Investigation of AE Features in Grinding

Xun Chen¹ᵃ, Arif Mohamed²ᵇ and Akinjide Oluwajobi³ᶜ

¹ General Engineering Research Institute, Liverpool John Moores University, Liverpool L3 3AF, United Kingdom
² Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, Nottingham NG7 2RD, United Kingdom
³ School of Computing and Engineering, University of Huddersfield, Huddersfield, HD1 3DH, United Kingdom

ᵃ x.chen@hud.ac.uk, ᵃᵇ eaxam2@nottingham.ac.uk, ³ᶜ j.o.oluwajobi@hud.ac.uk

Abstract. This paper presents recent investigation of acoustic emission (AE) behaviours in grinding processes. It demonstrated the acoustic emission features characterized in time and frequency domain are influenced by thermal behaviours of materials. By control laser conditions, the temperature elevation under laser irradiation can be similar to that in a grinding process. Therefore, an innovative concept that grinding process can be monitored by using thermal AE signatures from laser irradiation tests has been proposed. Accordingly, an artificial neural network (ANN), built on laser irradiation tests, was applied to monitor grinding thermal performance. The results showed that grinding performance variation due to wheel wear can be identified by using the ANN. This development could bring great benefits by reducing experimental works in the preparation of an ANN for grinding monitoring.

1. Introduction
Grinding is a material removal process using bonded abrasive grits as cutting media. To maintain a high efficient grinding process, the grits on the wheel surface need to be sharp. Tönshoff et al [1] reported that the thermal, mechanical and chemical effects in the grinding contact zone can cause wheel wear leading to different grinding behaviours. When a grinding wheel wears, the grits on the wheel surface become blunt, which reduces the grit penetration depth and the material removal rate [2]. This is a significant problem in grinding. The grinding wheel wear occurs in three different mechanisms: grit attritious wear, grit fracture and bond fracture. They take place simultaneously in different proportion during grinding.

The attritious wear develops wear plateau on the grits which are the results of mechanical abrasion and chemical reaction between abrasive grain and workpiece surfaces due to frictional interaction. The wear plateaus reduce grit sharpness and protrusion height leading to wheel glazing which is often the indication of the end of wheel life [3, 4]. Blunt grits often cause higher grinding temperature leading to grinding burn and workpiece material damage.

Jackson et al [5] reported the grit fracture occurs as results of mechanical forces of chip formation, or thermal shocks by instantaneous high temperature. Bond fracture occurs by dislodging the abrasive from the bond due to the chip formation forces and the friction between the chip and the wheel bond. The bond and grain fractures occur simultaneously during grinding. Fracture wear could normally
bring new sharp grits engage with material removal. But severe grit dislodging could cause wheel form lose leading to grinding chatter.

The grits are continuously abraded, fractured, or dislodged from the bond, new grits are exposed and the combination of cutting, ploughing and rubbing is changing continuously. If the grit and bond fracture does not occur during grinding then the plateau area on the grit widens and the attritious wear rate increases. Blunt grits will be more difficult to penetrate into workpiece materials leading to high proportion of rubbing and ploughing in grinding. A high percentage of the energy used for rubbing and ploughing goes into the workpiece, but when chips are formed, 95% to 98% of energy (heat) goes into the chip [6]. This affects the grinding thermal performance significantly. If fracture delayed further, as with hard grinding wheels, then the wheel become glazed. The workpiece may thermally be damaged due to higher temperature caused by higher percentage of rubbing and ploughing in grinding.

The measurement of grinding zone temperature directly is a very difficult task. Different sensing techniques have been tried to detect grinding burn as it is the most common type of thermal damage during grinding [7, 8]. The application of acoustic emission (AE) sensors has become very popular over last few decades. An AE signal can be defined as the transient elastic energy spontaneously released in materials undergoing deformation, fracture or combination of both [9]. The AE in grinding is a type of elastic energy which is released due to material particle displacement under stresses during grinding[10]. The AE sensor has much higher sensitivity and responsive speed compare to force or power sensors because the AE phenomenon is related to the elastic energy release at a very high frequency range. The AE signal can easily pick up an event occurs in materials that are related to grinding burn [10]. The commonly used AE feature parameters for the AE are the peak of RMS values, crest factors analysis (i.e. the ratio of the peak to the RMS level of a signal), kurtosis analysis and moving average technique. The advantage of AE sensor is easy to mount and works at relatively low cost. There is no negative influence on the stiffness of the machine tools and is even capable of transmitting a signal from its rotating parts.

Liu et al [8] investigated grinding burn on nickel based alloy (CMSX4) using AE signals and a thermocouple. In their research, they separated thermal induced AE signals from other AE signals in grinding by using a laser irradiation simulation method. The features of AE at high and low grinding temperatures were identified in relation to grinding burn or no burn situation. The Short Time Fourier Transformation (STFT) and Wavelet Packet Transforms (WPTs) were applied to extract the features of an AE signals in the time and frequency domains. It has demonstrated that thermal AE signals have different feature under different temperatures. Focusing on these features, an artificial neural network (ANN) model with the back-propagation learning rule had been developed for the classification of burn and no burn in the grinding process [11]. All aforementioned ANN models used in grinding monitoring were trained directly from the AE signals in grinding processes, which included not only thermal AE signals but also mechanical AE signals from mechanical deformation of materials and machine tools as well as environment noise. Therefore the application of these models is case dependent. When application conditions change, the ANN models have to be trained again.

The temperature of grinding is a function of the sharpness of grits on the wheel surface. As grinding continues, the wheel surface will change due to different wear processes. Therefore monitoring grinding thermal behaviour can reflect the status of wheel wear. This paper present the feasibility study on using thermal AE features to monitor grinding thermal performance in relation to wheel wear. The research focuses the detection of high, medium and low grinding temperatures to demonstrate the influences of wheel wear on the grinding temperature. As the thermal AE features in grinding and laser irradiation are similar, it is possible to train an ANN using laser irradiation tests and then apply trained ANN to grinding monitoring.

2. Extraction of Thermal AE Features through Laser Irradiation
In order to investigate thermally induced acoustic emission in grinding, it is important to have a pure thermally induced acoustic emission for the AE feature analysis. When laser irradiated on a material sample, the quick temperature elevation will create extreme high thermal stress in the sample. Such
high thermal stress will cause a pure thermal acoustic emission. A series of laser irradiation tests was undertaken in a Lumonics JK704 Nd: YAG laser machine. This experimental rig consists of an AE sensor, thermocouple and nickel alloy samples of Inconel 718 and MARM002. An E-type of thermocouple is positioned at the laser irradiation spot on the front surface of the test sample and an AE sensor is placed at the opposite side of the workpiece as shown in Figure 1. The thermocouple of E-type (commercially available) covers a linear temperature response range from -40 °C to +900 °C. The thermocouple temperature measuring system was calibrated with sensitivity 10 mV/ºC. A Physical Acoustic WD sensor (responsive frequency range 100 kHz to 1 MHz) was used for AE signal detection. To reduce the amount of tests, the laser irradiation tests only set three levels of off-focal distances (34 mm, 40 mm and 46 mm) to provide different laser power densities. When laser were applied on the nickel alloy samples, pure thermal AE signals emitted in relation to different levels of temperatures elevation.

![Laser irradiation setup and schematic diagram of optical arrangement.](image)

**Figure 1.** Laser irradiation setup and schematic diagram of optical arrangement.

The conditions of laser irradiation experiment are presented in Table 1. The laser power density is the function of the off-focal length. When laser pulses focus on a point on the surface, it can be considered as a point source of heat. When the focal point moves off the sample surface, the laser power density will reduce as indicated in Eq. 1; where \( P_0 \) is laser total power; \( E_0 \) is laser total energy; \( \omega_1 \) is the initial waist radius of the laser beam; \( \omega_2 \) is the laser spot radius; \( f_1 \) is the laser focal length; \( f_2 \) is the laser off-focal length. When absorbing the laser heat energy, the workpiece thermal expansion emits acoustic emission waves which are purely related to material thermal performance. During the Laser irradiation tests, the AE sensor will convert thermal AE wave into a voltage signals which were amplified by the preamplifier and stored in a computer for further analysis. The signals are sampled at 5 MHz with Kaiser Filter.

| **Laser Parameter** | **Conditions** |
|---------------------|----------------|
| Laser               | Lumonics: JK 704Nd:YAG |
| Wave length         | 1.06 µm         |
| Pulse energy        | 1.5 J           |
| Maximum peak power  | 2.5 kW          |
| Irradiation time    | 0.6 ms          |
| Focal length        | 120 mm          |
| Light beam diameter | 12 mm           |
| Off-focal length    | 34, 40, 46 mm   |
A model of surface temperature was developed based on the thermal energy absorption during laser irradiation [12].

\[
T(0, t) = \frac{2I_0}{K} \eta \left( \frac{\kappa}{\pi} \right)^{1/2}
\]

where \( I_0 \) is the density of laser peak power; \( K \) is the thermal conductivity; \( \kappa \) is the thermal diffusivity; \( t \) is the time that the laser irradiates on the material surface; \( \eta \) is the absorption coefficient. The absorption coefficient was calculated approximately as 19.16% for Nd: YAG laser for nickel based alloy [8, 12]. The equation 2 shows the surface temperatures under laser irradiation depends on laser power density, irradiation time and the absorption coefficient. The higher power density, longer irradiation time and higher absorption rate will give higher surface temperature. The condition of the laser tests were chosen to make the temperature elevation on the sample surface similar to that in grinding. A set of experimental surface temperature results is shown in table 2, where temperature rise scale are classified as high, medium and low according to the laser off-focal distances for further analyses.

### Table 2. Temperature calibration results.

| Laser offset (mm) | Inconel718 (°C) | MarM002 (°C) | Temperature rise scale |
|-------------------|-----------------|--------------|------------------------|
| 34                | 698             | 493          | high                   |
| 40                | 324             | 318          | medium                 |
| 46                | 239             | 235          | low                    |

The short time Fourier transform (STFT) signal processing technique is applied to extract the thermal features of AE signals in laser irradiation tests. After signal processing, the results in Figure 2 and figure3 show that the AE data extracted from 34 mm offset distances has higher amplitude at higher frequency range than that extracted from 46 mm offset distances. This means the AE frequency features will shift to higher frequency range when temperature increase. The figures also show that AE features of different materials are different, which indicates the influence of material properties.

![Figure 2. STFT results of AE signal from laser irradiation on Inconel 718.](image-url)
3. Extraction of Thermal AE Features in Grinding

The grinding experiments were undertaken on a Makino A55 machine centre as shown in figure 4. The experiment aimed to provide grinding AE signatures in relation to grinding temperature on grinding aerospace materials (Inconel718). The AE sensor was placed on the workpiece to detect the AE responses. Other grinding behaviours were also monitored including force, power and vibration. The sampling rate for AE signal sampling was set to 5 MHz to ensure that there was no aliasing. Two surface grinding trials with different depth of cut were carried out to illustrate the AE features in relation to grinding burn. The grinding speed was 55 m/s, federate is 1 m/min and depths of cut are 0.02 and 0.2 mm. No coolant applied in grinding. Figure 5 and figure 6 illustrate the STFT features of the grinding AE in relation to grinding workload. Though grinding of different materials gives different AE features, it is clear that larger depth of cut (represents higher temperature) gives high AE amplitude at higher frequency range. Such feature is similar to what was found in laser irradiation tests. Such similarity of AE features in grinding and laser irradiation provide a foundation for a new grinding monitoring method. The idea is to use an ANN model trained by laser irradiation AE signal as a classifier to detect thermal AE signals in grinding process that represent grinding temperature at different level. Compare to the AE features in figure 2 and figure 3, the difference of AE features in figure 5 and figure 6 demonstrate the grinding AE signals are not pure thermal AE signals. As grinding wheel condition changes due the wheel wear, grinding temperature will change accordingly. Therefore, the variation of AE signals from different sources should illustrate the effects of the wheel surface condition change.

![Figure 4. STFT results of AE signal from laser irradiation on MARM002.](image)

![Figure 3. STFT results of AE signal from laser irradiation on MARM002.](image)
4. Grinding Monitoring using a Thermal AE Feature Trained Artificial Neural Network

The neural network tool has been used since the 1960s [13]. The advantages of neural networks over pattern recognition are that it can easily constitute optimum nonlinear multi-input functions for pattern recognition and the accuracy of pattern recognition is easily improved by learning processes. In this research, a back propagation neural network has been applied to classify high, medium and low temperatures in relation to grinding burn. During the ANN training process, the STFT of AE data from laser irradiation tests were used as inputs with the outputs being high, medium and low temperatures. Once the network architecture has been defined, the network can be created and optimised according to its error function.

The training data set consisted of thermal AE data which were extracted from the laser irradiation tests. The input data consists of AE data extracted from 34mm, 40mm and 46mm off-focal distances which are concatenated together as training input. The target vector in relation to the network was defined in such a way that the high temperature was assigned a value of 3, medium temperature was assigned a value of 2 and the low temperature was assigned a value of 1. The outputs of the trained
network represented each case correctly as shown in figure 7, where the straight line is defined target value and points of circles are actual outputs.

![Training Results: Laser AE data(Inconel718)](image)

**Figure 7.** The learnt training set for a NN classification system.

Once the network has been trained by laser thermal AE data, it becomes a classifier to identify different material behaviours under different temperature elevation. Therefore the trained ANN can be applied for grinding monitoring using the AE data extracted from grinding experiments. Six grinding trials were arranged on an Inconel 718 sample with 0.02 mm of depth of cut, 1 m/min of workspeed and 55 m/s of grinding speed in a sequential manner. The wheel was dressed only once just before the trials. Thirty sets of AE feature data were extracted from each grinding test using STFT technique. By using trained ANN, the proportion of different thermal AE features represent different temperature levels are listed in Table 3 presents.

| Material :Inconel718 | cut1 | cut2 | cut3 | cut4 | cut5 | cut6 |
|----------------------|------|------|------|------|------|------|
| Depth of cut: 0.02    | 30 set | 30 set | 30 set | 30 set | 30 set | 30 set |
| ANN output value = 3  | 3.33% | 0 | 0 | 0 | 0 | 13.33% |
| ANN output value = 2  | 60.66% | 70% | 30% | 56.66% | 50% | 83.33% |
| ANN output value = 1  | 30% | 30% | 70% | 43.34% | 50% | 3.33% |

ANN output value: 1 – low temperature; 2 – medium temperature; 3 – high temperature

Due to the random nature of grit positions on the wheel surface, the instant grinding temperature in relation to individual grit may vary significantly. Therefore the AE signals in each grinding trial may present different proportion of thermal features that represent different temperatures. Such information is particularly useful for grinding wheel wear monitoring. From looking at Table, it can be seen that 60.66% AE data are classified as medium temperature and 30% AE data are classified as low temperature in the first cut. Only minute AE signals (3.33%) illustrated high temperature features. This may be due to some multi-edge grits may act bluntly right after wheel dressing. After initial wheel wear stage, these grits will dislodge and the wheel surface will settle in a stable sharp status as it can be seen in the 2\textsuperscript{nd} cut. The newly dressed wheel wears quickly as the sharp edges of the grits are quickly worn away. As grinding continues, the wheel will keeping its sharpness because the self-sharpening ability. The grinding temperature will keep low until the wheel reach its life as shown in cut 6, where the proportion of high temperature increases. From this example, it can be concluded that grinding performance can be monitored by using the thermal AE feature identified from laser irradiation test. By applying this method preparation of ANN for grinding monitoring could be much easier and cheaper, because grinding trials can be eliminated for ANN training.

---

25th International Congress on Condition Monitoring and Diagnostic Engineering
Journal of Physics: Conference Series 364 (2012) 012090
doi:10.1088/1742-6596/364/1/012090
5. Conclusion
The investigation had leaded a new method for grinding process monitoring. It has clearly shown that thermal induced AE signals in a material have similar features irrespective of heat sources from laser irradiation or grinding. Because grinding wheel wear has a great influence on the grinding temperature, the AE features extracted from laser irradiation can be applied to grinding monitoring. The feasibility of using thermal AE features learnt from laser irradiation to monitor grinding wheel wear has been demonstrated in this paper. With the support from trained ANN, it has clearly demonstrated the grinding thermal performance in relation to wheel wear behaviours. This provides an innovative concept that could save many grinding experiments in ANN training for grinding process monitoring, since the laser irradiation test is independent from grinding conditions.

References
[1] Tönshoff H K, Friemuth T and Becker J C, 2002, CIRP Annals - Manufacturing Technology. 51(2): p. 551-571.
[2] Tawakoli T, et al., 2009 Advances in Abrasive Technology Xii, 76-78: p. 21-26.
[3] Malkin S, 1989 Grinding Technology - Theory and Application of Machining with Abrasives, Dearborn, Michigan: Society of Manufacturing Engineers.
[4] Chen X, 2002, Journal of Engineering Manufacture, Proceedings of IMechE, Vol.216, B2, p. 829-832.
[5] Jackson M J, 2007, Modelling of fracture wear in vitrified cBN grinding wheels. World Academy of Materials and Manufacturing Engineering.
[6] E. Paul DeGarmo, J.T.Black, and R.A. Kohser, Materials and processes in manufacturing. 10th ed. 2007: Wiley.
[7] Wang Z, et al., 2001, International Journal of Machine Tools and Manufacture, 41(2): p. 283-309.
[8] Liu Q, Chen X and Gindy N, 2006, International Journal of Machine Tools and Manufacture, 46(3-4): p. 284-292.
[9] Dornfeld D A and Kannateyasibu E, 1980, International Journal of Mechanical Sciences, 22(5): p. 285-296.
[10] Chen X, Griffin J and Liu Q, 2007, International Journal of Manufacturing Technology and Management, v. 12 (1-3), p. 184-199.
[11] Griffin J, Limchimchol T and Chen X, 2006, Proceedings of the 12th Chinese Automation & Computing Society Conference in the UK, p. 211-216.
[12] Steen W M, 2003, Laser Material Processing. 3rd ed. Springer.
[13] Duda R O, Hart P E, and Stork D G, 2001, Pattern Classification, 2nd Edition. John Wiely & Sons, INC.