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Tool Condition Monitoring in Micro-End Milling using wavelets

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Tool Condition Monitoring in Micro-End Milling using wavelets

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Abstract.

In this work, Tool Condition Monitoring (TCM) strategy is developed for micro-end milling of titanium alloy and mild steel work-pieces. Full immersion slot milling experiments are conducted using a solid tungsten carbide end mill for more than 1900 s to have reasonable amount of tool wear. During the micro-end milling process, cutting force and vibration signals are acquired using Kistler piezo-electric 3-component force dynamometer (9256C2) and accelerometer (NI cDAQ-9188) respectively. The force components and the vibration signals are processed using Discrete Wavelet Transformation (DWT) in both time and frequency window. 5-level wavelet packet decomposition using Db-8 wavelet is carried out and the detailed coefficients D1 to D5 for each of the signals are obtained. The results of the wavelet transformation are correlated with the tool wear. In case of vibration signals, de-noising is done for higher frequency components (D1) and force signals were de-noised for lower frequency components (D5). Increasing value of MAD (Mean Absolute Deviation) of the detail coefficients for successive channels depicted tool wear. The predictions of the tool wear are confirmed from the actual wear observed in the SEM of the worn tool.

Keywords: tool condition monitoring; wavelet transform; DWT; tool wear;

1. Introduction

Micro-machining is the fabrication of features having one of the dimensions less than 1mm. In recent years, applications for micro-machined features are increasing in the fields of biotechnology, medicine, electronics, display and optics etc. Among the various micro-fabrication processes, micro-milling process, has evoked a lot of interest because of its ability to fabricate 3-D features cost effectively on a wide range of materials and the developments in the micro-milling tools. The quality of the product i.e. surface finish, form accuracy etc. are well affected by tool wear and can easily be controlled by providing feedback from the machining system. This is very important in case of precision and ultra-precision machining such as fabricating lenses for missile guiding systems and nanometrically-smooth optics by diamond turning process and also in mechanical micro-machining.

Tool deterioration is defined in terms of tool wear. Tool wear alters the tool geometry. In the recent era the manufacturing industry is more concerned about the automation of the operation in order to achieve better quality product. It is very important to look into the performance of the tool during the cutting process. Thus, a tool monitoring system is required to do a specific operation without human intervention becomes increasingly important.

The tool condition monitoring(TCM) comprises of three stages such as: acquiring data for physical parameters such as cutting forces and vibration obtained using different sensors, processing the signal using different techniques such as fast Fourier transform (FFT), wavelet transform etc. and correlating with tool wear. It’s very difficult to obtain tool wear information directly in case of micro-milling, that’s why indirect approaches are used.

Many researchers have tried to develop tool wear monitoring strategy on the basis of cutting force signal [1-4]. The cutting force signal depends on the cutting tool- workpiece pair as well as many other cutting parameters making it highly specific to the experimental conditions. Using vibration signals obtained during machining was considered as easy and effective way for monitoring tool wear [1]. Dan and Mathew [1] discussed the pros and cons of this technique. Bonifacio and Diniz [5] checked the effectiveness of vibration signal as the signature of tool wear during machining. In their work, the authors correlated the root mean square values of the vibrations and the surface quality of the workpiece. Dimla [6] investigated the effectiveness of signal analysis in frequency domain as well as in time domain for monitoring tool condition in metal cutting and put forward their relative importance in each case. Freyer et al. [7] conducted simulation experiments to test the efficacy of piezo-electric devices in controlling the tool offsets with cutting time. Prasad et al. [8] attempted to investigate flank wear by considering the changes in the acousto-optic emission parameters with cutting time. The positive correlation between the surface texture parameters, vibration amplitude and tool wear is also reported in literature. There have been attempts to analyse the signals in time domain, frequency domain to obtain better correlations between the measured signal and progression of tool wear such that the tool condition monitoring will be more effective. Rajesh and Narayanan [9] conducted non-linear time series analysis to establish a positive correlation between vibration signal and flank wear. Prakash and Kanthababu [10] have analysed acoustic emission signal during micro-end-milling experiments to devise tool condition monitoring strategies. The tool condition monitoring strategies depend on the machining conditions to a large extent and a lot of methods for different situations are already reported in literature. However, still there are no efficient online cutting tool monitoring methods.

In this work micro-end milling operation is performed on Titanium alloy (Grade 5) and Mild Steel work-pieces. In this present study, signals are collected during micro-end-milling using force dynamometer and accelerometer sensors. Signals are acquired using highly reliable data acquisition system (DAQ system) and stored in a personal computer. Data are analysed using FFT and discrete wavelet transform, to develop qualitative relation between signal parameters with tool wear of micro end mills.

2. Experimental Details

Micro-end milling experiments have been carried out on Ti-6Al-4V and mild steel specimen of size 55 mm x 45 mm x 3 mm on a micro-machining centre (DT 110i Microtools) using solid carbide tools. Tool overhang in all the cases is kept at 10 mm to avoid the tool deflection and run-out effects. The Ti-6Al-4V workpiece material composition is verified by Energy Dispersive Spectroscopy (EDAX). Feed per tooth in case of Ti6Al4V workpiece is taken as 0.5 µm/tooth, whereas in case of mild steel its value is 4 µm/tooth. Cutting force signals are recorded at a sampling rate of 50000 Hz. Vibration signals are recorded at a sampling rate of 25000 Hz. In case of Ti6Al4V each channel length is 30 mm whereas in case of mild steel it is taken as 45 mm for each channel. The force and vibration data are recorded for duration of 10 s. To have appreciable tool wear, in between two data recordings, tool is engaged in cutting the workpiece material. Table 1 and 2 shows the cutting condition of experiments for Ti6Al4V and mild steel.

Table 1: Cutting conditions and time intervals for data recording for Ti6Al4V workpiece

Channel Number	Speed (RPM)	Feed (µm/rev.)	Depth of cut (µm)	Time duration of recording (s)
1	20,000	1	40	270 to 280
2	20,000	1	40	540 to 550
3	20,000	1	40	810 to 820
4	20,000	1	40	1080 to 1090
5	20,000	1	40	1350 to 1360
6	20,000	1	40	1620 to 1630
7	20,000	1	40	1890 to 1900

Three orthogonal components of the cutting force (F_x, F_y and F_z) are measured using KISTLER dynamometer (model: 9256C2). Among them, signals of feed force (F_y) and transverse force (F_x) are taken for online condition monitoring. Force in the axial direction (F_z) is not considered for tool wear estimation. Workpiece is mounted on the KISTLER dynamometer 9256C2. Acceleration on top of base plate is measured using DC response accelerometer sensor type 4570 made by Bruel & Kjaer. Accelerometer sensor is connected to the Chassis-NI-cDAQ9188 through module-NI9215. Experimental setup for the micro-milling is shown in Fig 1. Tool wear of micro end mills are measured using scanning electron microscope made by Zeiss. Fig 2 shows the Ti6Al4V and mild steel plate after the experiments accomplished.

Table 2: Cutting conditions and time intervals for data recording for Mild steel workpiece

Channel Number	**Speed (RPM)**	**Feed (μm/rev.)**	**Depth of cut (μm)**	**Time duration recording (s)**
1	20,000	8	50	51 to 61
2	20,000	8	50	102 to 112
3	20,000	8	50	153 to 163
4	20,000	8	50	204 to 214
5	20,000	8	50	255 to 265
6	20,000	8	50	306 to 316
7	20,000	8	50	357 to 367
8	20,000	8	50	408 to 418

3. Results and discussion

The force data obtained for the components F_x and F_y are plotted in time domain and analysed. However, no significant trend was observed. Further, the data was analysed using FFT and wavelet transforms.

3.1 Frequency analysis

FFT is a very powerful tool for signal processing and have been used widely for various applications. FFT have been obtained for vibration signals (Figure 3) and force signals in feed and traverse direction (F_x and F_y) (Figure 4 and Figure 5) for the Titanium alloy workpiece. As we can see from the plots of FFT of vibration from Ti6Al4V workpiece, amplitude peaks are increasing with time. So, it is giving clear indications of increasing peak with progressive tool wear. In Figure 3, it has been observed that at higher frequency (11000-12000 Hz) there are increasing amplitude peaks as tool wear progresses with time. Further, it is observed from Figure 4 and Figure 5 the amplitude peak at frequency 100 and 200 Hz are more dominant as compared to the peak at other frequencies.

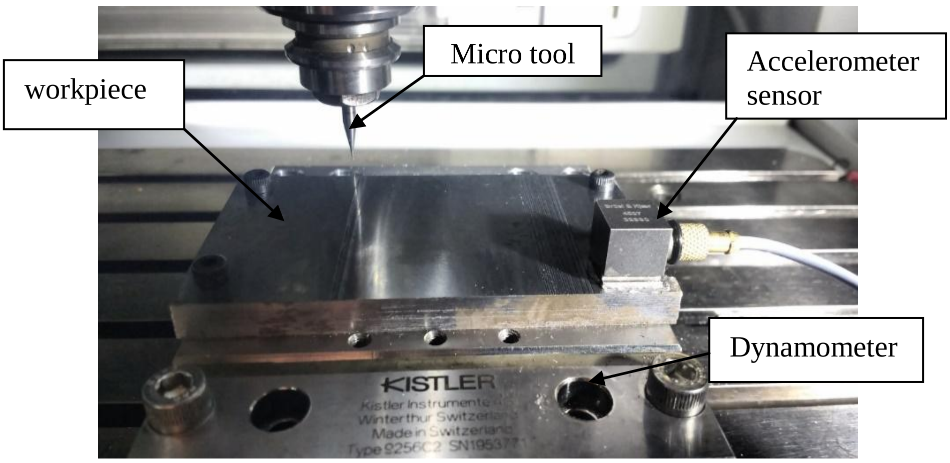
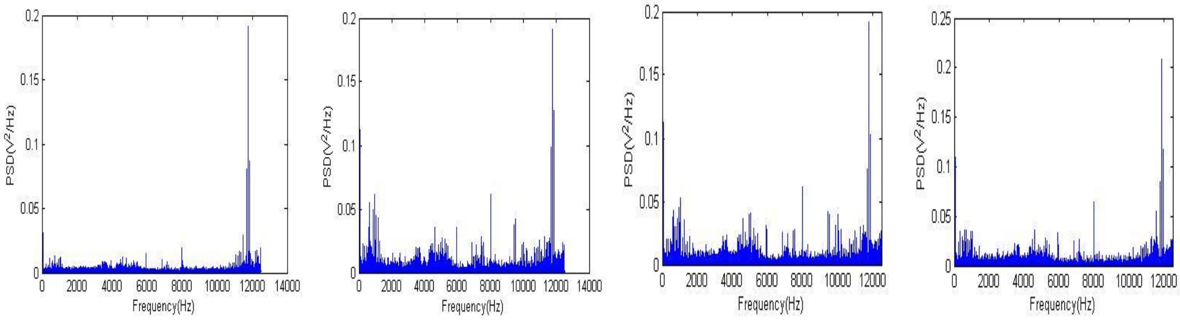


Figure 1. Experimental set up

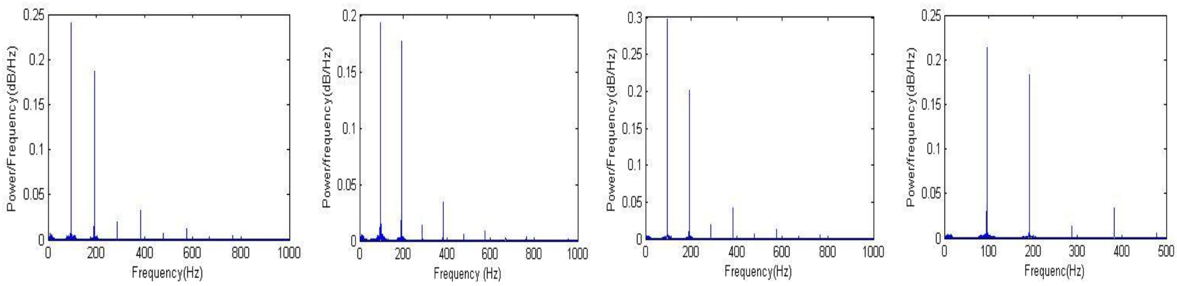
Figure 2. Specimens after micro-end milling experiments: (a) Titanium alloy; (b) Mild steel



(a) (b) (c) (d)

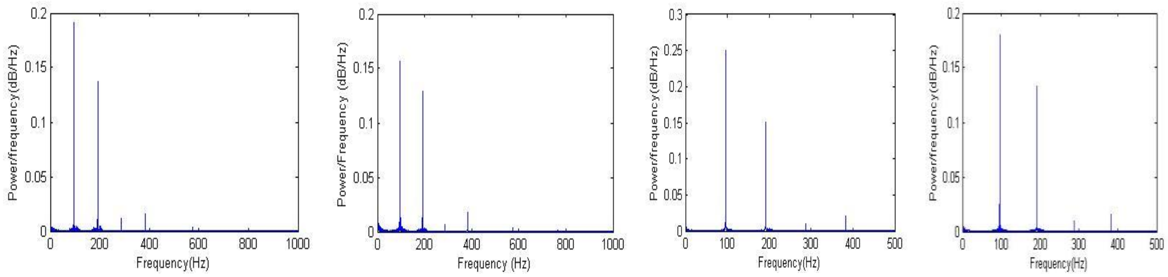
Figure 3. FFT of vibration signal from top surface of plate in Ti6Al4V work-piece at different time intervals: (a) 270-280s (b) 810-820s (c) 1350-1360s (d) 1890-1900s

In case of FFT plots from mild steel it has been seen the vibration level increases as the tool wear progresses. However, at a spindle speed of 20,000 rpm which is very common in micro-machining, there are many frequency components are observed. Moreover, the data is also having significant amount of noise due to high spindle speed. So from this analysis, it is found that FFT is useful to analyse the signals but it is not as much reliable as to figure out clear information from the signals from the experiments for prediction of flank wear.



(a) (b) (c) (d)

Figure 4. FFT of cross feed Force (F_x) in Ti6Al4V workpiece at different time intervals: (a) 270-280s (b) 810-820s (c) 1350-1360s (d) 1890-1900s



(a) (b) (c) (d)

Figure 5.FFT of feed Force (F_y) in Ti6Al4V workpiece at different time intervals: (a) 270-280s (b) 810-820s (c) 1350-1360s (d) 1890-1900s

3.2 Wavelet analysis

The wavelet transform is used to analyse the signal by comparing the original signal with a suitable wavelet by translating the wavelet throughout the signal. Also the wavelet can be modified by using some scaling function. From this, various scaling coefficients known as ‘approximation A’ and the wavelet coefficients known as ‘details D’ are obtained. In the present study 1-D wavelet decomposition of signals is performed using the Discrete Wavelet Transform (DWT). The processing of vibration signals and the force signals for all the experiments are carried out using 5-Level 1-D Wavelet Decomposition method and Db-8 wavelet is used for this purpose. The de-composed vibration and force signals for the channel 1 are shown in Figure 6. The analysis is carried out at the conditions as shown in Table 3 and Table 4.

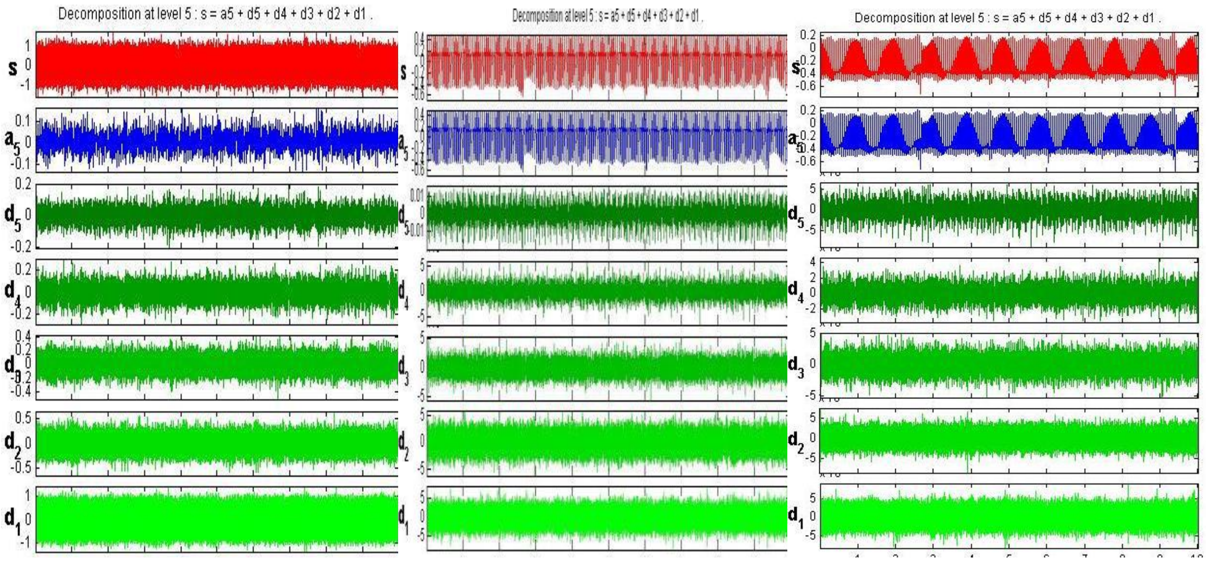
After decomposition the signals into its approximate and detailed coefficients, mean absolute deviations (MAD) of the signals are plotted for the channels. From the observations of these plots, the noise from the signals are identified and removed through the process of de-noising. From the vibration 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 (D5) to be dominating. Using wavelet packet decomposition, D1 coefficient from vibration signals and D5 coefficient from force signals are removed for both the workpiece. After de-noising the mean absolute deviation for different channels are again plotted (Figure 7 and Figure 8).

Table 3. Detailed coefficient related to frequency band for vibration signal

Detailed coefficient	Frequency band (in kHz)
D1	12.5 – 25
D2	6.25 – 12.5
D3	3.125 – 6.25
D4	1.5625 – 3.125
D5	0.78125 – 1.5625

Table 4. Detailed coefficient related to frequency band for force signal

Detailed coefficient	Frequency band (in kHz)
D1	25 – 50
D2	12.5 – 25
D3	6.25 – 12.5
D4	3.125 – 6.25
D5	1.5625 – 3.125

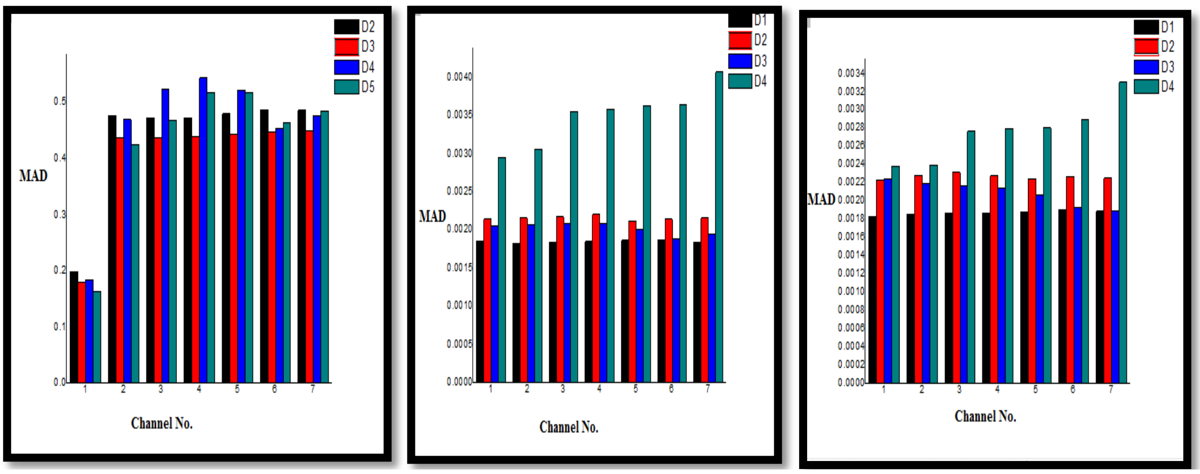


(a) (b) (c)

Figure 6. 5-Level wavelet decomposition for channel 1 of titanium workpiece: (a) vibration signal (b) Force (F_x) signal (c) Force (F_y) signal

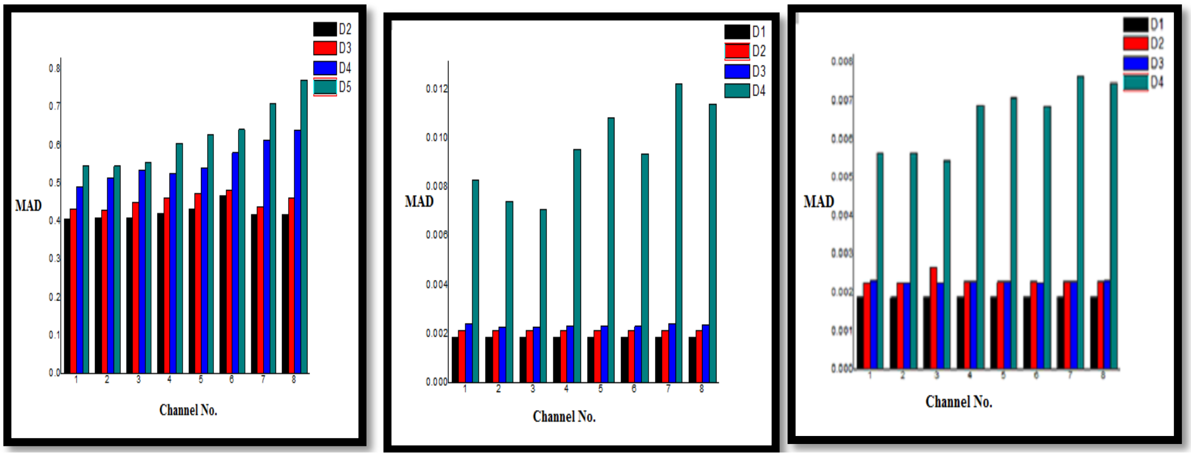
FFT which transforms the signal from time domain to frequency domain gives much information about tool wear. In vibration signal, there exists a repetitive pattern of the peaks which gives information about the nature of the process from which it is recorded. However, through FFT the information is not available in the time domain. Also the signals get corrupted by high frequency noise at higher speeds. Therefore, the analysis to obtain information in both time and frequency simultaneously is more useful. So, Wavelet Transform is a useful technique in such applications as it analyses the signal in both the domains. It also helps to filter noise components from the signal through de-noising. The changes in tool shape can be directly observed through SEM images of the tool tip (Figure 9).

The value of the mean absolute deviation is correlated well with the flank wear and increasing trend of detailed coefficient D4 in titanium means more flank wear.



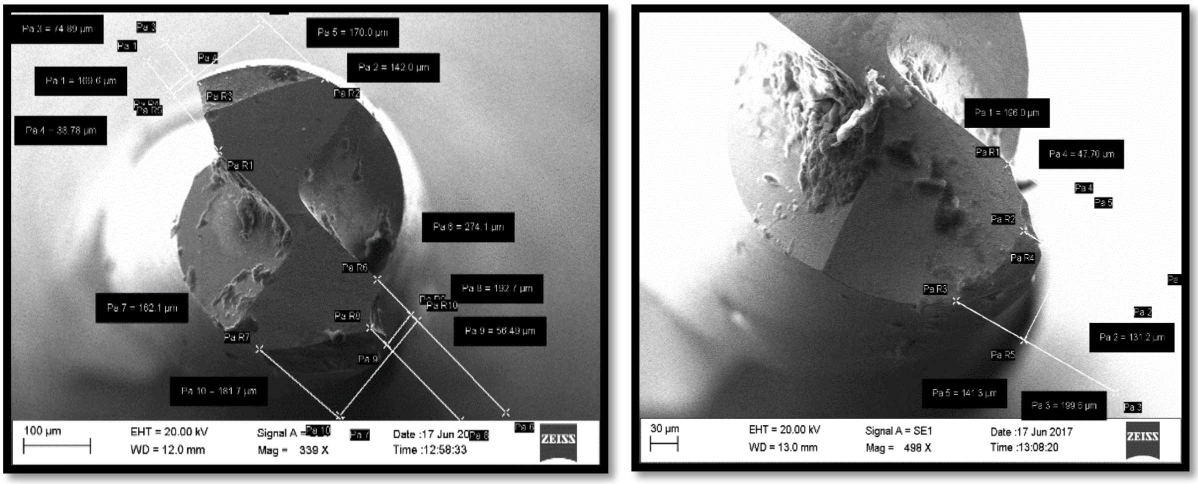
(a) (b) (c)

Figure 7.Mean absolute deviation vs. channel no. after de-noising for titanium alloy (a) vibration signal(b) F_x (c) F_y



(a) (b) (c)

Figure 8. Mean absolute deviation vs. channel no. after de-noising for mild steel (a) vibration signal (b) F_x (c) F_y



(a) (b)

Figure 9.SEM images of worn micro-end mill after machining (a) titanium alloy (b) Mild Steel

4. Conclusions

Tool condition monitoring has been investigated and reported for micro-endmilling of titanium alloy Ti6Al4V and mild steel workpiece. In this work, frequency analysis and the wavelet analysis has been carried out. The wavelet analysis relates more effectively with tool wear through the mean absolute deviation values obtained through de-noising and de-composition of the vibration and cutting force signals. Further, based on the spindle rpm a suitable detail coefficient such as D4 in the present case to quantitatively determine the tool wear.

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