Tool Condition Monitoring using multiple sensors in Microturning of Stainless Steel

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Abstract- In this work, an attempt has been made to monitor the tool condition using multiple sensors such as acoustic emission (AE), accelerometer (ACC) and cutting force dynamometer in the microturning of stainless steel with coated tungsten carbide insert upto 60 minutes. Signal processing are carried out in time domain, frequency domain and discrete wavelet transformation (DWT) technique. The AE_{RMS}, ACC_{RMS} and the dominant frequencies are found to be uniformly increasing with respect to increase in the tool wear, while R_a, chip width and cutting forces show non-uniform trend. From the frequency domain analysis, it is found that the dominant frequency of the AE_{RMS} and ACC_{RMS} signals are between 80-108 kHz and 2.2-4.3 kHz respectively. The result of DWT, indicates that the specific energy of AE_{RMS} and ACC_{RMS} of level D4 (62.5-125 kHz) and level D2 (2.5-5 kHz) respectively are found to be dominating among the five levels (D1 - D5) due to the shearing and elastic fracture mechanisms. In the case of force analysis, it is found that the tangential force (F_y) is found to be more sensitive than that of the thrust force (F_x) and feed force (F_z). This study will be useful for the manufacturers, for monitoring the condition of the tool, using the multiple sensors in the microturning of stainless steel 304.

Keywords: Microturning, Stainless steel, Acoustic Emission, Accelerometer, Cutting force dynamometer, Tool Wear, Surface Roughness, Chip morphology.

I. Introduction

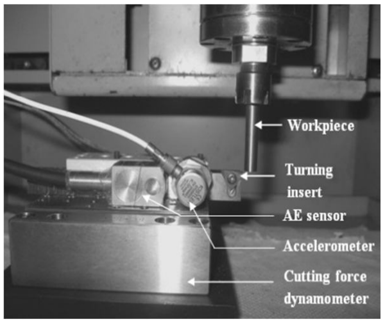
Tool based micromachining plays an important role in the manufacture of micro components in various fields. It is the mechanical cutting of features with geometrically defined cutting edge/edges of size less than 1 mm and with no constraints on the size of the components [1]. The different types of tool based micromachining processes are microturning, micromilling, microdrilling, etc. Typically, microturning is the scaled down version of the conventional turning process, but operating on a microscale level of machining parameters [2]. It is used to manufacture three dimensional micro-components such as microshafts, microelectrodes, etc with high aspect ratio and high geometric complexity. Such microturned components are widely used in different fields such as automotives, biotechnology, health care, communication, security, defense, etc [3], [4], [5], [6]. In microturning, the micro components are usually produced with a insert of nose radius 0.1 or 0.2 µm. Therefore, the tool is subjected to large cutting forces, vibrations due to size effects, minimum chip thickness, etc. [7]. Hence, researchers and manufacturers find it difficult to detect tool wear, damages to the cutting edges, broken tool, etc. The worn out tool results in poor dimensional accuracy and surface quality. Hence, there is a need for tool condition monitoring (TCM) system in tool based micromachining processes.

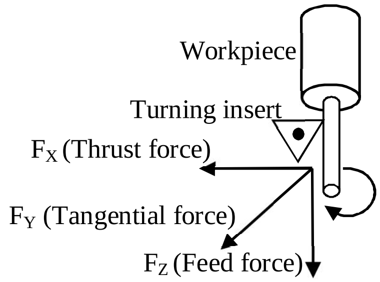
TCM is an in-process (online) system, which detects the tool condition during machining and informs the operator about the status of the tool. The TCM system has been demonstrated successfully in conventional/macro-regime machining processes using single and multiple sensors [8], [9], [10]. From their studies, it is observed that the integration of different sensors in the TCM system is necessary in order to increase the productivity and quality in the components. TCM has the potential to reduce the cost and improve productivity with a safer environment. In TCM system, selection of suitable sensor, acquisition of the sensor signal and processing the signal play an important role. Few researchers made attempt to monitor the tool condition in microturning using different sensors such as acoustic emission (AE), accelerometer (ACC), cutting force dynamometer and temperature, etc [2], [11], [12], [13]. However, very limited attempt has been made to monitor the tool condition using multiple sensor approach especially in microturning environment. Hence in the present work, TCM has been carried out for a coated tungsten carbide insert with 0.1 mm nose radius in the microturning of stainless steel 304 using multiple sensors such as AE, ACC and cutting force dynamometer simultaneously.

Literature review related to the monitoring of tool condition in microturning using AE, ACC and cutting force dynamometer is briefly presented here. In the use of AE sensor, Balan [14] correlated tool wear with different AE parameters such as AE_{RMS}, ringdown count and rise time for monitoring the cermet insert during microturning of copper. They observed that AE parameters increases with the increase in the tool wear. Ranjith et al [15] used AE sensor to monitor the tool wear in microturning of copper while machining with cermet inserts. They observed that there is a good correlation between the tool wear and the AE_{RMS} signals. A rise in the AE_{RMS} values with the increase in the cutting velocity is also observed. In the case of vibration signal analysis, from the literature review, it is observed that only few attempt has been made to measure vibration during microturning. Gopikrishnan et al [12] processed the vibration signal using time and frequency domains during the microturning of titanium alloy. They found that R_a and tool wear are increasing linearly with the machining time while ACC_{RMS} follows non-uniform trend. Mostly the vibration signal are occurs between 1.25-2.5 kHz. In the case of cutting force analysis, Rahman et al [2] invsetigated cutting forces in microturning using different tool materials such as PCD and cermet inserts by varying depth of cut, spindle speed and feed on brass, aluminum alloy and stainless steel. They found that the thrust force (F_x) dominates over the tangential force (F_y), with the increased depth of cut. From the literature review, it is observed that AE, ACC and cutting force dynamometer are widely used in the TCM system, individually. However, only few attempts have made to use these sensors simultaneously using multiple sensor approach. If one sensor fails during the monitoring process, the signal obtained from the other sensors is found to be useful for monitoring the tool condition. To the author's knowledge, there were only few attempts have been made by researchers to monitor the tool condition in microturning. Therefore, in this work, an attempt has been made to monitor the condition of the tool in microturning of stainless steel 304 using multiple sensors approach. Microturned Stainless steel have been widely used in various fields like bio-medical, aerospace, etc [2].

II. Experimental Details

The experiments were carried out with a MIKROTOOLS made DT110 integrated multi-process machine tool driven by a 100 W AC servo drive motor, with a speed range of up to 5000 rpm (Figure 1). The machine tool has a maximum traverse range of 200 mm (X-axis), 100 mm (Y-axis), and 100 mm (Z-axis). Microturning is carried out up to 60 minutes at a speed of 47 m/min, feed of 20 μm/rev and depth of cut of 50 μm. The levels of these parameters are selected based on the preliminary experiments carried out by Response Surface Methodology (RSM). The cutting tool used in this study is the Sumitomo make triangular shaped multi-coated tungsten carbide insert, with a 0.1 mm nose radius, 15^{0} rake angle, 11^{0} relief angle and 2 mm thickness. The tool is coated using the PVD process (using super ZX multilayer coating technique by M/s. Sumitomo Electric Hardmetal). It consists of 1000 alternating layers of TiAlN and AlCrN at nanometer levels. The cutting tool inserts are clamped to the tool shank which is mounted on the tool post. The workpiece is clamped on the spindle unit of the machine tool in the vertical direction. The workpiece material used in the work is stainless steel 304 (Composition: C 0.01%, Mn 1.7%, Si 0.2%, S 0.004%, P 0.03%, Ni 8.5%, Cr 18.7%, SS 70.5%) in the form of a cylindrical rod with an initial diameter of 6 mm and machined length is 20 mm. Tool wear is measured by the non-contact video measuring system (VMS) (Make: Rational Instruments, Model: VMS-2010F). Due to the lower depth of cut, the nose wear is found to be more dominant than that of the flank wear. The flank wear is found to be not significant. The nose wear is measured from the top surafce of the tool to the damaged portion at the bottom in the nose edge of the tool. The surface roughness (R_a) is measured with the non-contact 3D Profiler (Make: Taylor Hobson, UK, Model: Talysurf CCI LITE). Chip width (Figure 3) is taken using the scanning electron microscope (SEM) (Make: JEOL, Japan, Model: TSM-5300).





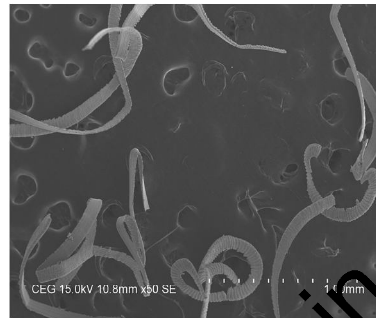


Figure 1. Photograph of the experimental setup Figure 2. Schematic of the cutting force component Figure 3. SEM image of the chip (60th min)

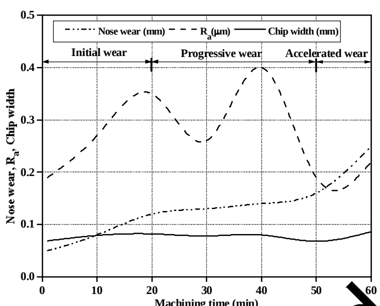
AE sensor is used to measure the transient elastic energy released when the material undergoes deformation. In this work, the AE signals were acquired, using the AE sensor (Make: Kistler, Model: 8152) with a frequency range of 50 to 900 kHz. A compatible coupler (Make: Kistler, Model: 5125B) is used to amplify the AE signals obtained from the AE sensor. Thereafter, the amplified AE signals are converted into digital signals by using the 16 bit multi-channel analog to digital (A/D) conversion card (Make: National Instruments, Model: PCI-6133). The sampling frequency of the AE signal is 2 MHz. ACC is used to collect the vibration that arises due to the influence of the tool during the machining process [16]. In this work, the vibration signals were acquired using a piezoelectric accelerometer (Make: Kistler, Model: 8702B), with a frequency range from 1 to 10 kHz. A compatible coupler (Make: Kistler, Type: 5110) is used to amplify the vibration signals obtained from the accelerometer. The sampling rate of the vibration signal is 250 kHz (2,50,000 samples per second). The data collected from the AE and ACC are transferred to the PC and then analyzed off-line in the time domain, frequency domain and Discrete Wavelet Transformation (DWT) at regular interval of time (10 minutes), to derive the necessary information about the condition of the tool. Two lakh data points are recorded for each machining trial. Out of which first 65536 data points were selected for the time domain analysis and first 2048 data points were selected for the dominant frequency analysis using MATLAB (R2010a). The cutting forces such as thrust force (F_x), tangential force (F_y) and feed force (F_z) are measured using piezoelectric cutting force dynamometer (Make: Kistler, Model: 9256C2), and the sampling rate is 1000 Hz. The cutting force dynamometer is connected to a charge amplifier, which in turn connected to a PC for acquiring the data using data acquisition system with suitable software. The schematic diagram of the cutting force components is shown in Figure 2. Three forces acting on the tool/workpiece was measured and plotted against the machining time at a regular interval of 10 minutes (Table 1(g)).

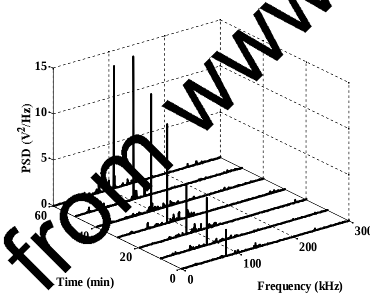
III. RESULT AND DISCUSSION

The following section deals with the analysis of tool wear, R_a, chip width, AE signal, ACC signal and cutting forces (F_x, F_y and F_z) with respect to machining time.

Table I: Statistical Values of the Experimental Results

Ex. No.	(a) Machining Time [min]	(b) Surface Roughness (R_a) [μm]	(c) Tool wear [mm]	(d) Chip width [mm]	(e) Acoustic Emission (AE)			(f) Accelerometer (ACC)			(g) Cutting force (N)		
					(i) Time domain	(ii) Frequency domain		(i) Time domain	(ii) Frequency domain		Thrust force [F_X]	Tangential force [F_Y]	Feed force [F_Z]
					AE_{RMS} [V]	Frequency [kHz]	Amplitude [V]	ACC_{RMS} [V]	Frequency [kHz]	Amplitude [V] x 10^{-5}			
1	1	0.19	0.05	0.069	0.33	79.59	2.82	0.0004	2.20	1.90	0.58	1.31	[illegible]
2	10	0.27	0.08	0.079	0.36	83.50	5.11	0.0004	2.51	1.13	1.38	2.11	1.03
3	20	0.35	0.12	0.082	0.44	85.94	5.42	0.0049	2.75	1.25	1.39	1.24	0.98
4	30	0.26	0.13	0.078	0.49	89.36	10.8	0.0051	3.06	[illegible]	1.27	3.07	1.04
5	40	0.4	0.09	0.08	0.54	99.12	12.7	0.0062	3.61	1.31	1.36	1.95	0.97
6	50	0.19	0.16	0.068	0.72	105.5	15.6	0.0067	[illegible]	1.55	1.68	1.56	0.97
7	60	0.22	0.25	0.086	0.76	108.9	13.3	0.0086	4.39	1.20	1.45	2.44	1.02





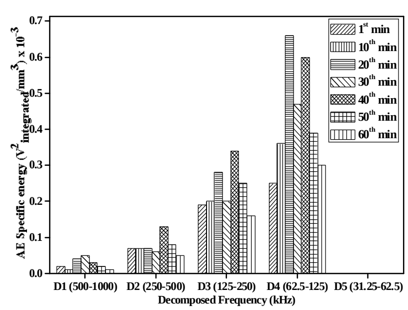


Figure 4. Output parameters with respect to machining time Figure 5. Spectra of the AE Signal Figure 6. Energy distribution of the AE Signal

A. Analysis of Tool Wear, R_a and Chip Morphology

Table 1 shows the result of tool wear, R_a, chip width, AE_{RMS} and ACC_{RMS} (time domain and frequency domain) and cutting forces. From Table 1, it is observed that the tool wear is found to be increasing with respect to machining time, while R_a is found to be non-uniform trend with respect to machining time (Figure 4). The tool wear is found to be lesser than that of macro-regime turning, which is also similarly observed by Sharma et al [17]. The increase and decrease in the R_a may be due to the interrupted chip formation that occurs between the cutting edge and the workpiece. In the case of chip width, there is no significant changes are observed. Chip morphological studies indicate that arc (loose and continuous) types of chip were observed during the 1st to 20th minute. During the 21st to 50th minute, long snarled chip is observed and thereafter from 51st to 60th minute, ear type broken chips are observed. Based on the tool wear and the formation of chips, the tool wear regions may be classified as initial wear (1st to 20th minute), progressive wear (21st to 50th minute) and accelerated wear (51st to 60th minute) in microturning of stainless steel 304.

B. Analysis of AE Signal

The AE signal is analyzed in the time domain and frequency domain by calculating the root mean square (RMS) value and power spectral density respectively. In case of time domain, the AE_{RMS} shows a uniform trend with the machining time (Table 1(e)). In case of frequency domain, the amplitude of the AE signal shows a increasing trend with respect to machining time. Figure 5 shows the power spectra of the AE signal. From Table 1(e) and Figure 5, it is observed that the dominant frequency of the AE signal increases from 80 kHz to 109 kHz with increase in the tool wear from 1st to 60th minute which is also similarly observed as in the macro-regime machining by Sharma et al [17].

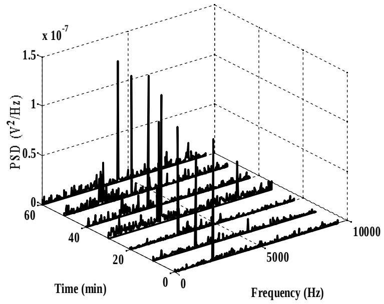
Table II: Experimental Results

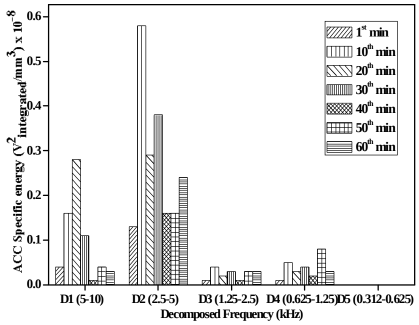
Ex. No.	Machining time (min)	(a) AE Specific energy ($V^2_{integrated}/\mu m^3$) $\times 10^{-3}$					(b) ACC Specific energy ($V^2_{integrated}/\mu m^3$) $\times 10^{-8}$				
		D1	D2	D3	D4	D5	D1	D2	D3	D4	D5
1	1	0	0.00	0.14	0.25	0.00	0.01	0.01	0.78	0.00	0.00
2	10	0	0.00	0.17	0.53	0.01	0.84	1.33	0.50	0.15	0.11
3	20	0	0.00	0.32	1.76	0.10	0.30	3.41	0.13	0.28	0.11
4	30	0	0.00	0.17	0.89	0.01	0.53	5.79	0.40	0.46	0.24
5	40	0	0.01	0.46	1.44	0.04	1.01	4.06	0.83	0.01	0.36
6	50	0	0.00	0.25	0.62	0.00	2.54	2.02	0.25	0.62	0.48
7	60	0	0.00	0.10	0.37	0.00	3.08	2.41	0.42	0.30	0.17

Discrete Wavelet Transformation (DWT) has been used to analyze the AE signal and it is decomposed into five levels of frequency bands, namely, D1 (500-1000) kHz, D2 (250-500) kHz, D3 (125-250) kHz, D4 (62.5-125) kHz and D5 (31.25-62.5) kHz (Table 2 (a) and Figure 6). From Figure 6, it is found that the dominance of the D4 level (62.5-125 kHz) is found to be significant. This indicates that the release of the AE during microturning is mainly due to the occurrence of shearing [18]. Figure 6 shows the increasing and decreasing trend of AE specific energy at D4 level with the increase in time. It also indicates that there is an increasing trend in the AE specific energy during the 1st to 20th minute (initial wear region), which indicates effective machining. During this period arc (loose and continuous) types of chip are also observed. Thereafter, the AE specific energy is found to be decreasing and increasing during the progressive wear region from 21st to 50th minute and during the 51st to 60th minute (accelerated wear region), the AE specific energy is found to be decreasing. This may be due to the chip clogging during machining.

C. Analysis of ACC Signal

The ACC signal is also analyzed in time domain, frequency domain and DWT. In case of time domain, ACC_{RMS} shows a uniform trend with machining time (Table 1 (f)). However, in case of frequency domain, the amplitude of the ACC signal shows decreasing and increasing trend with respect to machining time. Figure 7 shows the power spectra of the vibration signal and indicates that the dominant frequency of the vibration signal increases from 2.2 kHz to 4.39 kHz, during 1st to 60th minute. This indicates that the dominant frequency of the ACC signal is also found to be similar to that of the macro-regime turning, which falls between 2-5 kHz [19]. Figure 7 also indicates during the 1st to 20th minute the dominant frequency is found to be around 2.2 kHz to 2.7 kHz, thereafter it increases around 3.06 kHz - 3.91 kHz during the 21st to 50th minute and after the 51st minute, the dominant frequency increases to 4.39 kHz. This may be attributed to the increase in the tool wear as the machining time progresses. The vibration signals are decomposed in to five levels of frequency bands, namely, D1 (5-10 kHz), D2 (2.5-5 kHz), D3 (1.25-2.5 kHz) D4 (0.625-1.25 kHz) and D5 (0.312-0.625 kHz) (Table 2 (b)) using DWT technique. From Figure 8, it is found that the dominance of the D2 level (2.5-5 kHz) is found to be significant. This indicates that the vibration occurs during microturning is mainly due to the occurrence of elastic fracture [18]. Figure 8 indicates that there is an increasing and decreasing trend in the ACC specific energy during the 1st to 60th minute. This may be due to the chip clogging during machining.





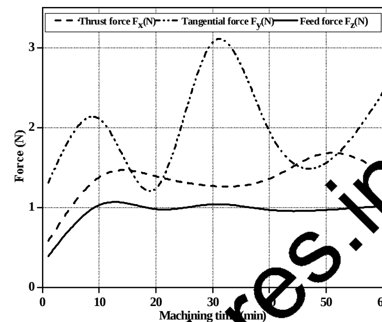


Figure 7. Spectra of the ACC signal

Figure 8. Energy distribution of the ACC signal

Figure 9. Response of Cutting forces with time

D. Analysis of Cutting Forces

Table 1 (g) and Figure 9 shows the behavior of cutting forces with machining time. From Figure 9, generally it is also observed that the cutting forces are found to behave increasing and decreasing trend with the increase in the machining time. This may be due to the deflection of the workpiece during machining. This is also similarly observed by Rahman et al [4] in microturning. In case of thrust force (F_x), it is observed that it is found to be increasing and decreasing from 1st to 60th minute and the maximum thrust force (F_y) is found to be 1.68 N. In the case of tangential force (F_y), it follows a non-uniform trend with the machining time and the maximum force is found to be 3.07 N. In case of feed force (F_z), it is found that there is no significant variation is observed after 10th minute and the maximum force is found to be 1.04 N. Among the three forces, the tangential force (F_y) is found to be more sensitive to the tool wear status compared to that of the thrust force (F_x) and feed force (F_z). This may be due to the resultant force acting towards the thrust direction. This is also similarly observed by Sharma et al [17] in the macro-regime turning.

IV. Conclusion

In this work, analysis of the tool wear, R_a, AE signal, ACC signal, cutting force signal and chip morphology were carried out to monitor the condition of the tool in microturning of stainless steel SS 304. The signals are analysed in the time domain, frequency domain and DWT. The tool wear, AE_{RMS}, ACC_{RMS}, and dominant frequency shows uniform trend with respect to machining time while non-uniform trend is observed in the case of R_a, chip width and cutting forces (F_x, F_y and F_z). Chip morphological study indicates that the arc, long and snarled and ear type of chips were observed. The dominant frequency of the AE and ACC signal are observed between 80-108 kHz and 2.20-4.39 kHz respectively. They are found to be increasing uniformly with the machining time. The specific energy of the AE and ACC signal show that the decomposed level D4 (62.5-125 kHz) and D2 (2.5-5 kHz) respectively are found to be dominant. Among the three cutting forces, the tangential force (F_y) is found to be more sensitive to the tool wear status compared to the thrust force (F_x) and feed force (F_z).

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