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Review Article

Applicability of Tool Condition Monitoring Methods Used for Conventional Milling in Micromilling: A Comparative Review

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Micromilling is a contact based material removal process in which a rotating tool with nose radius in microns is fed over a stationary workpiece. In the process small amount of material gets chipped off from the workpiece. Due to continuous contact between tool and workpiece significant damage occurs to the cutting tools. Mitigating tool damage to make micromilling systems more reliable for batch production is the current research trend. In macroscale or conventional milling process a number of methods have been proposed for tool condition monitoring. Few of them have been applied for micromilling. This paper reviews different methods proposed and used in last two decades for monitoring the condition of micromilling tools. Applicability of tool condition monitoring methods used in conventional milling has been compared with the similar ones proposed for micromilling. Further, the challenges and opportunities on the applicability issues have been discussed.

1. Introduction

Micromilling process has achieved significant popularity in production industries due to its exceptional capability to generate precise holes to complex 3D features. Micromilling process involves removal of material from a workpiece by a rotating tool with nose radius in microns. The material removal process results in a host of effects such as tool wear, generation of contact machining forces leading to tool deformation, chatter and vibration, and tool stress causing tool breakage [1]. These stated effects heavily depend on type of milling operation (vertical, horizontal, ball end, and face) [2], operating conditions [3] (temperature [4] and tool-workpiece alignment), parameter selection (feed, rpm, and depth of cut) [5], tool (PCD, CVD, PCBN, and metallic) [6], and workpiece materials (metals, polymers, semicrystalline, and amorphous) [7]. Due to influence of tool condition on myriad parameters, monitoring the same seems to be a real time multivariate problem. It is a well-known fact that almost all CNC milling machine manufacturers state the optimum machining conditions in their industrial datasheets. Even on maintaining these conditions strictly, tool damage is prevalent in micromilling process as no datasheet can provide all combination of optimum machining parameters. In addition, micromilling process in total requires a number of critical steps. Tool positioning at beginning of the process demands dexterity of the machine operator as a slight error may lead to tool failure before any machining has taken place [8]. Due to miniature footprint of the tool, often a tool with broken tip remains unnoticed while the micromilling operation takes place. Thus it can be understood that monitoring the condition of the tool in micromilling is important as it enhances the fidelity of the process by cutting off unnecessary shutdowns at batch production units leading to enhancement in productivity.

On the other hand conventional milling process does not suffer from all of these critical limitations. This is due to the fact that the cutting dynamics of macro- and microscale milling processes is entirely different [9]. Whereas the macroscale material removal is believed to be frictional shearing and deformation at the tool tip, in microscale upsetting and consequent material dislodgement are associated [10]. The size effect as explained in the next paragraph changes the entire cutting dynamics. Further the miniature nose radius is prone to frequent wear which leads to higher forces on the cutting edge of the tool leading to extensive stress related breakage in micromilling.

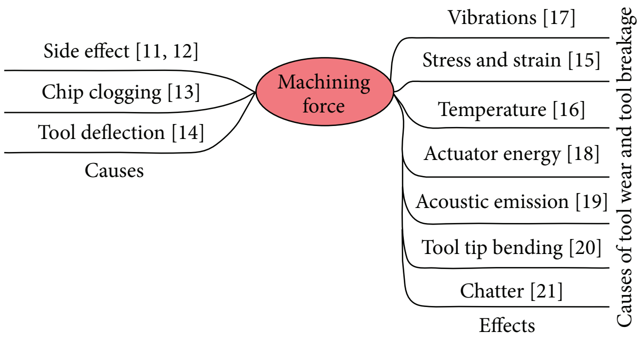

Figure 1: Primary causes and effects of machining forces.

In previous two decades issues related to tool condition monitoring of micromilling process has been extensively dealt in literature. Primarily, the phenomenon of tool breakage in micromilling is justified by the following inferences.

(a) The size effect: when the material is removed by micromilling tool, the specific energy required for material removal decreases gradually, as the chip thickness decreases [11]. This can also be stated otherwise as the tool has to sustain a greater magnitude of cutting force as machining progresses as if the tool has to cut harder material gradually [12].

(b) Chip clogging: the clogged chip at the tool work interface results in sharp increase in the machining force leading to tool breakage [13].

(c) Tool tip deflection: the tool gradually loses its cutting edge due to tool wear. The work material imposes more force on the tool for machining and hence increases the tool stress leading to tool breakage [14].

From the above discussions it can be understood that the machining force is the primary measurable quantity leading to tool wear and breakage. As machining force is related to a number of parameters like stress [15], temperature [16], vibration [17], actuator energy (motor currents) [18], acoustic emission [19], tool tip bending [20], and tool chatter [21] and it is difficult to measure forces at all points on the cutting tool during machining operations, different methods are used to monitor the tool condition. Figure 1 shows a cause effect relation of tool breakage and tool wear in micromilling operations.

As discussed in earlier paragraphs, the cutting mechanics of macro- and micro-scale varies greatly. In spite of this, almost all the tool condition monitoring methods proposed for micromilling trace their roots from conventional milling ones. In this paper we present an extensive review of various methods and state of the art for tool condition monitoring in micromilling process and state a comparison with the ones used in conventional milling process. Such review has basically two advantages. Firstly, it renders the readers a vivid idea of various approaches, their advantages, and limitations for tool condition monitoring at macro- and microscales. In addition such study opens up new vistas for other researchers to invoke their thought process for utilizing conventional tool condition monitoring approaches at microscale thus leading to evolution of similar methods at microscale.

2. Review of Proposed Methods

The proposed methods for tool condition monitoring in micromilling include use of acoustic emission sensors and related signal processing approaches, measurement of dynamic cutting force and its classification, use of vibration sensors, use of motor current signature, machine vision, combination of the preceding approaches, and sensor fusion. Before we proceed further, an account of all well-known processes for tool condition monitoring at micro- and macroscales for milling operation is summarized and is presented in Table 1.

The proposed methods in literature for tool condition monitoring are explained in following paragraphs in detail.

2.1. Use of Acoustic Emission Sensors. Use of acoustic emission (AE) sensor is one of the oldest techniques applied for condition monitoring of machine tools at macro- and microscale. The use of AE sensors for tool condition monitoring in micromilling traces its citation back in 1998 [22] in which a general overview of its use with relevance to machining perspective was presented.

An AE sensor converts the mechanical energy carried by an elastic wave into electrical parameter [23]. Such sensors are particularly applicable in systems where the residual high frequency noise during machining operation is lower as compared to the acoustic signal [24]. An AE sensor like all others faces the challenge of appropriate mounting on the milling machine for accurate parameter measurement. Industrial milling machines mostly use the AE sensors mounted on the tool surface [25–27], though the position and alignment may vary. Standard AE sensors tailored for tool condition monitoring applications are available from vendors like Artis, Brankamp, Kistler, Montronix, and so forth. Few machines use communication modules with AE sensors so that they can be placed on high speed rotating tool [28, 29]. Yet few others use other materials like fluid or coolant as a path for acoustic signal transmission [30]. These stated methods are well established ones in industries at macroscale milling process. However, the current research trend of use of AE sensors relies on integration of the sensor with intelligent algorithmic methods. The simplest algorithmic method uses the root mean square value (RMS) of the captured data using AE sensors [31]. Advanced ones include artificial neural networks [32], use of statistical classifiers (SVM and ARD) [33], and signal processing approaches like time domain analysis [34].

At microscale, utility of AE sensors is at a research stage and its applicability is justified by even more complex algorithm to process the sensor data. For instance, very recently Yen et al. [35] has proposed self-organizing feature map (SOM) algorithm to monitor tool wear based on AE sensors. The methodology uses collection of sensor data followed by its Fourier domain analysis. Next feature extraction from the frequency domain data uses SOM based genetic algorithm. The performance verification of this approach adapts learning

TABLE 1: Summary of methods used for tool condition monitoring of milling process at micro- and macroscale.

S. number	Methods for tool condition monitoring	Citations for macroscale	Citations for microscale
1	Acoustic emission sensors	[22–34]	[35, 36]
2	Cutting force measurement sensors	[37–39]	[40–42]
3	Machine vision sensors	[43–48]	Not available
4	Acceleration and vibration measurement	[49–53]	[54]
5	Actuator current measurement	[55–58]	[59]
6	Stress/strain measurement	[60–62]	Not available for milling
7	Machine learning and prediction estimation based approaches	[66–77]	[78]
8	Sensor fusion	[79–83]	[84]

vector quantification (LVQ). Thus a number of algorithms had to be integrated for tool health monitoring at microscale. This evokes the primary question of whether such complex algorithms can be used in real time micromilling operations.

An approach using wavelet analysis of AE sensor signal was proposed for tool breakage monitoring in micromilling [36]. They have stated that the frequency of acoustic signal obtained is given by equation

$$f = Z_n \times \frac{n}{60}, \quad (1)$$

where f is the AE sensor signal frequency, Z_n is number of cutting edges in the tool, and n is the rpm.

In one of the experiments they stated that the cutting frequency obtained was about 3 KHz and it matches with normal hearing spectrum (20 Hz to 20 KHz). Thus we cannot guarantee that noise figure has not crept into the system. Further the experiments were conducted at high spindle speeds (>20000 rpm) and hence fidelity of the same at lower spindle speeds cannot be assured.

It can thus be inferred that the use of acoustic emission sensor at microscale has following limitations.

(a) Complex algorithms and feasibility issues in real time.

(b) Signal filtering from noise and signal detection at low spindle rpm.

(c) Accurate placement and alignment of acoustic sensor due to limited footprint of tool.

2.2. Use of Cutting Force Measurement. Cutting force measurements in milling process primarily rely on the use of piezoelectric dynamometer as the sensor followed by various intelligent algorithms [37]. For instance Promotech's PROMOS system measures the cutting force during machining and incorporates dynamic limits to detect tool breakage. Unlike previous section (use of AE sensors) where the applicability of the same was a challenge at microscale in comparison to macroscale, cutting force measurement methods are versatile and their use is well established at both scales.

Cuš and Župerl [38] has proposed a real time cutting tool monitoring process and flank wear estimation in milling process using a dynamometer followed by processing with an ANFIS algorithm and has claimed that the method is real time one and can be used at low cost as compared to multisensory systems. Saglam and Unuvar [39] have used ANN for tool condition monitoring and have stated the relationship of various machine parameters on cutting force during milling.

Approaches similar to these stated ones were used for tool health monitoring for micromilling process, however with slight modifications. This is due to the fact that the magnitude of cutting forces is lesser at microscale as compared to macroscale which makes the signal immune to noise [40]. In [40] authors have used a hidden Markov model (HMM) for noise robust tool condition monitoring in micromilling. A similar method based on HMM was used in [41] for tool wear monitoring in micromilling. A fuzzy logic based approach was used by authors in [42] where they mapped the force patterns using pattern recognition to compute machine parameters dynamically thus aiding in tool condition monitoring.

Following can be summarized regarding advances in tool condition monitoring in milling process using cutting force data.

(a) The methods and algorithms at microscale are at par with ones used at macroscale in present state of research.

(b) The trivial challenge faced by this method is reduction of noise from cutting force data specifically at microscale.

(c) Force based tool condition monitoring strategy has got significance due to the fact that the cost is lesser as compared to other sensors. Further the methods of alignment of sensor are simple and robust.

2.3. Use of Machine Vision Sensors. Machine vision sensors are perhaps the most reliable way for tool condition monitoring [43]. In citations use of machine vision sensors is used to monitor the tool wear rather than tool breakage. Different techniques had been used for the same. Few use a high resolution, high zoom based camera and few others use binocular microscope which captures the image of the tool tip and performs further algorithmic processing [44]. Algorithms to process the tool image cover a wide domain ranging from simple texture recognition [45] to complex statistical filtering [46]. To the best of author's knowledge, use of machine vision sensors for tool condition monitoring directly has not yet been explored for micromilling; however methods exist for other operations like microturning [47]. This is due to the fact that background lighting during image capturing is the trivial requirement for machine vision systems. For micromilling where the tool rotates at a very high speed, capturing the tool image needs a high speed frame grabber camera. Such cameras usually work at low illumination as high light intensity can damage the CMOS sensor in the camera [48].

Following are the challenges and limitations of use of machine vision sensors for milling.

(a) Use of machine vision sensors for tool condition monitoring is a naive field both at micro- and macroscale.

(b) The technology faces serious challenges in terms of acquisition of image data. Further proper calibration of measuring instrument and alignment of optical parts are mandatory for accurate results.

(c) Direct use of machine vision sensors for tool health monitoring is still a nonreal time approach. This is due to the fact that the process consists of a number of critical steps, namely, image capturing, preprocessing, and postprocessing which consumes time in any image processing hardware.

(d) The cost of machine vision sensors used for image capturing is very high. For example, a high speed camera coupled with a binocular microscope may cost more than 50 K USD.

2.4. Acceleration and Vibration Measurement. Acceleration and vibration of a milling machine are the signature of the machine and tool condition during its dynamic operation as they are directly related to the cutting force. Advanced accelerometer and vibration sensors integrated with the tool or shank is available and efficient algorithms exist for real time tool breakage detection [49]. Suprock et al. [50] has proposed an effective method to capture the vibrations during milling process using electret dynamometer. They claimed that they could capture vibration signals, aiding in tool breakage prevention due to chattering. It has been further claimed in [51] that scalogram which represents power spectral density of a signal can be used on vibration signals to arrive at the state of the tool in milling. In [52], Zhang and Chen have proposed tool monitoring approach using vibration signals and pattern recognition approach with the algorithm hosted on a microcontroller. This achievement led to the establishment of the fact that use of accelerometer and vibration sensors for tool condition monitoring is apt to be applied for real time CNC applications. A list of conventional methods on use of accelerometer and vibration sensors used for tool condition monitoring in milling is listed in [53].

Whereas frequent citations could be found on embedding an accelerometer sensor on the tool at macroscale milling process, microscale accelerometers and vibration sensors are usually mounted on the machine or spindle due to limited footprint [54]. With advances in MEMS (microelectromechanical systems) based fabrication technology accelerometers within limited footprint and consuming a few nanoamperes current are available. One of them is ADXL345 manufactured by analog devices. In [54] authors have proposed a tool positioning strategy for micromilling using an accelerometer sensor. Tool positioning is the most crucial issue for condition monitoring in micromilling as stated in Section 1. In the same article submicron level accuracy in tool-workpiece contact was detected based on power spectral characteristics of vibration signal.

Following can be inferred on present state of the art on use of acceleration and vibration sensors for tool condition monitoring in milling.

(a) With advances in MEMS technology accelerometer and vibration sensors have got profuse advancements which have led to small footprint. Hence they are suitable for tool condition monitoring at microscale.

(b) The algorithms for data interpretation from sensor signals are simple both at micro- and macroscales because of the fact that these parameters are directly related to machining forces and hence complex conversion look up tables or interpretation techniques are not required.

(c) The process is simple and can be achieved in real time for condition monitoring.

2.5. Actuator Current Measurement. Actuator current measurement technique for condition monitoring of milling tool is an indirect way to assess the health of the tool. In this process no external sensors are usually required. The spectrum of the current signal assessed by the motor driver is itself used for condition monitoring. The basic principle relies on the fact that the load current signature of the motor driving the spindle or the feed stage varies as per torque requirement, speed, and cutting forces [55].

Li [56] has proposed a method of tool health monitoring in end milling using feed motor current signatures. In this paper the author has claimed that the method has potential to be applied online. Hall effect sensors were used to measure the motor currents in real time. Subsequently, time domain averaging (TDA) of the procured signal was carried out which detects the periodicity of the signal in a given interval of time. In cases of tool damage the periodicity changes and hence detection of the same is possible. A similar approach was adapted for face milling operations in [57], where the authors suggested the use of tool fracture index (TFI) based on periodic variations in load. In [58], a new strategy of signal processing, namely, discrete wavelet transform (DWT) was used to decompose the motor current signals into hierarchical levels. Such multilevel signal decomposition system is advantageous as it combines both time domain and frequency domain signal analysis, thus enhancing the process fidelity.

At microscale Ogedengbe et al. [59] has tested for the feasibility of the approach for micromilling operations recently. They claimed that despite of the advantage of low cost and simplicity of this method, it has not been applied in research or in industry. They also stated that the spindle and feed motor current signatures changes remarkably over time as the tool wear progresses.

From the preceding discussion following can be concluded.

(a) Use of current signature for tool condition monitoring at microscale still demands research. As similar successful approaches have been dealt extensively at macroscale, so there is a lucrative scope in this area.

(b) The method is least expensive and is simple as no sensors need to be mounted on the machine or machine tools.

(c) Analysis algorithms are simple and can be applied in real time.

(d) The signal procured is not affected by mechanical noise unlike other methods where noise filtering in the captured signal is a crucial issue.

2.6. Stress/Strain Measurement. Stress/strain measurement methods for tool condition monitoring are established in literature using a variety of techniques. They include use of thin film sensors [60], photoelastic method [61], use of strain gauge [62], and use of optical fibre sensors [63]. In [60] authors have demonstrated a technique to capture the strain on milling tool using thin film polyvinylidene fluoride (PVDF) sensor and has proved its accuracy using back calculation of induced forces and matching them with the obtained ones using dynamometer. A strain gauge based milling dynamometer was proposed in [62], wherein strain gauges bonded on octagon rings were used to finally procure the cutting force. Photoelastic methods are used for tool health monitoring by residual cyclic stress measurement for turning operation [61]; however it is not applied for milling operations. Similarly fiber Bragg grating sensor has been used to detect tool stress for turning operation both at macro- [63] and microscale [64] but is not applied for milling. At microscale, due to challenges in placing the sensor near to the tool, stress or strain assessment methods have not gained popularity.

Following points are to be noted regarding advancement in stress/strain measurement for micromilling systems.

(a) As it is preferred to measure the stress/strain on the tool surface and the footprint limitations combined with high spindle speed renders difficulty in sensor mounting, using this technology is a daunting task.

(b) Use of photoelastic technology can be an alternative solution in near future. However present technology does not allow the use of this method for tool stress determination in micromilling due to issues like requirement of high speed frame grabber with high intensity sustaining capacity of CMOS sensor along with high magnification power.

(c) Use of fibre Bragg grating sensor can be a promising solution for strain measurement and subsequent tool condition monitoring at microscale due to its small footprint. Further availability of high speed fibre optic rotary joints [65] makes its suitable for micromilling applications.

2.7. Machine Learning and Prediction Estimation Based Approaches. This technique of tool condition monitoring uses prior feature based knowledge or some empirical relation of tool condition and tool health to estimate the same in real time [66]. More specifically, a set of recorded data is used to predict the state of condition in real time [67]. In few cases a mathematical model is first established and based on that, prediction of tool wear and breakage is carried out. In [68], authors have used cutting power model to determine a cutting threshold, which is used to monitor tool wear during milling operations. In [69], regression and ANN models were used to predict the tool wear and predict tool life. In this paper authors initially used design of experiments (DOE) for five level three factors full factorial technique and subsequently a final regression model was constructed to estimate the tool wear. Similar approach was followed in [70] using physically segmented hidden Markov models to estimate tool condition during milling. Prediction of tool wear merely by using the machining parameters was conducted in [71]. In this response surface methodology (RSM) was utilized to predict the effect of machining parameters on tool wear.

Statistical approaches to monitor tool breakage in milling have also evolved. In [72], authors have proposed a statistical approach to detect tool breakage in end milling operation. They claimed the fact that merely classifying a tool as good or broken one cannot solve the problem of tool breakage. In order to address the same and to make the process more versatile towards various tool work-material combinations they used multiple regression model. In 2008 [73], a method using state vector machine (SVM) was proposed to predict tool breakage in face milling. Use of SVM over other approaches like fuzzy, ANN, and so forth has the advantage that the final results depend on very few parameters which lie on the classifier boundary. Thus computational load is reduced greatly which increases its prediction efficiency in real time.

Approaches to predict tool chatter also find citations in the literature. In [74], single frequency solution approach was used to predict tool chatter using a continuous beam model for tool-spindle combination. In [75], authors used a set of differential equations to predict tool chatter. The model relies on damping factor of the system. In [76], authors proposed a technique to predict multiple dominant chatter frequencies unlike in others where a single frequency was predicted. This method is beneficial from the viewpoint that chatter in a machine is regenerative and nature. Regenerative chatter also has deteriorating impact on tool life [77].

At microscale the use of prediction estimation methods have evolved very recently. In late 2012, Hung and Lu [78] have proposed a model to estimate the tool wear in micromilling based on the acoustic signals.

Following can be inferred from the above discussions.

(a) Use of prediction estimation based algorithms for tool condition monitoring is an emerging area at microscale.

(b) At macroscale numerous methods can be found in the literature. Applicability of these methods at microscale has not yet been significant in research.

(c) Prediction estimation based algorithms are beneficial from the viewpoint that they do not employ complex and costly sensors but rather focus on computation based on some known facts. Further due to speed improvement in computer hardware over years these methods are suitable for real time applications. There is no delay in signal output neither does it need any signal processing.

(d) These algorithms suffer from a limitation that over prolonged periods of time the known relationships may change. This can lead to erroneous results. Thus time to time calibration and algorithmic debugging are essential.

2.8. Sensor Fusion. Today's research trend for tool condition monitoring in milling process emphasizes multisensor approach or sensor fusion based approach [79]. Under this a number of sensors mounted at various places of tool and tool holder are used to procure multiple parameters in a synchronous way and is processed using algorithms [80]. The resultant signal is used for condition monitoring of the tool.

Cho et al. [81] has claimed that force, vibration, and AE sensor combination together with correlation based feature selection of the captured data yield the best accuracy in tool condition monitoring. The method of sensor fusion in the stated paper deals with using sensors directly for the purpose. In [82], a solution to reduce flank wear and breakage in milling tool using a combination of machine vision and an indirect relation with cutting force was proposed. Self-organizing feature map was trained in batch mode using the captured data from the sensors. Authors claimed that they could achieve real time monitoring of tool condition using this process. Dutta et al. [83] used force and vibration sensors and processed the signals using fuzzy controlled back propagation neural network and also claimed that their proposed method could be used online.

Similar techniques were used for micromilling in [84]. In this research the authors used a combination of accelerometer, force, and AE sensors and fused the captured signals using neuro-fuzzy method. Further the tool wear was evaluated online using an optical microscope.

From the above discussions following points can be concluded.

(a) Multisensor approach is very reliable method of tool condition monitoring at both micro- and macroscales as a number of parameters could be monitored simultaneously.

(b) At microscale cost and alignment issue for the sensors are still a challenge.

(c) The algorithms used for multiple sensor based methods are complex due to demand of proper data fusion and accurate feature extraction.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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