Online Tool Wear Monitoring

Tool Wear Monitoring Using Acoustic Emission

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Abstract—**This research work highlights the effects of acoustic emission (AE) signals emitted during the milling of H13 tool steel as an important parameter in the identification of tool wear. These generated AE signals provide information on the chip formation, wear, fracture and general deformation. Furthermore, it is aimed at implementing an online monitoring system for machine tools, using a sensor fusion approach to adequately determine process parameters necessary for creating an adequate tool change timing schedule for machining operations.**

Keywords-Tool Wear Monitoring, acoustic emission, milling

I. INTRODUCTION

Due to the rapid growth in cutting edge technology the need for a sustainable manufacturing sector is essential to meet the market demand. Machining is animportant process to consider in large scale industrial production. Numerous cutting operations are employed in a machining environment. These operations are aimed at the removal of material by power-driven machine tools to mechanically cut the material togenerate required geometry. Modern day machining is controlled by the use of computers. Computer Numerical Control (CNC) machines are driven by abstractly programmed commands which automate machining to facilitate the cutting process.

The influence of CNC machining on the automation of the manufacturing process is substantial but this innovation fails to monitor the quality of its operations. The challenge of wear formation on the edges of the tools, which causes defects on the workpiece, poses a threat to total automation. Thus, the introduction of an adequate tool condition monitoring system is vital.

The research is conducted on a Deckel Maho DMU 40 CNC machine. The 5 axis CNC machine is used for machining simple or complex workpieces used for medical technology, aerospace, automobile as well as tool and mould making.

II. TOOL CONDITION MONITORING

A. *Tool Condition Monitoring in industries*

The industrial revolution of today's manufacturing industryis anchored around various cutting operations. Such processes range from milling, cutting, drilling, turning and grinding operations. These operations which form a potent underlying factor in the production of engineering products are constrained by low efficiency and high cost. Due to these challenges an adequate monitoring system is essential to ensure optimal yield.

Tool Condition Monitoring (TCM) is a modern monitoring approach used in the industrial sector for machining operations. This monitoring process oversees the state of the workpiece during cutting operations to pre-empt deplorable machining state.

TCM in machining operations of today's manufacturing is also paramount for high productivity. This system of monitoring machining operation is used to determine the Overall System Effectiveness (OOE) of the production line. Prickett [1] defines OOE as a factor determined by the system availability rate, performance rate and quality rate. The performance rate relates the on-time and downtime ratios.

In monitoring on-line downtime conditions, two problem sources are identified. One problem is caused by the transfer of work piece between machines and the other by excessive wear and breakage generated on tools during machining [2]. The downtime generated from transfer of work pieces is unfortunately unavoidable during operation, but tool wear can be monitored and controlled.

TCM is performed on various cutting operations to determine the wear rates. Operations such as cutting, grinding, milling and drilling are common industrial machining operations being monitored today. Numerous research efforts have been conducted in this field but there has been significant interest in the monitoring and study of face-milling and turning operations. The specifics why these researches are delineated towards these conventional cutting operations are based on the ease of monitoring, expenses involved and quality of obtained signals.

Other segregations of research are based on the sensing technology and analysis methodologies employed. Sensors such as sound, acoustic, force and vibration sensors are utilized.

Sensors are positioned at various stages of the machine process to:

- Ascertain the performance of the machines
- Observe the process evolution

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- Evaluate the quality of the output
- Supervise and control process parameters utilized.

Research proves that sensor positioning affects data quality [3]. Sensors are most often found placed on the machine, tool or the workpiece.

Numerous articles enumerate various merits of Acoustic Emission (AE) based monitoring methodology. These werebased on its frequency range which prevents the intrusion of environmental noises, ease of placement of sensors, low cost involvement and its sampling speed which does not interfere with the cutting operations. [4]. From the literature, AE is termed one of the most efficient TCM sensing methods which can be applied to machining processes [5].

III. REVIEW` OF TCM

The design of TCM as a precautionary tool in machining can be viewed as a categorization model. The classification of states of the tool forms its objective. The TCM framework in figure 1 shows the various stages employed in the acquisition and classifications of features from the machine tool.

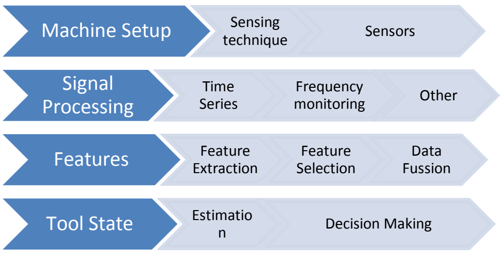

Figure 1. Framework of TCM

A. *Sensor Fusion Process*

Sensor fusion or multisensory fusion techniques are greatly used in TCM. Dimla [6] describes the utilization of more than one sensor signal from different sources to detect the same parameter as sensor fusion. Noise from the process infiltrates signals and influences the correlation efficiencies of signals. Thus, signal to noise ratio forms a decisive parameter to estimate whether the measurement provides significant correlation to the anticipated quantity. In multisensory fusion techniques, signal features from different sensors determine the output state of the tool. This technique however, executes the fusion process at the decision level of the TCM framework.

The integration of the many sensory correlated features with a single or different process parameters gives a more sensitive and reliable prediction than a single sensory feature. This led Sick [7] to conclude that only a sensor fusion approach provides sufficient information in a monitoring system. However practice has shown that in some cases a multisensory fusion with neural networks may produce worse results than a single sensor approach. This scenario may occur due to over-generalization of the output by an excessive pattern learning [7].In general, research conversely shows a higher efficiency from multisensory fusion techniques.

B. *Tool life*

Tool life is defined as the time elapsed to produce acceptable workpiece before tool failure [8]. The time of usability of the tool is influenced by the rate of wear formation on its surface. This wear weakens the tool yielding to an eventual tool failure. The life of a cutting tool can thus be determined by the amount of wear that has occurred on the tool profile. This state which reduces the efficiency of cutting until an intolerable level or eventual tool failure occurs.

Several definitions have been postulated for tool life. These definitions are founded on the time criterion of usability, output production of the tool or even wear rate standards. Tool life model have been designed to determine the rate of wear formation on the tool. One of the most common tool life models are Taylor's equation.

Equation 1Taylor's equation

$$T = \frac{A_t}{V^{b_t}} \qquad (1)$$

Where T is tool life, V is cutting speed; and A_t,and bt are constants.

Equation 2 Extended Taylor's equation

$$TL = f(a_{p,}, f, v, VB) = G \cdot a_p^a \cdot f^b \cdot vc \cdot VB^d \qquad (2)$$

Where *TL* is the tool life, f is the feed, v the speed of cutting, *a* the depth of cut and *VB* is the flank wear width. *G*, *a*, *b*, *c*, *d* are extended Taylor's equation coefficients. Taylor's extended equation is based on the determination of tool life using all cutting parameters and the amount of wear formed whereas its predecessor emphasises only on significant parameters i.e. the cutting speed. Although Taylor's equation provides information on the relationship of tool life with the cutting parameters, it also possesses an easy implementation process; it is limited only to the information about tool life. The use of empirical equations to calculate tool life based on cutting parameters such as the depth of cut, feed rate and speed of cutting has been greatly common in research works [8]. Other empirical relations have related the tool life to tool temperature and also modelled tool life as a stochastic process.

C. *Mechanism of Wear*

Wear formed on the tool edge could occur based on some certain mechanisms. Some common wear mechanisms normally found in the machining environment are as follows:

Abrasion wear: Abrasive wear occurs as a result of the interaction between the face of the tool and the workpiece. This is characterized by a loss of relief on the flank of the tool. Abrasive wear occurs due to the dissimilarity of the hardness of the two mating materials.

Adhesive wear: Adhesive wear occurs in metal when the force elements of the material are not as strong as the interactive forces with the workpiece. This yields to the transference of material between the metals.

Attrition wear: Attrition is a form of erosive wear effect, occurring on cutting tools. It is caused by the impact of particles (liquid, gaseous, solid) on metal surface. This effect gradually erodes fragments of the surface due to its momentum effect.

Fatigue wear: Fatigue wear is the weakening of the material surface by the cyclic loading and unloading during machining. Generally, cracks announce the presence of fatigue wear on the tool surface, which eventually leads to total fracture.

Diffusion wear: Diffusion wear, also known as dissolution wear is an outcome of the gradual dissemination of solid element from one material to the other due to extreme heat and machining conditions. It involves the decomposition of part of the surface of one material and its integration into its opposing mating surface. This normally occurs at a slow sliding velocity. Diffusion wear is greatly dependent on the material composition of the machined surface. The affinity of some elements in the material, towards opposing elements could enhance the rate of diffusion wear experienced in machining. This wear mechanism is mostly experienced in the machining of ceramic materials with diamond tools.

Corrosive wear: Corrosive wear also known as chemical wear is brought about as a result of chemical attack on the surface of the tool. Continuous friction on the tool depletes the protective oxidation films on that surface. This oxidation may accelerate the wear formation on the tool. The effect of high temperature and frictional forces over a long term would eventually alter material composition.

Fracture wear: Fracture wear is commonly experienced in machining. Fracture wear occurs as the gradual chipping and cracking of solid surface due to the sudden loading and collision of both materials. These operations are evident during run time operations.

These wear mechanisms could be found in various combinations during machining. Dominant wear mechanisms found in wear modes are influenced by various factors, such as the cutting parameters, the geometry of the tool, the temperature, and the speed of cutting operations.

D. Formsof Wear on Tool Edge

Tool wear generally occurs in a combination of wear modes. Dominant wear modes depend on cutting conditions and process specifications. These dominant features are mainly responsible for wear formation. Some common identified wear modes are:

- Flank wear
- Crater wear
- Chipping
- Breakage
- Nose wear
- Plastic deformation
- Cracking
- Notch wear.

Wear modes are also dependent on a dominant wear mechanism [9]. Four of the above listed modes are generally more rampant in cutting operations. These are flank wear, crater wear, nose wear and notch wear. Figures 2 and 3 show the various wear zones, region of wear and measurement parameters.

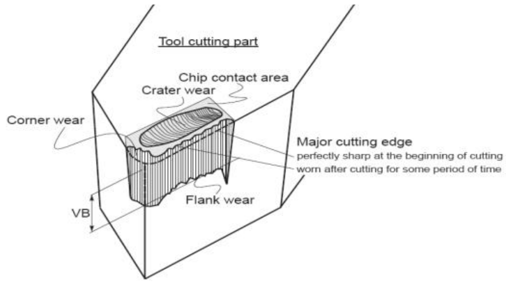

Figure 2. Cutting tool part with wear zones [9]

Flank Wear: Flank wearis dominated by abrasion. It arises due to both abrasive and adhesive wear mechanism from the intensive rubbing action of the two surfaces in contact i.e. the clearance face of the cutting tool and the newly formed surface of the workpiece. This action leads to increase in surface contact area and heat generation which in turns impair the surface quality. The rate of flank wear generated during machining operations varies along the cutting process [6].

Nose Wear: Nose wear is found on the nose point of the cutting tool. It occurs predominantly due to abrasive effects on the edges of the tool yielding to an increase in the negative rake angle. At high cutting speed, the wear deforms plastically and may result in the loss of the entire nose. Wear formed on the nose affects the quality of the surface finish [10].

Crater Wear: Crater wear arises due to the combination of wear mechanisms: adhesion, abrasion, diffusion, thermal softening and plastic deformation. This mode of wear is generally formed on the rake face some distance away from the tool edge as a crater. The crater wear is quantified by depth and cross-sectional area of the crater for measurement. The most important factors influencing crater wear are temperature at the tool–chip interface and the chemical affinity between tool and work piece materials [11].

Notch Wear: Abrasion and adhesion are the main mechanisms involved in notch wear. Notch wear is formed at the boundary of the machined surface with no chip contact during cutting. This mode of wear also known as groove wear, is predominant in ceramic cutting tools with low toughness value. [11]

Amidst the group, flank wear is often selected as the tool life criterion because it determines the diametric accuracy of machining, its stability and reliability [12].

IV. TOOL WEAR EVOLUTION

Research has shown that tool wear evolves at different rates in cutting operations. The rate of wear formation on the tool is largely dependent on the wear mechanisms occurring in the process. In flank wear, abrasion and adhesion cause a rapid rise on the tool flank face at the initial stage followed by a relatively slowly increase wear rate and ends with another rapid formation of wear before fracture. This curve form is generally accepted by numerous researches as the categorical identification of the three basic stages of wear: the initial stage, the regular stage and the fast stage. Ertunc [13] classifies wear into five major stages from the tool life progression curve shown in figure 3. These stages of wear are:

1. Initial wear;
2. Slight wear (regular stage of wear);
3. Moderate wear (micro breakage stage of wear);
4. Severe wear (fast wear stage); and
5. Worn-out (or tool breakage).

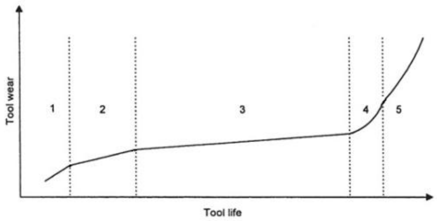

Figure 3. Tool life progression curve [13]

A. Factors influencing tool life

Tool wear formation is subjective to some machining parameters. The parameters, which affect the rate of tool wear, are

- Cutting conditions (cutting speed, feed , depth of cut)
- Cutting tool geometry (tool orthogonal rake angle)
- Properties of work and tool material.

It is generally known that the tool life is directly related to its rate of wear. Therefore the parameters influencing tool wear would as well adversely affect its tool life. The tool life of a cutting tool is not only dependent on the wear but can be influenced by numerous other factors relating to the microstructural properties of the material.

The following factors affect the life of a cutting tool:

- type of material being cut
- microstructure of the material
- hardness of the material
- type of surface on the metal (smooth or scaly)
- material of the cutting tool
- profile of the cutting tool
- type of machining operation being performed
- speed, feed and depth of cut [10]

In theirresearch, Dimla concludes that the cutting speed has the strongest influence amidst these. They postulates that "Regardless of the differences in the values and trends of the normal and shear stresses at the contact interfaces, minimum tool wear occurs and apparent friction coefficient reaches its lowest value at the optimum cutting speed [14]".

V. Tool Monitoring Techniques

In the past, various methods of tool wear monitoring methods have been proposed but due to the complex machining process an ideal model has not yet been found. Scheffer [15] classifies the various techniques based on the type of sensor used, the parameter monitored and the state of machine process. Amidst all sensor type ranging from sound, temperature, forces and current, methods sensing parameters have been classified into direct and indirect sensing methods according to the sensors used [16].

Direct sensing method directly monitors actual quantity of wear variable during operation [7]. It is less utilized in the industrial sector due to its cost implication and intricacy of implementation. Direct sensing is greatly affected by environmental machining factors such as illumination, the use of cutting fluid, chips formation and temperature of material. Some examples of sensing technologies employing this method are the optical sensing, radioactive, laser beams and electrical resistance amidst others.

Indirect sensing has been greatly utilized in the industry despite its lower accuracy due to its ease of implementation and cost-effectiveness [15]. Unlike direct sensing, this method monitors the process parameters correlated with tool wear. Indirect method employs the heavy usage of statistical and analytical models on the tool wear correlations to draw its conclusions. Some of the sensing methods used in the indirect method are acoustic emission, spindle motor current, cutting force, vibration, cutting temperature etc…

The monitoring techniques could be executedduring real-time or off-line conditions. Continuous monitoring permits the instant recognition of wear formation and provides a corrective methodology of wear identification. Despite these advantages, on-line tool wear monitoring has been a challenging area of research and industrial implementation due to the various influences from the machining environment and technical set-up.

AE technologies are one of the most effective sensing technologies in monitoring tool wear [16]. AE signals are very effective in indirect method due to its non-intrusiveness, ease of operation and fast dynamic response [17].

VI. Acoustic mission

A Comprehensive survey on the use of AE in TCM was conducted by Li [16]. In their survey Li iterates the efficiency and reliability of AE as a viable TCM sensing technique. The impressive amount of research in the last decade also indicatesthe present day interest in AE [18] [19] [3]. AE originates from the strain energy released as the rubbing process of cutting takes place. This is caused by the considerable amount of plastic deformation which occurs in metal cutting. AE signal refer to transient elastic waves due to the rapid energy release from a localised source within a material [19]. Li [16] reiterates the basic sources of AE during tool monitoring as the following:

- Plastic deformation during cutting in the work piece;
- Plastic deformation in the chip;
- Frictional contact between the tool flank face and the work piece resulting in flank wear;
- Frictional contact between the tool rank face and the chip resulting in crater wear;
- Collisions between chip and tool;
- Chip breakage;
- Tool fracture.

Figure 4 shows the various AE wear zones generated during the cutting operation and how they relate to the various faces of the tool. The interaction of these various AE sources is responsible for the noisy signal generation of AE waves.

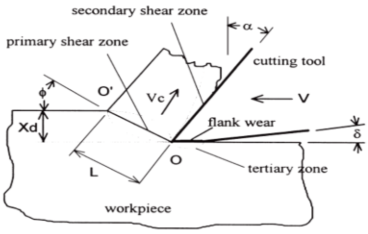

Figure 4. Zones of AE generation during metal cutting [18]

Piezoelectric devices are suitable in the measurement of AE stress waves on the workpiece. Piezoelectric devices convert mechanical stress waves into electrical AE signals. They are resilient to process a higher sensitivity ratio to most other sensors i.e. capacitive, electrodynamics and laser optical [20]. Piezoelectric possess sensitivities as high 1000 V/µm which exceed environmental noise. The AE transducer operates with a flexible range of 20kHz to 1Mhz [5] which can be used to detect most significant machining conditions, but most research were conducted in the range 100kHz – 800kHz. Most recent articles use piezoelectric sensors to establish the wear rate on flank face of the tool [5] [16].

A. *Types of AE signals*

There are numerous types of AE signals produced in the course of machining, continuous and burst type. Continuous AE signal are associated with plastic deformation in ductile materials [3]. This form of AE signal represents the gradual wear which is generated on the tool. Burst AE signal have been observed to determine brusque coalitions and fractures in metal working. These burst can be generated owed to the engagement and disengagement with the work piece [21]. It is generally acknowledged that AE signals generated are due to plastic deformationand crack growth in the material. Burst AE signal are thus termed to more efficient in identifying fractures than monitoring machining processes AE processes are more successful in continuous machining operations. Due to the frequent nature of entry and exist, AE sensing faces challenges in adequately monitoring intermittent machining process such as milling. These collisions during cutting generate confusing data values about the present tool state. Numerous research works also identify a link between the magnitudes of the high peak AE parameters with catastrophic tool failure detection [21].

B. *Advantages of AEmonitoring system*

AE signals are easily identified in machining due to their higher frequency rate to machine vibrations and environmental noise which enhances the analysis of the signals. The application of non-destructive sensors therefore plays a major role in the monitoring process. These sensors are of different types and are sensitive to the property of the material involved such as the gauge thickness [22]. The sensors utilized are coupled with the sample to provide uninterrupted elastic energy signal based on the operation performed besides information about the dynamic changes observed on the sample. In the positioning of the sensor, further research on the properties of the transducers confirms a dominant relationship between the choice location and the quality of the observed signals. Inasaki [3] proves the effect of sensor positioning in machining by affixing an AE sensor on the cutting fluid supply nozzle, using the fluid as a medium for the generated signals. This system was conceived to avoid to fluctuations in signal magnitude caused bythe variation of the distance connecting the spindle head and the cutting point. They concluded by stating the need to enhance the reliability of a monitoring process due to the high sensitivity of the AE sensing technology.

AE sensing technology can be based on numerous principles for data acquisition. Capacitance based AE sensors possess a high accuracy and are used to calibrate other AE sensors. Unfortunately, capacitance type displacement sensors are very sensitive to sensor position and surface mounting and thus not suitable for machining process monitoring [23].

The basic advantages in using acoustic signals in determining tool wear originate from its high frequency and sensitivity as well as its ease of placement and affordability.

C. *AE Signal Parameters*

Some feature parameters are used in AE analysis and empirical models to determine tool state. Features such as skew, kurtosis, ring-down count, rise time, event duration; frequency and RMS value are identified. Jemielniak [21] in his article statistically analysed the AE signal from the sensor to determine catastrophic Tool failure. The skew measures the symmetry of the distribution about its mean value but the kurtosis is a measure of the sharpness of its peak. These features have shown to respond to changes in flank wear during machining.

VII. Proposed Designed model

This research is aimed atimplementing an online monitoring system using a multi-sensor approach to adequately determine process parameters necessary for creating and adequate tool change timing schedule for machining operations in an automated environment.

In the research we will monitor milling machining operation at high speed when cutting tool steel to link the rate of wear generated on the tools to the AE data. Three AE sensors from Kistler with a band pass frequency from 50 KHz to 1 MHz would be connected to piezotron couplers for signal processing and successively to the BNC 2110 block of the National Instrument (NI)for data acquisition. The data acquisition unit consists of a NI PCI 6110 simultaneous sampling card integrated on a computer and relayed to the sensor via a custom built connection (Figure. 5).

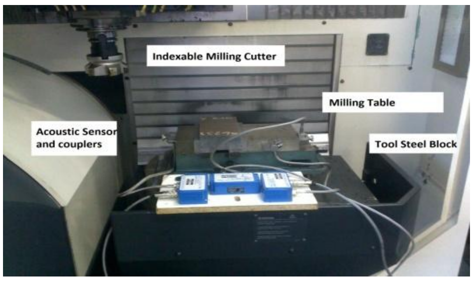

Figure 5. Machine Setup on DMU 40 CNC Machine

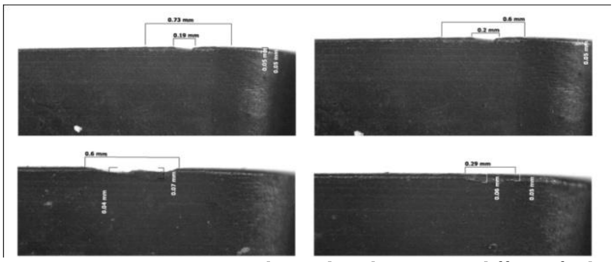

Figure 6. Wear observed on the inserts at different feeds

Figure 6 above showsthe first results (after one pass of machining) of the wear observed on the inserts while machining tool steel at various feeds and speed. Numerous experiments are performed following a combination of these parameters to link the parameters to the wear formed.Figure 7 shows the machining setup diagram.

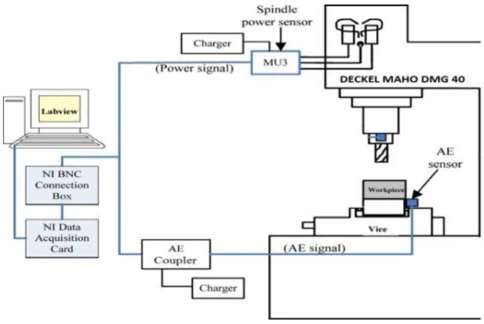

Figure 7. Tool Wear monitoring diagram

The data values will besampled at 2 M/s and processed using a time-based statistical method to obtain relevant features parameters. Concurrently, the acquired features will beutilized to train a neural network. Artificial intelligence would be used to create a solution for the classification of wear and establish a model which describes the effects of cutting parameters on tool life. In this research only three categories of wear would be under consideration; light, middle and severe wear.

Based on its high sampling rate and multisensory approach, this model is anticipated to further optimize TCM. Future areas of research geared towards determining an optimal choice number of sensors.

CONCLUSION

In conclusion, the proposed model presents more information on the cutting process and would provide a more efficient method in AE monitoring.

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