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# PROCESS MONITORING AND CONTROL FOR PRECISION MANUFACTURING

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***Abstract:*** *New demands are being placed on monitoring systems in precision manufacturing because of recent developments and trends in machining technology and machine tool design. This paper first discusses the requirements for sensor technology for precision manufacturing process monitoring in general. Then, background and details are given about acoustic emission (AE) and the application of AE sensing to process characterization and monitoring in ultraprecision machining. A review of the research on AE in machining (including, polishing, lapping and diamond turning) and signal processing at the University of California at Berkeley is included.*

**Keywords:** *Production Process***,** *Precision Machining, Sensors*

## INTRODUCTION

In-process sensors play a significant role in assisting manufacturing systems in producing quality products at a reasonable cost and are used to generate control signals to improve both the control and productivity of manufacturing systems [1]. Numerous different sensor types are available for monitoring and control of the manufacturing and machining environments [2]. This paper first discusses the requirements for sensor technology for precision manufacturing process monitoring and control in general. Then, background and details are given about acoustic emission (AE) and the application of AE sensing to process characterization and monitoring, primarily in material removal processes at the Laboratory for Manufacturing Automation at Berkeley.

## REQUIREMENTS FOR SENSOR TECHNOLOGY FOR PRECISION MANUFACTURING

Precision machining takes place at the sub-micron to nano scale dimensions (with respect to the uncut chip thickness, for example.) Critical sensor information in precision machining is required mostly for assessing material removal at the sub-micron level, surface finish and subsurface damage. In addition, it is of interest to track for control purposes 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).

Not surprisingly, different sensors have different applicability at different levels of precision, or displacement or MRR. Fig.1 [3] shows a schematic diagram of different types of sensor applications for different precision levels and control parameters. The boundary represents the approximate range of usage with the shaded area emphasizing the core application range. Acoustic emission 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.

When material removal reaches the sub-micron level, essential signal features may be difficult to obtain. Conventional 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 (AE) exhibit improved response in the high frequency range, where much of the machine induced low frequency disturbance signals are diminished and the frequencies from sub-micron level precision machining activity becomes dominant (see fig.2 & fig.3, from [4]).

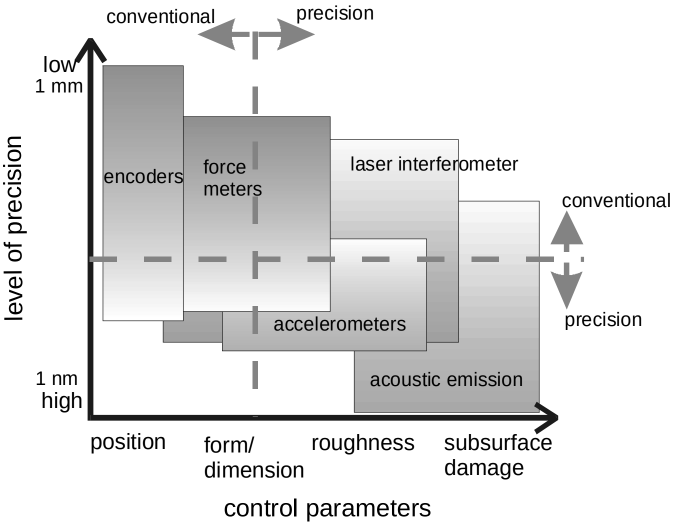


*fig. 1: Sensor application vs. level of precision and error control parameters, [3]*

## SENSING FOR PROCESS CHARACTERIZATION AND MONITORING

The transformation of stand-a-lone 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 over the last decade. In the late 1980's and early 1990's, [2], the influence of advanced signal processing techniques and artificial intelligence were felt in the development and application of sensors and sensing systems. These are often called intelligent sensors. The focus of monitoring is on either the machine (diagnostics and performance monitoring), the tools or tooling (state of wear, lubrication, 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.

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 by [2, 5], covering monitoring and control, and [6] on sensors for unmanned machining.

## SOURCES OF AE IN PRECISION MACHINING AND SIGNAL PROCESSING

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 [7]. Traditionally, the bulk of the processes monitored are drilling, milling and turning. The most potential for acoustic emission-based monitoring are material deformation-based manufacturing processes. They use either continuous or discontinuous application 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. Sensor location and signal processing are not always straightforward considerations.

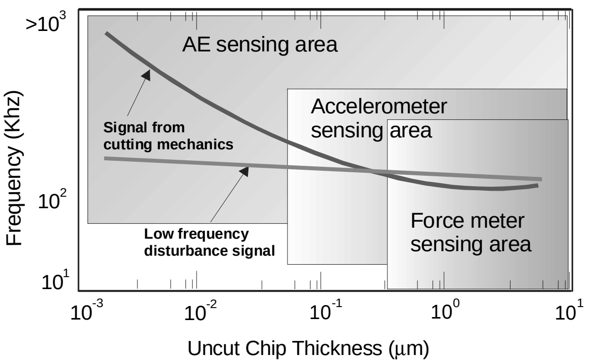


*fig. 2: Noise and Cutting Signal Frequencies and Sensor Effectiveness, [4]*

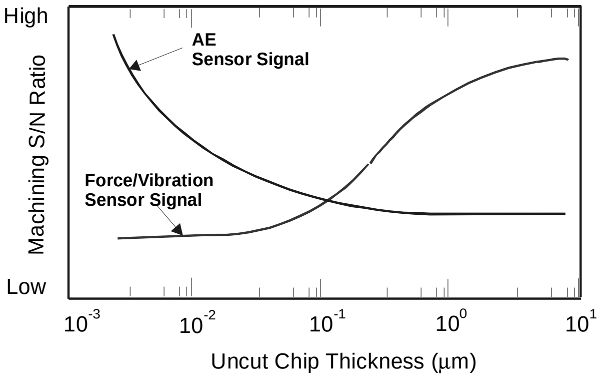


*fig. 3: Signal/Noise Characteristics of AE vs. Force/Vibration Sensors at Different Uncut Chip Thickness ($a_C$), [4]*

Research over the past several years has established the effectiveness of AE based sensing methodologies for machine tool condition monitoring and process analysis. Investigations of AE from metal cutting have often been limited to two-dimensional 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 occurs, 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 milling (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. Extension of the analysis of the basic signal characteristics to other process features, such as surface finish, have also been proposed, [8].

For loose abrasive processes, lapping for example, the sources of AE are due to the varied interaction between the tool, work and abrasive. Depending upon the velocity and slurry characteristics, there are three differing types of interaction between the polishing pad/lap plate, work and abrasive slurry. At high relative velocities the work will move over the 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, is most likely primarily two-body abrasion due to asperity contact. Acoustic emission energy and other signal features are a very sensitive indicator of the degree and nature of contact between surfaces and are the basis for the monitoring of the loose abrasive processes. A schematic of AE sources in lapping is shown in fig. 4 from [27].

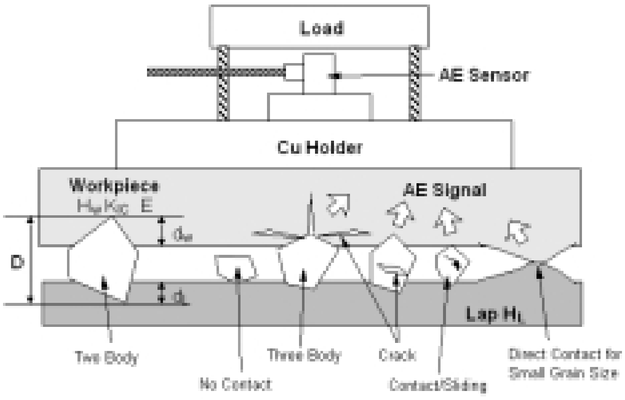


*fig. 4: Acoustic emission sources in lapping process, [27]*

A number of studies on developing models of AE generation in machining (Dornfeld [9], Dornfeld and Kannatey-Asibu [10, 11], and Rangwala and Dornfeld [12, 13]) have established the principle role of process parameters, especially cutting speed, in the determination of RMS energy of the signal. A basic model for the generation of AE during machining (in this case primary and secondary shear generated AE in orthogonal machining) was proposed. 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. The extension of this model to precision machining is done by scaling the process with the uncut chip thickness. 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. For precision machining, such as diamond turning, the model-based predictions for AE sources are much more accurate. Both event-based (count-rate) and energy-based techniques are employed in research on AE from metal cutting.

## APPLICATIONS OF AE SENSING IN ULTRAPRECISION MACHINING

Diamond turning- The acoustic emission energy and specific energy has been shown to scale with the uncut chip thickness. AE-RMS is directly proportional to the chip thickness defined as $t_{emax}$ in fig. 5 below. Here f, d and V represent feed, depth of cut and cutting speed, respectively. Also R represents the tool tip radius and W is the chip length. Fig. 6 shows the sensitivity of specific AE-RMS to uncut chip thickness for both worn and sharp diamond tools for single point turning of Al2024-T35. Sensitivity down to less than 0.01 micron is seen [15-17]. Specific energy increases with decreasing uncut chip thickness as expected and is affected by the tool condition.

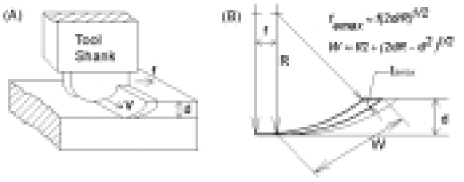


*fig. 5: Tool-chip geometry and uncut chip thickness*

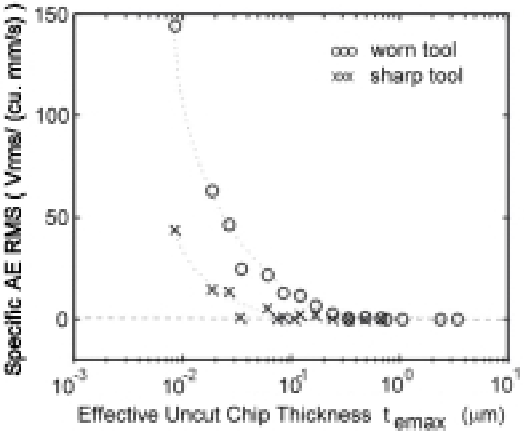


*fig. 6: Specific AE-RMS vs. uncut chip thickness*

A critical issue in precision machining is ductile vs. brittle material removal, Bifano [18]. During scratch tests a distinct transition occurs in the nature of the acoustic emission signal as the indentor, or tool, transitions from no contact, elastic rubbing without cutting, cutting in ductile mode and, finally, brittle mode removal. Using an experimental technique similar to that of Brinksmeier [19], Lee was able to demonstrate this variation in acoustic emission signal with mode of contact and removal in single point diamond scratching of bare and chemically treated Si wafers, [20]. Fig. 7 shows the transition in signal properties.

The ductile-brittle transition was also analyzed with AE signals by Daniel [21]. 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 and verified experimentally using a specially designed AE transducer sensitive in the 1-3 MHz range during diamond turning/scratching experiments on BK7 glass at increasing depths of cut. The ratio of peak dipole of the AE signal to AE-RMS voltage showed a clear transition in machining from ductile to brittle as the depth surpassed the ductile-brittle transition. Fig. 8 illustrates this ratio as a function of number of test scratch. The transition from ductile to brittle mode occurs at scratch number 77. This discrimination can also be accomplished by the use of Wavelet packet analysis to distinguish AE bursts to characterize the “relative brittleness” of the removal process, [22]. Both approaches have application to the in-process control, or diagnostics, of machining of brittle materials.

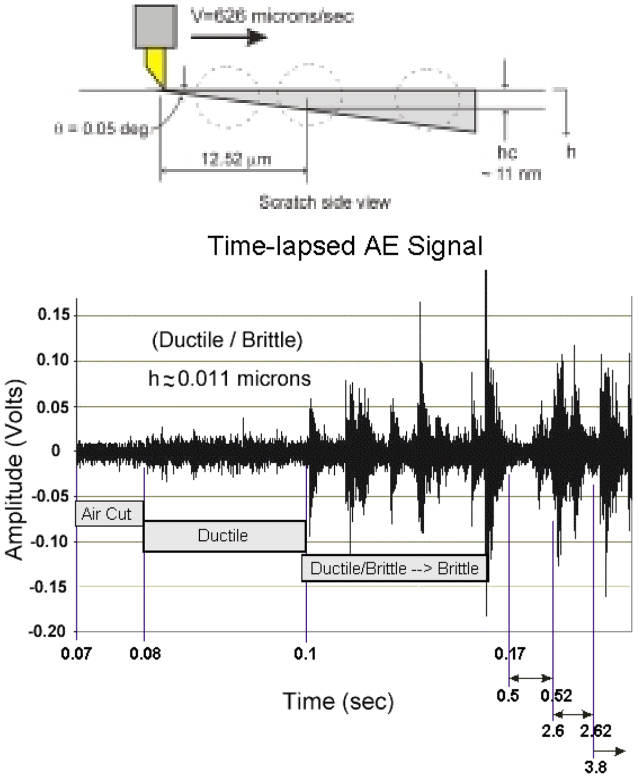


*fig. 7: Ductile to brittle transitions indicated by change in AE signal, from Lee [20]*

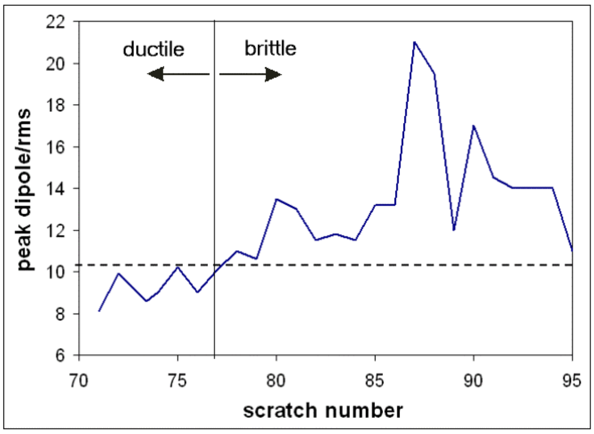


*fig. 8: Peak dipole to AE-RMS ratio vs. scratch number; ductile/ brittle transition at scratch 77, [21].*

In ultraprecision machining, understanding the influence of material properties such as crystallographic orientation and grain boundaries and their effect related to material removal is critical in creating the desired surface quality. These material properties issues were previously studied by Furukawa [32] and Brinksmeier [19] using force sensors. Using an acoustic emission sensor, the transition from one grain to another during scratch testing was successfully observed by Lee et al. [33]. Fig. 9 shows the AE signal variation at the grain boundary crossing. The work material was a coarse-grained OFHC copper with an average grain size of 300 microns. The workpiece was plunge cut and the AE signal was captured using a data acquisition board. Later, the material was micro-etched to reveal the grain structure and, using an optical microscopy, the significant grain structural elements were matched with the observed AE signal.

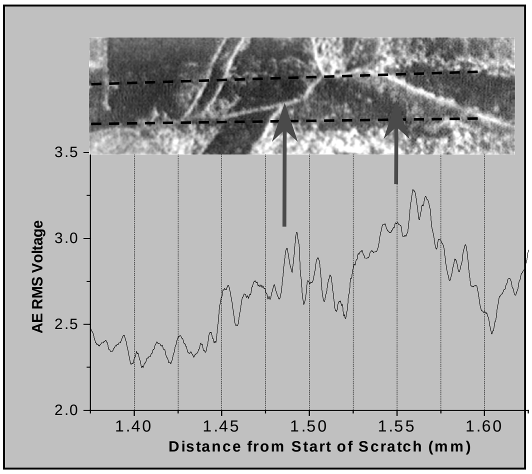


*fig. 9: Correlation between AE-RMS and material structure of coarse grain OFHC copper [31]*

The influence of the macro directionality of OFHC copper was also investigated by Lee et al. [34] using an acoustic emission sensor. The OFHC copper was cold-worked at 67% and turned using a 1 micron uncut chip thickness on a Pneumo diamond turning machine. Fig. 10 shows the effect of the cold-work on the AE signal. Fig. 11 is a polar plot of the right side graph in fig. 10. The elliptical plot reflects the directionality of the cold-working process. A schematic of the cold-work direction change encountered at the tool tip relative to the orientation of the polar plot is shown in fig. 12.

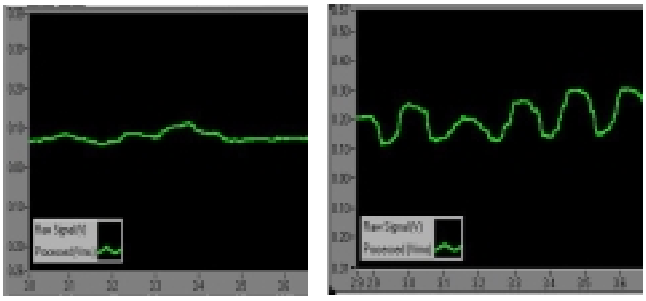


*fig. 10:  AE output of non-coldworked OFHC copper (left) and OFHC copper with 67% cold work. Uncut chip thickness is  1 micron [34]*

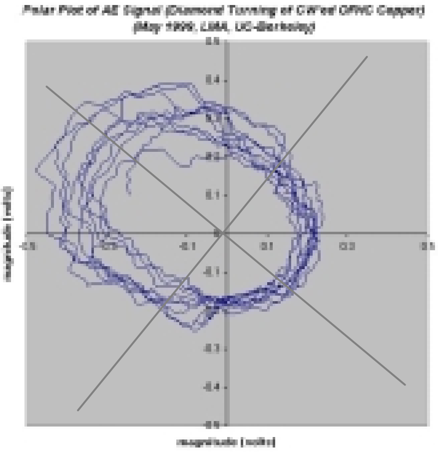
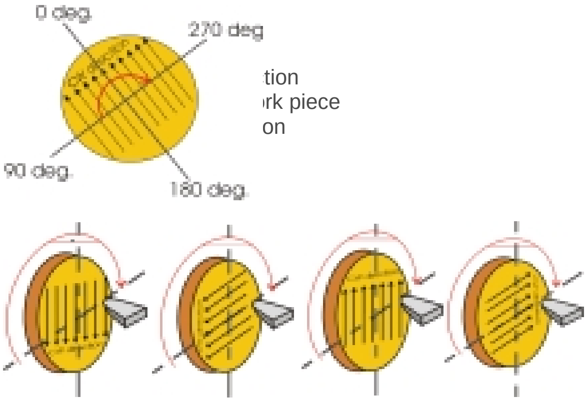


*fig. 11:  Polar plot of AE-RMS and cold-work direction during diamond turning of OFHC copper [34]*



*0 deg.:* machining against the CW

*90 deg.:* machining perpendicular to the CW direction

*180 deg.:* machining with the CW direction

*270 deg.:* machining perpendicular to the CW direction

*fig. 12:  Schematic of material orientation during diamond turning of cold-worked OFHC copper [34]*

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, contact and wheel dimensional characterization in grinding [1,23,24]. The fundamental sensitivity of acoustic emission to the abrasive action has encouraged additional studies. Jiaa and Dornfeld [25] investigated the friction and wear behavior of metals in sliding contact using AE signal analysis techniques.

Liu and Dornfeld [26] applied AE for an abrasive texturing and burnishing process monitoring. 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 and Dornfeld [27] used AE to monitor the material removal rate (MRR) in lapping and observed a linear trend between AErms and MRR, fig. 13. They also used AE to assess the degradation of abrasive size during the process and as a basis for re-freshing the slurry supply, fig. 14. Sensing in fine grinding applications is reported by Akbari *et al* [28]. 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.

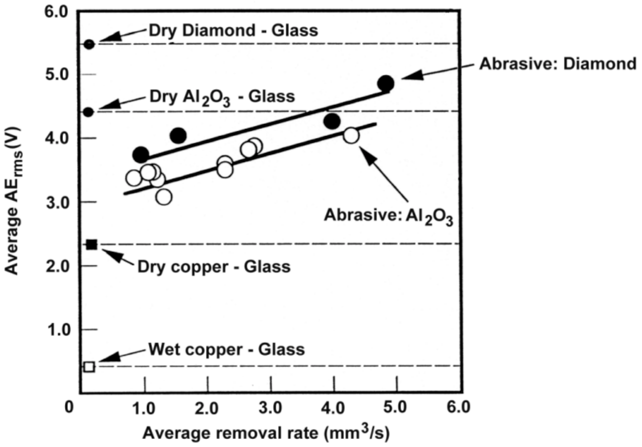


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*fig. 13: Correlation between AE-RMS and metal removal rate for diamond and alumina, from Chang et al [27]*

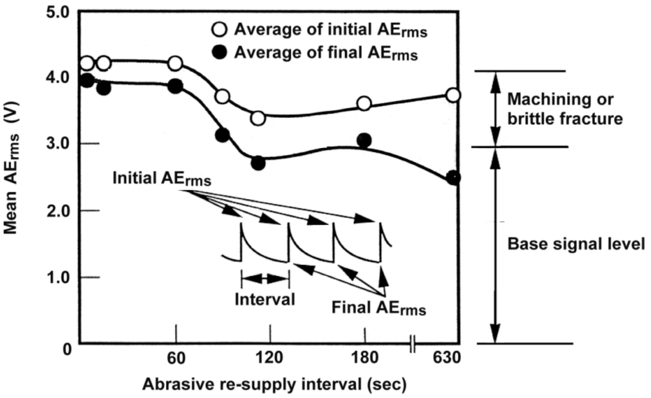

*Fig. 14: AE-RMS signal level versus re-supply interval of abrasive slurry, from Chang et al [27]*

Chemical Mechanical Polishing- Chemical mechanical polishing (CMP) has become one of the key bottleneck or roadblock issues in semiconductor manufacturing today. It is used to insure the interconnects between multilayer chips are achieved reliably and that the thickness of dielectric material is uniform and sufficient. This must achieve surface roughnesses on the order of 1-2 nm arithmetic average ($R_a$) and global planarity in the order of sub 0.5 micron. Polishing results from the interaction of an abrasive slurry with specific chemical properties, a polishing pad with specific density and texture with the surface of a semiconductor device in wafer form. 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 between 8.5-11 and transmits the abrasive/fluid load to the wafer surface.

The process stages, pad condition, end point, slurry characteristics and frictional interactions, etc. can be monitored using AE. Fig. 15 below, from [29], shows the AE-RMS signal variation during three distinct stages of CMP with a 200 mm bare silicon wafer polished with SC112 slurry, IC1000 pad and Strasbaugh CMP machine. The process instability due to wafer set down in the early stage of polishing (about 15 seconds) can be clearly identified from the raw data of fig. 15.

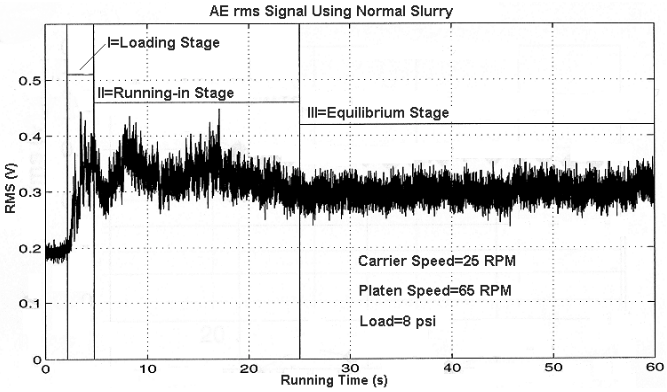

*fig. 15: Typical AE-RMS signal in conventional CMP process, Strasbaugh machine, from [29]*

# APPLICATION OF OPEN ARCHITECTURE CONTROL, MONITORING AND PLANNING FOR PRECISION MACHINING

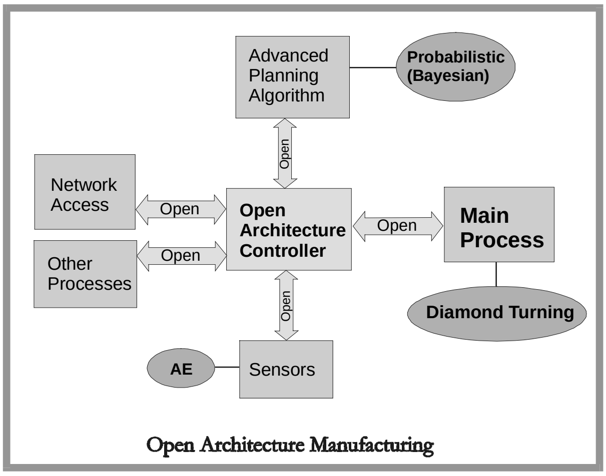

*fig. 16: Schematic of open architecture system for precision manufacturing [30]*

In precision machining it is often very difficult to control the process to obtain the required results. This is largely because the processes operate under different environments than in conventional machining. Most closed control systems used in conventional machining fall short in terms of integrating sensors necessary to control the critical design parameters such as residual stress, subsurface damage, ductile regime cutting, etc. Fig. 16 shows an integration of high level planning strategy [30], advanced monitoring scheme and custom control algorithm to create a suitable environment for precision manufacturing using an open architecture system. Fig. 17a and 17b show an example of AE monitoring and control using an open system for diamond turning.

A PC based open architecture controller is used to machine precise flat and non-flat surfaces. An AE sensor is attached to the diamond tool holder. The controller can monitor small changes in the depth of cut and differences in cutting speed during diamond turning on-line, to control tool depth of cut with a micro actuator. The AE data for changes in depth of cut and cutting speed (proportional to radial position in this facing operation) was recorded, fig. 17a. A square wave input was applied for a 0.8 micron change of depth of cut. Using the AE output as feedback signal, the form error was reduced as shown in fig. 17b [31].

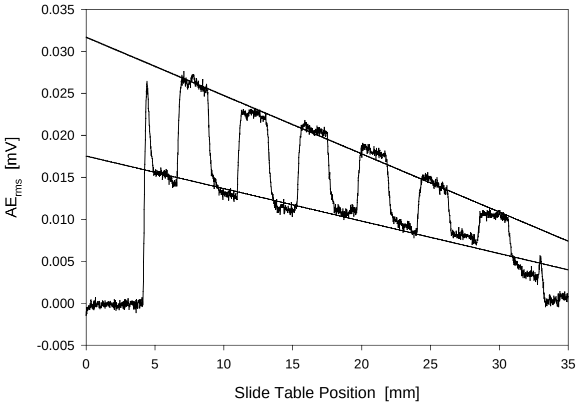

*fig. 17a: AE-RMS signal of diamond turning of aluminum (6061) with square wave input [31]*

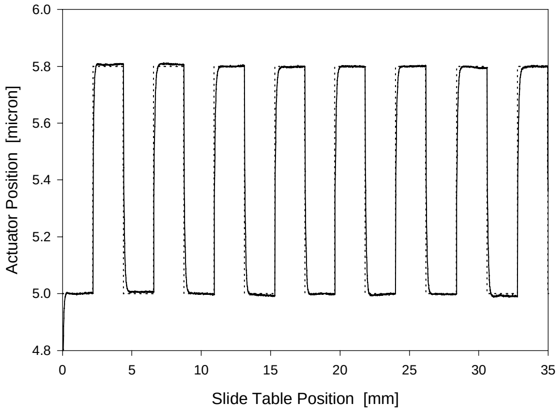

*fig. 17b: Square wave input and output response after AE and position feedback [31] (dotted: input, solid: output)*

## CONCLUSIONS

It is difficult to summarize in a short paper the results of over a decade of research investigating the application of acoustic emission in precision manufacturing processes. As workpieces require finer and finer surfaces, tighter tolerances and stringent requirements on sub-surface damage, sensing systems must be able to ensure that the sensitivity of the sensor must be consistent with the magnitude of the phenomenon under investigation. And, it would be useful if the sensor output had some relationship with the process mechanics as it can help in developing a better understanding of the process. Acoustic emission is capable to meet these requirements, especially for material removal process parameters like material removal rates (and very low rates by comparison to conventional processes) and very small uncut chip thicknesses. If one adds the sensitivity of AE to subsurface damage or ductile/brittle transitions in processing difficult to machine materials, one can see the potential for this sensing technology in precision manufacturing.

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