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# Characterising Acoustic Emission Signals for the Online Monitoring of a Fluid Magnetic Abrasives Finishing Process

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## Abstract：

To implement an automated fluid magnetic abrasive (FMA) finishing process, an online monitoring scheme is proposed based on characterising acoustic emission (AE) signals in this paper. According to the material removal mechanisms during the FMA finishing process, the AE generation and characteristics are predicted analytically to be dominated by the interactions between the surface asperities and the abrasive particles. Moreover, the interactions and corresponding AE events will become weaker as the finishing process progresses and the surface becomes smoother. Experimental studies show that the amplitude and the occurrence rate of continuous AE waves and intermediate bursts reduce gradually with the progression of the finishing process. Based on these features, root mean squared (RMS) values and burst occurrence rates (BOR), being of the lowest computational requirements, are suggested as online monitoring parameters for an automated and intelligent finishing in FMA manufacturing. The proposed method is verified experimentally, showing that the RMS values are highly consistent with measured surface roughness values, which confirms the dynamic mechanisms between the FMA finishing and AE generation sources examined.

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Fluid Magnetic Abrasive Finishing; Acoustic Emission; Precision Machining; Surface Morphology; Intelligent Manufacturing.

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## 1 Introduction

Fluid magnetic abrasive (FMA) finishing is a relatively new surface finishing manufacturing process which deburrs, polishes and removes recast layers, thereby improving the fluidity of air or liquid enclosed by the surfaces. It removes surface material through a complex microscopic interaction between the microscale particulates mixed the fluid and the asperities of the workpiece surface, which eventually is able to obtain nanometer scale finishing even for sub-nanometer surface roughness. In addition, it does not cause any subsurface damages [1-2], maintaining a lone service life of the workpiece. Since magnetorheological fluids (MRF) were introduced by Jacob Rabinow in 1949, FMA based MRFs have received much attention and many applications have been developed, such as shock absorbers, clutches, hydraulic valves, etc. [3-5]. In order to utilize the rapid and adjustable magneto rheological effects of MRF for machining, Sun et al [2] added micrometer-scale abrasive particles into an MRF fluid to improve its grinding performance and hence made it possible to finish metal surfaces more efficiently. This was subsequently known as fluid magnetic abrasive (FMA) manufacturing and has been used for finishing various surfaces, especially small holes or inner surfaces for attaining a very low surface roughness value.

However, the material removing rate and surface roughness level in a FMA finishing process are related to magnetic field intensity, abrasive pressure, abrasive flow rate, workpiece material and other parameters including ambient temperature. To achieve a desired surface quality in a high-speed finishing process, a number of trials are usually required to tune these manufacturing parameters by highly experienced operators. Even though, it has been found by off-line measurements that many finished workpieces often show unsatisfactory quality distribution, which may come from the gradual reduction of MRF performance with process duration and small changes in fluid temperatures and pressures. It means that this off-line inspection method cannot guarantee FMA manufacturing quality and efficiency to meet the requirements of the mass production of large scale applications [6-8]. Therefore, an online, real-time method is needed to control the FMA process so that the finishing process can be terminated automatically when the surface roughness is reaching the specification.

Currently, acoustic emission (AE) measurements have received much attention for monitoring different machining processes such as tool wear and fracture, micro-machining, grinding etc. AE signals arising from different machining processes exhibit as transient elastic waves in the frequency range from 25 kHz to several MHz [9-10]. This frequency range is outside most of the extraneous electrical and mechanical noise found with manufacturing equipment. So AE can be used to characterize these processes more accurately and reliably. Yum et al [11] used a two-step feature selection method to select AE signals for monitoring tool wear in grinding. In [12] a relationship between the AE signal generation and tool wear was developed for cutting processes in micromilling. Hase et al [13] explored the relationship between AE signals and cutting phenomena for turning processes. Griffin et al used short time Fourier transforms (STFT) to process AE signals for identifying and classifying the rubbing, ploughing and cutting process of single-grit (SG) phenomena [15]. In addition, the AE monitoring technique has been widely used in several examples of online monitoring of machining [11-20]. These publications show that AE monitoring could be a viable method for on-line monitoring of

FMA polishing. Specifically, AE monitoring technology was investigated on charactering abrasive flow machining (AFM) [14], which showed that the AE characteristics of conventional polishing can be reflected by the AE root mean squared (RMS) value.

Although these manufacturing methods all share the similar mechanisms of AE generations, FMA finishing is a much finer micro-scale abrasive process, in which the particle sizes are much smaller than conventional AFM. Moreover, the magnetic field in FMA applied is not only to enhance the interactions for faster material removal but also control the particle distribution for attaining smoother and more uniform surface finishing [18]. This means that AE characteristics such as amplitude distribution, frequency bands and the transient wave patterns, especially their change rate with finishing progression can be very different from those of the reviewed processes including AFM and they need to be rigorously understood in order to achieve a higher performance of FMA finishing.

Therefore, this study starts with analysing the possible sources of AE in the FMA process, and then a symmetric experimental study was carried out to characterise the AE signals at various stages of a FMA finishing. Eventually, these allow an effective AE monitoring parameter to be determined for the online monitoring and automation of the FMA finishing process.

## 2 AE generation mechanisms

### 2.1 FMA finishing

Typically, FMA fluid is composed of nanometer scale ferromagnetic particles, abrasive particles and various necessary additives for the purpose of anti-settling and antirust [1, 2]. As shown in Fig.1 (a), in its stable suspension state it has good fluidity and therefore low grinding capacity. Once a magnetic field is applied, its rheological behaviour changes from Newtonian to Bingham plastic in milliseconds. Correspondingly its shear strength and viscosity will also be greatly increased. As illustrated in Fig.1 (b), the fluid becomes a semi-solid abrasive material which will stick to the workpiece surfaces and forms a flexible abrasive layer. When this FMA semi-solid fluid is forced by pressure differences to flow through a restrict passage in a workpiece placed under a magnetic field, abrasive particles held by ferromagnetic particle chains will scratch and shear the asperities on the passage surfaces, illustrated in Fig. 2. Thereby it achieves the purpose of precise finishing. When the FMA abrasive fluid moves away from the magnetic field it will return to normal free-flow state and is sent back to an accumulator, ready for pumping back to the workpiece for a continuous finishing process.

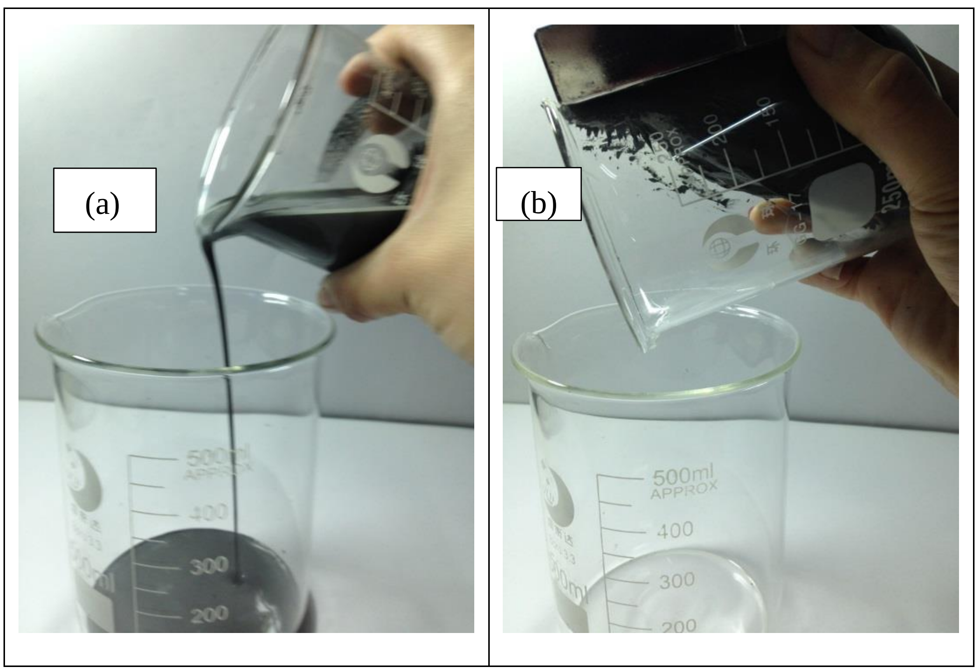



**Fig.1.** FMA abrasives (a) without a magnetic field applied, and (b) with a magnetic field

In the FMA finishing process, each abrasive particle is subject to a clamping force which is applied by the magnetic particles and a resistance forces which is provided by the workpiece. When the tangential component of the maximum clamping force acting in the abrasive particles (shear stress τ in FMA abrasive fluid) is smaller than the resistance provided by the work piece, the magnetic chain structure will be destroyed under the resistance action. When the tangential component of maximum clamping force is stronger than the resistance, the abrasive particles will be rolling and cutting the work piece surfaces. The tangential component of clamping force is sufficient to cut very small asperities, as shown in Fig.2 (a) and (b). Multiple successive particles may be required to remove larger asperities. In addition, the tangential component of the clamping force can cause tiny plastic deformation or fatigue cracks on the surface, as shown in Fig.2 (c) and (d). When the successive tiny plastic deformations superimpose and exceed the material yield limit or fatigue crack expansion, the asperities will be fatigued fractured, stripping off from work piece [2].

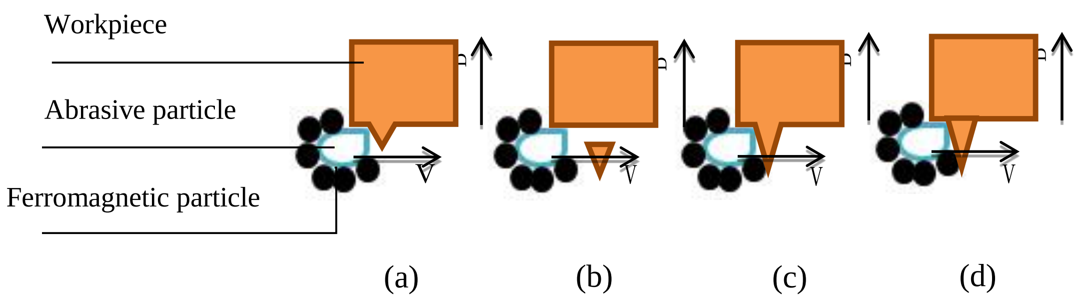



**Fig.2.** Material removal models in a FMA finishing process

(a) Abrasive particle takes a small cut on roughness peak; (b) Microchips may be removed;(c) Abrasive particle contact with roughness peak; (d) Abrasive particles roll over the surface, micro-fatigue occurs.

FMA finishing is mainly achieved through shearing forces with low positive pressure. Therefore, the number of surface asperities declines rapidly during early processing. The surface roughness and waviness values decrease along with the removal of asperities. Consequently, after the asperities are largely polished, the subsequent removal rate becomes smaller and eventually reaches a steady state in which the polishing capacity of FMA abrasive fluid declines significantly [2], indicating that the finishing process is nearly completed. However, if the finishing process continues beyond this state, abrasive particles can still grind on the surface, potentially causing new scratches on the surface which are then ground out by other abrasive particles. This means that when the surface roughness value reduces to a certain level, continuous finishing will not improve the surface but rather fluctuates within a certain range, governed mainly by the size of the abrasive particles and influenced by the magnetic field and flow rate. This means that this continuous finishing will lead to an excessive change of workpiece size. Thus, an FMA finishing process can have two stages: the desired polishing process and undesired grinding process. Therefore, it is vital to identify the transition between these two processes to determine optimally the end of the desired finishing process and avoid the waste of unnecessary finishing.

### 2.2 AE generation by FMA

As outlined in Section 2.1, the FMA finishing process is a complex micro-grinding and micro-polishing process. It can have many potential AE sources from the micro perspective point of view. Based on the understandings that AE energy is proportional to material removal rate and that it correlates to frictional interactions and impacts, the generation of AE events in FMA finishing process can be viewed to have five possible sources or mechanisms: (1) metal chip breakages; (2) sliding friction; (3) abrasive particle breakages; (4) elastic impacts; and (5) magnetic chain ruptures. As shown in Fig.3, during an FMA finishing process the interactions between abrasive particles and surface asperities result in metal chip breakages for major material removal. In the meantime, the pressurized fluid drives the particles to move relative to the stationary surface, which can produce sliding friction effects and lead to minor material removal. These two mechanisms may be regarded as the main AE sources, as they are likely to produce a much higher level of stress due to material removal in comparison with other sources. Moreover, at the early phase of FMA finishing, these two sources are more prevalent because the surface has more and larger micro asperities. With the progression of FMA finishing, these two sources will become weaker and eventually disappear when these asperities are gradually removed. This agrees with the theory that the power of AE signals depends mainly on material removal rate investigated by Ericks [14] and Dornfeild [21].

As the distribution of surface asperities usually exhibit randomness, the stress waves and corresponding AE signals generated by removing them will exhibit multiple random bursts in amplitude and the time domain. Therefore, it is possible for AE sensors with appropriate bandwidth and sensitivity to detect these AE phenomena. Comparatively, the other three sources may show more continuous features since the finishing process usually operates under a constant flow rate and a magnetic field.

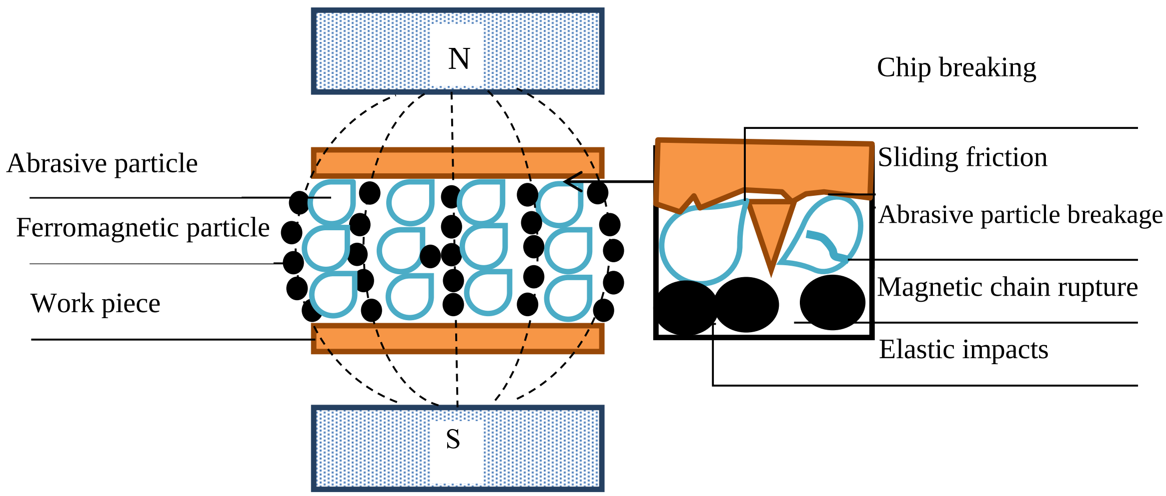



**Fig.3.** AE source illustration during a FMA finishing process

## 3 Experimental Study

### 3.1 Experimental methods

In order to verify the aforementioned theoretical analysis and develop AE based online monitoring, an experimental study was carried out based on an in-house FMA finishing test platform. As shown in Fig.4, the platform consists of a typical FMA finishing system and an AE measurement system. The finishing system has a high pressure pump to circulate the FMA fluid to flow through the target hole in the workpiece via a high pressure hose. As the workpiece is placed within a magnetic field with variable strength, the fluid rheology property is affected by the magnetic field to achieve a phase transition and hence the hardness and the shear stress of abrasive fluid will increase during the finishing process. In this way the inner surface of the hole can be polished effectively as the fluid flows through the hole. When the fluid flows away from the magnetic field, it recovers its free-flow state and goes to the fluid tank from which it can be pumped in order to continue the flow and finishing cycle.

During the FMA finishing process, a wide frequency band AE sensor, as detailed in Table 1, is mounted to the outer surface of the workpiece. With 20dB amplification the output of original AE signals is sampled at 2MHz continuously during the whole course of an FMA finishing operation. The sampled data is divided into consecutive segments, each segment lasting 5.25 seconds and saved onto hard drive. For one full FMA test process, about 200 segments were collected, which covers the whole process of about 20 minutes and hence allows the detail of AE behaviour at different finishing phases to be examined offline in order to define optimal monitoring parameters.

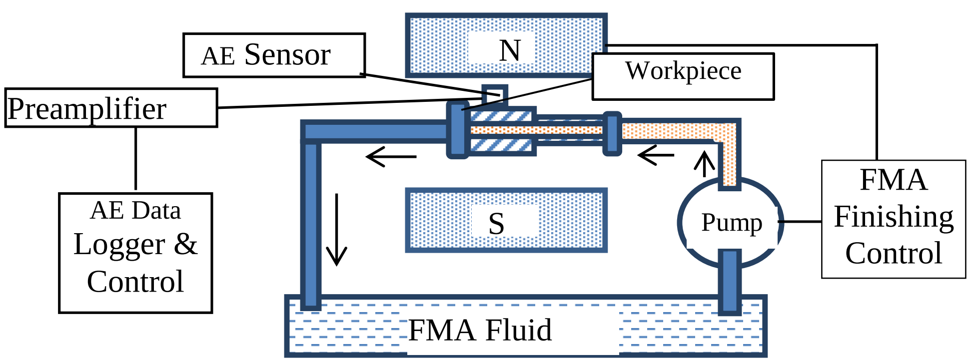



**Fig.4.** Experimental setup

**Table 1.** Experimental conditions

| **Category** | **Specification** | **Value** |
|---|---|---|
| FMA fluids | Size of abrasive particle (mesh) | 1000 |

| | | |
|---|---|---|
| | Particle size of carbonyl iron powder | 4μm |
| | Mass ratio of abrasive and carbonyl iron powder | 1:2 |
| Work piece | Workpiece material | Brass |
| | Diameter of work piece | 3mm |
| Finishing Process | Magnetic field intensity | 0.3T |
| | FMA entrance pressure | 0.6MPa |
| Signal collecting | The sensor frequency range | 100-1000kHz |
| | The sensor resonant frequency | 500kHz |
| | Sensor sensitivity | >70dB |
| | AE preamplifier | 40dB |

### 3.2 Characteristics of AE signals

Fig.5 presents representative AE signals corresponding to four typical finishing phases which are: the stationary FMA system at the time 00:00; the flow of FMA fluid but without a magnetic field at the time 00:05; the FMA finishing with a magnetic field applied at different time instants; and the FMA finishing at the completion stage, respectively. It shows that when the finishing system is inactive, shown in Fig.5 (a), the AE system has nearly zero outputs, indicating that there is no AE activities and also that the background noise of the measurement system is very low.

Once the FMA fluid starts to flow across the workpiece, the AE events are clearly observable to have two distinctive responses. As shown in Fig 5 (b), the intermittent bursts with short duration but high amplitudes indicate the major material removal, whereas continuous AE signals with low amplitudes show slight maternal removal due to fictional effects. This indicates that both the micro-grinding and micro-polishing are coexisting in the finishing process. In addition, the clear profile of periodic AE signal agrees with is the periodicity of fluid pressure impulses due to the reciprocating motions of the pump. This also indicates that the FMA finish is stronger under the high flow rates.

Once the magnetic field is applied, more AE bursts are evident in Fig 5 (c) and (d), showing the significant effect of the magnetic field on removing large asperities. This is expected according to the FMA mechanisms discussed in Section 2. It can also be observed that the periodic effect becomes less apparent because of the increase in the average pressure due to the flow throttling when the fluid begins to display the Bingham plastic behaviour. Moreover, the AE bursts have relatively smaller amplitudes but with much higher presence rates. These important changes in the AE signals indicate that the removal of material by both the micro-grinding and the micro-polishing are more uniform and rapid, which is more desirable to achieve a uniform finished surface.

As the finishing proceeds, AE bursts occur only occasionally, mainly due to particle breakages and impacts, and the continuous AE wave amplitude also becomes smaller, as shown in Fig. 5(e). This shows that the sizes of particles and asperities are balanced and only a small amount of material removal is happening i.e. the micro-polishing is more dominant. Therefore, the finishing process can be stopped. In the meantime, this also proves that the magnetic chain breakages, particle breakages and impacts are much less significant sources compared with that of metal chip breakages resulted from the finishing process.

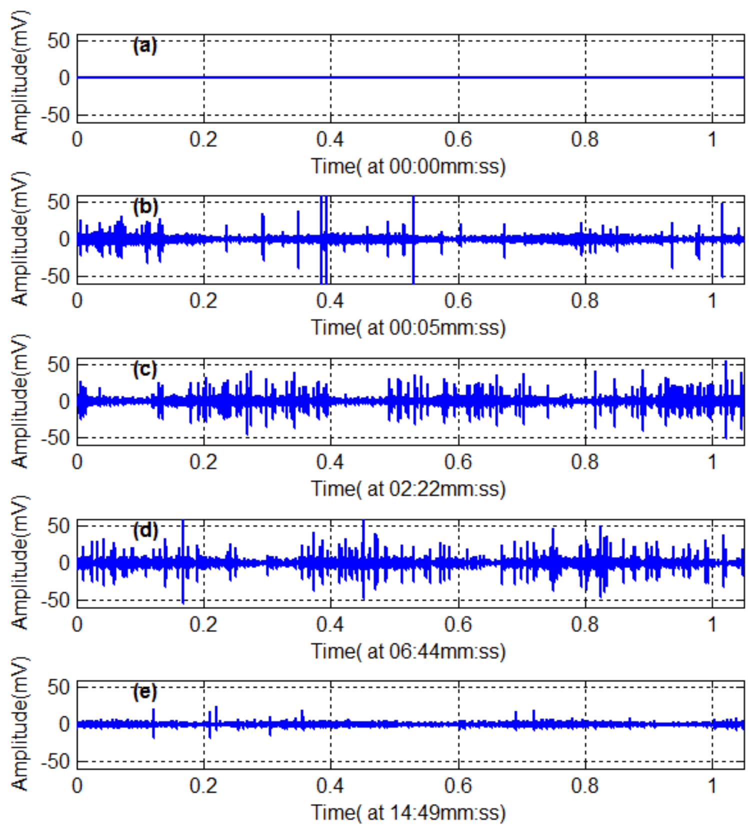



**Fig.5** AE signals at different machining phases

To further examine the correlation and characteristics of AE signals with FMA finishing, a short time Fourier transform (STFT) was applied to the signals in Fig 5 to obtain corresponding time-frequency representations (TFR) in Fig. 6. Note, there is no corresponding TFR for the stationary case, so Fig 6(a) is omitted for clarity. Clearly observed are the distinctive intermediate AE bursts which spread across wide frequency bands to indicate the major material removal. Additionally, TFRs show that the AE contents dominate around two frequency bands around 50kHz and 160kHz, highlighting the minor material removal due to the micro-polishing process. However, these frequency contents advance with finishing time at the fixed frequency values. In other words, their frequencies are relatively stable throughout the finishing process, which may indicate that the properties of the FMA fluid and operating parameters are maintained for the full process.

Moreover, the TFR without magnetic fields in Fig. 6 (b) shows wider frequency spreads for the AE bursts and stronger modulation effects for the two dominated frequency components compared with that of Fig. 6 (c) and (d) for the cases with active magnetic field. This again shows that the magnetic field makes the finishing process more uniform and efficient, which can result in a better surface finish.

In general, the magnitudes for both the AE bursts and the constant frequency components decrease gradually with finishing time. In particular, the TFR during the final phase shows fewer bursts and lower amplitude modulation profiles, indicating that the interactions between the abrasive particles and surface asperities are reduced and hence the finishing operation can be terminated.

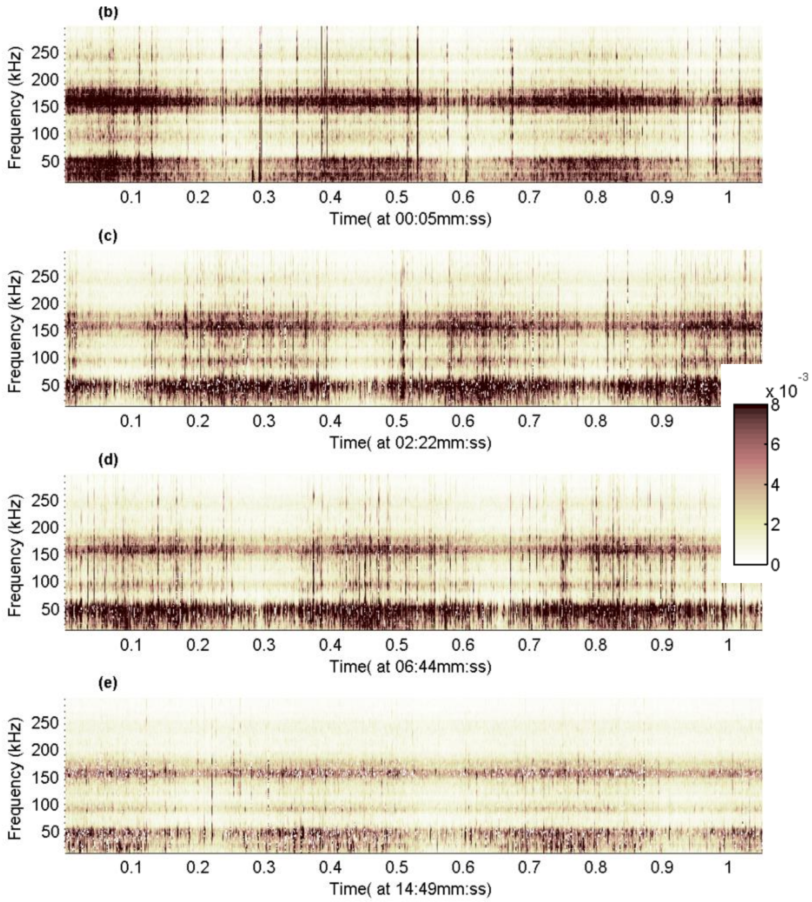



**Fig.6** Time-frequency representation of AE signals at different machining phases

### 3.3 Feature parameters for online monitoring

Based on the understanding of AE characteristics, two AE parameters are proposed to represent the AE content variation during a finishing process. The first one is the root mean squared (RMS) which is calculated based on the raw AE signal by

$$RMS(t) = \sqrt{\frac{1}{N}\sum_{i=0}^{N-1}[x(\mathrm{t}+i) - \overline{x}(t)]^2} \tag{1}$$

where $x(\mathrm{t}+i)$ is the raw AE signal at the time index *i*, *N* is the number of discrete data points in a specified time duration. For the presented study, the duration is 1.04s as it covers sufficient number of AE bursts to yield a stable values at different time instants. In addition, RMS values represent AE energy and are widely used in quantifying AE signals.

The other parameter for charactering AE signals is defined as AE burst occurrence rate (AE-BOR) to highlight the occurrence rate of the high amplitude AE bursts and can be obtained by

$$BOR(t) = \frac{1}{N}\sum_{j=1}^{M}\delta_j \quad and \quad \delta_j = 1 \quad if\ [|x(t+i)| - \Delta]^2 > 0\,. \tag{2}$$

where $\Delta$ is the predefined threshold that can be 50% of the average of RMS values during initial stage of the finishing process.

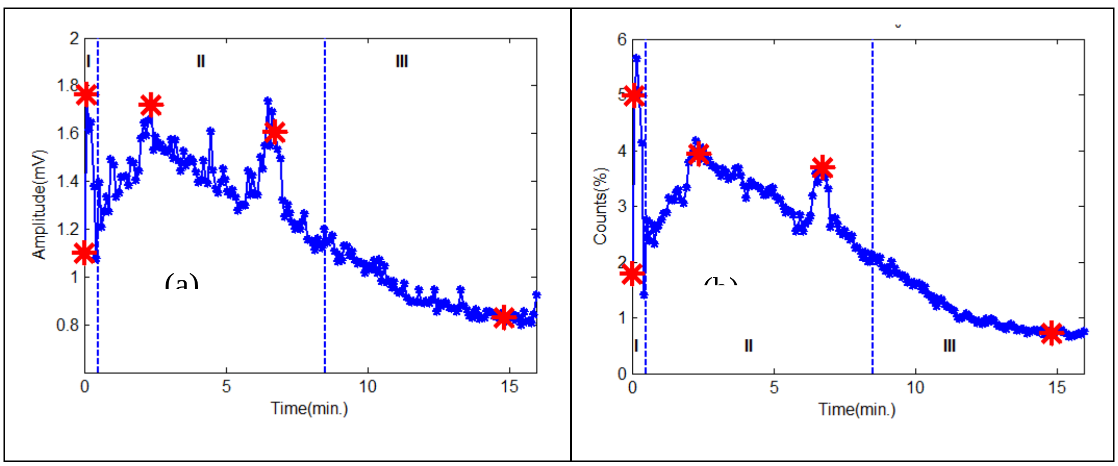



**Fig. 7** Monitoring parameters for FMA finishing process: (a) RMS values of AE, and (b) AE burst occurrence rate

Fig. 7 presents the variation in AE monitoring parameters with the increase in finishing time. It can be seen that the process exhibits three clear phases. Phase I is the finishing process when there is no magnetic field applied, in which both RMS and BOR values show higher amplitudes during approximately the first 20 seconds and then drops rapidly.

This indicates that the fluid flow-driven finishing, typical mechanism of FMA, sustains a short duration before it behaves as sliding friction. Obviously, the short duration can removes only a limited number of large asperity peaks and has little improvement on overall surface quality.

In Phase II, applying the magnetic field maintains the removal of material for a relatively long duration of about 8 minutes, which is shown by the high fluctuation of feature values. In particular, there are two occasions around 2.3 and 6.5 minutes (highlighted by asterisks in Fig 7 when major material removals happen within these short durations. The removal of relatively large asperity peaks because they can become more dominant after the gradual removal of some of the smaller asperities.

Phase III shows a monotonic decreasing trend with minor fluctuations. The signal becomes relatively level by approximately 15 minutes, showing that the material removal is very small and steady, and so it can be taken as the end of the finishing process.

The RMS responds slightly more during the small material removal period (phase III) compared with that of the BOR. It may therefore give a better indication of the transition to excessive finishing. For instance, the time instance illustrated by the marker '*' in Phase III of Fig 7.(a) can be taken as the optimal time to stop the process since the RMS values around this instant are relatively stable. Further finishing may induce excessive abrasion, which is shown by the higher RMS values at the last instant. However, the stable behaviour of BOR can be commentary parameters to show the occurrence amount of burst AE events to confirm the development of the finishing process.

### 3.4 Verification

To confirm the consistency between AE signals and surface quality, further tests were carried out to inspect the roughness values at a number of time instants and corresponding RMS values. Fig. 8 shows the correlations between the roughness values and RMS values. Clearly, there is a close correlation between the two and hence it is confirmed that AE RMS values can be a good indicator to show the surface quality dynamically. Moreover, the nonlinear correlation shows that FAM finishing is particularly effective between the roughness values from 1 to 1.5 when the cutting effect is high as particle edges have goo matches with the sizes of asperities.

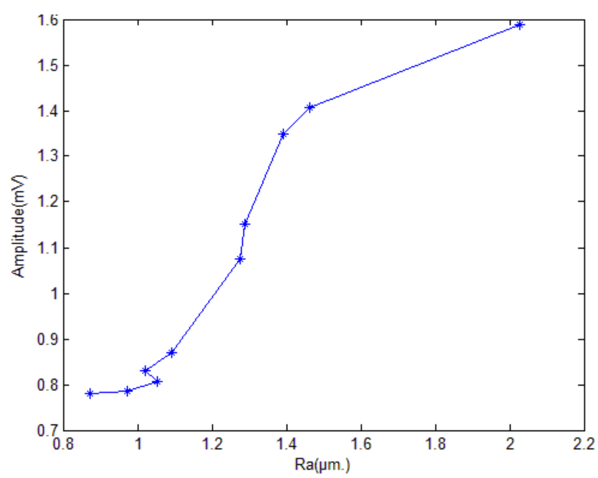
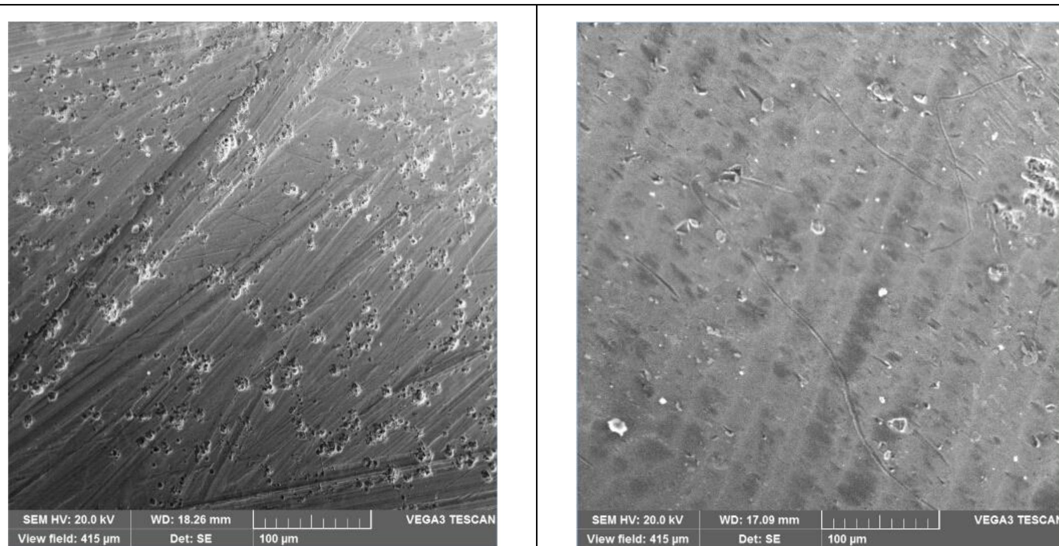



**Fig.8** Correlation between AE RMS and surface roughness

Furthermore, the microstructures were also examined by using a scanning electron microscope (SEM). Fig. 9 shows the comparison of SEM images (with 500x magnification) of the specimen before FMA finishing and after the FMA finishing controlled by the proposed RMS monitoring system. It clearly shows that after the FMA finishing process, the original drilling scratches were removed and microscopic peaks and troughs have been smoothed, resulting in a more uniform surface morphology. In addition, no excessive processing phenomenon was observed. These show that AE signals and their associated feature parameters are effective for indicating the finishing progress of the FMA finishing processes.




(a) Surface before FMA finishing (b) Surface after FMA finishing

**Fig.9** SEM image comparison

## 4 Conclusion

Material removal mechanisms in FMA finishing process can be viewed to have two main sub-processes: the grinding process in which large asperities are removed due to the cutting by metal particles, and the polishing process in which small asperities are removed by both the cutting effect and sliding friction. The former is reflected by AE larger bursts that have high amplitudes but discrete short durations, whereas the latter is indicated by continuous AE waves with lower amplitudes. Moreover, the grinding and polishing actions reduce with the progression of the finishing process as the surface becomes smoother. Those evolution processes can all be detected by changes in the AE signals in both the time and frequency domains. In the meantime, other AE effects such as particle impacts and breakages are insignificant to influence the variation of the AE characteristics relating to the finishing.

The validation test results show that the RMS values and burst occurrence rate values from AE signals exhibit fluctuation in the early phase of the finishing process but approximate to monotonically decreasing trends in the latter stages of the finishing process. Thus, monitoring these trends online allows the implementation of process automation and quality control, confirming that the AE-based online monitoring system is a promising solution.

# Acknowledgments

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