Research Journal of Applied Sciences, Engineering and Technology 7(10): 2083-2097, 2014
DOI:10.19026/ajfst.7.502
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: July 1, 2013 Accepted: July 12, 2013 Published: March 15, 2014

Research Article

A Review of Sensor System and Application in Milling Process for Tool Condition Monitoring

[1, 2]Muhammad Rizal, [2]Jaharah A. Ghani, [2]Mohd Zaki Nuawi and [2]Che Hassan Che Haron
[1]Department of Mechanical Engineering, Faculty of Engineering, Syiah Kuala University (UNSYIAH), 23111, Darussalam, Banda Aceh, Indonesia
[2]Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600, Bangi, Malaysia

Abstract: This study presents a review of the state-of-the-art in sensor technologies and its application in milling process to measure machining signal for Tool Condition Monitoring (TCM) systems. Machining signals such as cutting force, torque, vibration, acoustic emission, current/power, sound and temperature from milling operation are briefly reviewed with the goal of indentifying the parameters for TCM. Sensors reviewed include both commercial and research devices that can measure machining signals. In this study describes trends in the sensor systems used and its potential for future research.

Keywords: Milling process, sensor, sensor systems, tool condition monitoring

INTRODUCTION

The milling operation is a machining process that is very versatile, capable of producing a flat or curved surface, or complex geometric parts, by feeding the work piece against a rotating cutter containing a single or a number of cutting edges. Many phenomena affecting productivity, such as tool wear, chatter and even tool breakage naturally occur during milling operations. These phenomena if not monitored, degrade the quality of machined parts and cause dimensional errors. Under certain conditions, when tool wear or chatter has been excessive, they can cause machine downtime, as a result of catastrophic tool failure. Catastrophic tool failures in machine tools should be avoided, because they damage the machined parts and the machine tool itself and expose operating personnel to significantly hazardous situations (Cho *et al*., 2005).

Downtime always has a significant effect on productivity and causes a rise in production costs. It has been reported that tool failure contributes up to 6.8% to the downtime of machining processes (Yeo *et al*., 2000). Certain types of downtime that are caused by excessive wear or chatter during the milling operation can be avoided by implementing a Tool Condition Monitoring (TCM) system. This system attempts to maintain the machined part quality and to avoid catastrophic tool failure by detecting wear status, chatter, tool breakage and even tool collision. Previous studies reported that implementation of a reliable TCM system increases the productivity by about 10-50% and increases savings by up to 40% (Najafi and Hakim, 1992; Lim, 1995; Rehorn *et al*., 2005).

Traditionally, the measuring techniques in TCM have been implemented in two categories of approach: direct and indirect. In the direct method, the actual geometric parameters of the cutting tool, for example, tool wear, are measured. Tool wear is measured by using a microscope, a CCD (Charge-Coupled Device) camera, radioactive isotopes, laser beams and electrical resistance (Kurada and Bradley, 1997; Wang *et al*., 2007). The direct method has become a conventional method that requires more time for dismantling and tool set up purposes and can only be used in laboratory techniques. This is due to the practical limitations caused by access problems during machining, illumination and the use of cutting fluids. However, direct measurement has a high degree of accuracy and has been employed extensively in research laboratories to support the investigations of fundamental measurable phenomena during the machining processes (Teti *et al*., 2010).

The indirect methods are achieved by empirically determined correlations or deducing suitable sensor signals to the actual quantity of tool wear. In this method, a variety of sensors are deployed to determine the machining signals, such as cutting force, torque, vibration, acoustic emission, motor current or power, temperature, sound and so on (Byrne *et al*., 1995; Sick, 2002). The advantages are that it has a less complicated

Corresponding Author: Muhammad Rizal, Department of Mechanical Engineering, Faculty of Engineering, Syiah Kuala University (UNSYIAH), 23111, Darussalam, Banda Aceh, Indonesia, Tel.: +603 8921 6505; Fax: +603 8925 9659

setup and is suitable for practical applications but it is less accurate than the direct method. In contrast to the conventional method of tool-wear measurement, the approach is that the machining processes are continuously monitored via sensing devices to quantify the process performance or provide information for process optimization (Teti *et al*., 2010).

The main objective in this study is to present an overview of sensor systems and their applications in TCM during milling operations. The remainder of this study comprises three sections. Section one introduce the sensor system in milling process. Second, focuses on sensor systems and their applications currently used in milling operations. Third, provides a critical review of sensor systems in the milling process and identifies the trend of future sensor systems used in TCM during milling operations. Finally, concludes.

MACHINING SIGNALS IN MILLING PROCESS

The milling process is the removal of metal by feeding the work piece past a rotating multi-toothed cutter as shown in Fig. 1. The action of the milling cutter is different from a drill or a turning tool. In turning and drilling, the tools are kept continuously in contact with the material to be cut, whereas milling is an intermittent process, where the thickness of the cut for each cutting edge varies during the cut. Besides, the cutting tool in the turning process is singular and is always stationary in the tool holder, whereas the cutting tool in the milling process can be singular or with a multi cutting edge. Therefore, the cutting force generated from the process is also different. The magnitude of the cutting force in the turning process is always constant since the edge of the cutting tool is continuously engaged with the work piece during cutting. But, the cutting force in the milling process is a periodic series of interrupted cuts. This depends on the number of tool edges, the geometry of the milling cutters and the operation itself (Altintas, 2000). Another important parameters measured in the milling process for monitoring application are torque, vibration, acoustic emission, sound, ultrasound, current, power and also temperature.

SENSOR SYSTEM AND APPLICATIONS

There are several sensors system have been developed and applied in milling process in the previous, both commercial and research device. The sensor system deployed based on machining signals measurement including cutting force, torque, vibration, acoustic emission, current/power and temperature.

Cutting force: The cutting force is one of the most sensitive indicators of machining performance, including tool condition and chip formation and also because it optimizes the machining process and the design of proper machining tools. Recently, a commercial force transducer and a dynamometer for the milling process have been developed, both a table and rotating dynamometer. A number of these techniques have evolved mainly due to the efforts of the Kistler Company over the past 40 years (Kistler, 2012). The work piece table dynamometers have been widely used in industry and research laboratories for cutting force measurement in face and end milling as shown in Fig. 2a. The principle of the dynamometer is pressure detection using piezoelectric materials that are used in dynamometer construction as the main element and are converted to a proportional electric charge in three directions as shown in Fig. 2b. The most well-known piezoelectric material is quartz crystal (SiO_2). Quartz rings are employed, including two shear-sensitive quartz pairs, for *Fx* (yellow) and *Fy* (blue) and *Fz* (violet), a pressure-sensitive pair. The pressure-sensitive quartzes are arranged in the middle so that they lie in the neutral axis under bending. All the *x*, *y* and *z* channels respectively are electrically paralleled. This makes the measurement independent of the momentary force application point.

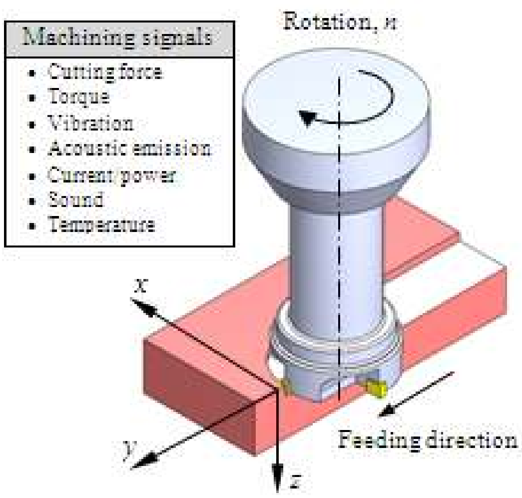


Fig. 1: Milling operation and its generated machining signal

(a) (b)

Fig. 2: Construction of three axis components dynamometer (Kistler, 2012)

The table dynamometer based on piezoelectric material has been widely used for cutting force measurement in the milling process. It has the most sensors used in machining to detect changes in tool wear, tool breakage and tool chatter. For instance, Lin and Lin (1996) used a piezoelectric dynamometer to measure cutting force signals during a face milling operation to estimate tool wear. Yan *et al.* (1999) investigated indices of tool wear based on the milling force using the dynamometer. Ghani *et al*. (2010) also used this type of dynamometer to measure the cutting force in estimating tool wear. Cho *et al*. (2005) used a dynamometer to detected tool breakage by recording the three-channel cutting force in the milling process. Kim *et al*. (2007) measured the cutting force signal using a piezoelectric dynamometer and compared it with the prediction model for detecting chatter in a ball-end milling operation. The other authors who applied the piezoelectric dynamometer in tool-wear monitoring include Choudhury and Rath (2000), Sarhan *et al*. (2001), Susanto and Chen (2003), Choi *et al*. (2004), Chen and Chen (2004), Bhattacharyya *et al*. (2007a), Chen and Li (2009), Girardin *et al*. (2010), Kious *et al*. (2010) and Čuš and Župerl (2011). On the other hand, it is also used for detecting tool breakage (Ko *et al*., 1995; Huang *et al*., 1999; Huang and Chen, 2000) and tool chatter (Lacerda and Lima, 2004; Pongsathornwiwat and Tangjitsitcharoen, 2010; Huang *et al*., 2012b; Huang *et al*., 2012a).

Likewise, a rotating dynamometer has also been developed by the Kistler Company (Stirnimann *et al*., 2012) based on a piezoelectric sensor that is equipped with quartz crystals. It enables measurement of the torque and axial force on a rotating tool up to 25,000 rpm. The data are transferred by induction from the rotating sensor to a spatially fixed receiver. Kuljanic and Sortino (2005) deployed a rotating dynamometer that was clamped between the cutter and the spindle. The dynamometer signals were stored in a computer by using a data acquisition board consisting of the main cutting force F_c, the cutting perpendicular force F_{cN}, the axial cutting force F_a and torque M_c. They investigated the characteristics of cutting forces in face milling and determined the tool-wear indicators by simple analysis of the feature parameters of the cutting force signals. In another study, Kuljanic *et al*. (2009) used the rotating dynamometer for chatter detection by measuring the axial force F_a, the feed force F_f and the feed perpendicular force F_{fN}. The rotating dynamometer has several advantages over the fixed or table dynamometers, such as the cutting forces can be measured on the rotating tool independently of the size of work piece and measurement can be performed on any spatial position (four or five axis milling) (Kaya *et al*., 2011).

Besides measuring the cutting force in the milling process using the commercial dynamometers that exist in the market, it can also be measured based on elastic deformation of the materials by using a strain gauge. The resistance of the strain gauge changes due to the deformation that occurs in a material under mechanical load. The amount that the resistance changes depends on how the gauge is deformed, the materials from which it is made and the design of the gauge (Figliola and Beasley, 2000). A strain gauge is a low cost, simple sensor that can be mounted directly onto the surface of the tool holder to measure the cutting force in turning (Ghani *et al*., 2011). However, milling needs metal-based components, such as a table dynamometer, on which to place the strain gauge. For instance, Korkut (2003) has successfully developed a three-force component analogue dynamometer based on a strain gauge sensor. This dynamometer consists of four elastic octagonal rings, made from AISI 1040 steel, on which

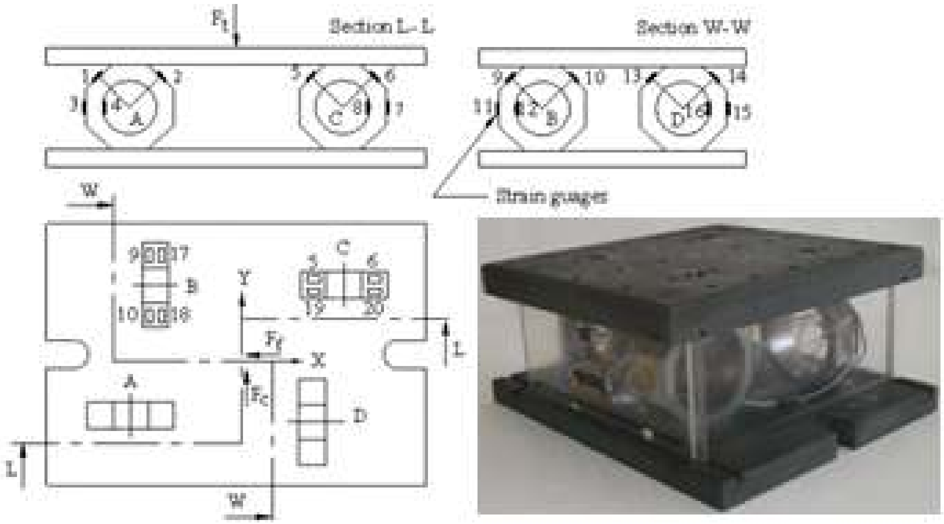
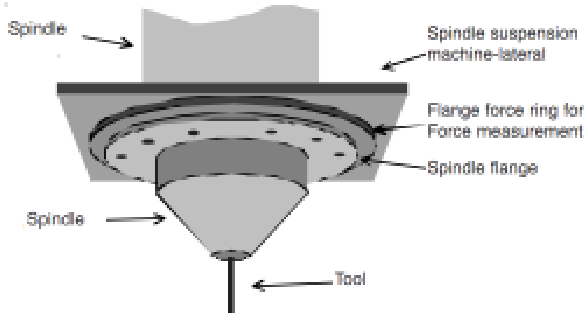


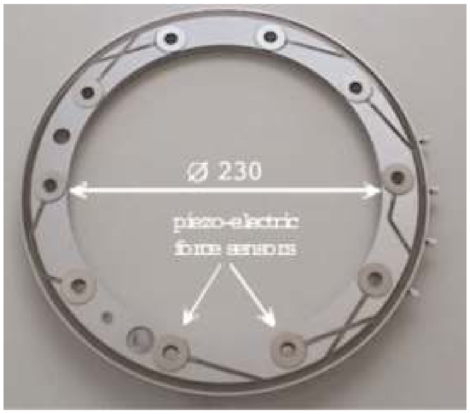
Fig. 3: Milling operation and its generated machining signal (Yaldız *et al*., 2007)

strain gauges were mounted, clamped between upper and lower plates, forming a platform, as shown in Fig. 3. The precision of this dynamometer was 5 N, with dynamic response bandwidth 192.2 Hz and maximum loading 1,500 N. There were differences from the dynamometer designed by Yaldiz *et al*. (2007). They developed a table dynamometer to measure three perpendicular cutting force components and torque. The system combined the strain gauge and piezoelectric accelerometer to measure static and dynamic cutting forces. Saglam and Unuvar (2003) used a strain gauge-based dynamometer for TCM in face milling. They correlate between the cutting parameters and the cutting force components with flank wear and surface roughness and the cutting force data were taken as a reference in order for on-line observation.

A spindle-integrated force sensor is one of the rotating cutting force transducers in the milling process that has been developed by Scheer *et al*. (1999) and Park (2004). The force transducers that in the form of a force ring sensor integrated to the spindle housing. The machine spindle is retrofitted with a flange force ring, which can be placed between the spindle flange and the spindle suspension as shown in Fig. 4a. This flat ring contains several piezoelectric force sensors as shown in Fig. 4b, which measure the process forces in the x, y and z directions and the torque in the axial direction. The data is transmitted from the rotating part of the sensor to a stator via telemetry. Byrne and O'Donnell (2007) combined the spindle-integrated force sensor for the drilling process with two piezoelectric force sensing rings, a flange and a bearing sensor ring. The flange sensor ring consisted of a precision machined steel housing in which a combination of compressive and shear force sensors were installed. The flange sensor ring was located behind the spindle housing, measuring forces in three directions. The construction of the bearing sensor ring consisted of a precision machined steel housing in which 22 piezoelectric elements were incorporated with a single output signal representing axial force. The bearing sensor ring was located behind the front thrust bearing measuring the force components in the feed direction. As shown in Fig. 5, the sensors were arranged in diagonally opposite pairs in the flange sensor ring in order to account for thermal instability.



(a)



(b)

Fig. 4: Construction of a spindle-integrated forces sensor, (a) position of the flange ring, (b) flange force ring with piezoelectric sensors (Scheer *et al.*, 1999)

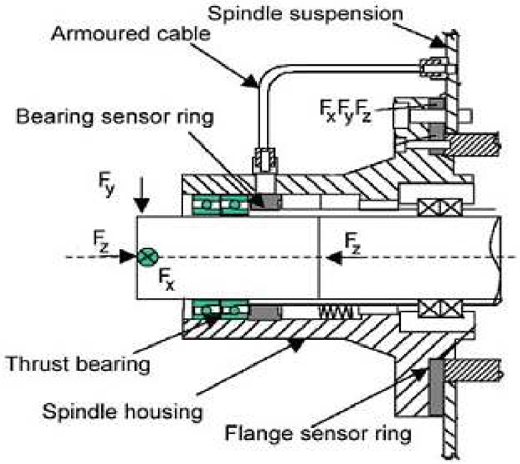


Fig. 5: Detail of spindle-integrated forces sensor combined with bearing and flange sensor rings (Byrne and O'Donnell, 2007)

However, integration of the force ring into the spindle machine structure raises some concerns (Byrne *et al*., 1995). These include the possibility of weakening the spindle dynamics, increased drift due to temperature changes inside the spindle, higher cross-talk between X, Y and Z channels due to structural deformation and the effect of spindle-internal forces on the measured signal. However, Jun *et al*. (2002) evaluated the effect of integration of the force ring on the dynamics of the spindle, the drift behavior due to temperature change inside the spindle, the cross-talk between the channels and the existence and compensation of the spindle-internal forces. The results show that the dynamic stiffness of the spindle machine tool decreased by less than 10% after the installation of the force ring, the drift behavior also varied by less than 10% and the average value of the force ring cross-talk in any direction was less than 9%. So, they concluded that the piezoelectric-based force ring is a strong transducer to be used in process model-based monitoring and fault diagnosis techniques.

The cutting force measurement on multi cutting edges in face milling has also been successfully developed. Adolfsson and Stahl (1995) have been pioneering the building of equipment for measuring cutting force components at each cutting edge. They developed a rotating dynamometer, based on strain gauges, measuring the main cutting force and feed cutting force components at each cutting edge. Strain gauges were mounted on a modified standard face mill, with a diameter of 125 mm and originally eight cutting edges. Every second cutting edge position was removed, giving space for the mounting of strain gauges, as well as weakening the tool in order for the strain gauges to be subjected to a larger strain. The signals from the strain gauges were processed in a serial stream and sent via a fibre optic cable to an LED (Light Emitting Diode). Then, the signals were transmitted by Infrared (IR) light signals over an air gap in the rear of the hollow spindle, at a speed of 1.28 Mbps. This equipment has been used for experimental studies of cutting force variation in face milling (Andersson *et al*., 2011). In contrast, Totis *et al*. (2010) used three direction (3D) piezoelectric for measuring triaxial cutting force components. Each cutting edge is provided with an integrated triaxial force sensor. Kistler 9251A, clamped between the modular cartridge and the cutter body by means of the preloading screw. The signals transmission is via a telemetry system with a 12 bit resolution and a sampling rate of 13 kHz. The rotating pulse test result shows that the frequency bandwidth is greater than 1.5 kHz.

The third method of measuring the cutting force in the milling process is the measurement of the elastic deflection of the spindle machine tool. Deflection is the displacement of a structural element from its static position as a result of force acting on the body. Matsubara *et al*. (2000) deployed two displacement sensors near a set of front bearings in the spindle unit so that they could detect a small scale cutting force of the spindle in the X and Y directions. A thin collar with a fine cylindrical surface was attached to the spindle as a sensor target. An electrically conductive sensor, based on the Eddy current principle with a dynamic response of about 1.3 kHz was used. Sarhan *et al*. (2004) studied the performance of this sensor compared to the table dynamometer and indicated an error between the displacement sensor and the dynamometer of about 20-50 N. They found that the relationship between the spindle displacement sensor output and the cutting force signals from the dynamometer showed a non-linear characteristic, for which the cutting force can be estimated with a 90% confidence interval of ±30.9 N in the X-axis direction and ±35.4 N in the Y-axis direction. As well as force acting on the body, displacement also can occur in structures due to temperature changes. Therefore, a displacement sensor can be potentially compensated for by controlling the temperature during the machining process (Sarhan *et al*., 2006). The inductance sensor effect of Villari has also been proposed by Aoyama and Ishii (2004) to detect cutting force elements, cutting torque and tool deflections. In addition, tool deflection due to the cutting force in the milling operation can also be measured by using a thin film PVDF piezoelectric strain sensor and a wireless data transmitting system (Ma *et al*., 2010).

On the other hand, the use of capacitance sensors to detect the spindle shaft displacement due to the cutting load was investigated by Albrecht *et al*. (2005). A capacitive displacement sensor was integrated into the spindle to measure the static and dynamic variations of the gap between the sensor head and the rotating spindle shaft under load. The bandwidth of the uncompensated indirect force sensor system is limited to 350 Hz. A Kalman filter-based scheme was used to compensate for the spindle dynamic effects (Park and Altintas, 2004). They indicated that the use of a Kalman filter, which quasi inverts a model of the dynamic compliance between the tool tip and the displacement sensor reading point, increased the bandwidth of the proposed sensor system from 350 to almost 1,000 Hz. Auchet *et al*. (2004) also measured the shaft displacement of the motor spindle using command voltages of magnetic bearing to indirectly determine the cutting forces. The bandwidth of the indirect force measurement using active magnetic bearings is about 4 kHz and the cutting forces calculated from the command voltages were found to be in good agreement with those of a platform dynamometer. However, as reported by Castillo-Castañeda (2003), the displacement of the milling cutter can also be measured using a fibre optic (photonic) sensor for on-line tool-wear detection.

Another technique that can be used to measure the cutting force is indirect measurement using a current sensor. Lee *et al*. (1995) proposed the indirect cutting force sensing method using the current of the AC servo drive. Kim *et al*. (1999) presented the indirect cutting force measurement method in the milling processes by using current signals of the servo motors. Jeong and Cho (2002) also reported that the cutting force can be estimated by measuring the feed-motor current. Meanwhile, Spiewak (1995) used a three-component accelerometer as a sensor to develop an instrumented milling cutter for measuring dynamic cutting forces. The system converts accelerations from the rotating spindle into stationary coordinates.

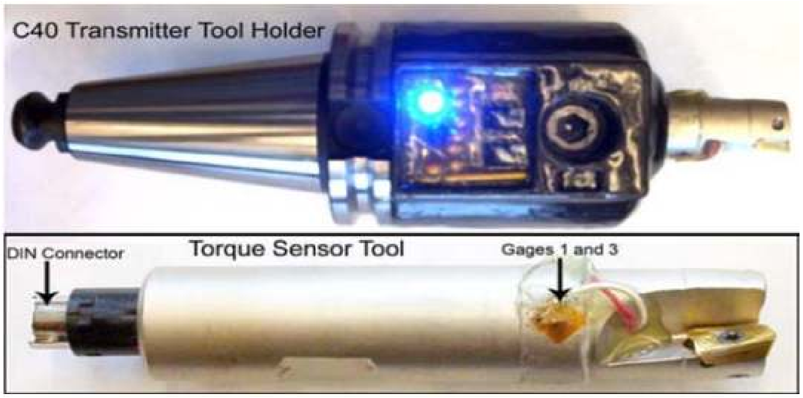


Fig. 6: Construction of spindle for torque measurement based on a strain gauge (Suprock and Nichols, 2009)

Torque: The measurement of torque is an important part of the milling operation due to the rotating cutting tool spindle. Traditionally, milling torque has been determined from the measurement of the rotational speed of the spindle motor and the power consumption, or from the measurement of the motor current (Lee *et al*., 1997). Spindle power related to rotational speed and torque may be written as:

$$P = \omega T \tag{1}$$

where,
P = The spindle power (W)
ω = The rotational speed (rad/s)
T = The torque (Nm)

The milling torque is directly proportional to the tangential cutting force. The instantaneous torque, T, is expressed as the sum of the products of the tool holder radius and tangential cutting force for each tooth engaged in the cut (Schmitz and Smith, 2009).

Generally, torque is measured once with cutting force by using a commercial dynamometer for tool-wear monitoring (Kuljanic and Sortino, 2005; Kaya *et al*., 2011). These sensors are based on piezoelectric elements as used by Dini and Tognazzi (2007). They measured cutting torque by using a commercial rotating torque dynamometer (Montronix Accu Torque^{TM} sensor) mounted on a standard ISO40, DIN69871-A tool holder. The power was supplied to the sensing system by the induction effect and the signal was transmitted by wireless telemetry to the stator, properly placed near the spindle. The tool holder was modified by reducing the external diameter from 48 to 26 mm for a total length of 24 mm, so the natural frequencies of the modified tool holder were decreased from 1867 to 1028 Hz. A piezoelectric composite element was also used by Tansel *et al*. (2011). They designed and developed mechanical hardware to measure torque using a piezoelectric composite element that was held between two extensions separately attached to the lower and upper halves. The system is called a Torque-based Machining Monitor (TbMM) and they used the system for chatter detection and wear estimation from the torque signals (Tansel *et al*., 2012).

Another technique to measure the torque in the rotating spindle uses a strain gauge. Smith *et al*. (1998) developed a milling torque dynamometer based on a strain gauge sensor. They installed the strain gauge between the tool and the tool holder on a conventional milling tool. The sensor provided virtually distortionless torque measurements over a bandwidth from DC to 2 kHz for a 100 mm diameter face milling cutter with sampling frequency of the A/D set at 10 kHz. The signals were transmitted by LEDs or the optical telemetry technique with a bandwidth of 0.5 MHz. Suprock and Nichols (2009) also developed sensor-integrated tooling based on a strain gauge for measuring torque in an end milling cutting tool as shown in Fig. 6. A Bluetooth A2DP transmitter and an AD 623 instrumentation amplifier are integrated into an ABS plastic shroud mounted on the exterior of a C 40 set screw-type tool holder. The tool holder was modified to house the female mini DIN connector and route the signal cables to the amplifier circuit. The system contains an analogue band-pass filter from 10 to 20 kHz, with the observed response attenuates at approximately 17 kHz. Deyuan *et al*. (1995) have applied torque signals from a strain gauge in detecting tool breakage in the milling process.

Vibration: A wide variety of transducers exist for use in sensing vibration. Vibration measurements are also referred to as displacement, velocity or acceleration measurements. Accelerometers are sensing transducers that provide an output proportional to acceleration and vibration. The piezoelectric accelerometer is the most common type in the vibration sensing of machining operations. Its transducer has the highest frequency response and range for the dynamic events (Figliola and Beasley, 2000). The piezoelectric element is placed in such a way that when the unit is in vibration, a mass applies a force, proportional to the acceleration, to the piezoelectric element. The element acts as a spring, which has a stiffness k and connects the base of the accelerometer to the seismic masses. The frequency response of the sensor is determined by the resonant frequency of the sensor, which can generally be modelled as a simple single-degree-of-freedom system. Using this system, the resonant frequency (ω) of the sensor can be estimated by (Wilson, 2005):

$$\omega^2 = k/m \tag{2}$$

Application of an accelerometer in the milling operation for TCM has been attempted over a number of decades to detect tool wear, tool breakage, surface roughness and chatter. Mehta *et al*. (1983) investigated the effect of the interaction between tool wear and vibrations using a piezoelectric accelerometer in a vertical milling machine using a single-tooth milling cutter with a diameter of 125 mm. Chen and Chen (1999) applied an ICP (Integrated Circuit Piezoelectric) accelerometer to detect tool breakage in the milling operation. Lou and Chen (1999) used a PCB accelerometer to measure vibration signals in the end milling operation for surface roughness prediction using a neural fuzzy system. Kim *et al*. (2007) predicted the chatter in a ball-end milling operation using an accelerometer and dynamometer. The chatter can be detected from the calculated cutting forces and their frequency spectra. Other authors, including Atlas *et al*. (2000), Yesilyurt and Ozturk (2007), Sun *et al*. (2007), Orhan *et al*. (2007), Zhang and Chen (2008), Huang *et al*. (2008), Wright *et al*. (2008), Chuangwen *et al*. (2009), Kalvoda and Hwang (2010b) and Insperger *et al*. (2008), applied an accelerometer for TCM to detect tool wear and breakages in the milling process by placing the accelerometer in various locations, such as on the side surface of the work piece in the feed direction, on the fixture or vice jaws and even on the lower bearing of the spindle housing (Norman *et al*., 2007; Kalvoda and Hwang, 2010a).

Optical techniques like laser displacement sensors for vibration detection have also been used in the milling process for TCM (Ryabov *et al*., 1998). The main advantage of this method is that it is possible to perform remote non-contact measurements on a rotating milling tool very close to the cutters. Tatar and Gren (2008) proposed the measurement technique of milling cutter vibration using laser vibrometry. They used a Polytec PSV 300 scanning laser vibrometer, standing steadily on a support located at about 1,800 mm from the measurement point. The vibration signals were compared with the cutting force and spindle head vibrations and the result showed that vibration velocities or displacements of the tool can be obtained with high temporal resolution during the cutting load. This technique is suitable for monitoring vibration, chatter and tool wear in a rotating spindle (Nakagawa *et al*., 2008).

Acoustic emission: Piezoelectric ceramics are most commonly used in AE transducers due to their high sensitivity and response, primarily for normal displacement at the surface of contact. The transducer can detect stress-wave motions that cause local dynamic material displacement and convert this displacement to an electrical signal. The frequency range in an AE transducer varies between 20 kHz and 1 MHz and the meaningful information of the AE signals in the machining are mostly above 100 kHz (Li, 2002). An AE transducer consists of several parts, including:

- A piezoelectric ceramic element with electrodes on each face
- One electrode connected to an electric ground, the other to a signal lead
- A backing material behind the element designed to minimize reflections back to the element and to damp the signal around the resonance frequency
- A case providing an integrated mechanical package that may also serve as a shield to minimize the electromagnetic interference (Muravin, 2012)

AE transducers have been successfully applied to detect tool wear in the micro end-milling operation (Tansel *et al*., 1998). Its application to the milling operation has been less straightforward, because the milling operation is an interrupted cutting operation with the rotating cutting tool causing pulse shock loading during the entry and exit of each individual tooth to the work piece. The magnitude of these shock pulses is possibly equivalent to those generated by tool fracture during end milling (Li and Guan, 2004). However, AE signals have high frequency and low amplitude, resulting in some studies focusing on the AE signal transmission system. Inasaki (1998) and Govekar *et al*. (2000) reported that coolant can be used as a transmission path by locating the AE transducer on the coolant supply nozzle. Hutton and Hu (1999) developed a liquid-coupled sensor system mounted on the end of the spindle drive shaft to collect AE signals. Li and Yuan (1998) also developed a simple device to collect AE signals from the tool holder through a magneto-fluid. But, for the detection of tool wear and breakage, some researchers have used AE transducers in the milling operation directly mounted on the machine vice (Pai and Rao, 2002; Mathew *et al*., 2008), on the machine table (Jakobsen *et al*., 2005), on the workpiece (Tansel *et al*., 1998; Cao *et al*., 2008) and even on main machine spindle or on the cutting tool holder (Xiqing and Chuangwen, 2009; Haber *et al*., 2004).

However, a fibre optic interferometer has been used to measure AE in the machining process by McBride *et al*. (1993). The system is based on a

Michelson interferometer that generates antiphase outputs and incorporates some novel polarization features. The light from a laser diode is a 780 nm wavelength. The laser output is coupled into the input fibre. The guided beam is then amplitude divided at a directional coupler into the signal and reference arms of the interferometer. The signal arm terminates in a rugged optical probe containing a lens to focus the light onto the workpiece surface, with a 40 µm spot size at a working distance of 25 mm (Carolan *et al*., 1997a). Carolan *et al*. (1997a, 1997b) reported the application of a fibre optic interferometer for the in-process measurement of AE during face milling to provide tool wear information with AE energy and frequency analysis. Wilkinson *et al*. (1999) even used two kinds of AE sensors, a fibre optic sensor and a piezoelectric transducer, for tool-wear prediction.

Sound and ultrasound: Sound generated from a machining process is a common result of friction between the tool and the work piece. But, if there has been tool wear or chatter, the normal sound will be disturbed. Therefore, sound pressure levels from the cutting zone can be a parameter in detecting tool wear, breakage or chatter. Generally, sound signals can be measured by an electric microphone and then analyzed using a spectrum analyzer. Applications of sound signals for tool wear monitoring in the milling process have been conducted by Ai *et al*. (2012). The milling sound signal is extracted using acoustic spectrum characteristic parameters and analyzed with a Linear Predictive Cepstrum Coefficient (LPCC) to correlate to tool wear. A sound signal has also been used by Kopac and Sali (2001) and Nuawi *et al*. (2009) in the turning process and by Rubio and Teti (2009) in monitoring the milling process. Weingaertner *et al*. (2006) also used audio signals to evaluate stability based on work piece surface roughness. Because sound waves can travel through the air, sound signals are often used both in turning and milling by putting the microphone as close as possible to the cutting zone. Audible sound signals have an accepted standard range of frequencies of 20 to 20,000 Hz. If the sound frequency is greater than 20 kHz, it is ultrasonic and is beyond the upper limit of human hearing. The use of ultrasonics has also been attempted by Abu-Zahra and Yu (2000), Nayfeh *et al*. (1995) and Nuawi *et al*. (2007) for tool wear monitoring in the turning process, but there has been no report in the milling process. Usually, application sound signals are combined with AE, cutting force, current, vibration (Ghosh *et al*., 2007; Abbas *et al*., 2011) and laser techniques (Mannan *et al*., 2000).

Motor current and power: Current and power from the spindle motor are needed to drive the tool holder in the milling process. Their signals can be detected by power sensors to measure spindle power or current consumption. When the tool is worn or broken, as compared to the normal cutting condition, the current consumption changes (Sevilla-Camacho *et al*., 2011; Shao *et al*., 2011). Generally, the current signal is measured by the Hall Effect and an inductive sensor. The current conductor passes through a magnetically permeable core that concentrates the conductor's magnetic field. The Hall effect device is mounted in the core at a right angle to the concentrated magnetic field. A constant current in one plane excites the Hall device. When the energized Hall device is exposed to a magnetic field from the core, it produces a voltage that can be measured and amplified into process-level signals such as 4-20 mA. The inductive sensor has a wire-wound core and a signal conditioner. The current conductor passes through the core that magnifies the conductor's magnetic field. The AC current constantly changes potential from positive to negative and back again, generally at the rate of 50 or 60 Hz. The expanding and collapsing magnetic field induces current in the windings. This secondary current is converted to a voltage and conditioned to output process-level signals.

The Hall effect sensor (PCB Mounting Hall Effect Current Transducer) has been used by Li and Guan (2004), Li (2001, 2002), Li and Yuan (1998), Li *et al*. (2008) and Sevilla-Camacho *et al*. (2011) to collect the current signal to monitor tool breakage in end milling by using a threshold method. They compared the marked feature with the threshold value; if the marked feature was over the threshold value, an alarm signal was generated. Lee and Tarng (1999) and Lee *et al*. (1997; 1999) also used a current-to-voltage sensor (LEM Module LA 50-P) that works based on the Hall effect to monitor tool failure in end-milling operations, while Bhattacharyya *et al*. (2007b) used it for continuous on-line estimation of tool wear during face milling. In addition, Jeong and Cho (2002) used the Hall effect sensor to estimate the cutting force on a milling machine. Axinte and Gindy (2004) assessed the spindle power for tool wear monitoring. They used a dynamometer to collect the feed force and the feed perpendicular force. Based on their relationship, cutting forces can be obtained at a certain feed motion angle. Then, based on the relationship between the cutting force and cutting speed, the cutting power can be estimated. Tseng and Chou (2002) reported that the workload fluctuates by 1.5% when the tool is worn and torn. They extracted the workload of the spindle motor from the CNC controller and then transmitted the data via the I/O card for further processing. Jesús *et al*. (2003) implemented the band-pass analogue filter to minimize the spurious signals and to enhance the cutting force signal from the driver current signal. Lee *et al*. (2007) also reported that acquiring the spindle current is enabled by regulating the cutting force.

Temperature: Temperature and heat generated at the tool-chip and the tool-work piece interface during machining operations have been recognized as major factors that influence tool performance and work piece geometry. High temperatures at the interface accelerate the tool wear mechanisms and promote plastic deformation on the machined surface. Therefore, the increasing temperature during the cutting process can be used as reference for TCM (Young, 1996). There are two basic types of temperature sensing:

- Contact temperature sensing requiring the sensor to be in direct physical contact with the media or object being sensed.
- Non-contact measurement which interprets the radiant energy of a heat source in the form of energy emitted in the IR portion of the electromagnetic spectrum (Wilson, 2005).

For instances of contact cutting temperature measurement, Wright *et al*. (2006) used Resistive Temperature Detectors (RTDs) installed on the rear of the end-mill inserts and data were transmitted using a wireless system. RTDs are temperature sensors that contain a resistor that changes resistance value as its temperature changes. RTD elements consist of a length of fine coiled wire wrapped around a ceramic or glass core. In contrast, thermocouples consist of two dissimilar metals, joined together at one end. When the junction of the two metals is cooled or heated a voltage is produced that can be correlated back to the temperature. Kim *et al*. (2001) used a K-type thermocouple to measure the work piece temperature implanted into the work piece with a 0.5 mm diameter hole. They studied the influence on cutting temperature according to the change in the cutting environment and compared the temperature and tool wear. Ng *et al*. (2000) also used an embedded thermocouple technique to measure the cutting temperature when milling Inconel 718 with ball-nose coated tools. Dewes *et al*. (1999) measured the tool/workpiece interface and chip temperatures during ball-end-milling of H13 hardened steel. The measurements were performed by using thermocouple and IR camera techniques. They also studied the effect of workpiece angle and tool wear on the interface temperature. The results show that a worn tool generates higher temperatures than a new tool. Coz *et al*. (2012) implanted a K-type thermocouple into the rotating end-mill tool holder. They used a wireless connection system with a transmitter integrated into the tool holder and a radio frequency antenna placed near the tool holder.

A non-contacting device that intercepts and measures thermal radiation is called an IR pyrometer. IR sensors measure the IR energy emitted from an object in the 4-20 micron wavelength and convert the reading to a voltage. A typical IR pyrometer uses an optical system to concentrate radiated energy onto a thermopile. The resulting voltage output is amplified and conditioned to provide a temperature reading (Wilson, 2005). A previous study by Ueda *et al*. (2001) used a two-color pyrometer with an optical fibre to measure the temperature of the flank face of a cutting tool in high-speed milling. The fibre was inserted into a fine hole drilled into the workpiece and accepted IR energy that was radiated from the flank face of the cutting tool when it passed above the hole. Then, Sato *et al*. (2007) and Ueda *et al*. (2008) developed an IR radiation pyrometer with two optical fibres connected by a fibre coupler and applied it to the measurement of the tool-chip interface temperature in end milling with a binderless CBN tool. The IR rays radiated from the tool-chip interface are accepted by one optical fibre, which is inserted into the tool and fixed into the main spindle of the machine tool. Then the IR energy is sent to the other fibre, which is fixed to the column of the machine tool and led to the two-color pyrometer. The cyclical temperature variation in the cutting tool during cutting and non-cutting periods in end milling using this measurement technique was also studied (Sato *et al*., 2011). However, the use of cutting temperature for TCM in the milling operation is still rare and, in addition, few studies relate to the turning process.

CONCLUSION

The applications of sensors in TCM are many and varied. The use of sensors in machining provides significant information about tool conditions, including tool wear, breakage and chatter, which influence the quality of the machined surface and the production time. In order to be applied in industry, the sensors should be low cost, small in size, robust, non-invasive and should not interfere with the working space. The value of this technology can be best realized when reliable sensors are deployed in milling operations with rotating tools using wireless data transmission systems. Implementation of innovative sensors and their integrations into systems in TCM will be a research challenge in the future to enhance machining systems and their operations.

RECOMMENDATIONS AND CHALLENGES

After describing sensor systems and their applications in the milling process, it is possible to determine the state and direction of sensor systems in TCM research and to suggest some directions that should be developed in future research.

As was found in the literature related to milling, currently available sensors are adequate to detect machining signals, such as force, torque, vibration, AE, sound, current and temperature. In order to be widely used by machining industries, the sensor systems in TCM must be low cost, not reduce the stiffness of the machine tools and not restrict the working space; the sensor must be as close as possible to the machining point, have a reliable application and have good dynamic characteristics. The problem lies in how to deploy the sensors to pick up the signals on a rotating spindle during the milling operation. Certainly, the sensors based on cables for data transmission cannot be deployed on a rotating tool holder. However, machining signals, such as the cutting force and audible sound, can be detected without placing the sensor on the rotating tool. The cutting force is a popular signal for TCM and many authors used a table dynamometer. However, commercial dynamometers are not suitable instruments for industrial use due to their high cost. As well as sound signals, they are sensitive to other events including coolant flow, noise on the workshop floor and parallel machining operations. Current and power signals are also considered to be robust, but these signals are greatly influenced by the viscous damping of the feed system and the friction of the mechanical system. The use of vibration and AE signals can also be directly detected by the piezoelectric transducers that are placed on the workpiece. However, the quality of the signal is not stable, because the distance between the cutting zone and the sensor is constantly changing due to the relative movement of the cutting spindle in the three axes during cutting. The cutting zone temperature can also be measured by a non-contacting device, like an IR pyrometer, but it can be costly. Alternatively, many researchers use thermocouples to measure the cutting zone temperature by implanting them into the workpiece, so making the temperature reading not completely illegible during the cutting.

Therefore, a wireless data transmission system is essential since the sensor has to be mounted on a rotating tool holder. Recently, two standard technologies for Wireless Sensor Networks (WSN) have been developed: ZigBee and Bluetooth. Both operate within the Industrial Scientific and Medical (ISM) band of 2.4 GHz (Callaway, 2004). Wireless data acquisitions in TCM have been used in previous studies. Suprock and Nichols (2009) and Suprock *et al*. (2008) developed a wireless system using Bluetooth for transmitting machining signals in an end-milling tool holder. They used an A2DP transmitter as a strain gauge sensor that measured torque and a Jabra BT 350 transmitter as an accelerator to measure vibration in the tool tip. The system is capable of sending a stereo audio signal to the Bluetooth receiver at 48.0 kHz. Wright *et al*. (2006) used MEMS (Micro-Electro-Mechanical Systems) for tool temperature measurement. They used a move that is integrated between signal conditioning and radio units and RTDs as a sensor. Coz *et al*. (2012) also measured temperature by using the embedded thermocouple in the tool, thus data is sent to an amplifier using a transmitter integrated in the tool holder and a Radio Frequency (RF) antenna placed near the tool holder. Ma *et al*. (2010) applied a thin film PVDF piezoelectric strain sensor to measure deflection in the tool holder and wireless data as the transmitting platform built upon the IEEE 802.15.4 standard. Totis *et al*. (2010) used a wireless telemetry system for transmitting a force form load cell transducer in the face milling tool holder. However, the number of publications in TCM research that used wireless data transmission as compared to publications using a cable system and a commercial dynamometer are very few. Moreover, integrated multiple sensors in one wireless system with a tool holder has yet to be reported, whereas sensor fusion ensures a more precise and accurate measurement. More specifically, if multi-sensors are employed, the overall uncertainty of the resulting measurement can be reduced and thus, the resolution and precision of the system can be improved. The system provides a better estimation of accuracy over a wide range of operating conditions. The combined sensory information also provides more accurate, more complete, more robust and more reliable than a single sensor. Therefore, applications of wireless data transmission and sensor fusion for TCM systems in the milling process will provide good research opportunities in the future.

ACKNOWLEDGMENT

The authors would like to thank the Government of Malaysia and Universiti Kebangsaan Malaysia for their financial support under Grant 03-01-02-SF0843.

REFERENCES

Abbas, J., A. Al-Habaibeh and D. Su, 2011. Sensor fusion for condition monitoring system of end milling operations. Key Eng. Mater., 450: 267-270.

Abu-Zahra, N.H. and G. Yu, 2000. Analytical model for tool wear monitoring in turning operations using ultrasound waves. Int. J. Mach. Tool. Manu., 40: 1619-1635.

Adolfsson, C. and J.E. Stahl, 1995. Cutting force model for multi-toothed cutting processes and force measuring equipment for face milling. Int. J. Mach. Tool. Manu., 35(12): 1715-1728.

Ai, C.S., Y.J. Sun, G.W. He, X.B. Ze, W. Li and K. Mao, 2012. The milling tool wear monitoring using the acoustic spectrum. Int. J. Adv. Manuf. Tech., 61(5-8): 457-463.

Albrecht, A., S.S. Park, Y. Altintas and G. Pritschow, 2005. High frequency bandwidth cutting force measurement in milling using capacitance displacement sensors. Int. J. Mach. Tool. Manu., 45: 993-1008.

Altintas, Y., 2000. Manufacturing Automation: Metal Cutting Mechanics. Machine Tool Vibrations and CNC Design. Cambridge University Press, New York.

Andersson, C., M. Andersson and J.E. Stahl, 2011. Experimental studies of cutting force variation in face milling. Int. J. Mach. Tool. Manu., 51: 67-76.

Aoyama, H. and T. Ishii, 2004. Sensor to detect cutting force components, cutting torque and cutting tool deflections. J. Manuf. Processes, 6(2): 141-147.

Atlas, L., M. Ostendod and G.D. Bernard, 2000. Hidden markov models for monitoring machining tool-wear. Proceeding of International Conference on Acoustics, Speech and Signal Processing. Istanbul, pp: 3887-3890.

Auchet, S., P. Chevrier, M. Lacour and P. Lipinski, 2004. A new method of cutting force measurement based on command voltages of active electro-magnetic bearings. Int. J. Mach. Tool. Manu., 44: 1441-1449.

Axinte, D. and N. Gindy, 2004. Assessment of the effectiveness of a spindle power signal for tool condition monitoring in machining processes. Int. J. Prod. Res., 42(13): 2679-2691.

Bhattacharyya, P., D. Sengupta and S. Mukhopadhyay, 2007a. Cutting force-based real-time estimation of tool wear in face milling using a combination of signal processing techniques. Mech. Syst. Sig. Process., 21: 2665-2683.

Bhattacharyya, P., D. Sengupta, S. Mukhopadhyay and A.B. Chattopadhyay, 2007b. On-line tool condition monitoring in face milling using current and power signals. Int. J. Prod. Res., 46(4): 1187-1201.

Byrne, G. and G.E. O'Donnell, 2007. An integrated force sensor solution for process monitoring of drilling operations. CIRP Ann-Manuf. Techn., 56(1): 89-92.

Byrne, G., D. Dornfeld, I. Inasaki, G. Ketteler, W. Konig and R. Teti, 1995. Tool condition monitoring (TCM)-the status of research and industrial application. CIRP Ann-Manuf. Techn., 44: 541-567.

Callaway, E.H., 2004. Wireless Sensor Networks: Architectures and Protocols. Auerbach Publications, New York, NY, USA.

Cao, H., X. Chen, Y. Zi, F. Ding, H. Chen, J. Tan and Z. He, 2008. End milling tool breakage detection using lifting scheme and Mahalanobis distance. Int. J. Mach. Tool. Manu., 48: 141-151.

Carolan, T.A., S.R. Kidd, D.P. Hand, S.J. Wilcox, P. Wilkinson, J.S. Barton, J.D.C. Jones and R.L. Reuben, 1997a. Acoustic emission monitoring of tool wear during the face milling of steels and aluminium alloys using a fibre optic sensor Part 1: energy analysis. P. I. Mech. Eng. B-J. Eng., 211: 299-309.

Carolan, T.A., S.R. Kidd, D.P. Hand, S.J. Wilcox, P. Wilkinson, J.S. Barton, J.D.C. Jones and R.L. Reuben, 1997b. Acoustic emission monitoring of tool wear during the face milling of steels and aluminium alloys using a fibre optic sensor Part 2: frequency analysis. P. I. Mech. Eng. B-J. Eng., 211: 311-319.

Castillo-Castañeda, E., 2003. On-line wear detection of milling tools using a displacement fiber optic sensor. J. Appl. Res. Technol., 1(2): 164-174.

Chen, O.C. and A.L. Chen, 1999. A tool breakage detection system using an accelerometer sensor. J. Intell. Manuf., 10: 187-197.

Chen, J.C. and J.C. Chen, 2004. A multiple-regression model for monitoring tool wear with a dynamometer in milling operations. J. Technol. Stud., 75: 71-77.

Chen, X.Q. and H.Z. Li, 2009. Development of a tool wear observer model for online tool condition monitoring and control in machining nickel-based alloys. Int. J. Adv. Manuf. Tech., 45: 786-800.

Cho, S., S. Asfour, A. Onar and N. Kaundinya, 2005. Tool breakage detection using support vector machine learning in a milling process. Int. J. Mach. Tool. Manu., 45: 241-249.

Choi, Y., R. Narayanaswami and A. Chandra, 2004. Tool wear monitoring in ramp cuts in end milling using the wavelet transform. Int. J. Adv. Manuf. Tech., 23: 419-428.

Choudhury, S.K. and S. Rath, 2000. In-process tool wear estimation in milling using cutting force model. J. Mater. Process. Technol., 99: 113-119.

Chuangwen, X., L. Zhe and L. Wencui, 2009. A frequency band energy analysis of vibration signals for tool condition monitoring. Proceeding of International Conference on Measuring Technology and Mechatronics Automation.

Coz, G.L., M. Marinescu, A. Devillez, D. Dudzinski and L. Velnom, 2012. Measuring temperature of rotating cutting tools: Application to MQL drilling and dry milling of aerospace alloys. Appl. Therm. Eng., 36: 434-441.

Čuš, F. and U. Župerl, 2011. Real-time cutting tool condition monitoring in milling. J. Mech. Eng., 57(2): 142-150.

Dewes, R.C., E.G. Ng, K.S. Chua, P.G. Newton and D.K. Aspinwall, 1999. Temperature measurement when high speed machining hardened mould/die steel. J. Mater. Process. Technol., 92-93: 293-301.

Deyuan, Z., H. Yuntai and C. Dingchang, 1995. On-line detection of tool breakages using telemetering of cutting forces in milling. Int. J. Mach. Tool. Manu., 35(1): 19-27.

Dini, G. and F. Tognazzi, 2007. Tool condition monitoring in end milling using a torque-based sensorized toolholder. P. I. Mech. Eng. B-J. Eng., 221: 11-23.

Figliola, R.S. and D.E. Beasley, 2000. Theory and Design for Mechanical Measurements. 3rd Edn., John Wiley and Sons, Inc., New York.

Ghani, J.A., M. Rizal, M.Z. Nuawi, C.H.C. Haron, M.J. Ghazali and M.N.A. Rahman, 2010. Online cutting tool wear monitoring using I-kaz method and new regression model. Adv. Mater. Res., 126-128: 738-743.

Ghani, J.A., M. Rizal, M.Z. Nuawi, M.J. Ghazali and C.H.C. Haron, 2011. Monitoring online cutting tool wear using low-cost technique and user-friendly GUI. Wear, 271: 2619- 2624.

Ghosh, N., Y.B. Ravi, A. Patra, S. Mukhopadhyay, S. Paul, A.R. Mohanty and A.B. Chattopadhyay, 2007. Estimation of tool wear during CNC milling using neural network-based sensor fusion. Mech. Syst. Sig. Process., 21: 466-479.

Girardin, F., D. Remond and J.F. Rigal, 2010. A new method for detecting tool wear and breakage in milling. Int. J. Mater. Forming, 3(1): 463-466.

Govekar, E., J. Gradisek and I. Grabec, 2000. Analysis of acoustic emission signals and monitoring of machining processes. Ultrasonics, 38(38): 598-603.

Haber, R.E., J.E. Jiménez, C.R. Peres and J.R. Alique, 2004. An investigation of tool-wear monitoring in a high-speed machining process. Sensor Actuat. A-Phys., 116(3): 539-545.

Huang, P.T. and J.C. Chen, 2000. Neural network-based tool breakage monitoring system for end milling operations. J. Ind. Technol., 16(2): 1-7.

Huang, P.T., J.C. Chen and C.Y. Chou, 1999. A statistical approach in detecting tool breakage in end milling operations. J. Ind. Technol. 15, (3): 1-7.

Huang, P., J. Li, J. Sun and M. Ge, 2012a. Milling force vibration analysis in high-speed-milling titanium alloy using variable pitch angle mill. Int. J. Adv. Manuf. Tech., 58(1-4): 153-160.

Huang, P., J. Li, J. Sun and J. Zhou, 2012b. Vibration analysis in milling titanium alloy based on signal processing of cutting force. Int. J. Adv. Manuf. Tech., 64(5-8): 613-621.

Huang, S., D.H. Zhang, W.Y. Leong, H.L. Chan, K.M. Goh, J.B. Zhang and Kristo, 2008. Detecting tool breakage using accelerometer in ball-nose end milling. Proceeding of the IEEE 10th International Conference on Control, Automation, Robotics and Vision (ICARCV). Hanoi, Vietnam, pp: 927-933.

Hutton, D.V. and F. Hu, 1999. Acoustic emission monitoring of tool wear in end milling using time-domain averaging. J. Manuf. Sci. E-T. ASME, 121: 8-12.

Inasaki, I., 1998. Application of acoustic emission sensor for monitoring machining processes Ultrasonics, 36: 273-281.

Insperger, T., B.P. Mann, T. Surmann and G. Stépán, 2008. On the chatter frequencies of milling processes with runout. Int. J. Mach. Tool. Manu., 48(10): 1081-1089.

Jakobsen, M.L., P. Wilkinson, J.S. Barton, R.L. Reuben, D. Harvey and J.D.C. Jones, 2005. The effects of progressive wear on the frequency characteristic of acoustic emission acquired during face milling. P. I. Mech. Eng. B-J. Eng., 219: 803-810.

Jeong, Y.H. and D.W. Cho, 2002. Estimating cutting force from rotating and stationary feed motor currents on a milling machine. Int. J. Mach. Tool. Manu., 42: 1559-1566.

Jesús, R.T.R.D., H.R. Gilberto, T.V. Iván and J.C.J. Carlos, 2003. Driver current analysis for sensorless tool breakage monitoring of CNC milling machines. Int. J. Mach. Tool. Manu., 43(15): 1529-1534.

Jun, M.B., O.B. Ozdoganlar, R.E. DeVor, S.G. Kapoor, A. Kirchheim and G. Schaffner, 2002. Evaluation of a spindle-based force sensor for monitoring and fault diagnosis of machining operations. Int. J. Mach. Tool. Manu., 42: 741-751.

Kalvoda, T. and Y.R. Hwang, 2010a. Analysis of signals for monitoring of nonlinear and non-stationary machining processes. Sensor Actuat. A-Phys., 161(1-2): 39-45.

Kalvoda, T. and Y.R. Hwang, 2010b. A cutter tool monitoring in machining process using Hilbert-Huang transform. Int. J. Mach. Tool. Manu., 50: 495-501.

Kaya, B., C. Oysu and H.M. Ertunc, 2011. Force-torque based on-line tool wear estimation system for CNC milling of Inconel 718 using neural networks. Adv. Eng. Software, 42: 76-84.

Kim, S.J., H.U. Lee and D.W. Cho, 2007. Prediction of chatter in NC machining based on a dynamic cutting force model for ball end milling. Int. J. Mach. Tool. Manu., 47: 1827-1838.

Kim, T.Y., J. Woob, D. Shin and J. Kim, 1999. Indirect cutting force measurement in multi-axis simultaneous NC milling processes. Int. J. Mach. Tool. Manu., 39: 1717-1731.

Kim, S.W., C.M. Lee, D.W. Lee, J.S. Kim and Y.H. Jung, 2001. Evaluation of the thermal characteristics in high-speed ball-end milling. J. Mater. Process. Technol., 113(1-3): 406-409.

Kious, M., A. Ouahabi, M. Boudraa, R. Serra and A. Cheknane, 2010. Detection process approach of tool wear in high speed milling. Meas., 43: 1439-1446.

Kistler, 2012. Brochure of Cutting Force Measurement. Retrieved from: http://www.kistler.com/CH_en-ch/ 46_ Product Finder_ Manufacturing 3000.-.17/ Product- Finder- Manufacturing.html. Also Retrieved from: <http:// www. kistler. com/ CH_en-ch/46_ Product Finder_ Manufacturing/ 3000.-.17/ Product- Finder-Manufacturing.html>. (Assessed on: April 9, 2012).

Ko, T.J., D.W. Cho and M.Y. Jung, 1995. On-line monitoring of tool breakage in face milling using a self-organized neural network. J. Manuf. Syst., 14(2): 80-90.

Kopac, J. and S. Sali, 2001. Tool wear monitoring during the turning process. J. Mater. Process. Technol., 113: 312-316.

Korkut, I., 2003. A dynamometer design and its construction for milling operation. Mater. Des., 24: 631-637.

Kuljanic, E. and M. Sortino, 2005. TWEM: A method based on cutting forces-monitoring tool wear in face milling. Int. J. Mach. Tool. Manu., 45: 29-34.

Kuljanic, E., G. Totis and M. Sortino, 2009. Development of an intelligent multisensor chatter detection system in milling. Mech. Syst. Sig. Process., 23: 1704-1718.

Kurada, S. and C. Bradley, 1997. A review of machine vision sensors for tool condition monitoring. Comput. Ind., 34: 55-72.

Lacerda, H.B. and V.T. Lima, 2004. Evaluation of cutting forces and prediction of chatter vibrations in milling. J. Braz. Soc. Mech. Sci., 26(1): 74-81.

Lee, B.Y. and Y.S. Tarng, 1999. Application of the discrete wavelet transform to the monitoring of tool failure in end milling using the spindle motor current. Int. J. Adv. Manuf. Tech., 15: 238-243.

Lee, B.Y., H.S. Liu and Y.S. Tarng, 1997. Monitoring of tool fracture in end milling using induction motor current. J. Mater. Process. Technol., 70: 279-284.

Lee, K.J., T.M. Lee and M.Y. Yang, 2007. Tool wear monitoring system for CNC end milling using a hybrid approach to cutting force regulation. Int. J. Adv. Manuf. Tech., 32: 8-17.

Lee, J.M., D.K. Choi, J. Kim and C.N. Chu, 1995. Real-time tool breakage monitoring for NC milling process. CIRP Ann-Manuf. Techn., 44(1): 59-62.

Li, X., 2001. Detection of tool flute breakage in end milling using feed-motor current signatures. IEEE-ASME T. Mech., 6(4): 491-498.

Li, X., 2002. A brief review: Acoustic emission method for tool wear monitoring during turning. Int. J. Mach. Tool. Manu., 42: 157-165.

Li, X. and Z. Yuan, 1998. Tool wear monitoring with wavelet parket transform-fuzzy clustering method. Wear, 219: 145-154.

Li, X. and X.P. Guan, 2004. Time-frequency-analysis-based minor cutting edge fracture detection during end milling. Mech. Syst. Sig. Process., 18: 1485-1496.

Li, X., G. Ouyang and Z. Liang, 2008. Complexity measure of motor current signals for tool flute breakage detection in end milling Int. J. Mach. Tool. Manu., 48: 371-379.

Lim, G.H., 1995. Tool wear monitoring in machine turning. J. Mater. Process. Technol., 51: 25-36.

Lin, S.C. and R.J. Lin, 1996. Tool wear monitoring in face milling using force signals. Wear, 198: 136-142.

Lou, S.J. and J.C. Chen, 1999. In-Process Surface Roughness Recognition (ISRR) system in end-milling operations. Int. J. Adv. Manuf. Tech., 15: 200-209.

Ma, L., S.N. Melkote, J.B. Morehouse, J.B. Castle and J.W. Fonda, 2010. On-line monitoring of end milling forces using a thin film based wireless sensor module. Proceedings of the ASME 2010 International Manufacturing Science and Engineering Conference, ASME, ASME, Erie, Pennsylvania, USA.

Mannan, M.A., A.A. Kassim and M. Jing, 2000. Application of image and sound analysis techniques to monitor the condition of cutting tools. Pattern Recogn. Lett., 21(11): 969-979.

Mathew, M.T., P.S. Pai and L.A. Rocha, 2008. An effective sensor for tool wear monitoring in face milling: Acoustic emission. Sadhana, 33(3): 227-233.

Matsubara, A., Y. Kakino and T. Ogawa, 2000. Monitoring of cutting forces in end-milling for intelligent machine tools. Proceedings of the 5th International Conference on Progress of Machining Technology (ICPMT). Beijing, P.R. China, pp: 615.

McBride, R., T.A. Carolan, J.S. Barton, S.J. Wilcox, W.K.D. Borthwick and J.D.C. Jones, 1993. Detection of acoustic emission in cutting processes by fibre optic interferometry. Meas. Sci. Technol., 4: 1122-1128.

Mehta, N.K., P.C. Pandey and G. Chakravarti, 1983. An investigation of tool wear and the vibration spectrum in milling. Wear, 91(2): 219-234.

Muravin, B., 2012. Acoustic Emission Sensors, Equipment. Retrieved from: http:// www. muravin. com.

Najafi, B. and H. Hakim, 1992. A comparative study of non-parametric spectral estimators for application in machine vibration analysis. Mech. Syst. Sig. Process., 6(6): 551-574.

Nakagawa, H., Y. Kurita, K. Ogawa, Y. Sugiyama and H. Hasegawa, 2008. Experimental analysis of chatter vibration in end-milling using laser doppler vibrometers. Int. J. Automat. Technol., 2(6): 431-438.

Nayfeh, T.H., O.K. Eyada and J.C. Duke, 1995. An integrated ultrasonic sensor for monitoring gradual wear on-line during turning operations. Int. J. Mach. Tool. Manu., 35: 1385-1395.

Ng, E.G., D.W. Lee, A.R.C. Sharman, R.C. Dewes and D.K. Aspinwall, 2000. High speed ball nose end milling of inconel 718. CIRP Ann-Manuf. Techn., 49: 41-46.

Norman, P., A. Kaplan, M. Rantatalo and I. Svenningsson, 2007. Study of a sensor platform for monitoring machining of aluminium and steel. Meas. Sci. Technol., 18: 1155-1166.

Nuawi, M.Z., F. Lamin, A.R. Ismail, S. Abdullah and Z. Wahid, 2009. A novel machining signal filtering technique: Z-notch filter word academic science. Eng. Technol., 54(54): 24-29.

Nuawi, M.Z., F. Lamin, M.J.M. Nor, N. Jamaluddin, S. Abdullah and C.K.E. Nizwan, 2007. Integration of I-kaz Coefficient and taylor tool life curve for tool wear progression monitoring in machining process. Int. J. Mech., 4(1): 44-50.

Orhan, S., A.O. Er, N. Camuscu and E. Aslan, 2007. Tool wear evaluation by vibration analysis during end milling of AISI D3 cold work tool steel with 35 HRC hardness. NDT&E Int., 40: 121-126.

Pai, P.S. and P.K.R. Rao, 2002. Acoustic emission analysis for tool wear monitoring in face milling. Int. J. Prod. Res., 40(5): 1081-1093.

Park, S.S., 2004. High frequency bandwidth cutting force measurements in milling using the spindle force sensor system. Ph.D. Thesis, University of British Columbia.

Park, S.S. and Y. Altintas, 2004. Dynamic compensation of spindle integrated force sensors with Kalman filter. J. Dyn. Syst. Meas. Contr., 126: 443-452.

Pongsathornwiwat, N. and S. Tangjitsitcharoen, 2010 Intelligent monitoring and detection of chatter in ball-end milling process on CNC machining center. Proceeing of the 40th International Conference on Computers and Industrial Engineering (CIE).

Rehorn, A.G., J. Jiang and P.E. Orban, 2005. State-of-the-art methods and results in tool condition monitoring: A review. Int. J. Adv. Manuf. Tech., 26: 693-710.

Rubio, E.M. and R. Teti, 2009. Cutting parameters analysis for the development of a milling process monitoring system based on audible energy sound. J. Intell. Manuf., 20: 43-54.

Ryabov, O., K. Mori and N. Kasashima, 1998. Laser displacement meter application for milling diagnostics. Opt. Las. Eng., 30: 251-263.

Saglam, H. and A. Unuvar, 2003. Tool condition monitoring in milling based on cutting forces by a neural network. Int. J. Prod. Res., 41(7): 1519-1532.

Sarhan, A., R. Sayed, A.A. Nassr and R.M. El-Zahry, 2001. Interrelationships between cutting force variation and tool wear in end-milling. J. Mater. Process. Technol., 109: 229-235.

Sarhan, A.A.D., A. Matsubara, S. Ibaraki and Y. Kakino, 2004. Monitoring of cutting force using spindle displacement sensor. Proceedings of the 2004 JUSFA Japan-USA Symposium on FlexibleAutomation. Denver, Colorado.

Sarhan, A.A.D., A. Matsubara, M. Sugihara, H. Saraie, S. Ibaraki and Y. Kakino, 2006. Monitoring method of cutting force by using additional spindle sensors. JSME Int. J. Ser. C, 49(2): 307-315.

Sato, M., N. Tamura and H. Tanaka, 2011. Temperature variation in the cutting tool in end milling. J. Manuf. Sci. Eng., 133: 021005-1-021005-7.

Sato, M., T. Ueda and H. Tanaka, 2007. An experimental technique for the measurement of temperature on CBN tool face in end milling. Int. J. Mach. Tool. Manu., 47: 2071-2076.

Scheer, C., P. Hoffmann, A. Kirchheim and G. Schaffner, 1999. Spindle-integrated force sensors for monitoring drilling and milling processes. Proceeding of the 9th International Conference for Sensors, Transducers and Systems. Nürnberg, Germany.

Schmitz, T.L. and K.S. Smith, 2009. Machining Dynamics: Frequency Response to Improved Productivity. Springer, New York.

Sevilla-Camacho, P.Y., G. Herrera-Ruiz, J.B. Robles-Ocampo and J.C. Jáuregui-Correa, 2011. Tool breakage detection in CNC high-speed milling based in feed-motor current signals. Int. J. Adv. Manuf. Tecnol., 53: 1141-1148.

Shao, H., X. Shi and L. Li, 2011. Power signal separation in milling process based on wavelet transform and independent component analysis. Int. J. Mach. Tool. Manu., 51: 701-710.

Sick, B., 2002. on-line and indirect tool wear monitoring in turning with artificial neural networks: A review of more than a decade of research. Mech. Syst. Sig. Process., 16(4): 487-546.

Smith, D.A., S. Smith and J. Tlusty, 1998. High performance milling torque sensor. J. Manuf. Sci. Eng., 120: 504-514.

Spiewak, S.A., 1995. Acceleration based indirect force measurement in metal cutting processes. Int. J. Mach. Tool. Manu., 35(1): 1-17.

Stirnimann, J., P. Tschanz and K. Unzicker, 2012. New Rotating Dynamometer for the Analysis of High Speed Cutting Processes. Retrieved from: <http://www.kistler.com/ mediaaccess/en-us/920-229e-11.02.pdf>, (Assessed on: April 10, 2012).

Sun, J., P. Zhu, X. Li, H. Liu, Z. Yuan and X. Qin, 2007. The online monitoring system of tool wear in numerical control plunge milling based on PC104 bus. Proceeding of the International Conference on Automation and Logistics. Jinan, China, pp: 1679-1683.

Suprock, C.A. and J.S. Nichols, 2009. A low cost wireless high bandwidth transmitter for sensor-integrated metal cutting tools and process monitoring. Int. J. Mechatr. Manuf. Syst., 2(4): 441-454.

Suprock, C.A., B.K. Fussell, R.Z. Hassan and R.B. Jerard, 2008. A low cost wireless tool tip vibration sensor for milling. Proceeding of the International Manufacturing Science and Engineering Conference (MSEC2008). ASME, ASME, Evanston, IL, USA, pp: 1-10.

Susanto, V. and J.C. Chen, 2003. Fuzzy logic based in-process tool-wear monitoring system in face milling operations. Int. J. Adv. Manuf. Tech., 3: 186-192.

Tansel, I.N., M. Demetgul, K. Bickraj, B. Kaya and B. Ozcelik, 2011. Basic computational tools and mechanical hardware for torque-based diagnostic of machining operations. J. Intell. Manuf., 24(1): 141-161.

Tansel, I.N., M. Li, M. Demetgul, K. Bickraj, B. Kaya and B. Ozcelik, 2012. Detecting chatter and estimating wear from the torque of end milling signals by using Index Based Reasoner (IBR). Int. J. Adv. Manuf. Tech., 58: 109-118.

Tansel, I., M. Trujillo, A. Nedbouyan, C. Velez, W.Y. Bao, T.T. Arkan and B. Tansel, 1998. Micro-end-milling-III. Wear estimation and tool breakage detection using acoustic emission signals. Int. J. Mach. Tool. Manu., 39: 1449-1466.

Tatar, K. and P. Gren, 2008. Measurement of milling tool vibrations during cutting using laser vibrometry. Int. J. Mach. Tool. Manu., 48: 380-387.

Teti, R., K. Jemielniak, G. O'Donnell and D. Dornfeld, 2010. Advanced monitoring of machining operations. CIRP Ann-Manuf. Techn., 59: 717-739.

Totis, G., G. Wirtz, M. Sortino, D. Veselovac, E. Kuljanic and F. Klocke, 2010. Development of a dynamometer for measuring individual cutting edge forces in face milling. Mech. Syst. Sig. Process., 24: 1844-1857.

Tseng, P.C. and A. Chou, 2002. The intelligent on-line monitoring of end milling. Int. J. Mach. Tool. Manu., 42: 89-97.

Ueda, T., A. Hosokawa, K. Oda and K. Yamada, 2001. Temperature on flank face of cutting tool in high speed milling. CIRP Ann-Manuf. Techn., 50(1): 37-40.

Ueda, T., M. Sato, A. Hosokawa and M. Ozawa, 2008. Development of infrared radiation pyrometer with optical fibers: Two-color pyrometer with non-contact fiber coupler. CIRP Ann-Manuf. Techn., 57: 69-72.

Wang, W.H., G.S. Hong, Y.S. Wong and K.P. Zhu, 2007. Sensor fusion for online tool condition monitoring in milling. Int. J. Prod. Res., 45(21): 5095-5116.

Weingaertner, W.L., R.B. Schroeter, M.L. Polli and J.D.O. Gomes, 2006. Evaluation of high-speed end-milling dynamic stability through audio signal measurements. J. Mater. Process. Technol., 179: 133-138.

Wilkinson, P., R.L. Reuben, J.D.C. Jones, J.S. Barton, D.P. Hand, T.A. Carolan and S.R. Kidds, 1999. Tool wear prediction from acoustic emission and surface characteristics via an artificial neural network. Mech. Syst. Sig. Process., 13(6): 955-966.

Wilson, J.S., 2005. Sensor Technology Handbook. Elsivier Inc., Burlington, USA.

Wright, P.K., D. Dornfeld and N. Ota, 2008. Condition monitoring in end-milling using Wireless Sensor Networks (WSNs). Trans. NAMRI/SME, 36: 177-183.

Wright, P.K., D. Dornfeld, R.G. Hillaire and N.K. Ota, 2006. A Wireless Sensor for Tool Temperature Measurement and its Integration within a Manufacturing System. LMAS, Laboratory for Manufacturing and Sustainability (LMAS), Berkeley.

Xiqing, M. and X. Chuangwen, 2009. Tool wear monitoring of acoustic emission signals from milling processes. Proceeding of the 1st International Workshop on Education Technology and Computer Science.

Yaldız, S., F. Unsacar, H. Saglam and H. Isık, 2007. Design, development and testing of a four-component milling dynamometer for the measurement of cutting force and torque. Mech. Syst. Sig. Process., 21: 1499-1511.

Yan, W., Y.S. Wong, K.S. Lee and T. Ning, 1999. An investigation of indices based on milling force for tool wear in milling. J. Mater. Process. Technol., 89-90: 245-253.

Yeo, S.H., L.P. Khoo and S.S. Neo, 2000. Tool condition monitoring using reflectance of chip surface and neural network. J. Intell. Manuf., 11: 507-514.

Yesilyurt, I. and H. Ozturk, 2007. Tool condition monitoring in milling using vibration analysis. Int. J. Prod. Res., 45(4): 1013-1028.

Young, H.T., 1996. Cutting temperature responses to flank wear. Wear, 201: 117-120.

Zhang, J.Z. and J.C. Chen, 2008. Tool condition monitoring in an end-milling operation based on the vibration signal collected through a microcontroller-based data acquisition system. Int. J. Adv. Manuf. Tech., 39: 118-128.