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Use of Acoustic Emissions to Detect Change in Contact Mechanisms Caused by Tool Wear in Abrasive Belt Grinding Process

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Abstract

Abrasive belt tools are widely used for finishing processes, where the abrasive grains on the belt tool serve as the cutting edge to remove materials. The interaction between abrasive grain and the material surface might result in three contact mechanisms, i.e. rubbing, ploughing and cutting, where their nature are not fully understood. On the other hand, the performance of a coated abrasive belt tool is highly affected by the grain wear. A single grain scratch test with different abrasive grain wear conditions is conducted to explore the three contact mechanisms. Through scratch experiments of prismatic Aluminium Oxide (Al_2O_3) grain on Aluminium 6061 workpiece, Acoustic Emission (AE) frequency signatures that correspond to the three mechanisms are examined. Dominant frequencies and energy signatures occupied by the three contact mechanisms are analysed using Short-Time Fourier Transform (STFT). The energy content of the dominant frequency signatures revealed that the cutting mechanism is more predominant on belt tool with new grains, which gradually becomes less significant as the grain wears. A similar trend is also observed in ploughing and rubbing modes with respect to the wear flat level of the belt tool. The general conclusion suggests that the intensity of contact mechanisms changes according to the condition of the abrasive grain, i.e. tool wear, and can be correlated with AE sensor data.

Keywords: Coated abrasive machining; Material removal modes; STFT; Tool wear;

1. Introduction

Abrasive finishing is a tertiary manufacturing process employing multiple grain tool with geometrically indeterminate edges for cutting. While rigid abrasive tools are well-known for the capability of self-sharpening and regeneration with the degradation of the outer abrasive layer, they do not conform to the shape of the component surface, which lead to the loss of the form as illustrated Fig.1. On the other hand, compliant abrasive tools outweigh rigid abrasive tools as they conform to the shape of the surface profile due to their compliance. Compliant abrasive tools in the form of a disk, flap wheel and belt are widely used in industries for tertiary finishing operations of complex geometry parts, e.g. turbine blades. The coated abrasive layer is fastened around an elastomer contact wheel, which enables the grinding process to machine free-form surfaces owing to its capability to adapt to the workpiece geometry. However, unlike rigid abrasive tools, the grains are not regenerative, which makes the grain layer to wear with cycle time. As the grains in the coated abrasive tool approach the end of its life, the deterioration in the surface quality of the machined workpiece will also be noticeable. Fig.2 illustrates a cross-section and components of a coated abrasive tool, which includes an abrasive grain type, backing material and base coat.

The material removal intensifies when the number of the interaction of the abrasive grains per unit time is maximised [1]. However, the efficiency of the coated abrasive tool will drop with grain wear on continuous grinding. Newer abrasive grains exhibit a better ability to achieve higher cutting depth that result in higher material removal compared to that on worn-out grains. In turn, the wear and breakdown of abrasive grains consequently will decrease the material removal rate and surface integrity. Wear of the abrasive is nearly impossible to be compensated for, and it will lead to a variation of the number of active cutting edges on the tool and degradation in the surface quality. Therefore, understanding the stages of abrasive grain wear in coated abrasives and corresponding contact mechanism will facilitate us in optimizing the performance of the process and predicting the tool life in real-time.

Fig.1. Comparison of the difference in contact characteristics of rigid and compliant finishing tools.

Fig.2. Schematic of the cross-section of the coated abrasive tool.

In recent years, utilizing a belt grinder on a robotic system arm has emerged in finishing process applications of complex geometry parts like turbine blades. Mezghani et al. [2] confirmed that the transition in material removal mechanism could be associated with a change in the abrasiveness properties of the abrasive grains in connection with the produced surface condition based on its abrasion energy or applied pressure. The material removal is directly influenced by the topography of the grains in the belt surface, which determines the depth of penetration during belt grinding.

However, due to the nonlinear nature of the process, some aspects of the contact mechanism in compliant belt grinding processes are not fully understood [2, 3]. Grinding mechanics are easily affected by minuscule variations in the geometry of the abrasive grains, which require high sensitive sensors to observe the variation. AE sensors are commonly used to optimise, understand and control processes such as in grinding [4-6]. In [7, 8], the frequency spectrums from AE sensor reading during single grain scratch experiments have been shown to be an effective means to characterise the material removal phenomenon. Caesarendra et al. [9] presented that AE energy is the most sensitive feature for monitoring wear in slew bearing running at low rotational speeds. AE energy in specific frequency bands provide rich information on the wear condition compared to other AE time-domain features such as RMS, Average Signal Level (ASL) and hit count.

The main objective of this research is to investigate the dominant contact mechanism with respect to the granularity of the abrasive grain using AE sensor. The frequency ranges at which rubbing, ploughing, and cutting occur will also be investigated. By understanding the relationship between the frequency characteristics and contact mechanisms on tool wear state, the remaining useful life (RUL) of the belt tool, together with its performance can be sketched out in real time.

This paper is organised as follows: a brief overview of the coated compliant abrasive process and the problem statement is presented in Section 1, followed by a brief outline of belt grinding process, contact mechanism and STFT in Section 2. The scratch tests and corresponding frequency components for the three modes of the contact mechanism are reported in Section 3. The machining conditions and belt grinding experimental setup are discussed in Section 4. Results of the belt grinding tests investigated using the energy of the frequency components for different tool states are summarised in Section 5. Finally, the conclusions of this research work are reviewed in Section 6.

2. Theoretical basis

2.1 Abrasive belt grinding process

Abrasive belt grinding is a variant of traditional rigid grinding processes where the contact wheel consisting of a thermosetting elastomer acts as a compliant tool. The tool can be deformed to machine intricate shapes and geometry [10]. The tool consists of a coated abrasive belt that functions as a cutting edge that is fastened around, at least, two rotating polymer contact wheels as illustrated in Fig.3. Due to continuing grain wear, the surface quality of the machined workpiece gets degraded. The changes in material removal rate in the coated abrasive belt grinding are primarily attributed to the formation and the increase of the worn flat area on grain tips [11]. Hamann [12] proposed a linear mathematical model that indicates the relationship between the overall material removal rate and the belt wear factor. Khellouki et al. [13] revealed the effect of abrasive grain wear on surface texture in the belt finishing process and concluded that the material removal rate changes with the wear level of abrasive grains. The studies on the effects of belt finishing parameters, e.g. abrasive and cutting parameters, on surface finish quality suggest that the granulometry of abrasive grains is also high significant factor [14, 15]. Material removal in belt grinding, like any other abrasive processes, is the result of three physical mechanisms, the so-called rubbing, ploughing and cutting [2, 16]. However, based on authors' knowledge, in literature, studies on belt grinding processes have not emphasised on quantifying the abrasive grain wear to the three contact mechanisms.

Fig.3. Schematic of a typical belt grinding process.

2.2 Contact mechanisms

Abrasive grains have a negative rake angle that allows high specific energy at the machining point. As the force is applied, the abrasive grain tip penetrates the workpiece, resulting in a plastic flow of the material after the elastic deformation phase is surpassed. The minimum chip thickness in any abrasive machining process corresponds to the grain cutting depth on the workpiece material. However, as a result of the complex interaction between the abrasive grain and the workpiece material, many events occur in the interaction zone, as illustrated in Fig.4. Of the various events occurring in the interaction zone, only three events, namely rubbing (surface modification), ploughing (material displacement) and cutting (material removal), are significantly responsible for material removal [2, 7, 17]. The three modes of contacts are illustrated in more detail in Fig.5. Rubbing is typically characterised by the interaction of the grain with the surface without any plastic deformation, i.e. it does not leave any mark on the material surface. As the interaction of grain increases, it results in more plastic deformation, which manifests itself in two phenomena, namely cutting and ploughing. Ploughing results in only plastic deformation that forms

dislocated material as typically indicated by a continuous groove with ridges on the workpiece. When the interaction between grit and workpiece intensifies, it results in the formation of the chip via plastic deformation referred to as cutting. The forces at the contact points between the abrasive grains and machined surface give rise to severe plastic deformations. The interactions of individual grains with the workpiece cause compressive and tensile loading of the workpiece.

Fig.4. Schematic representation of various events that occur in the grinding zone.

Fig.5. Various interactions in the grinding zone as a result of three contact mechanisms.

Transition in contact mechanism can be associated with a change in the geometry of the abrasive grain [2, 18]. On the other hand, the interaction between abrasive grain and the workpiece is related to the material stress release process, which eventually emits specific acoustic waves. The grinding process can be monitored by analysing the spontaneously released transient elastic energy as the materials undergo deformation or fracture, or a combination of both [6, 8, 19]. These transient elastic energy components are typically associated to high frequency contents, which can be captured using AE sensors, which are sensitive to high frequency signals. Therefore, the evolution of the contact mechanism associated with the grain can be continuously monitored in real time using AE sensors.

2.3 Short Time Fourier Transform (STFT)

Fast Fourier Transform (FFT) analyzes the frequency contents over the duration of the extracted signal. However, the results do not localise the frequency content in the time domain. Thus, it is not suitable for non-stationary signals. Short Time Fourier Transform (STFT) is a practical tool for time-frequency representations.

Fig.6. Window and overlap used in STFT.

STFT is technically a Fourier-based transformation technique that determines the frequency and phase contents of local sections in a signal as it evolves over time [24]. STFT processes the entire set of a signal by splitting it into several fixed time sections (windows) and applying Fourier Transformation at each section iteratively. This will result in sets of spectrum for each window, as illustrated in Fig.6. STFT has been used to represent the degradation condition of the slew bearing from non-stationary vibration signals [25]. It also has been used to identify features for condition monitoring of grinding wheel wear from force signals [26]. Torres and Griffin [27] used STFT to correlate elastic and plastic contact mechanisms to control the grinding dressing ratio. However, the performance of STFT depends on the shape and size of the employed window. Wider windows give proper frequency resolution while narrower windows give good time resolution. A choice of suitable window function (such as Hamming or Kaiser window) in STFT will help to provide quick and accurate results.

3. Material removal modes

3.1 Single grain groove measurement analysis

Single grain scratch tests were carried out to identify the dominant physical contact mechanisms and their corresponding material removal modes during the evolution of grain wear. A single Aluminium oxide (Al_2O_3) abrasive grain holding fixture was designed to hold the prismatic grain firmly and to provide a protruding feature for the experiment, as shown in Fig.7. A specially designed fixture mounted on a CETR tribometer setup as shown in Fig.8 was used to experiment the single grain cutting interaction. The single grain scratch experiments were carried out with a normal force of 5N, reciprocating length of 4 mm and with a slider speed of 12.5 mm/sec. All scratch tests were performed on Aluminium (Al-T6061) workpieces with uniform surface conditions to allow for a consistent groove cut area measurement to signify all material removal modes.

Fig.7. Dimensions of aluminium oxide (Al_2O_3) grain considered for single grain scratch.

Fig.8. Tribometer experimental setup for single grain scratch test.

Three states (State 1, 2 and 3) of Aluminium oxide (Al_2O_3) abrasive grain representing different wear levels from new to the worn-out grain respectively, as shown in Fig.9, were used in the scratch tests. The tests were carried out by feeding the Aluminium oxide (Al_2O_3) grain fixture through a slider driven along X-axis towards the flat aluminium sample and eventually a scratch groove will be generated on the surface. Removal of material during the scratch pass depends on the cutting action of a single grain to workpiece interaction. Depending on the wear flats of the single grain, the cutting depth would vary to the abrasive grain states considered. The contact mechanisms in a single grain scratch experiments are quantified in terms of the material and groove geometry, as indicated in Fig.10.

Fig.9. Evolution of the grain geometry after successive grinding

Fig.10. Schematics of dominant contact mechanisms and corresponding material removal modes in single grain scratch experiments.

Fig.11. Comparison between scratch profiles acquired in 3D and 2D from three different aluminium oxide (Al_2O_3) grain states.

Physical material removal modes, i.e. rubbing, ploughing and cutting, were justified by measuring the material profile from scratch tests and by comparing the volume of material displaced in the groove and the ridge. Talyscan Profiler was used to provide an accurate 3D measurement of the single grain scratch groove. Referring to Fig.11 as one of the experimental results, it is evident that the mechanism of material removal progresses more towards ploughing and rubbing from cutting action as the grain starts to wear down. The type of contact primarily influences the single grit scratch experiment results. The type of contact is defined by the shape, geometry of the grain and hardness property of the surface. It is to be noted that varying any of the above will have significant change in the groove and ridge geometry.

3.2 Dominant frequencies in different material removal modes

As we have discussed in the previous sections, contact mechanism at microscale during the grinding process comprises rubbing, ploughing and cutting stages [28-30]. A scratch test was carried out on a new Aluminium oxide (Al_2O_3) single grain using CETR tribometer setup to characterize the contact mechanisms, as shown in Fig.8 on listed conditions in Table 1. The scratch groove was initiated by the rubbing mechanism followed by the combination of ploughing and cutting as illustrated in Fig.12.

Table 1. Single grain scratch test conditions

Scratch parameter	Condition
Depth of cut	66 $\mu\text{m}/\text{sec}$
Slider speed	15 mm/sec
Workpiece material	Aluminium 6061
Abrasive grain material	Aluminium oxide
AE sensor range	25 kHz–450 kHz (Vallen VS45-H)
Data acquisition rate	5 MHz

The scratch groove was measured using Talysurf profilometer and as shown in Fig.13, there is a transitional mode observed from ploughing to cutting stages based on the chip formation. Initially, when the grain starts to interact with the workpiece surface, the normal force and elastic deformation of the workpiece is minimum as the grain slides on the surface, which represents the rubbing phase. Subsequently, as the depth of cut increases, the vertical force becomes immense. The grains that are pressed against the surface cause plastic deformation, which results in the grain ploughing the material. Finally, when the cutting depth increases, the vertical force and stress become much more significant, which results in a cutting process and chips creation from the workpiece. In this experiment, frequency signatures from the AE sensor reading of the three contact mechanisms will be investigated. Based on experimental conditions, for a ≈ 35 mm of the scratch, the groove depth would be $\Delta h \approx 154 \mu\text{m}$ as shown in Fig.12. However, it is to be noted that the depth of cut is influenced by the hardness property of the material as well as the tribometer scratching parameters.

Fig.12. Three stages of chip generation on the surface.

Fig.13. Scanned scratch profile using profilometer.

The AE sensor is placed as close as possible to the workpiece and the grain interaction zone. Fig.14 schematically illustrates how the AE signals were connected to the data acquisition system. The collected signals from the AE sensor were passed through pre-amplifiers with a gain of 38 dB to boost the magnitude and to filter any noise from the environment. The amplified AE signal is passed to a bandpass filter that passes frequencies between 25 kHz and 450 kHz.

The AE signal recorded from the scratch test is shown in Fig.15. It should be noted that the AE intensity starts to rise at the instance the grit starts to interact with the surface. The frequency spectrum of the AE signal, as shown in Fig.16, suggests four principal peak frequencies at four distinct bands, i.e. at band 1 (25–75 kHz), band 2

(75–125 kHz), band 3 (125–220 kHz), and band 4(220–350 kHz) that might be associated to the material removal modes. In general, the results indicate that the AE energy for material removal modes is present at high frequency.

However, presenting the spectrum of the signal in terms of FFT does not provide any indications on how the frequency components associated with the removal modes evolved during the process. STFT is, therefore, applied to present the time-frequency representation of the signal based on the parameters listed in Table 2. Considering the three different mechanisms occurring in the scratch test, STFT is a viable solution to observe the evolution of the spectrum in time compared to that from FFT.

Fig.14. AE monitoring system for grinding process and single grain scratch tests.

Fig.15. Raw extracted AE time signal during single grain scratching.

Fig.16. FFT analysis for extracted AE signal and corresponding frequency ranges for different material removal modes.

Table 2. STFT parameters

Parameter	Value
Window length	65536
Hop size (step size)	16384
Number of FFT points/ window	4096
Window function	Hamming
Low-pass/ High-pass filter	25 kHz-450 kHz

Fig.17. The 3D spectrogram plot of STFT analysis for extracted AE signal.

The time-frequency representation of the AE signal is shown in Fig.17. The plots suggest the evolution of the three mechanisms, where at the beginning (the first 3 seconds) only two major frequency components are present. These two signatures correspond to the ploughing and rubbing modes. It is important to note that these two modes dominating the frequency range of 25-125 kHz are inseparable. Subsequently, the two more frequency peaks are developed starting from 3s at the range of 125-350 kHz, which are associated with the cutting mode. Analysing the STFT, it is also evident that ploughing and rubbing modes always occur throughout the process. Though rubbing occurs separately, there is only a very short momentary transition which was difficult to be captured with our tribometer setup. In the plastic regime, as the materials get dislocated from the surface, intricate rubbing action happens with the grain. Finally, in the cutting regime, all the contact mechanisms are prone to happen as the material gets dislodged as well as dislocated, and there is also a rubbing contact with the grain.

The four apparent frequency bands can now be associated in the frequency spectrum to their respective material removal modes based on the STFT analysis, as shown in Fig.16. Based on the STFT analysis two classifications can be made based on the first two frequency peaks, at band 1 and band 2, that indicates rubbing and ploughing modes (1) and the two subsequent peaks, at band 3 and band 4, that correspond to the cutting mode (2).

4. Change in contact mechanism

An electric belt grinder is modified by attaching a fixture to secure it on an ABB 6660 robot arm as shown in Fig.18. The belt grinder runs at 11,000 rpm in the unloaded condition, and it can drive belts with a dimension of 8" to 3/4" wide $\times$ 18" long. A constant contact force of 20N is maintained in the normal direction (z-axis) through ATI force compensation unit attached at the end effector of the robotic arm, while ABB Robot Studio executes the linear tool path.

Fig.18. AE system for belt tool condition monitoring.

Table 3. Experimental condition for belt grinding trials.

Parameters	Values
Belt tool type	Aluminium oxide - 40 grit size
Normal force	20N programmed using ABB robot studio
speed	11,000 RPM, 50 mm/sec
Material	Aluminium (size 135 mm × 90 mm × 20 mm)
Polymer wheel	16 mm diameter, 80 Shore A Hardness
AE sensor range	25 kHz-450 kHz (Vallen VS45-H)
Sampling rate	5 MHz

Aluminium (Al-T6061) workpieces with planar surfaces of the same initial roughness are machined with the Aluminium oxide (Al_2O_3) abrasive belts. Three different belts representing three-different states, i.e. new (fresh grains), used (partly used) and wornout (old), are used in experimental trials. Based on the analysis of 3D laser profile reading with Abbott-firestone curve, as shown in Fig. 19, it is apparent that wear flats become prominent with the cycle time of the belt tool. It is also apparent that the grains become extinct from the backing material as the cycle time of a belt tool grows.

Fig. 19. 3-D laser profile scan of the grain structure evolution and Abbott-Firestone (material ratio curve) comparison of the wear flats distribution in the belt tool of different states.

Fig. 20. The 3D plot of STFT analysis for extracted raw AE signal during the belt grinding trials with three different belt wear states showing evidence of frequency components from single grain scratch experiments.

The experimental conditions used in the belt grinding trials are listed in Table 3. The contact wheel of the belt grinder was kept at a constant normal force of 20N to maintain uniform contact conditions. All the experiments were carried out in the dry condition. With an excellent acoustic coupling, the AE Sensor was placed near to the grinding zone in the workpiece as shown in Fig.18. The AE signatures during machining are captured at 5 MHz sampling frequency. The amplified AE signal was passed to a bandpass filter with the same cut-off frequency as in the single grain test. As shown in Fig. 20, STFT analysis for extracted raw AE signal during the belt grinding trial shows similar frequency signatures to those of the single grain scratch test.

AE signals collected during the processes for three different belt wear conditions are shown in Fig. 21. Evaluating the energy content of the AE signals from the experiments at two frequency bands, i.e. 25–125 kHz and 125–350 kHz that were identified to correlate to the material removal modes, the evolution in the contact mechanism is demonstrated.

Fig. 21. FFT analysis for extracted raw AE signal during the belt grinding trials with three different belt wear states.

In order to have a better understanding of the frequency components in the AE signal, experiments were performed with a new setup, as shown in Fig. 22. The experimental setup consists of a variable belt grinder running

at 5500 RPM, wheel of 90 shore A hardness, 60 grit Al_2O_3 belt and a wheel contact width of 1.25 inches. Aluminium 6061 was used as workpiece material, and AE sensor (Vallen VS45-H) was used for data acquisition.

Fig. 22. A variable speed belt grinding system equipped with the AE system for belt tool condition monitoring.

Examining the corresponding STFT plot and the frequency distribution of AE data as shown in the Fig.23 and Fig.24 below it is evident that the frequency components do not vary with the change of grinding parameters for a particular material and abrasive grain combination. However, there was a significant change in the energy content in the corresponding frequency ranges.

Fig.23. STFT analysis for extracted raw AE signal during grinding with the new experimental setup.

Fig.24. FFT analysis for extracted raw AE signal during grinding with the new experimental setup.

5. Result and Analysis

This section summarizes in detail the observation results of the material removal modes in three different belt states during the belt grinding trials. From the STFT analysis of AE data in single grain scratch experiments, we can characterize the dominant contact mechanisms based on the frequency signatures. It is also confirmed that a similar phenomenon is observed in the actual belt grinding trial, where the frequency signatures are also identical. From the analyses presented in Section 3 and 4, it is found that the rubbing, ploughing and cutting modes are characterized by significant energy content in two frequency bands (25–125 kHz) and (125–350 kHz).

An energy comparison from the AE signals collected from a similar experiment with three different belt wear states, as presented in Section 4 is made to illustrate how these signatures help signify the wear state conditions. Four identical trials are used, where the results are subsequently averaged to confirm the repeatability of the results. The energy comparisons are shown in Fig.25. Evaluating the AE energy in the frequency band of 25–125 kHz as shown in the left panel of the figure, (a), it is demonstrated that rubbing and ploughing modes are more predominant in a new belt compared to those on the belts that have run for long cycle time. It is also clearly observed that the AE energy evolves from high to low as the belt tool wears down, which can be associated with the emergence of wear flats on the belt tool. Similarly, observing the energy on the second frequency band of 125–350 kHz as can be observed in Fig.25(b), we can see that cutting mode is very dominant in brand new belts. At the same time, it is also noticeable that the cutting mode gradually loses its existence with the cycle time of the belt tool (cutting still occurs, but it is significantly less).

The comparison of energy in the two bands shows that the three mechanisms of material removal diminish as the abrasive grains degrade by dulling or grit fracture or grit pullout with cycle time in the belt tool. This study proves that the three material removal modes rely heavily on the wear flats of the abrasive grain that is associated with the wear stage of the tool. As online wear monitoring is critical in some grinding processes, it has been shown the corresponding frequency signatures can be used as a mean of indirect sensing.

Fig.25. Comparison of AE energy signal for three different belt states.

6. Conclusion

The proposed work aims to quantify and characterise the frequency ranges at which contact mechanisms, namely rubbing, ploughing and cutting, occur in abrasive belt grinding processes as demonstrated using Aluminium oxide

(Al₂O₃) abrasive belt on Aluminium (Al-T6061) workpiece. Analysing the energy content of these ranges support the hypothesis that the contact mechanism changes with the change in the wear flats of the abrasive grain. Understanding material removal modes and corresponding energy help in the implementation of a real-time tool wear monitoring system in abrasive belt grinding processes. Based on the experimental results, the following generalised conclusions are drawn:

- AE energy for the three material removal modes is concentrated at the frequency range of 25 kHz to 350 kHz.
- The results show that the three material removal modes have their respective frequency signatures. From the time-frequency analysis, it is found that the frequency between 125–350 kHz corresponds to the cutting mode, while the range of 25–125 kHz is attributed to ploughing and rubbing modes altogether.
- Analysing the AE energy content on three different Al₂O₃ abrasive belt states suggests that more cutting mode manifests itself on the grinding process with new belt/grains and gradually losing its existence grain wears.

In general, the outcomes of this research confirm that the energy content at different frequency ranges can characterize the three contact mechanisms that correspond to the tool wear states. This also concludes that the signatures can be used as a basis of an online monitoring system to predict belt wear condition [31]. Out of all the event that happens in the interaction zone, only three contact mechanism are discussed in the research work. To understand frequencies associated with other phenomena and how they can be separated, will be part of our future work, which is in progress.

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Highlights

- The lifecycle of a coated abrasive belt tool deteriorates due to continuing grain wear resulting in tool failure.
- To understand the contact mechanisms (rubbing, ploughing and cutting) with grain wear, single grain scratch test is performed.
- The objective of this research is to correlate between material removal mechanisms and abrasive belt wear condition using Acoustic Emission (AE) signatures.
- Frequency and energy signatures from the AE sensor corresponding to three contact mechanisms are analysed using Short-Time Fourier Transform (STFT)
- The analysis shows that cutting is dominant during the interaction of the material surface with new grains and gradually becomes a non-existent mode as the grain wears.