TOOL CONDITION MONITORING IN MICRO-MILLING OF BRITTLE MATERIALS USING MULTISCALE SENSORS

Engr. Abu Afealiokha Lukman
Department of Mechanical Engineering Technology,
Delta State Polytechnic, Ogwashi-Uku, Delta State

ABSTRACT

The ability to fabricate 3-D features cost effectively on a wide range of materials has necessitated so much interest in micro milling operations. Despite its successes in the machining of miniature parts and complex shapes with high accuracy, micro machining still encounters problems such as tool wear, cracks, chatter, vibration, and tool stress, thereby causing tool breakage. This research is aimed at developing a robust approach for monitoring tool wear by employing Tool Monitoring Condition (TCM). Attention is focused on the performance of slot milling experiments on brittle materials (glass and silicon) using solid tungsten carbide end cutting tools. Raw experimental data are acquired from AE and force sensors. The signals are processed using Wavelet decomposition techniques. Features are extracted and selected from this decomposition and these features were further used to train and develop an effective TCM solution.

Keywords: Micro-Milling, brittle materials, tool wear, wavelet, tool condition monitoring

INTRODUCTION

Rigidity is one of the challenges faced by the miniaturization of conventional machining cutting tools had geared up for an alternative machining process such as micro milling. Micro-milling is a precision machining process aimed at facilitating an enhanced requirements of high machining efficiency, materials surface characteristics, extremely close tolerances, machine positioning accuracy and dimensions. [1, 2, 3]. These processes had gained tremendously grounds because of an increased demand in the miniaturization of manufactured engineering parts and complex structures. These processes are often expected to produce features (micro parts) of high integrity, good surface finish, and with accuracy lower than one micron [4, 5, 6]. Thereby becoming more fundamental in the automotive, communication, electronics, pharmaceuticals, biomedical, aerospace, and mechanical industries. [7]. Micro-milling possesses prominent capabilities in versatile material processing and complex 3D surface machining, and as such has varied applications in micro and ultra-precision devices. [8].

Globally, micro-manufacturing has gained much attention because of its methods and processes. Micro manufacturing encompasses many different technologies that can produce small parts with fine features. The "micro" in all these manufacturing methods refers to their ability to produce 0.5mm to 2mm objects with a resolution of 5μm to 20μm. [9] It is believed to be a small manufacturing setting that produces high precision products with downsized production processes. [10]. This simply means that with micro manufacturing process, all equipment is minimized to micro scale; thereby creating a user-friendly manufacturing environment with reduced overhead costs, energy consumption, material requirements, and pollution.

Presently, the trend of micro manufacturing focuses on producing micro products by miniaturizing and downsizing conventional and non-conventional processes. A good example is hybrid manufacturing processes, which combines two or more methods together. Micro manufacturing processes are applicable in high-technology fields such as automotive, communication, electronics, biomedical, optics and aerospace, incorporating micro mechanical devices (like gears, gear trains, cantilevers, probes, and accelerometers), microfluidic valves, particle filters, micro electronic connectors, and sensors, medical, automotive and aerospace components.

Key Issues with Micro-Machining

The need to fabricate high accuracy miniature components with dimensions ranging from a few hundred microns to a few millimetres or features ranging from a few to a few hundreds of microns has encouraged research on development of micro manufacturing processes. [11] Despite successfully machining of miniature parts and complex shapes with high accuracy, this encountered problems such as tool wear and tool failure. Tools which are small and long, could not withstand the generation of contact machining forces leading to tool formation, chatter and vibration, and tool stress, thereby causing tool breakage. [12, 13] Tool breakage is generally the result of accumulation of tool damage over time and has negative indirect (time) and direct (capital) effects.

In machining operations, tool wear is considered among the most critical conditions affecting the surface quality of workpieces. Developing a sustainable TCM system and algorithm towards high precision will not only solve these machining challenges but also improve material surface quality, reduced downtime, and lower production costs [14].

The Need for Machining Brittle Materials

Brittleness describes the property of a material that fractures when subjected to stress but has a little tendency to deform before rupture. Brittle materials are characterized by little deformation, poor capacity to resist impact and vibration of load, high compressive strength, and low tensile strength. Brittle material breaks while little to no energy is absorbed when stressed. They allow a resistance to the sliding of their atoms, due to their ionic bonds. Therefore, they cannot plastically deform, rather they fracture [15].

Brittle materials are generally chemically stable oxides with high chemical inertness in body fluids. They are known for their high compressive strength, and ease of fabrication, which makes them more useful in applications where high mechanical loads are expected, such as in orthopaedic devices [16].

Glass and silicon both have comparatively low index of brittleness which makes them susceptible to cracking. [17] These characteristics improves their susceptibility to cracking [11]. To meet with the demand of extreme applications, there have been much interest in enhanced silicon and glass materials with distinctive metallurgical properties. [18] Despite being hard and brittle, these materials are commonly used in the electronic industry; for micro-electrochemical system (MEMS), micro-fabricated devices and microelectronic packaging. In the biomedical industry, they used for DNA, biological instruments, micro valve, microfluidic device, biomedical device and micro flow sensor. In addition, silicon and glass has extensive applications in automotive industry for making transistors, computer chips sensors, windscreen, and cockpit windows.

Issues with Brittle Materials

With a wide scope of subtractive micro-machining processes, materials like metals, polymer, silicon, glasses etc., can be micro machined. [19, 20]. Brittle materials such as silicon and glasses are quite difficult to machine because of their high hardness and low toughness. These materials, glass, and silicon often deform elastically prior to fracture by the catastrophic propagation of a crack and fracture under impact and cutting [21].

It is not easy to machine brittle materials because they tend to undergo cleavage-based fracture, resulting in severe losses of material scrap and tooling cost. [22] Brittle materials can often result in undesirable micro-cracking, cut path deviation and undesirable heat effects such as recasts, spatter and debris. [23]

Apparently, the micro machining model is not suitable for brittle materials. Zhongwei et al experimentally shown that as a single particle impacts the brittle material, cracks generally occur at those impact positions that are flawed, as the particle impact velocity reached a certain value, the threshold velocity. The shape of the particle has a tremendous effect on crack initiation. Normally, two types of cracks (traverse and radial) appear on the surface Fig. 1.29 shows the crack propagation model. [24]

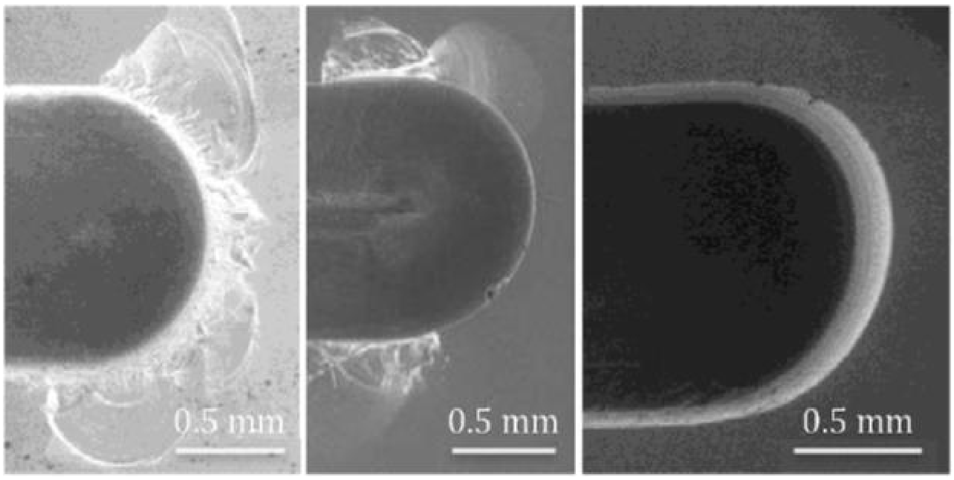
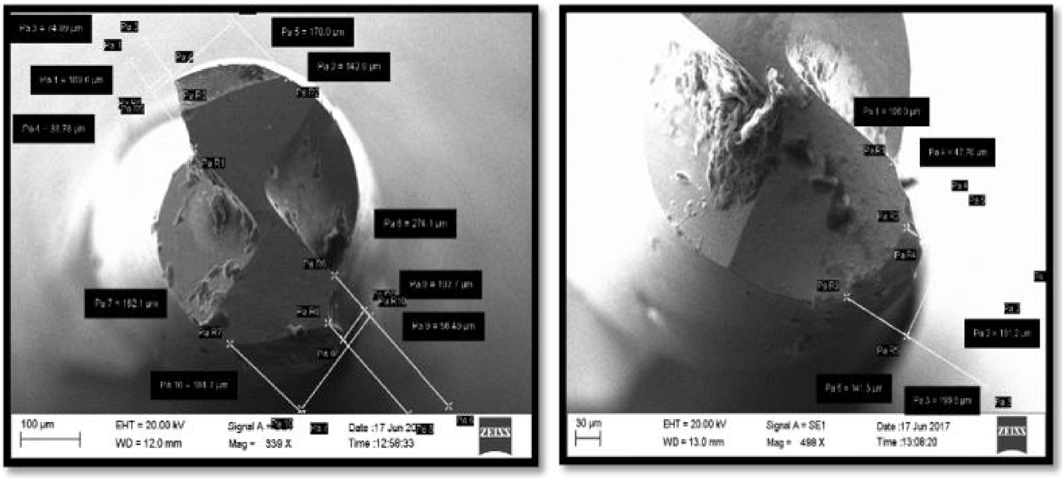


Fig. 1 chipping caused by the tool end deflection

Tool Wear

Tool wear is usually undesirable and must be controlled and minimize in any machining process. The friction that exists between the tool-workpiece interface often leads reduction in machining quality, higher cutting force, tool breakage, unnecessary tool replacement and severe cracks and damage to workpiece, which serves as common harmful effects of tool wear in micro machining [25]. The increase in friction and cutting temperature between the tool-workpiece contact interface is the primary cause of tool wear [12,26]. The cutting forces and an increase in the tool-workpiece contact area at the tool's flank face has great impact on tool wear in micro-milling process. An increase in the contact area leads to an increase in friction which eventually increases the flank wear of the micro tools [27].

Cutting tool wear is a micro or nano contact complications that's prone to occur during machining operations. This is as result of induced chemical, mechanical, and thermal stresses [28]. Tool wear is a continuous degradation of cuttings tool, during chip formation, thereby increasing cutting force and surface roughness. During machining operations, the primary sources of wear are the abrasion and corrosion scale of individual contacts [29]. Gao et al. [30] performed an experiment on tool wear mechanism in micro milling nickel-based super-alloy. During this machining process, the cutting tools and workpiece were found to have diffused into the chips and tool matrix respectively. The degree of diffusion was also found to be increasing with an increase in cutting distance, thereby decreasing the wear resistance.



(a) (b)

FIG. 2. Images of tool wear after micro milling a. titanium alloy b. mild steel

Tool Condition Monitoring

The evolution of different sensing and monitoring systems, in manufacturing engineering, plays a vital role in advancing micro machining processes in terms of accuracy, efficiency and stability [31]. In the recent times, many researchers have published several studies on tool wear monitoring in conventional machining processes [32-35]. However, not much has not been done on the development of an effective TCM in micro-milling processes.

Dubey et al [36] used frequency and wavelet analysis to develop TCM strategy for micro end milling experiments using solid tungsten carbide cutting tool on two different workpieces (Fig. 2). Wan-Hao [31] developed a TCM system with backpropagation neural network for a spindle vibration based micro milling process. Data acquisition and signal decomposition module was adopted. C. Wang et al [37] presented TCM with current signals using a low power spindle on a miniature machine tool. They observed that, with a low power spindle, current signals can effectively be used for monitoring tool wear in a micro milling process. Mohammad et al [38] examined the factors affecting tool wear and proposed a TCM system using neural fuzzy method. They also investigated the effectiveness of various sensors on tool wear monitoring. Yiquan et al [38] developed a TCM algorithm for tool wear in a micro-milling process using machine vision system. They observed that the proposed novel machine vision system was a good tool for monitoring progressive wear and examining tool life trend.

Experimental Set Up and Analysis

The machining task was performed using a CNC Mini-Mill/GX from MINITECH with an NSK NR-3060S ceramic bearing spindle powered by a NSK EM-3060 350W brushless motor. The allowable motor speed which the spindle could reach was 5,000-60,000rpm with an accuracy within 1µ for the spindle (Figure 1). A solid carbide KYOCERA 1610-0394.118 cutting tool of 0.5 diameter end mill (2 flute) with a 30° Helix angle was used. The milling-machine has an X-Y table resolution of 0.0001mm.

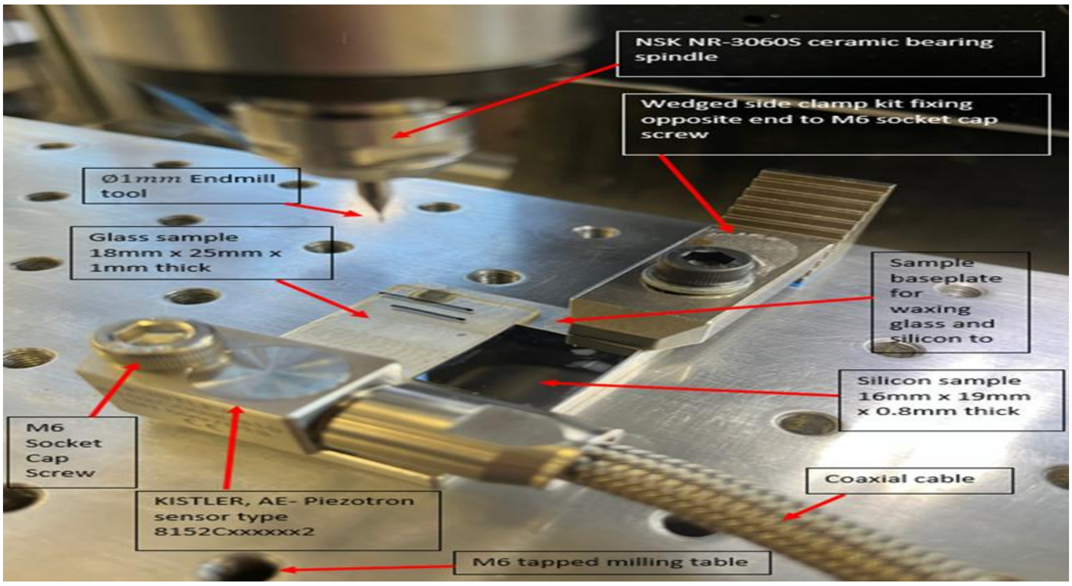


Figure 3. Experimental setup for Micro-Milling System.

For the measurement and inspection of chips, cracks and burrs formed after machining process, the following equipment are employed.

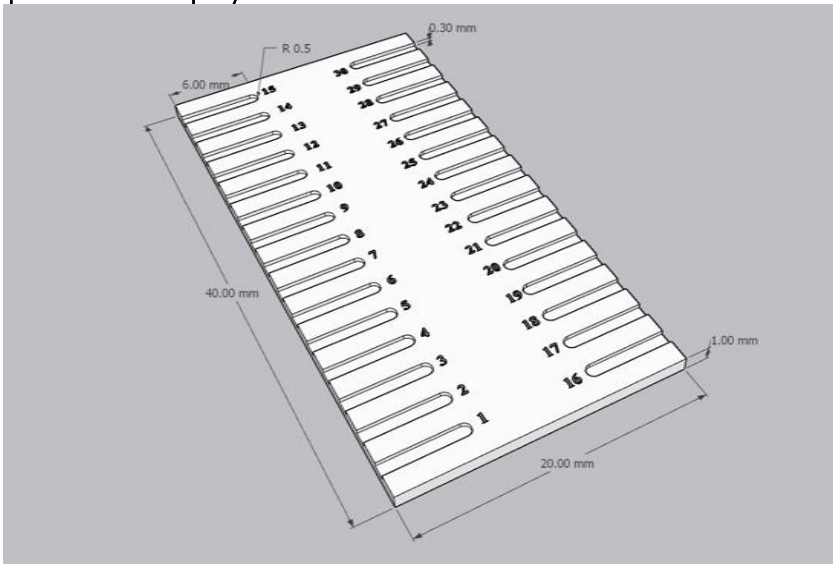


Fig. 4. Micro-milled Workpiece (brittle material)

To evaluate the accuracy of the proposed TCM model, a number of cutting experiments are carried out on a three-axis a CNC Mini-Mill/GX. The maximum rotation speed of the spindle of the machine tool is 25000 rpm, and the workpiece used in the cutting test is glass and silicon. The micro-milling cutter is a tungsten carbon uncoated double-edged. The experimental details are shown in Fig. 3. A series of repeated tests are completed under different spindle speeds (rpm), feed per tooth (μm/ tooth), and axial cutting depth (mm). The process parameters and lubrication details are shown in Table 1 and 2.

A three-way dynamometer and acoustic emission sensor are used in the experiment to monitor the tool wear trend. During the processing, the signals collected by the channels are transmitted to the data acquisition system (DH5956) through multi-channel charge amplifiers at a sampling frequency of 20 kHz. The wear value is measured by a high-precision electronic scanning microscope (SEM). In addition, the real-time deformation of the tool during machining can be measured using the laser displacement sensor (LDS) fixed on the machine tool.

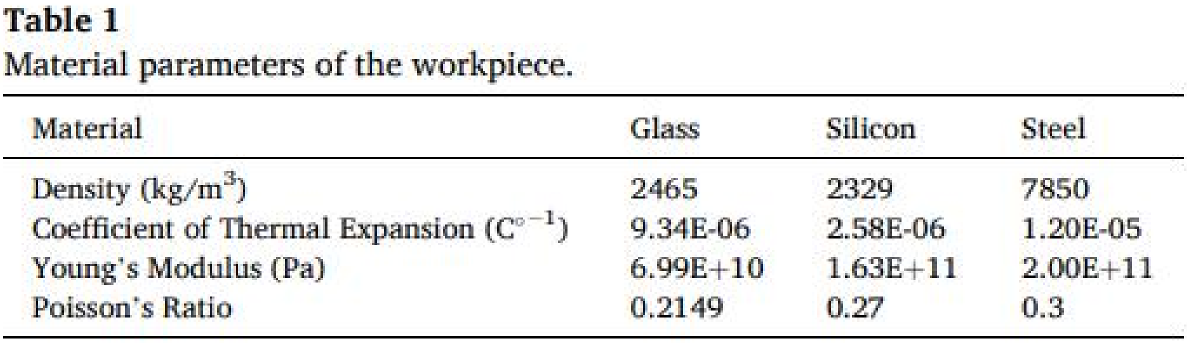


Table 1
Material parameters of the workpiece.

Material	Glass	Silicon	Steel
Density (kg/m^3)	2465	2329	7850
Coefficient of Thermal Expansion (C$^{\circ -1}$)	9.34E-06	2.58E-06	1.20E-05
Young's Modulus (Pa)	6.99E+10	1.63E+11	2.00E+11
Poisson's Ratio	0.2149	0.27	0.3

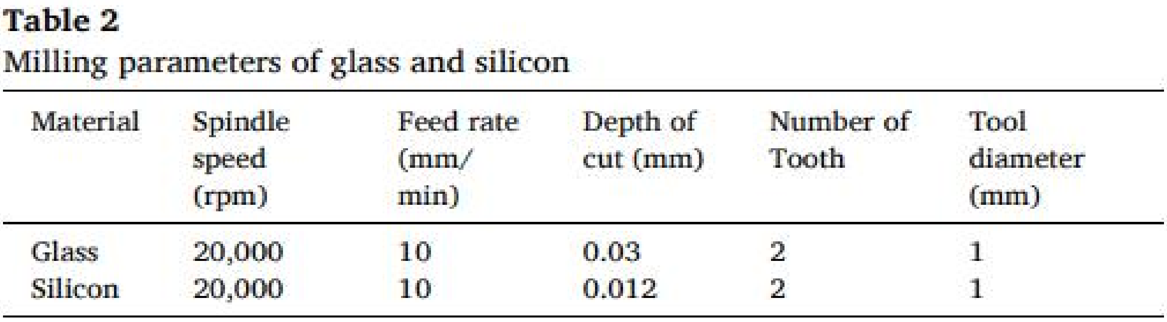
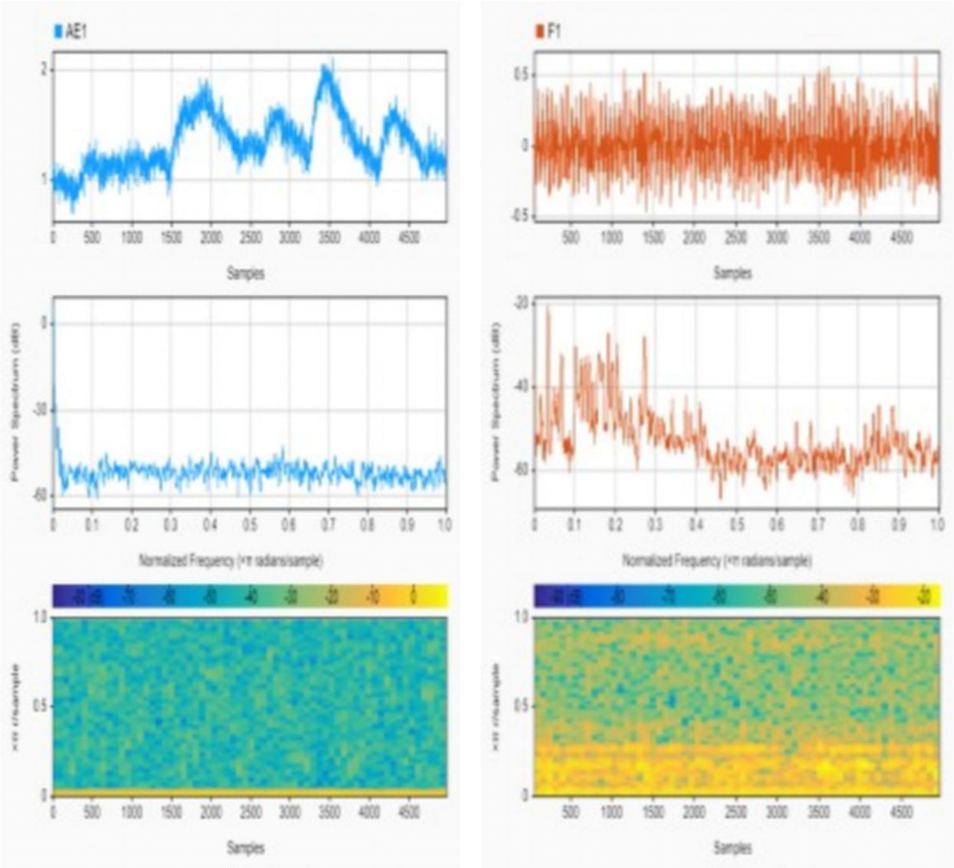


Table 2
Milling parameters of glass and silicon

Material	Spindle speed (rpm)	Feed rate (mm/ min)	Depth of cut (mm)	Number of Tooth	Tool diameter (mm)
Glass	20,000	10	0.03	2	1
Silicon	20,000	10	0.012	2	1

The wavelet transform is used to analyse the acquired signal. Various scaling coefficients known as ‘approximation’ and the wavelet coefficients known as ‘details’ are obtained. 1-D wavelet decomposition of signals is performed using the Discrete Wavelet Transform (DWT). The processing of force signals and the AE signals for all the experiments are carried out using 7-Level 1-D Wavelet Decomposition method and Db-4 wavelet is used for this purpose. The de-composed force and AE signals for the channel 1 are shown in Figure 5a.

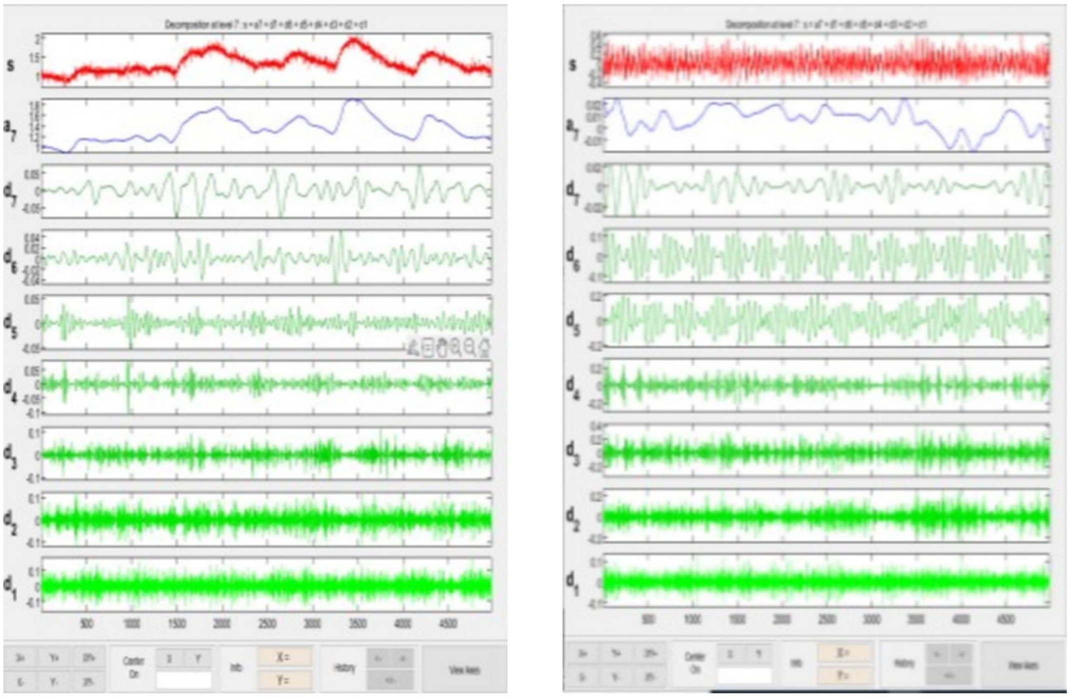
After decomposing the signals into its approximate and detailed coefficients, mean absolute deviations (MAD) of the signals are plotted for the channels as shown in figure 6. From the observations of these plots, the noise from the signals is identified and removed through the process of de-noising. From the AE plot it has been observed that high frequency detailed coefficient (D1) has high strength as compared to other detailed coefficients. Similarly, from the force plots it has been observed that low frequency detailed coefficient (D7) to be dominating. Using wavelet packet decomposition, D1 coefficient from vibration signals and D7 coefficient from force signals are removed for both the workpiece. After de-noising the mean absolute deviation for different channels are again plotted (Figure 5b).



(i) AE Signals

(ii) Force Signals

(a) Time and Frequency Domain plots



(i) AE Signals

(ii) Force Signals

(b) Wavelet Decomposition plots Using DWT

Fig. 5. Signal Processing Plots

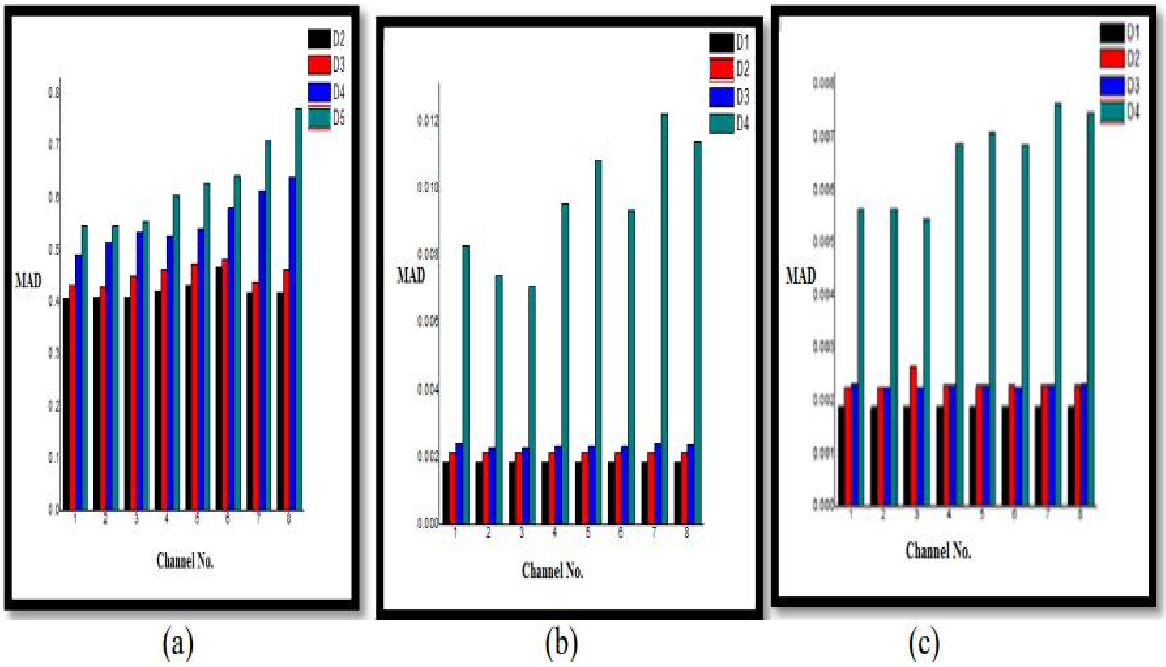


Fig. 6 Mean Absolute Deviations

The changes in tool shape can be directly observed through SEM images of the tool tip (Figure 7).

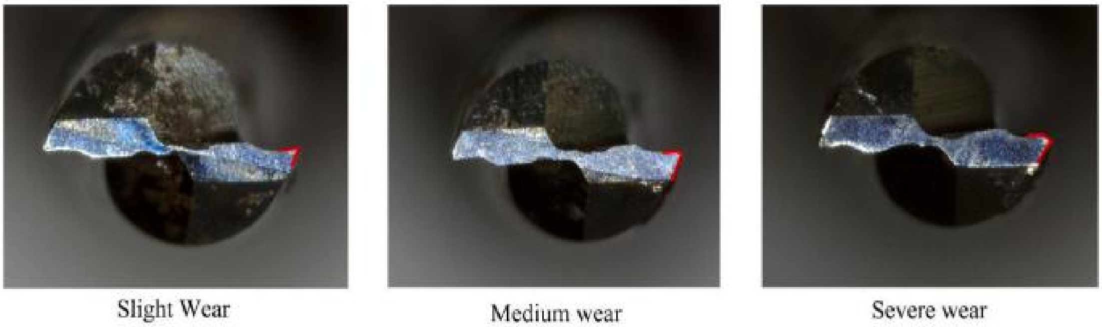

Slight Wear
Medium wear
Severe wear

Fig. 7. Tool Wear Stages

CONCLUSION

Tool condition monitoring has been examined, analysed, and reported for micro-end milling of glass and silicon workpiece. AE signals and force signals are collected during the milling experiments. The signals are processed using frequency and wavelet analysis. It was observed that the wavelet analysis relates more effectively with tool wear through the mean absolute deviation values after proper de-noising and de-composition of the acquired force and acoustic emission signals. The extracted features verified can be used for building TCM system for brittle materials, such as glass and silicon. The WDT method can be also applied to the ductile material, but the different features should be chosen. It was also observed that AE signals are found as the secondary features to different tool wear stages.

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