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Monitoring of Ultraprecision Machining Processes

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New demands are being placed on monitoring systems in the manufacturing environment because of recent developments in machining technology and machine tool design. In-process sensors are used to generate control signals to improve both the control and productivity of manufacturing systems. Numerous different sensors are available for monitoring and controlling the machining environment including force, power, and acoustic emission (AE) sensors. This paper first discusses the requirements for sensor technology for precision manufacturing process monitoring in general. Details are also given about AE and its application for process characterisation and monitoring in ultraprecision machining.

Keywords: Acoustic emission; Manufacturing; Precision; Process monitoring; Sensors

1. Sensor Technology for Precision Manufacturing Process Monitoring

New demands are being placed on monitoring systems in the manufacturing environment because of recent developments and trends in machining technology and machine tool design (high-speed machining, hard turning, “nano-machining”, precision polishing, for example). In-process sensors play a significant role in assisting manufacturing systems in producing products at a cost that is affordable to the mass consumer market. In-process sensors are used to generate control signals to improve both the control and productivity of manufacturing systems [1–3]. Further, consistency dictates more quantitative techniques for process monitoring and control. Incorporation of an in-process sensor requires a high level of engineering confidence in the ability of the sensor to detect the desired process characteristic reliably. Without this confidence, manufacturers justifiably do not apply in-process sensor technology to achieve the higher levels of process productivity they offer.

2. Requirements for Sensor Technology for Precision Manufacturing

Precision machining takes place at submicrometre to nanoscale dimensions (with respect to the uncut chip thickness, for example). At these levels, the machining process, surface finish, and chip formation are more intimately affected by the material properties such as ductile/brittle behaviour or transitions in grinding or single-point turning of brittle materials. These attributes can adversely affect the surface quality or integrity of the machined component. Critical sensor information in precision machining is required mostly for assessing material removal at the submicrometer level, surface finish, and subsurface damage. In addition, for control purposes, it is of interest to track the variation in process parameters such as material removal rate (MRR), tool condition (e.g. wheel in grinding, abrasive in lapping, pad in chemical mechanical polishing) as well as process cycle related characteristics (e.g. contact or sparkout in grinding, air time in machining). These parameters are generally measured using sensors with very high sensitivity and with effective frequencies ranging to several megahertz (MHz). In precision processes, sensor feedback information is critical for higher yields and process throughput. Not surprisingly, sensors have varying applicability depending on the level of precision, displacement, or MRR that is required. Figure 1 [4] shows a diagram of different types of sensor application for different precision levels and control parameters. The boundary represents the approximate range of use with the shaded area emphasising the core application range. Acoustic emission (AE), as illustrated here, shows the greatest sensitivity (with the lowest noise level, i.e. highest signal-to-noise ratio) to the most critical process conditions in precision machining. Precision machining requires attention to a number of work characteristics in addition to tolerance on dimensions and, as the control parameters approach subsurface damage, the conventional sensing technologies from conventional manufacturing are less suitable for these types of “on-line” measurement. When material removal reaches the submicrometre level, essential signal features may be difficult to obtain. Conventional

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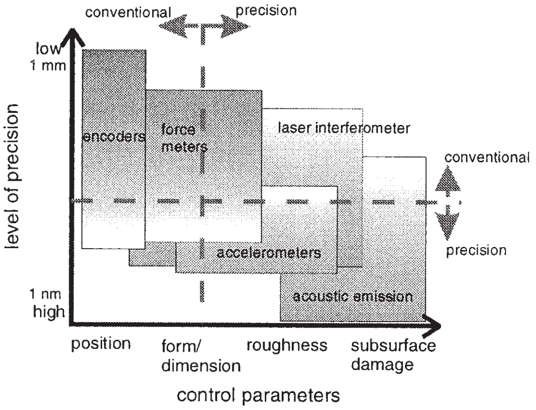

Fig. 1. Sensor application vs. level of precision and error control parameters [4].

sensors such as force and vibration sensors suffer from inaccuracies due to the loss of sensitivity in the extremely high-frequency range, where most of the micro cutting activities are sensed. However, sensors such as acoustic emission exhibit improved response in the high-frequency range, where much of the machine induced low-frequency disturbance signals are diminished and the frequencies from submicrometre-level precision machining activity becomes dominant (see Fig. 2 [5]). Therefore, by using AE sensors, noise from disturbance sources (bearings, slides, etc.) that generally contaminates the desired signal, can be minimised and the micro cutting mechanism can be more effectively monitored.

3. Sensing for Process Characterisation and Monitoring

Over the last decade, the transformation of stand-alone sensors, used primarily as diagnostic devices in a machining process, to sensors as part of an intelligent system for tool and process monitoring and control has occurred most actively. Kegg [6] summarised the history of machine tool applications of sensors, and from the 1950s to the 1980s, these sensors were characterised by application of specific physical phenomena to sensing (thermocouples, piezo crystals, accelerometers, strain gauges, acoustic emission, for example) a specific feature of the process (tool wear, spindle torque, tool vibration, for example). In the late 1980s and early 1990s [7,8], the influence of advanced signal-processing techniques and artificial intelligence was felt in the development and application of sensors and sensing systems. These are often called intelligent sensors. It also lays the groundwork for input to learning schemes, such as neural nets, to capture process knowledge when the process is sufficiently complex to defy clear mathematical modelling. The focus of monitoring is on the machine (diagnostics and performance monitoring), the tools or tooling (state of wear, lubrication, and alignment), the workpiece (geometry and dimensions, surface features and roughness, tolerances, metallurgical damage) or the process itself (chip formation, temperature, energy consumption). All four focus areas are subject to monitoring needs, often with competing requirements for time response or location of sensors. Thus, sensing systems for manufacturing processes must balance a number of options if they are to be effective [8].

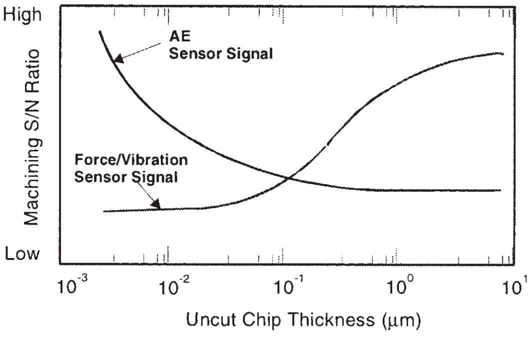

Fig. 2. Signal/noise characteristics of AE vs. force/vibration sensors at different uncut chip thicknesses (a_c), [5].

There is a substantial amount of information in the literature on this topic area – mostly associated with elements of the intelligent machine tool such as control or monitoring. Comprehensive surveys have been published [7,9] covering monitoring and control and sensors for unmanned machining [10]. Prior to that, one of the most complete reviews was by Birla [11]. Other detailed reviews have been published on various aspects of machining and tool/workpiece monitoring. For example, Shiraishi [12–14] reviewed, with numerous examples of applications and specifications on performance, sensors for machine, tool, workpiece, and process monitoring in machining, and Dornfeld et al. [8] reviewed recent sensing techniques with respect to future requirements and intelligent sensors. Iwata [15] published the results of a survey of Japanese machine tool builders on their requirements and preferences on machine tool monitoring, updating some of Birla's information on the same requirements. Finally, with a focus on drilling and tapping, Hoshi [16] reviewed techniques for automatic tool failure monitoring. Finally, Szafarczyk [17] has edited a volume of papers focusing on automatic supervision of manufacturing processes as part of an intelligent machine concept. It includes, perhaps, the most recent comprehensive review of the subject from the perspective of sensors, signal processing, control, process modelling, and integration with product design.

4. Sources of AE in Precision Machining and Signal Processing

Normally, for the most effective diagnostic application in manufacturing, the variation of only the source must be ensured. The reliability of the AE-based diagnostic system is dependent on the designer's ability to consider all of the potential process sources. In many cases, the major factors affecting the AE signal are sufficiently dominant as to render the "second order" effects inconsequential. These sources include material deformation and fracture, contact of tooling with work, phase change of materials, electrical signals or noise, boiling, fluid flow and turbulence, etc. Details of the characterisation of AE sources in manufacturing can be found in a number of papers [18,19]. The use of acoustic emission-based sensing for manufacturing process monitoring is much better documented. Whether or not it has been significantly more successful is not clear, as many applications are so complex that few, if any, competing sensing technologies exist. Traditionally, the bulk of the processes monitored are drilling, milling, and turning. Material deformation-based manufacturing processes have the most potential for acoustic emission-based monitoring. They use either continuous or discontinuous applications of energy to reform or remove material in one way or another. The process-monitoring or product-defect-monitoring scheme is based on either deformation (including friction and rubbing) or fracture derived AE. In some cases, material metallurgical transformation is an AE source. Thus, the appropriate signal processing must be used depending on the type of AE source and whether the source is expected to be steady or non-steady.

Work over the past several years has established the effectiveness of AE-based sensing methodologies for machine tool condition monitoring and process analysis. The problems of detecting tool wear and fracture of single-point turning tools motivated much of this early work. In addition, the sensitivity of the AE signal to the various contact areas and deformation regions in the cutting and chip formation process has led to the analysis of AE signals as a basic tool for the analysis of the cutting process. Investigations of AE from metal cutting have often been limited to 2D or orthogonal machining because of the simplicity of the geometry and chip flow. Principal areas of interest with respect to AE signal generation are in the primary generation zone ahead of the tool where the initial shearing occurs during chip formation, the secondary deformation zone along the chip–tool rake face interface where sliding and bulk deformation occur, and the tertiary zone along the tool flank face–work surface interface. Finally, there is a fourth area of interest, that associated with the fracture of chips during the formation of discontinuous chips. In the milling process (or other interrupted cutting), an additional source of AE is the impact of the tools on the workpiece and the noise due to the swarf motion on the tool and work. Moriwaki [20] reviews other sources of AE from metal cutting.

A number of studies on developing models of AE generation in machining [21–25] have established the principlal role of process parameters, especially cutting speed, in the determination of the r.m.s. energy of the signal. For conventional machining, the friction and rubbing accompanying the cutting are, perhaps, the most significant sources of AE, and are dependent on the cutting speed as well [26]. For precision machining, such as diamond turning, the model-based predictions for AE sources are much more accurate. Iwata and Moriwaki [27] review both event-based (count-rate) and energy-based research on AE from metal cutting.

A basic model for the generation of AE during machining (in this case primary and secondary shear generated AE in orthogonal machining) was proposed by Dornfeld and Kannatey-Asibu [22,23]. The formulation of the model is based on the simplified Ernst and Merchant model of orthogonal machining and builds a dependency of AE energy on material properties such as flow stress, volume of material undergoing deformation, and the strain rate. Incidentally, almost every attempt at modelling acoustic emission from deformation-based manufacturing processes is built on this approach. The model is extended to precision machining by scaling the process with the uncut chip thickness, as will be described in the next section.

5. Applications of AE Sensing in Ultraprecision Machining

5.1 Diamond Turning

The acoustic emission energy and specific energy have been shown to scale with the uncut chip thickness. AE_{rms} is directly proportional to the chip thickness. Figure 3 shows the sensitivity of specific AE_{rms} to uncut chip thickness for both worn and sharp diamond tools for single-point turning. Sensitivity down to less than 0.01 μm is seen [28–30]. Specific energy increases with decreasing uncut chip thickness, as expected, and is affected by the tool condition.

A critical issue in precision machining is ductile vs. brittle material removal. The mechanics of the transition have been analysed by a number of workers including Bifano et al. [31] who showed how this could lead to enhanced machining of brittle materials. The ductile–brittle transition was analysed with AE signals by Daniel and Dornfeld [32]. This work showed that the basic migration from plasticity dominated ductile removal, mechanisms to fracture dominated brittle mode material removal, can be observed by using acoustic emission. Surface displacements from representative ductile and brittle acoustic source functions are calculated using a Green's function approach. The predicted displacement waveforms for ductile and brittle acoustic source functions were verified experimentally using a specially designed AE transducer sensitive in the 1–3 MHz range during diamond turning/scratching experiments on BK7 glass. As machining progressed, the workpiece was "scratched" at increasing depths of cut. The ratio of peak dipole of the AE signal to r.m.s AE voltage showed a clear transition in machining from ductile to brittle as the depth surpassed the ductile-brittle transition. This has applications to the in-process control, or diagnostics, of the machining of brittle materials.

Lee [33] has shown the effectiveness of AE signals for monitoring grain orientation in the diamond turning of OFHC (oxygen-free high-conductivity) copper. Fine-grain OFHC copper was cold worked with a 67% reduction and then

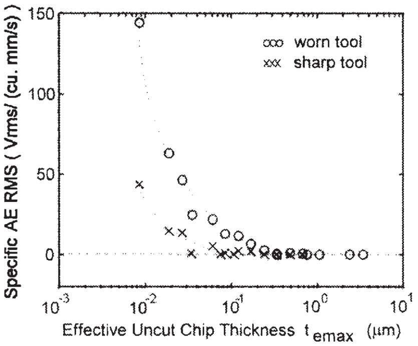

Fig. 3. AE_{rms} vs. uncut chip thickness.

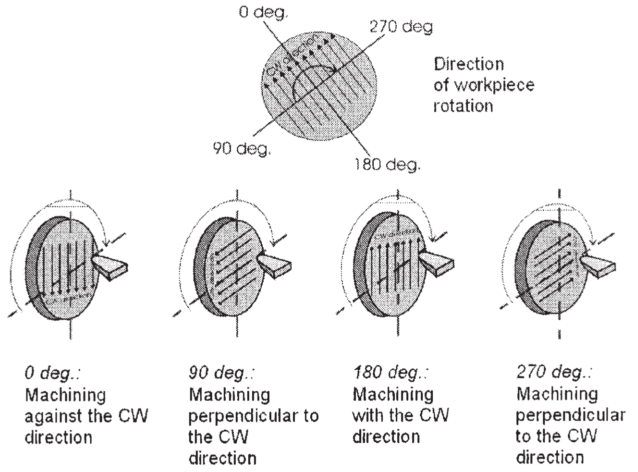

Fig. 4. Diagram of the variationof cold-worked grain orientation during diamond turning set-up.

planarised to prepare the surface and to minimise residual stress within the material. The workpiece was then mounted to a diamond turning machine and a 1 μm uncut chip thickness was maintained throughout the machining process (Fig. 4). An AE sensor was attached to the tool holder, and a data acquisition board captured the amplified AE signal. A number of cut-off and Butterworth filtering techniques were applied to the raw signal using LabView software. For comparative purposes, coarse-grain OFHC copper with no dominant grain orientation was machined using the same procedure.

Figure 5 shows variation in the processed AE signal for the case of the cold-worked specimen as compared to an isotropic coarse-grain workpiece. This graph indicates the change in directionality, as well as the direction of the cold-work encountered at the tool tip.

5.2 Grinding and Lapping

Acoustic emission sensitivity to abrasive processes and the inherent frictional interactions has been known for some time. This was first applied to detecting sparkout and contact in grinding [34,35]. Applications to grinding process monitoring such as wheel dimensional characterisation [36] and development of sensor-based "intelligent grinding systems" [37] are proposed and have been evaluated in practice.

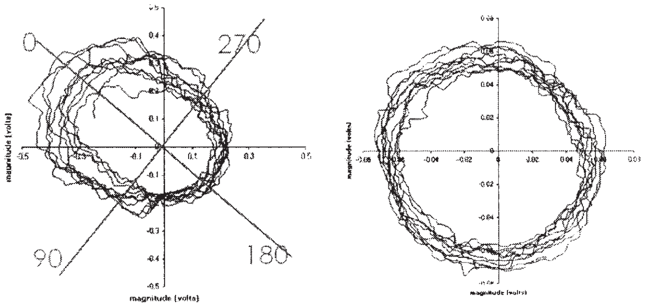

Fig. 5. Polar plots of the AE_{rms} signal from multiple revolutions of (*a*) strongly oriented cold-worked, and (*b*) isotropic coarse-grain copper workpieces.

The fundamental sensitivity of acoustic emission to the abrasive action has encouraged additional studies. Jiaa and Dornfeld [38] investigated the friction and wear behaviour of metals in sliding contact using AE-signal analysis techniques, it was determined that three different regions (running-in, steady state, and self-acceleration) in long-sliding distance tests can be distinguished from the results of AE_{rms} signal and measured wear rate.

The sensitivity of AE to the loading conditions and sliding velocity (strain rate) were also verified. The results showed that, under steady state, the AE_{rms} signal increases with increasing applied load and sliding velocity and is also affected by the mechanical properties of the materials in contact. Boness and McBride [39] studied adhesive and abrasive wear using acoustic emission. It has been demonstrated that measurements of the AE_{rms} signal provide a valuable tool in the study of wear between lubricated sliding contacts, measured AE_{rms} voltages were apparently due to asperity contact. It has been also shown that the time-dependent nature of the AE signal enables the presence of wear-reducing additives and the occurrence of the predominant wear process to be detected.

Dornfeld and Liu [40] applied AE to monitor an abrasive texturing and burnishing process. The AE_{rms} signal measured in texturing is found to be consistent with the friction coefficient and a correlation between friction coefficient and abrasive conditions was determined during tape burnishing or magnetic disk substrate. Chang et al. [41] used AE to monitor the material removal rate (MRR) in lapping and observed a linear trend between AE_{rms} and MRR. They also used AE to assess the degradation of abrasive size during the process and as a basis for re-freshing the slurry supply. Sensing in fine-grinding applications is reported by Akbari et al. [42] The AE signals generated during creep feed grinding of alumina were used for in-process detection of workpiece cracking and chipping. AE parameters show good correlation with the abrasive grain depth of cut.

5.2 Chemical Mechanical Polishing

Chemical mechanical polishing (CMP) has become one of the key bottleneck or roadblock issues in semiconductor manufacturing today [43]. It is used to ensure the interconnection between multilayer chips are achieved reliably and that the thickness of dielectric material is uniform and sufficient. These must be accomplished over a 300 mm diameter wafer achieving surface roughnesses of the order of 1–2 nm R_a and global planarity in the order of sub 0.5 μm to meet the requirements of lithography tools (recall that for line widths of the order of 0.25 μm the depth of field of the lithography machinery is very limited and the wafer flatness or planarity must be held to stringent tolerances). All this must be done at higher production rates to maintain a low cost of process. The decreasing line widths of semiconductor devices require new materials, such as copper and the so-called low-*k* dielectrics, which further challenge the process. Preferential polishing rates of adjacent materials, or surface features resulting from previous manufacturing steps, often lead to defects such as dishing, frustrating efforts to obtain planarity. The abrasive slurry can cause contamination on the surface, scratches on the surface, residual slurry, etc.

Chemical mechanical polishing is a planarisation technology suitable for logic and DRAM devices with feature sizes in the sub 0.5 μm range. CMP is also referred to as chemical mechanical planarisation. As a result of the interaction of an abrasive slurry and specific chemical properties, a polishing pad forms with the specific density and texture of the wafer surface of a semiconductor device. The pad "holds" and enhances the motion of the abrasive particles in slurry, composed of, for example 5–7 nm fused silica in an aqueous solution with pH of 8.5–11 (this will vary depending upon the material being polished and the abrasive used) and transmits the abrasive/fluid load to the wafer surface. The polishing operation comprises of the chemical creation of a silica layer which is then removed by the mechanical abrasive action. The mechanism differs with other materials, polymers for example. The chemically enhanced removal of layers of surface material including oxides, metals, and polymers to produce a "planarised" surface is a unique output of CMP. The process is similar to polishing processes for glass and other metals dating back thousands of years and is roughly governed by Preston's equation [44] which predicts the material removal rate as a function of the polishing pressure, relative pad–wafer speed, and a constant. It is not possible to review the CMP process in great detail here. Steigerwald et al. [45] is an excellent reference text on CMP. In addition, Komanduri et al. [46] give an excellent review of the process and place it in perspective with other conventional abrasive processes.

There are a significant number of input variables to the CMP process. These include [45]: slurry chemicals (pH, concentration, isoelectric point zeta potential, stability of the suspension, etc.), slurry flow rate, abrasive (including hardness, composition, size, shape, concentration), temperature, pressure, velocity and kinematic influences on the velocity of the pad and the wafer, pattern geometries including feature size and pattern density, pad and conditioning, etc., wafer geometry including curvature and mounting, and wafer size. The process outputs of interest to the manufacturer include [45]: polish rate, polish rate of underlying film, planarisation rate and "efficiency", polish rate uniformity, feature size dependency including polish rate, planarisation rate and damage, surface quality including roughness, particles and corrosion resistance, and surface damage.

The detailed interaction between the wafer, pad and abrasive (i.e. with the goal of tying the inputs to the outputs in some quantitative sense) has been the subject of research for some time. The earliest reference to an attempt to model the process, albeit for glass, is due to Preston [47] discussed above. It is commonly applied to Si wafer CMP even though, physically, the actual process mechanics are much more complex. Preston's equation is:

$$\mathit{Removal\ rate} = C_p P V \qquad (1)$$

where P is pressure and V is the velocity of wafer relative to the pad.

The coefficient in Preston's equation, C_p, is usually obtained experimentally and its sensitivity to the peculiarities of each CMP set-up emphasise the limitations of Preston's equation. The chemical aspects of CMP were investigated by Cook [47] who proposed several mechanisms governing the rate of surface removal. He also considered the mechanical aspects of the removal process as a travelling indenter moving along the wafer surface. Depending upon the velocity and slurry characteristics, there are three differing types of interaction between the pad, wafer, and slurry. At high relative velocities, the wafer will move over a fluid pad, as with a hydrostatic bearing, so that no contact exists between the pad and the wafer. The influence and action of the abrasive includes erosion and impact as well. At lower velocities, there may be some solid–solid contact in addition to support on a fluid layer. In this case, the action of the abrasive can appear as either two-body or three-body, depending on the action of the pad. Finally, at the lowest speed (or highest pressure) there can be direct wafer–pad contact where the entire load is supported on the solid structure. The abrasive action in this case, for the mechanical elements of CMP, is most probably primarily two-body abrasion due to asperity contact.

CMP planarisation of interlayer dielectric (ILD) is a combination of chemical reaction and free abrasive machining, in which the abrasives are allowed to rotate between the ILD surface and polishing pad and remove material by micro indentation or three-body abrasion. When an abrasive particle penetrates the pad surface, the abrasive can become embedded in the pad and remove material by micro scratching similar to that in fixed abrasive grinding or two-body abrasion. Our work has indicated that the acoustic emission is closely related to the material removal process in CMP and therefore it should be a reliable sensing method for CMP process monitoring.

It has also been confirmed that acoustic emission energy and other signal features are very sensitive indicators of the degree and nature of contact between surfaces and will be the basis for the monitoring of the CMP process. A schematic of AE sources in CMP is shown in Fig. 6 from [48]. The process stages, pad condition, end point, slurry characteristics, frictional interactions, etc. can be monitored using AE. Figure 7 (from Tang [49]) shows the AE_{rms} signal variation during three distinct stages of CMP with a 200 mm bare silicon wafer polished with SC112 slurry, an IC1000 pad and a Strasbaugh CMP machine. The process instability due to wafer set-down

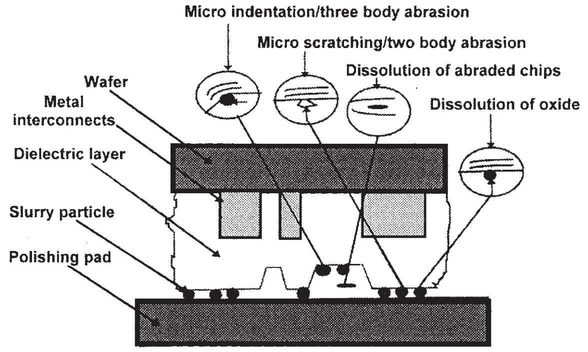

Fig. 6. AE sources in CMP, from [48].

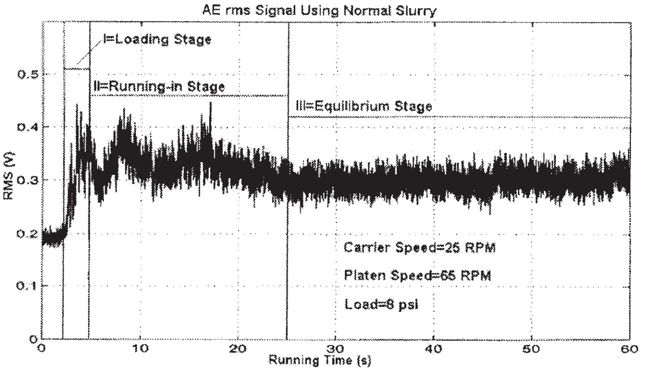

Fig. 7. A typical AE_{rms} signal in the conventional CMP process, Strasbaugh machine, from [49].

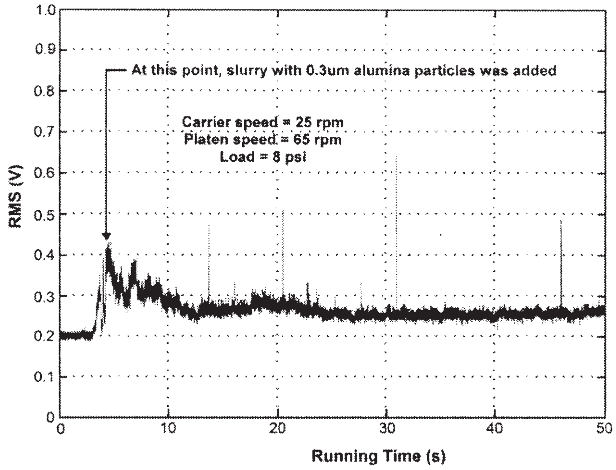

Fig. 8. The AE_{rms} signal with a silica-based slurry and 0.3 μm aluminium oxide particles to induce scratches, Strasbaugh machine, from [49].

in the early stage of polishing (about 15 s) can be identified clearly from the raw data of Fig. 8. Other tests have shown the sensitivity of AE to different materials polished (Fig. 9), and the usefulness of AE for end-point detection of oxide polishing (Fig. 10).

By microelectronic fabrication standards, CMP is an inherently "dirty" process and leaves micro defects, such as residual slurry, particles, pits and micro-scratches on the polished wafer surface. Some of the defects can be removed by post CMP cleaning, but defects such as micro-scratches cannot be recovered by simply cleaning the wafer, and therefore should be specifically addressed for the purpose of increasing chip yields. Tests were carried out to verify the feasibility of using AE for micro-scratch detection in the CMP process. In one set of tests, large diamond grits (here 1 μm) were artificially added to the slurry during CMP and the corresponding AE signals collected. In this case, a large number of mixed micro-scratches were observed in the polished wafer. Correspondingly, several spikes appeared in the AE_{rms} signals in each wafer carrier rotation period (typically, about 9 s in these tests) especially as the pad/wafer gap decreases at lower speeds. Any scratches in the wafer surface generated owing to abrasive action during the process are visible as spikes of AE activity on top of the basic signal during steady-state polishing, Fig. 7. This information will also be useful in the development process models including the fluid and abrasive interactions.

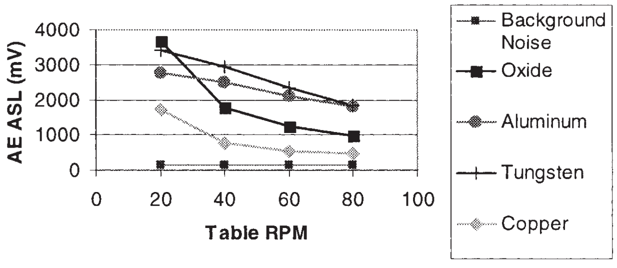

Fig. 9. AE average signal level of polishing from various material layers.

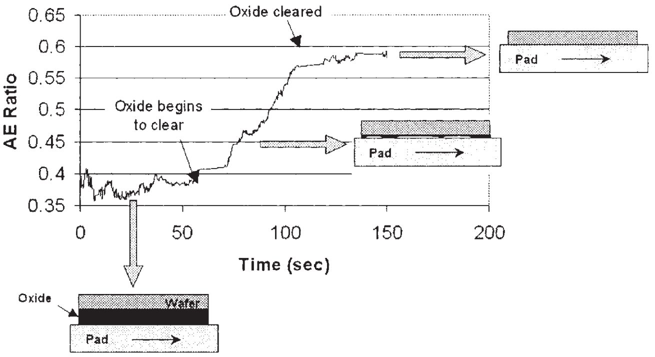

Fig. 10. The AE ratio signal used for end-point detection of the oxide layer.

6. Conclusions

It is difficult to summarise in a short paper the results of over a decade of research in many laboratories around the world investigating the application of acoustic emission in precision manufacturing processes. As workpieces require finer and finer surfaces, tighter tolerances and stringent requirements on subsurface damage, sensing systems is must be able to ensure that the sensitivity of the sensor is consistent with the magnitude of the phenomenon under investigation. Uniquely, acoustic emission is capable of meeting these requirements, especially for material removal process parameters such as material removal rates (and very low rates by comparison to conventional processes) and very small uncut chip thicknesses. If we add the sensitivity of AE to subsurface damage or ductile/brittle transitions in processing difficult to machine materials, we can see the potential for this sensing technology in precision manufacturing.

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