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MEASURING & CONTROL SYSTEMS IN INDUSTRIAL DIE FORGING PROCESSES

SYSTEMY KONTROLNO-POMIAROWE W PRZEMYSŁOWYCH PROCESACH KUCIA MATRYCOWEGO*

The paper presents portable measuring & control systems, designed and built by the authors, and their application to the analysis of two industrial processes: the precision hot forging of CV universal joint casings in closed dies in the crank press (GKN Driveline Oleśnica) and the forging of concrete slab carrying handles in a TR device in the eccentric press (INOP Poznań). The systems enable the measurement, archiving and analysis of forging force-time/displacement traces correlated with tool temperature, as well as the measurement of production speed and the quantity of produced forgings. Recently an acoustic emission (AE) signal registration capacity has been incorporated into the system to investigate the changes occurring during the forging process, especially progressive tool wear. The information obtained in this way is to be used to improve the operating conditions of the forging presses and to optimize the whole forging process by means of CAD/CAM/CAE software based on FEM. The measuring & control systems consist of an industrial computer (comprising a real-time controller, a multi-speed measurement card, RAM memory, large capacity hard disks and a set of amplifiers and transducers) and sensors (force, displacement, pyrometers, thermocouples, linear and angular encoders, accelerometers and AE). Two applications (based on LabView) have been developed for each of the systems. One of the applications is installed on the industrial computer and is used to control the system as well as to record and process the voltage signals received from the individual sensors. The other application enables the analysis of the processed signals.

Keywords: *portable measuring and control systems, industrial forging processes.*

W pracy przedstawiono zastosowania autorskich, przenośnych systemów pomiarowo-kontrolnych do analizy dwóch przemysłowych procesów: kucia na ciepło obudowy przegubów homokinetycznych na prasie korbowej w matrycach zamkniętych (GKN Driveline Oleśnica) oraz kucia zaczepów do przenoszenia płyt betonowych na prasie mimośrodowej w przyrządzie TR (INOP Poznań). Zbudowane przez autorów systemy pozwalają na pomiar, archiwizację i analizę przebiegów sił kucia w funkcji czasu/przemieszczenia skorelowane z pomiarem temperatury narzędzi, pomiary prędkości procesu oraz ilości wykutych odkuwek. Ostatnio wzbogacono je o rejestrację sygnału akustycznego AE w celu określenia zachodzących zamian podczas procesu a szczególnie postępującego zużycia narzędzi. Uzyskane informacje mają posłużyć również do poprawy warunków eksploatacji pras oraz do optymalizacji całego procesu kucia wykorzystując narzędzia CAD/CAM/CAE oparte o MES. Prezentowane systemy zbudowane są z komputera przemysłowego (kontrolera czasu rzeczywistego, wielokanałowej szybkiej karty pomiarowej, kości pamięci operacyjnej, dysków twardych o dużej pojemności, zestawu wzmacniaczy i przetworników) oraz odpowiednich czujników pomiarowych (siły, przemieszczenia, pirometrów, termopar, enkoderów liniowych i kątowych, akcelerometrów, czujników AE). Do każdego z systemów opracowano po 2 aplikacje (na bazie programu LabView). Pierwsza aplikacja jest zainstalowana w komputerze przemysłowym i służy do sterowania systemem oraz zapisem i przetwarzaniem sygnałów napięciowych uzyskiwanych z poszczególnych czujników. Druga przeznaczona jest do analizy zarejestrowanych sygnałów.

Słowa kluczowe: *przenośmy system pomiarowo kontrolny, przemysłowy proces kucia.*

1. Introduction

Because of their advantages, such as high productivity, small finishing allowances and the very good service properties of the finished products, forging processes belong to the most commonly used product manufacturing technologies [6, 11, 16, 18].

Industrial forging processes are conducted using powerful forming machines, usually presses and hammers. Today most forging shops use their own (often "old") machines, adapting them for the current production [1, 7]. It is seldom that they decide to purchase a new machine dedicated to a specific production. Forging machines and equipment usually have simple

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** measuring & control systems capable of controlling only the maximum forging force, the machine running speed, the number of forgings and the initial temperature of the preforms.

The great number and variety of factors affecting forging process correctness, and their interaction make die forging processes very difficult to analyze. For this reason FEM based CAD/CAM/CAE tools are increasingly often employed to design, analyze and optimize forging processes [4, 8, 9, 13, 14, 15, 17]. For a comprehensive analysis and verification of the results obtained in this way it is often necessary to measure many additional quantities which for various reasons are difficult to measure in the course of forging. In order to improve productivity and the quality of the forgings more precise control of process parameters than the one of which the current control systems are capable is needed [10, 12].

The authors have developed mobile systems for measuring and controlling the principal forging process parameters. The data acquired by the systems will be used to improve the operating conditions of forging presses, to increase the life of forging tools and to optimize the forging process by means of FEM based CAD/CAM/CAE software.

The measuring & control systems were employed in two forging processes: the hot forging of the CV universal joint casing in closed dies in the crank press (GKN Driveline Oleśnica) and the forging of concrete slab carrying handles in a TR device in the eccentric press (INOP Poznań).

2. Multioperation forging of CV universal joint casing

2.1. Process description

The industrial forging of the CV universal joint casing in the GKN Driveline Forge consists of four hot forging operations and one cold forging operation (fig. 1). The forging process has many stages and it proceeds as follows. From a storehouse bundles of metal bars are delivered to a cutting machine where they are cut into proper lengths. Then the preforms are heated in an induction heater to a temperature of about 900°C. It is critical that the process temperature remains constant in order to ensure the proper quality of the forgings. The preforms heated up to the proper temperature are fed into the press where they are deformed in four operations. The high quality of the forging is assured thanks to process stability and on-time control. After leaving the press the forgings are subjected to controlled cooling. Then they go to a shot-blasting machine where they are cleaned of graphite. Subsequently they are transferred to the mechanical working room and to the half-shaft assembly lines.

2.2. Description of measuring & control system

The system was to measure and record the forging forces versus punch path length or time (for the four operations), the temperature of the tools and the preforms. Another aim of the recording was to verify the numerical modelling of the forging process, being run in parallel. The measuring system, designed and built by the authors, was installed on a Shuler industrial press with a maximum press load of 20000kN. The system consists of a real-time controller based on the MPC5200 400MHz processor using the CompactRIO platform. An industrial computer, a reconfigurable chassis with FPGA circuits, and analog and digital input/output measuring cards (fig. 2a) form the whole setup working in tandem with a 1 terabyte hard disk. This configuration enables the high-rate recording of data from the sensors, offering many signal processing possibilities. The computer records data coming from four MP55 extensometer amplifiers (fig. 2b), a ZE-115-M encoder mounted on the press crankshaft and four 5B47 thermocouple amplifiers. The thermocouples are installed in four dies. Thanks to the FPGA circuits the computer can analyze the recorded signals in real time and control the production process. In response to an improper value of one (or several) of the process parameters the other parameters can be changed in order to bring the process back on course.

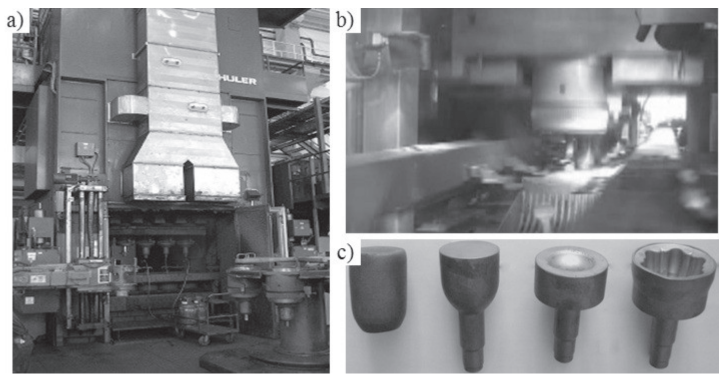

Fig. 1. Forging process: a) crank press, b) side view of press working chamber, c) forgings after successive operations

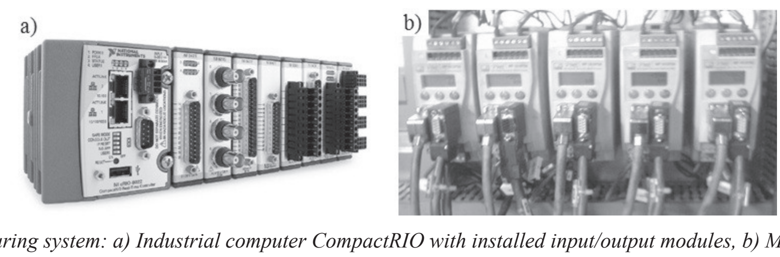

Fig. 2. Measuring system: a) Industrial computer CompactRIO with installed input/output modules, b) MP55 amplifiers

The special system data processing application has filters (whose settings are fixed by the operator) and tools for searching the saved files whereby characteristics fragments of force waveforms or defined events (e.g. an exceedance of a critical force or temperature value in a particular operation) can be easily and quickly found and compared for the particular operations. The program allows one to save the results to text file and to plot graphs in Excel (fig. 3).

2.3. Application of measuring & control system

The measuring & control system was used to analyze the forging forces during the particular operations and at the beginning and end of the forging process (after between 10-20 hours of work) and to compare them with the force waveforms obtained from FEM simulations (fig. 4).

One can notice close similarity between the FEM waveforms and the recorded traces, especially for the characteristic points corresponding to the successive degrees of cross section reduction. Some of the differences may stem from the imperfect tuning of the numerical model due to the different tribological conditions: constant friction coefficient values were assumed in the FEM model whereas in the industrial process the friction forces undergo changes. Research is underway to bring the numerical model as close as possible to the real industrial process, e.g. by increasing the precision with which the friction coefficient is calculated and taking into account the variation of the friction coefficient in the course of the process.

When one examines the traces for the particular operations, recorded over 10-20 hours, it becomes apparent that the maximum "parabolas" occur at the beginning of the process (the steady state after 20 minutes of forging) while the minimum force

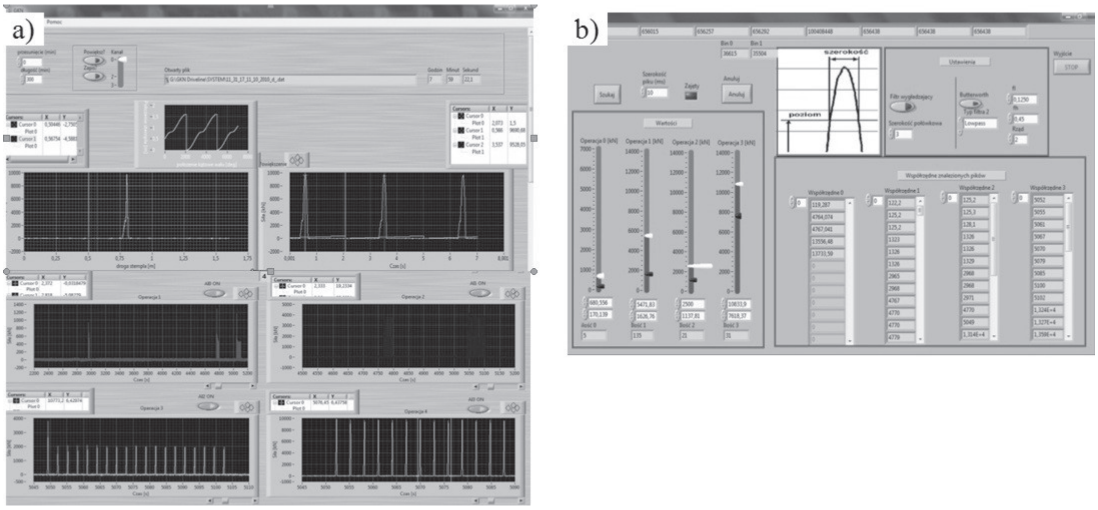

Fig. 3. Measuring system panels: a) main menu, b) menu with filters

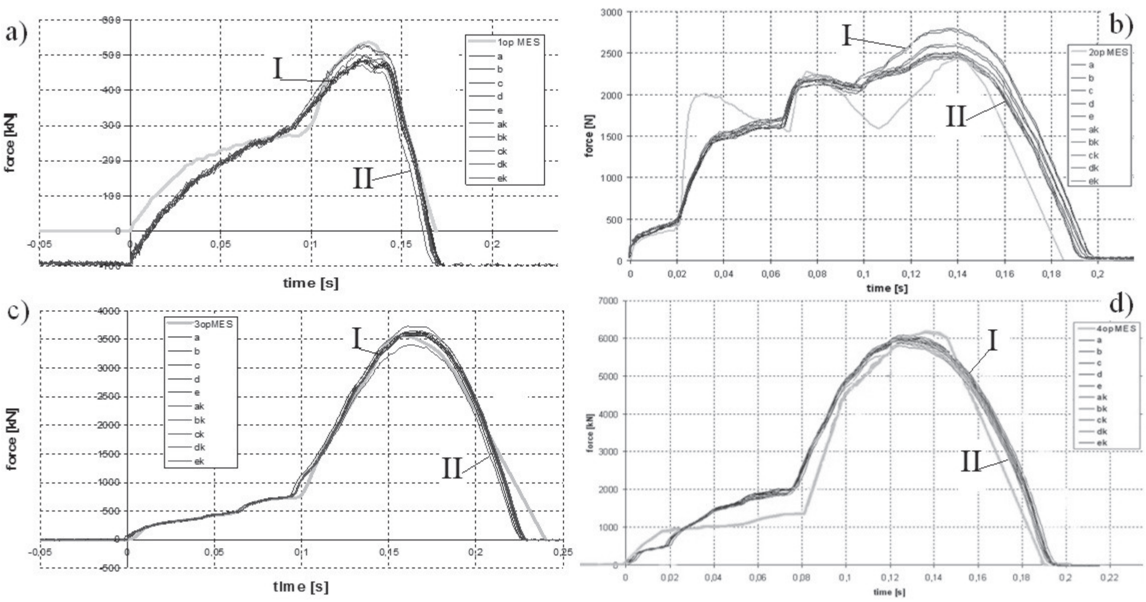

Fig. 4. Comparison of recorded force traces (I – at beginning and II – after 10-20 hours of continuous operation) and waveforms obtained from numerical modelling for: a) 1st forging operation, b) 2nd forging operation, c) 3rd forging operation and d) 4th forging operation

values occur towards the end of the forging process. Assuming that the whole process proceeded without disturbance, the reduction in the force may indicate progressive wear of the tools. This was confirmed by measurements of the post-forging die impressions by means of an optical scanner, statistical analyses of the tool life and microstructural examinations.

The results relating to the influence of the amount of the lubricating medium on tool temperature were found to be interesting, particularly for the industrial press operators. A water-graphite mixture was used in the forging of CV universal joint casings. Special sets of tools each with a hole into which a thermocouple would be inserted (4 mm below the tool surface) had been constructed to measure the temperature of the tools during the forging process.

In this way the real tool temperature during forging was measured. The measurements of real tool temperature by means of the measuring system and the thermocouples inserted through the special groove into the dies shows that many factors affect the temperature of the tools during the forging process (fig. 5a). When the flow rate of the lubricating mixture was doubly increased, the temperature dropped by about 100°C. Stopping the press for twenty seconds resulted in a further drop in temperature by about 100°C. A break lasting for the time needed to produce two forgings resulted in a temperature decrease of 20°C. On the basis of the obtained results the press operators were able to select the optimum lubricant amount and feeding time for the forging process in order to minimize the thermal shock causing the thermal-mechanical fatigue of the tools. The rationalization of the cooling and lubrication conditions ultimately resulted in increased durability of the dies. The measurements made with the thermocouples also served to verify the Finite Element Model of heat exchange for the die in the second operation in the forging of the CV universal joint (fig. 5b). The temperature of the preforms and forgings was also recorded by means of pyrometers and a thermovision camera (fig. 6). Thanks to the investigations also the temperature of rejected preforms was determined.

2.4. Expansion of measuring & control system

The system is to be expanded to include wireless operator panels displaying the actual process parameters and traces of the signals coming from the sensors. Moreover, a system for the remote configuring and control of the computer via a mobile phone and text messages and the Internet is to be added. Two-way communication with the user will make it possible to immediately notify the persons responsible for the proper running of the forging press about any irregularities and to send reports for particular periods.

3. Forging of concrete slab carrying handles

3.1. Description of forging process

The P1.3T carrying handle (an element fixed to concrete slabs for carrying the latter on construction sites) is hot forged from a bar (the temperature of the erforms was about 1100°C) in three operations in a PMS 160B eccentric press (fig. 7a) using a TR device (fig. 7b). Figure 7c shows the final product and the erforms. Figure 8 shows the tools used in the 2nd and 3rd forging operation. The punches and the die inserts are made of steel WCL and ORVAR SUPREME (WCLV).

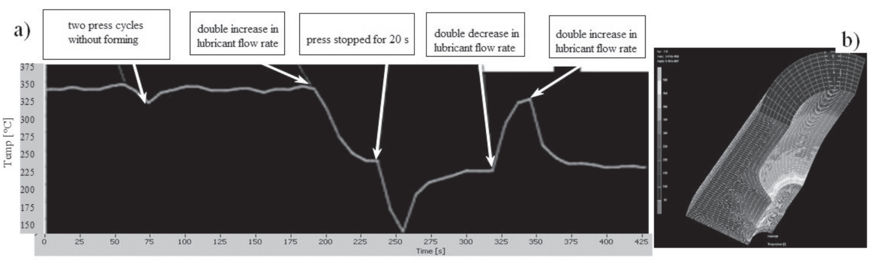

Fig. 5. Variation in temperature during analyzed forging process: a) variation in temperature during forging of CV universal joints , b) thermomechanical FEM model for two operations

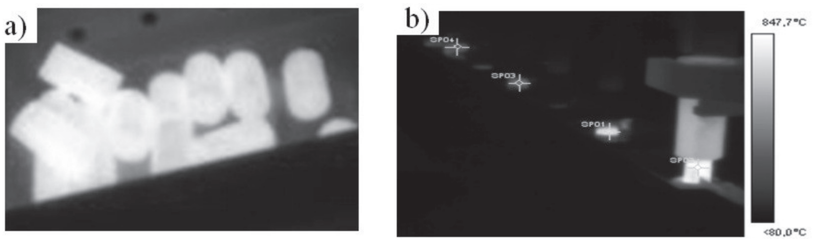

Fig. 6. Temperature measurement: a) rejected preforms, b) thermal photograph featuring heated up die impressions and preform

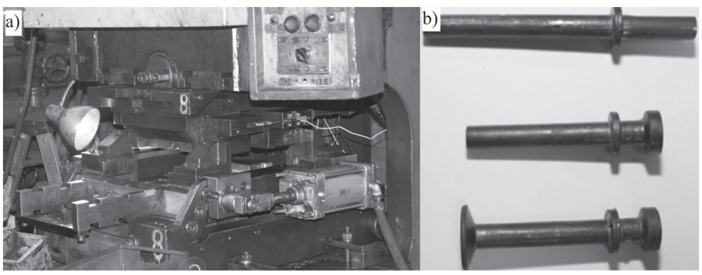

Fig. 7 Stand for forging carrying handles: a) TR device, c) final product with erforms

Fig. 8. Tools for forging carrying handles: a) dies for 2nd operation, b) matrices for 3rd operation, c)2nd and 3rd operation punch with AE sensor

3.2. Description of measuring & control system

The measuring & control system was designed in order to fully monitor the forging of the carrying handle (the measurement of the force versus time and displacement in conjunction with the measurement of the temperature of the tools and the AE signal). The system, designed and built by the authors, was installed on a special laboratory stand (in INOP in Poznań) which made it possible to conduct forging in semi-industrial conditions. The authors decided to use the system for pioneering acoustic emission investigations of tool wear (punches for the 2nd and 3rd operation were fitted with AE probes, fig. 8c). An industrial computer was designed and optimized for such investigations. The computer has a four-core processor, a 2GB fast operating memory, hard disks with a capacity of 2 TB and analog modules working directly with sensors. Four sensors are connected to the computer: a temperature sensor (a type K sheathed thermocouple, d = 0.5 mm) placed in the punch, a position sensor (mounted on the forging device), a sensor (K Nordic Transducer) registering the upsetting force and a broadband acoustic emission sensor (VS45-H Vallene) registering acoustic emission in a band of 20-450 kHz. The latter sensor is connected to an AEP3 preamplifier (Vallene, fig. 9b) with a configurable amplification of 35-49 dB and a band-pass filter with selectable characteristics.

The acoustic emission phenomenon is commonly used in on-destructive testing. The elastic wave generated as a result of a local dynamic change in the energy state, caused by, for example, a breach in the structure of the material can be registered on its surface by an acoustic emission sensor. The range of the generated frequencies is quite wide, extending from tens of kilohertz to megahertz [2, 3, 5, 10]. Piezoelectric AE sensors can register elastic waves and convert them into electrical signals. By using several AE sensors and analyzing the time of arrival of the elastic wave at the successive sensors one can determine the place from which the wave was emitted (fig. 10).

The computer supervising application analyzes the acoustic emission signal in real time. Recording on the hard disks starts when the voltage received from the AE circuit exceeds the set threshold and ends when the voltage falls below this threshold. Also a certain time before and after the event is included. Thanks to this solution the whole available information can be recorded and disk space saved. The duration of each AE event (since the moment the system is activated) is remembered whereby one can later correlate the AE events with the force, temperature and position traces. Thanks to the high computing power it is possible to analyze AE signals and those from the other sensors and make decisions contributing to longer machine life and preventing low quality products from being produced [3].

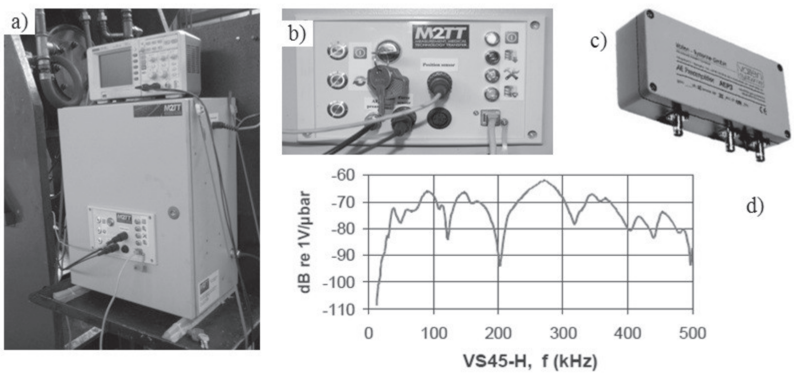

Fig. 9. Industrial computer: a) view of setup, b) front panel, c) AEP3 amplifier and d) characteristic of AE sensor VS45-H shown in fig. 7c

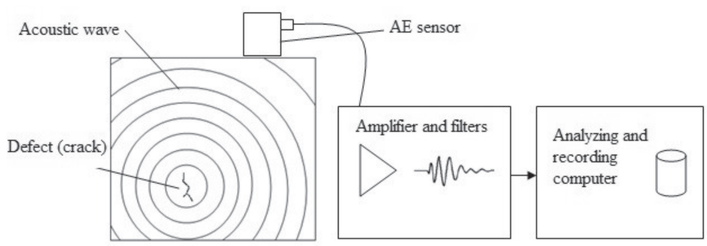

Fig. 10. Dynamically arising defect (microcrack) generating elastic wave which is registered by AE sensor. After it is amplified signal from sensor gets to recording computer

A special application (for system data handling) based on LabVIEW was also developed for the forging of carrying handles. Using its specialist filters one can search the whole saved file and easily and quickly find the defined events (an exceedance of the force in a given operation or a temperature exceedance). The results can be saved to text file. This virtual tool is operated by changing the particular user panels and the positions of the adjusters and switches by means of a keyboard or a computer mouse (fig. 11).

The application offers the possibility to select AE events correlated with force and temperature (fig. 12).

In order to enable a more in-depth analysis of the AE signal, the possibility of determining (for three selected AE events) two highly valuable parameters, i.e. the power spectrum (fig. 13a) and the Wigner-Ville transform, and filtering individual signals was included in the application.

The *power spectrum* allows one to determine the frequency of AE event occurrence for the maximum RMS signal amplitudes while the *Wigner-Ville transform* can be used to estimate the duration of an AE event for specified signal frequencies (e.g. the duration of wave propagation in a fractured tool).

3.3. Application of measuring & control system

Currently research is underway to explore the possibility of applying the measuring & control system to the AE analysis of the punches for the 2nd and 3rd operation since it is for these tools that thermal-mechanical fatigue is observed (fig. 14). The average life of the punches used in these operations is 10-12 thousand units, after which they are renovated (subjected to facing to a depth of 2 mm).

An analysis of the AE signal is difficult and arduous since each production process in real conditions is accompanied by events which may generate an elastic wave in the surroundings of the sensor. Such events are various tool impacts, fluid flows in the machine, vibrations of machine components and so on. In real systems, there are also many other acoustic emission sources besides the above interfering signals. Elastic waves originating in other machine parts and in the workpiece reach the sensor mounted on the surface of the punch. Therefore it is necessary to explore the machine and it surroundings with regard to acoustics. Various solutions, such as band-pass filtration making it possible to register AE signals with a specified frequency range and threshold registration consisting in registering the AE sensor signal only when the voltage exceeds a certain threshold, are used to eliminate interference. For this reason first the AE events (fig. 13) originating from known phenomena and elements (e.g. the interference generated by the operation of the press, the putting of a erform into the die, the closing and opening of the device, etc.) should be identified. After most of the AE events have been identified one can search the signal for new events. Then the broadband sensor is replaced with a resonance sensor. Thanks to the narrowing of signal frequency it is possible to increase the measurement sensitivity and identify the events being symptomatic of microcracs in the punch or of its wear.

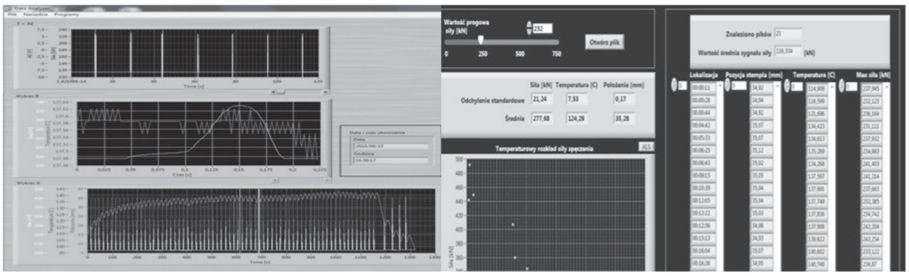

Fig. 11. Front panel of application for monitoring force versus time/displacement and panel for analysis of selected quantities, using signal filtration

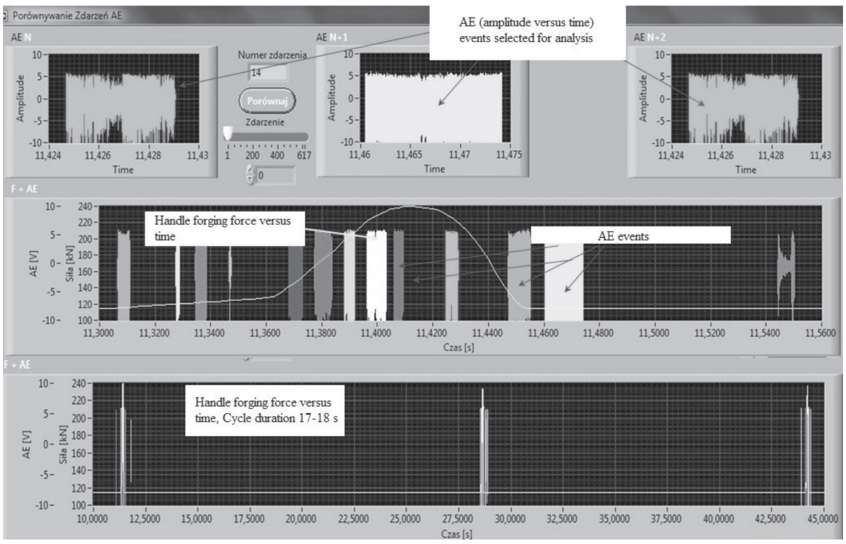

Fig. 12. Main panel for analysis and selection of AE events

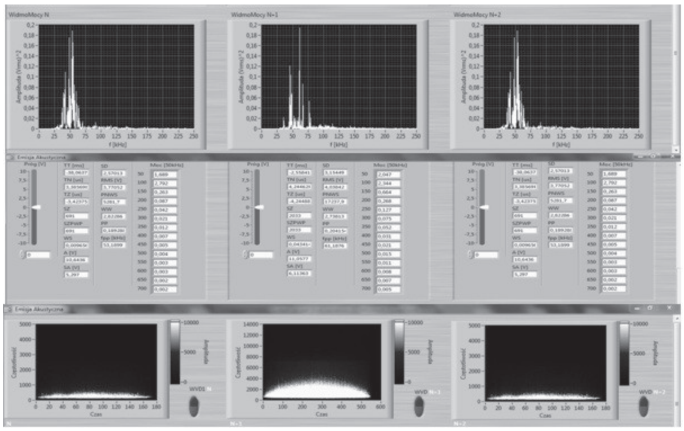

Fig. 13. a) Main application panel for determining signal power spectrum, b) panel for Wigner-Ville transform comparisons using signal filtration

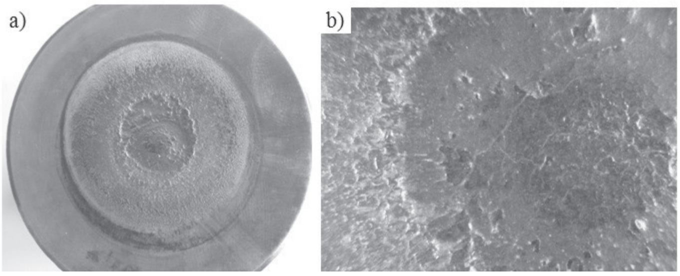

Fig. 14. Worn out punch for taper forging after 14 thousand forgings: a) macro view, b) magnification showing thermal-mechanical wear of most degraded front part of tool

4. Conclusions

The measuring & control systems presented in this paper enable the monitoring of selected parameters of industrial manufacturing processes. In the case of industrial forging the principal parameters are the forging forces as a function of time/displacement, and the temperature of the tools and the preforms. The systems, designed and built by the authors, enable the measurement, archiving and advanced analysis of the above (mutually correlated) quantities. In addition, one of the systems uses AE signal measurement to determine tool wear, which is an innovative solution. The setup consist of an industrial computer and proper sensors. The systems could be created thorough precise study of industrial forging processes (the forging forces, the distribution of strains, the temperature of the tools and the preforms). Their application will contribute to an improvement in the operating conditions of the presses and to a longer life of the tools. A comparison of AE signal measurements and the operating conditions will make it possible to more fully exploit the possibilities of tool materials for specific applications.

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