Observing Tool and Workpiece Interaction in Diamond Turning Using Graphical Analysis of Acoustic Emission and Force

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Abstract

A graphical mapping technique of the acoustic emission (AE) signal for a precision machining process has been developed for the in-situ characterization of the machining process physics. Machining at the precision scale involves chip formation at lengthscales representative of microstructural features of polycrystalline materials such as grain boundaries and grain orientation. The process-induced AE signal generated during precision machining can be used to characterize the interaction between tool and workpiece microstructure, and can be used as a way to characterize the workpiece microstructure and access the form error.

1. Introduction:

In precision machining, the uncut chip thickness typically ranges from several microns to several tenths of a micron. At such scales, surface finish and chip formation are much more intimately affected by the microstructure of the workpiece [1]. In particular, while cutting polycrystalline materials at the precision level, the material removal mechanism is highly influenced by individual grain size and orientation (see Figure 1). Therefore, unlike conventional metal cutting, the cutting mechanism in precision machining is significantly influenced by the crystallography and associated slip system within each randomly oriented grain.

![Figure 1: Relative scale comparison of conventional vs. precision cutting processes [1].](image)

It has been demonstrated that the sensitivity of the cutting mechanism with respect to the grain orientation and the transition of the cutting tool across grain boundaries of OFHC copper can be measured to a certain extent using very sensitive load cells [2, 3]. The significance of the sensitivity of the cutting forces to the cutting mechanism becomes important not only to help understand the physics of the microcutting process, but also as a potential means of monitoring and controlling the machining process. However, when the depth of cut decreases further, the ability to monitor changes in the cutting forces at the grain boundaries approaches the resolution limit of current force transducer technology.

An alternative approach is to use acoustic emission (AE) to monitor and characterize the microcutting mechanism. As a form of process-induced high-frequency vibration, AE is generated by a number of different mechanisms, such as shear in the primary shear zone during machining and contact between the tool/workpiece in the secondary/tertiary shear zones. However, unlike force sensors, different levels of AE can be detected even at extremely low depths of cut [4]. This is true even when the chip formation process diminishes and the only remaining tool-material interaction involves rubbing and burnishing of the surface along different grain orientations. AE is particularly well-suited because of its ability to detect micro scale
deformation mechanisms within a relatively ‘noisy’ machining environment, thanks to it’s improved signal-to-noise (S/N) ratio with the proper signal conditioning.

This paper proposes an innovative system where the interaction of the tool and workpiece during a precision cutting process can be represented in a 2D mapping of the process-induced AE and force signal. This graphical representation of the AE and force signal provides information about the cutting process parameters, such as cutting velocity and depth of cut, as well as the surface topography and microstructure features of the workpiece, such as grain boundaries and orientation. This system will serve as an in-situ means of monitoring and characterizing a precision cutting operation.

2. Experimental Setup:

The workpieces used for the experiment were 63.5 mm diameter (2.5”) OFHC Cu flats that were cold worked at 60% and subsequently recrystallized at 830°C. The workpieces were recrystallized for different time durations (20-60 min.), resulting in a variation in recrystallized grain size from approximately 0.1 mm to 4 mm in average grain diameter. The primary machine tool was a highly-modified Rank Pneumo MSG-326 precision lathe donated from the Lawrence Livermore National Laboratory. This machine was equipped with an air bearing spindle and precision air-bearing lays. An HP laser interferometer was used to measure tool infeed position, and a Heidenhain linear encoder was used to measure crossfeed position and velocity.

The first experiment involved the creation of a series of nearly-parallel slow speed scratches on the surface of an OFHC Cu workpiece. A 0.274 mm nose radius single crystal diamond tool was chosen as tool of choice, since this represents an ‘average’ tool used for the fabrication of an aspheric optical quality surface. The load cell was a custom Kistler 9317A piezoelectric load cell, coupled with a Kistler 5429 distribution box and two Kistler 5010 charge amplifiers. Despite a high preload, the presence of the load cell reduced the stiffness of the tool structure, limiting its use to slow-speed machining and precluding its use from full-speed machining operations. A DECI SE900-MWB AE sensor was used due to its relatively high bandwidth compared to other sensors. The AE sensor was positioned directly on the tool shank and coupled with petroleum jelly to minimize signal attenuation. The workpieces were clamped onto the spindle of the lathe, and the spindle was alternately rotated and locked to allow for slow-speed scratches (see Figure 2). A scratch speed of 0.7 mm/sec was used, and the infeed (depth of cut/DOC) setting was set at a constant value of 10 microns throughout the experiment. After each scratch, the spindle was unlocked and rotated slightly (~1 degree) to produce a radial pattern of scratches (although the scratch pattern can be approximated as a raster scanning pattern over this small angle of rotation). The AE signal was filtered through a high-pass filter with a 50 kHz cutoff frequency to minimize any ambient acoustic noise from the system. The signal was subsequently amplified by 40 dB. The AE signal was then passed through a Root-Mean-Square (RMS) filter with a time constant of 1 millisecond. Likewise, the signal from the load cell was filtered though a low-pass filter at 10 Hz to cancel out the 60 Hz AC outlet noise, which was sufficient for a slow-speed scratch. Cutting force (force parallel to the scratch direction) and thrust force (force normal to the scratch direction) were obtained. Both signals were collected by a National Instruments PC-LPM-16/PnP 12-bit data acquisition board at a sampling rate of 10 kHz. The signal was then reduced and processed with MATLAB.

The second experiment involved a full-speed precision face turning operation. However, full-speed machining experiments with the Kistler load cell produced very poor results, due to the lack of stiffness in the tool holder/load cell assembly structure that resulted in a transverse vibrational mode and degraded the surface finish. For the full-speed experiments, the load cell was removed, and only the AE RMS signal was obtained with an RMS time constant of 0.2 milliseconds. A constant RPM of 1000 was used, corresponding to a maximum cutting velocity of about 6.6 m/sec on the outer circumference of the workpiece. A constant depth of cut of either 2 or 10 microns was used, and a diamond tool with nose radius of 0.274 mm was used with a feed range of 8-22 microns/rev. LABVIEW was used to collect and post-process the data. Otherwise, the signal conditioning parameters and experimental setup was similar to that used for the parallel scratch test.
3. Results:

3.1. Parallel Scratch Experiment:

After collecting data from a series of scratches (typically on the order of 10 quasi-raster pattern scratches), the data was reduced, and a color intensity mapping function in MATLAB was used to plot the cutting force and AE signal as a function of position, with the color map representing the respective magnitude of the signal. Figure 3 shows a graphical representation of the cutting force and AE signal for a series of 15 scratches, along with a micrograph of the workpiece surface before scratching. Note that in the cutting force map, blue regions represent very low cutting force (on the order of 0.01 N), and red represents regions of high cutting force (on the order of 0.1 N). Likewise, red regions in the AE mapping correspond to AE RMS values of about 0.3 volts, while blue regions represent low (0.1 volt) AE RMS signal.
Both the cutting force and AE signal reproduce a crude representation of the grain structure of the material. The variation in force and AE signal is largely due to the fact that each grain has a particular crystallographic orientation, so as the tool passes from one grain to another, a new slip system in the grain is being activated, which changes the amount of applied stress (and cutting force) required to initiate deformation [5]. Likewise, the AE RMS signal has been found to be proportional to the specific energy (power divided by material removal rate) required to machine a material [6]. If the cutting speed and tool cross section are constant, then the AE RMS is simply proportional to the energy (and cutting force) required to initiate deformation. The activation of different slip systems as a function of grain orientation causes the energy of the AE signal to fluctuate accordingly.

The improved contrast in the force mapping seems to demonstrate that the force signal offers a more accurate representation of microstructure of the material. However, it is important to mention that the AE signal is extremely sensitive to any external or process-induced vibration. Phenomena not directly related to the cutting process, such as chip removal or non-process induced vibration (one source being imprecision in the slideways) could serve as noise sources and result in signal aliasing. Because of the low cutting speed, external noise sources (notably, the rubbing of the chip on the tool face during scratching) could be on the order of the cutting-induced AE signal, serving to alias the signal [7].

3.2. Contact Detection For Full-speed Machining:

For the second series of experiments, a face turning operation was conducted on a non-planar OFHC Cu workpiece without any pre-processing to demonstrate the contact detection capability of the mapping system. An initial touch-off operation was performed by visually aligning the tool with the workpiece, and an initial cutting pass was taken at 1000 RPM with a 1.4 mm nose radius diamond tool, initial depth of cut of 10 microns, and feed of 10 microns/rev. Figure 4 shows a polar map representation of the AE RMS signal, along with a Wyko Topo-3D interferometer image. Note that the AE RMS polar map matches the shape of the interferometer image, with dark yellow regions in the polar map representing contact between tool and workpiece, and black regions representing non-contact due to the initial non-flatness of the workpiece with respect to the plane of rotation of the spindle.

![Figure 4: Correlation between AE polar map and laser interferometer image.](image)

A series of four subsequent passes with DOC of 10 microns and cross-feed of 10 microns/rev were taken across the workpiece, and the resulting AE polar maps are shown in Figure 5. Note that the shape of the polar map evolves into a circle as the number of passes increases, corresponding to a greater portion of the workpiece being in contact with the diamond tool during machining. On the final pass, the polar map is a full circle, indicating that the entire surface of the workpiece has been machined. These plots demonstrate the capability of AE signal to be used as a contact detection tool.
3.3. Microstructure Mapping During Full-speed Machining:

In the last series of experiments, the workpiece was machined to an optical quality surface finish of 58.2 nm $R_a$ at 1000 RPM with a 0.274 mm nose radius diamond tool. No macro-scale surface defects could be observed with the naked eye. Figure 6 shows a polar intensity mapping of the AE RMS signal next to a micrograph of the actual OFHC Cu workpiece after etching with an ammonium hydroxide etch for 30 seconds to remove the process-induced strain hardened layer of material. Note that a rough correlation can be made between the large individual grains on the workpiece and the large dark regions on the AE polar map.

A total of 16 subsequent passes with DOC of 2 microns were taken over the same workpiece, for a total depth of 32 microns of removed material. AE polar maps were collected every 5 passes (see Figure 7).

As before, the AE polar map shows the presence of large recrystallized grains, demonstrating the capability of the polar map to detect microstructure variation in the workpiece. A variation in the mapping can be observed as the number of passes increases, corresponding to new grains being machined as previous layers of material are removed. Such a technique can be used, for instance, to verify whether a
workpiece has a coarse or fine grain structure. The polar maps can also indicate the position of large
grains. Also, since it has been previously established that surface finish is a function of grain orientation in
ultraprecision machining [5], the homogeneity of the polar map can also serve to represent overall
homogeneity in the surface finish, although a more discrete relationship between surface finish and AE
signal has yet to be found.

4. Conclusions/Future Work:

The AE mapping technique for precision machining has been performed with varying degrees of
success. For the machining of OFHC copper, the force and AE RMS signal mappings represent the
microstructure (grain orientation) of the workpiece, as well as large macro-scale defects like scratches.
Ultimately, the AE mapping system can serve as a technique for characterizing the variation of the cutting
process, which translates to a variation in the material properties or microstructure of the machined
workpiece. The degree of heterogeneity in the graphical mapping can serve as a process metric for the
quality of the machined part.

Some issues that need to be addressed in the future include…

1. Correlation between force and AE signal to the crystallographic orientation of individual grains.
2. Further cross calibration of the force and AE signal to other process metrics, such as surface
finish. This includes additional metrology (profilometry, optical interferometry, etc…) to further
characterize the surface.
3. Analytic modeling of the AE and force signal as a function of crystallography.
4. Investigation of the ability of the force and AE signal to detect other manufacturing defects in the
workpiece.

5. References:

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