/ERBCIPDCT930444
"Complex Motion Generation for Multibody Mobile Robots"
Participant, 1994 -1995.

UE Project co-financed by the European Regional Development Fund "Adaptation of educational infrastructure of Mechanical Engineering Faculty at Polotechnika Łódzka to the forecasted needs and expectations of the Łódź Province labour market through the purchase of equipment for modern teaching methods".
Participant, 2009 – 2011.

Key research project of the Innovative Economy Operational Programme co-financed by the European Regional Development Fund „Modern material technologies used in aerospace industry", Task ZB1.1 „An inteligent system for grinding of difficult for machining aerospace alloys"
Participant, 2009 - 2013 (scheduled completition).

UE Project co-financed by the European Social Fund "Automatist – Robotician – a key profession of the 21st century", the ordered major at the PŁ Mechanical Engineering Faculty.
Tutor, 2011-2014.

5.12. Foreign and Polish scholarships and trainings

Arizona State University, Phoenix, USA
Fulbright Scholarship
01.1987-02.1988

University of California, Berkeley, USA
Fulbright Scholarship
03.1988-05.1988

Universite Libre de Bruxelles, Belgia,
Realization of the MESSINA project
4 a few days' working visits from 1994-1995.

5.13. Prepared expertises

I was an expert in the field of mechatronics in the project „Technological Foresight for Łódź Region - LORIS WIZJA”, from 2007 – 2011.

5.14. Received awards and honourables

The Silver Cross of Merit – 2003.
The Silver Honourable Distinction of Polish Society of Mechanical Engineers – 2010.
The Golden Medal for Long Standing Service – 2011.
The Award of PŁ Rektor for achievements in research, teaching, organizational work – about 20 awards.

Łódź, 10.09.2012