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Analysis of Face Milling Operation Using Acousto Optic Emission and 3D Surface Topography of Machined Surfaces for In-Process Tool Condition Monitoring

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Abstract

In machining as a result of the cutting motion, the surface of workpiece will be influenced by cutting parameters, cutting force and vibrations etc. But the effects of vibrations have been paid less attention. Thus, by monitoring the machined surface topography of the workpiece and extracting the relevant information the cutting process and tool wear state should be able to be monitored and quantified. In a automated manufacturing systems, an accurate detection of the tool conditions under given cutting conditions so that worn tools can be identified and replaced in time. This work is aimed at to predict the effects of displacements due to vibration during face milling and to examine the surface topography of different workpiece materials so as to develop a base for on-line tool condition monitoring system. First part consists of a data acquisition and signal processing using acousto optic emission sensor (i.e., laser doppler vibrometer) for on line tool condition monitoring and the second part of the work presents the vision based surface topography analysis of machined surfaces during the progression of the tool wear. The encouraging results of the work paves the way for the development of a real-time, low-cost, and reliable tool-condition-monitoring system.

Keywords: Tool condition monitoring, acousto optic emission, surface textural analysis, laser doppler vibrometer and CCD camera.

1. Introduction

In manufacturing environments, it is often a challenge to find an effective means of reducing costs and improving product quality. The continuous demand for higher productivity and product quality asks for better understanding and control of the machining process. A better understanding can be achieved through experimental measurement and theoretical simulations and modeling of the process and its resulting product. On line tool wear identification is finding an important role in modern engineering. Many approaches have been proposed to accomplish tool condition monitoring, and some have been successfully employed in industry. Several conventional tool condition monitoring methods are compared on the basis of their strengths and weaknesses for on line monitoring. Most methods essentially involve processing information such as acoustic emission (AE), tool tip temperature, vibration signatures (acceleration signals), cutting force, etc. However acousto optic emission methods have recently introduced as a reliable way detect the vibration amplitudes with non contact mode to identify the corresponding tool wear. When employed efficiently, tool condition monitoring aids in attaining the above objectives in machining applications.

The wear and breakage of cutting tools will affect the accuracy of dimension and the surface quality of machined workpieces, even breakdown the machine. Tool wear dramatically affects the texture of the machined surface. Analyzing the texture of machined surfaces has been shown to be promising for tool wear monitoring [1]. Tool wear monitoring is a critical operation in automatic manufacturing. The recent development of highly automated machine tools and increase of competitiveness makes on-line tool condition monitoring (TCM) as an alternative to statistical tool life prediction more and more interesting for the reduction of manufacturing costs [2]. Although several models [3-6] have been developed to predict cutting tool life, none of these are universally successful due to the complex nature of the machining process. All these studies have pointed out the importance of sensing technology in the development of flexible manufacturing systems. Research has proved that the vibration produced by a machine tool gives useful information for the maintenance of its structural parts [7]. This is very important when the goal is to monitor the cutting process in real time and to establish automatically the end of tool life. If the vibration signal can indirectly monitor the tool wear growth, it is also able to monitor surface roughness growth and, consequently, to establish the end of tool life in this kind of operation.

One of the main difficulties of monitoring the tool life through vibration signal is to identify the frequency range

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that is actually influenced by the tool wear, since the machining process has a lot of factors that produces vibration, many of them not correlated with the wear and breakage processes. Frequency ranges sensitive to tool wear are discussed elaborately in and values are tabulated [8]. A.E.Diniz et al [9] have conducted experiments in an attempt to monitor the changing of workpiece surface roughness caused by the increase of tool wear, through the variation of acoustic emission in finish turning. G.H.Lim [10] performed vibration signature analysis during in-process turning. This work affirms that vibration acceleration feed direction consistently produces two peak amplitudes just prior to rapid tool degradation. This information can be can be used to assess the tool wear state. Martin et al. [11], after choosing the frequency range sensitive to tool wear, concluded that, when the ratio between the vibration signal generated by the worn tool and the signal generated by the fresh tool exceeded 10, it is time to change the tool. Measurement of vibration is a vital factor that limits the precision and accuracy of machining.

B.K.A.Ngoi et al [12]., proposed a novel method for measurement of vibration using an acousto-optic modulator which highlights an improved approach in measuring vibration. One of the main difficulties in on line monitoring the tool life through vibration signal is to identify the frequency range that is actually influenced by the tool wear being non - contact, to solve the problem S.J.Rothenberg et al [13] gave a comprehensive theory and practical application for rotational vibration measurement using laser Doppler Vibrometry. Peter Norman et al[14] demonstrated the use of non – contact Laser Doppler Vibrometer in the investigation for the behaviour of a high-speed rotating system, such as a machine tool spindle. Yuji Sugiyama et al [15] developed a method for on-line monitoring of chatter vibration in end milling process using laser Doppler Vibrometer. There are numerous machining factors that affect surface quality in machining using cutting tools, but those effects have not been adequately quantified. Feng and Wang [16]., demonstrated the procedure for calculating the experimental exponents for the regression models for surface roughness and flank wear by applying a logarithmic transformation. W. H. Cubberly et al [17],. developed a rough general rule, forces and power consumption increase with increasing workpiece hardness. As a result of the cutting motion, the surface of workpiece will be influenced by cutting conditions (cutting parameters, cutting force, and cutting tool state), and the surface topography of the workpiece will include much information pertaining to the cutting process [19] . Thus, by monitoring the machined surface topography of the workpiece and extracting the relevant information the cutting process and tool wear state should be able to be monitored and quantified.

L.Blunt et al [20], outlined the procedure based on surface texture parameters to characterise the machined surfaces of workpieces in order to evaluate the tool wear is outlined. A set of areal surface roughness parameters have been listed in [21] are used to differentiate anisotropic and isotropic machined surface textures. Evaluation of the surface topography on component functionality, a set of 3D surface parameters have studied and developed relation with functional aspects in J. Kundrak et al [22,23]. Roughness of the hard turned surfaces are analysed with and are the amplitude parameters of the so-called "Birmingham 14" parameters. A comprehensive characterization of 3D surface topography for isotropic and anisotropic surfaces is outlined in [24].

The present paper presents the application of acousto optic emission (AOE) techniques for tool condition monitoring (TCM) in face turning operation. An optic signal from laser doppler vibrometer (LDV) is focused on rotating workpiece and the way of mode conversion and reflection from the surfaces workpiece can lead to interference pattern during the machining. In the analysis of acousto optic signature in experimental data, a time domain is converted into frequency domain to obtain output in the specified range of frequency. In the present work the problem of overlapping of the modes is made for force calculation there by determination surface roughness (Ra) and flank wear(VB). An experimental setup is developed for acousto optic pulse generation and different cutting tool materials with different conditions (sharp, semi sharp & dull) of tool state introduced are tested in their stable, chatter and severe chatter vibratory conditions on the test setup.

In the present study multi point cutting operation face milling is identified to examine the effectiveness of proposed methodology for TCM. Forces and vibration are always a matter of concern in metal cutting. Forces relevant to size control and power requirements. Vibrations can be beneficial if they lead to lower friction and forces. On the other hand they can aggravate the problems associated with surface finish, tool life, energy requirements and temperature. Therefore a series of studies devoted to these problems. Vibration monitoring studies are made with workpiece stationary in the present case of face milling. Establishment of correlation between vibration analysis and workpiece surfaces texture is made with experimental data.

2. Mechanism in face milling

A milling operation is an 'intermittent cutting action' , where each individual cutting insert continuously enters and exit's the cut, unlike turning, which is basically a continuous machining operation, once the cut has been engaged. It follows that with each cutting tooth impacting onto the work's surface ('intermittent cutting'), its operation will be affected by: the cutter's inherent robustness, the machine tool's condition and the spindle power availability. These factors will have a great influence on the cutter's ability to efficiently machine the desired component features. The cutting operation is done by a rotating tool that moves along various axes while the workpiece is fixed. More complex parts can be produced by milling operation. Figure.1 presents the cutter path and this is the trajectory followed by the centre of the cutter. The cutting speed is the rate at which the cutter edge moves relative to part surface. The feed rate is the rate at which the uncut part moves towards the cutter. Schematic diagram for face milling operation shown in figure 2 is selected for experimental investigation where D is the diameter of the face mill, V is the cutting speed, fz is the feed per tooth, aa is the axial depth of cut, ar is the radial depth of cut and z is the number of teeth. Different kinds of damages can develop on the tool during the cutting process and some of these damages are called as tool wear. The amount of total tool wear and time horizon to reach the maximum limit of wear determine the tool life.

Milling forces can be modeled for given cutter geometry, cutting conditions, and work material. In face milling, cutter is perpendicular to the machined surface. The cutter axis is vertical. In face milling, machining is performed by teeth on both the end and periphery of the face-milling cutter. In face milling, the cutter rotates at 90° to that of the direction of radial feed against the workpiece. In conventional face milling operation the face-milling cutter machines the entire surface. The cutter diameter is greater than the workpart width.

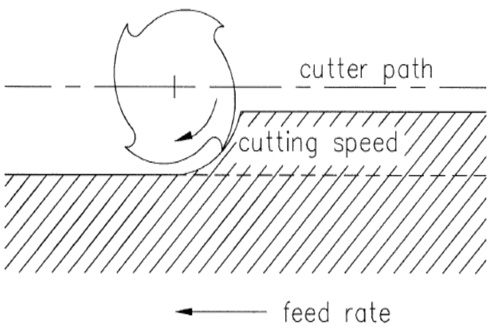


Figure 1: Cutter path motion.

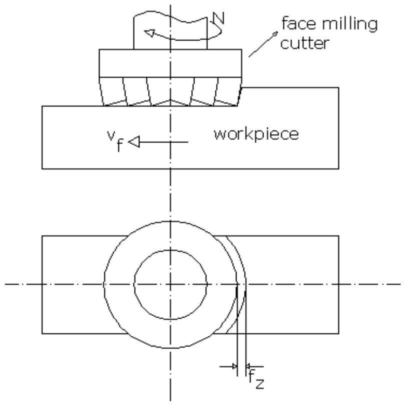


Figure 2: Schematic view of face mill.

The cutting forces exerted by the cutting tool on the work piece during a machining action to be identified in order to control the tool wear and occurrence of vibration, thus to improve tool-life. Modeling of cutting force in milling is often needed in machining automation to predict the effects of cutting parameters on the variations of cutting forces during face milling operation. Displacements in cutter due to cutting forces are measured for various feed rates using Laser Doppler Vibrometer. Free body diagram for Self excited vibration system for face milling operation is presented in figure .4 and actual machining zone is shown in figure 3.

Static deflection of workpiece in face milling may cause tolerance violation on machined parts. These deflection need to be modeled in order to check the tolerance integrity for potential compensation of the errors. Workpiece having rectangular cross-section is considered for static analysis. A cantilever beam model is used to perform the static analysis of the workpieces under load. Therefore, the primary objective of the static analysis is to determine the maximum deflection on the workpiece at the end.

The work piece deflection is important to evaluate surface error. In order to perform static analysis, a model of the workpiece is needed to determine the necessary geometric and loading parameters, moment of inertia and bending moments. A model has been developed to determine the maximum deflection using cantilever method. The cutting force is represented by a point force, which is an approximation. However, it should be noted that this model is used for both stiffness calculation and for final tool deflection also. Accurate surface generation models can be used for form errors, once the stiffness is determined. The cutting force in the feed direction is determined using the feed back signal from LDV.

Modeling and FEA can be impractical and time consuming for each tool configuration in a virtual machining environment. Therefore, simplified equations are created to predict deflections of workpiece for given geometric parameters and material properties (elastic modulus and density). The static characteristics of cutting workpiece can be easily determined by analytical expressions. Analytical model for workpiece deflection is developed and later compared with experimental results. In the analytical deformation equations, the evaluation of the integral formulas is very complex. In an attempt to further simplify the deflection calculation, the following analysis is performed. The maximum deflection could be determined using laser Doppler Vibrometer (LDV).

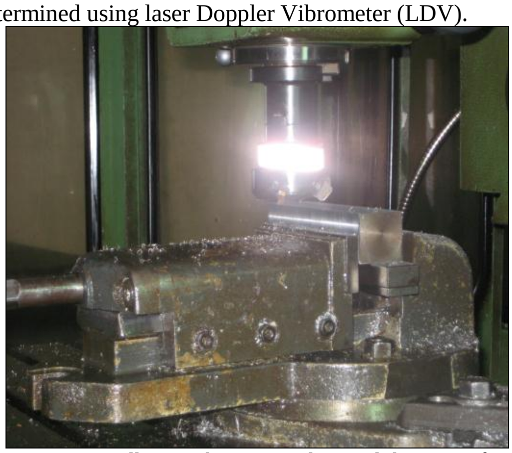


Figure 3: Face milling teeth are spaced around the circumference of the cutter body.

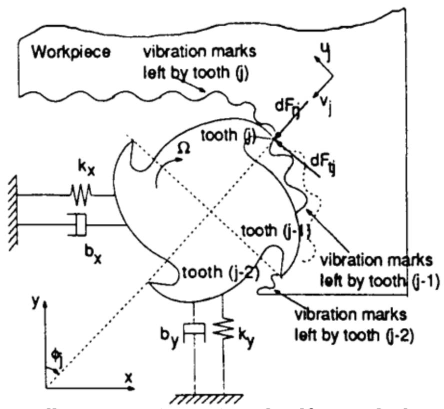


Figure 4: Milling system (2 DOF), with self-excited vibrations.

The boundary and loading condition shown in figure .5 in which the applied force (F) can be calculated by using the following equation:

$$F = k.q \quad (1)$$

where k- is the stiffness(N/mm) and q- is displacement (mm).

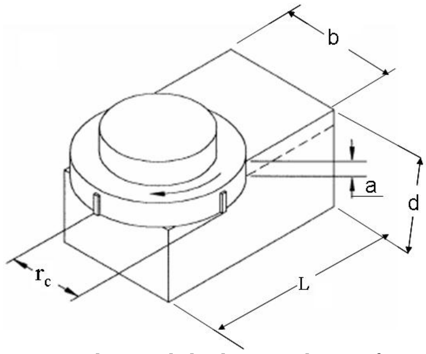


Figure 5: Boundary and loading conditions for rectangular specimen.

If the shape of the workpiece is assumed to be a rectangular the stiffness can be obtained from simplified equation.

$$k = \frac{3EI}{L^3} \quad (2)$$

$$I = \frac{b.d^3}{12} \quad (3)$$

where I-moment of inertia , diameter (D) and length (L) of the rectangle, width (b) and thickness(d) are in mm. E is elastic modulus in Gpa and q is the displacement (mm) measured with LDV.

2.1. Modeling of surface roughness and tool wear:

The mathematical model adopted for estimating the surface roughness and tool wear in this is similar to previous case except the change in values of stiffness of the workpiece after every pass of the cut. This change is due to cross section of the specimen used in the experimental investigation. In the case of steel, empirical relationships between hardness and specific power consumption (E_{sp}) or cutting force can be stated in terms of the E_{sp} value. Kronenberg has found the following approximate relationships:

For steel:

$$H = \frac{F^2}{A^2.(4.26)^2(85-\gamma_n)} \quad (4)$$

where cutting force (F), metal removal factor K_n (or specific power consumption, E_{sp}), depth of cut (d) , feed per revolution (f), A= (depth of cut).(feed per revolution) = $d.f$, γ_n – rake angle, and C_F is a constant whose value depends on the material being cut and the true rake angle of the tool, x and y are exponents. In machining of parts, surface quality is one of the most specified customer requirements. Major indication of surface quality on machined parts is surface roughness. Because of the elevated temperature in the cutting zone, the tool tip temperature increases, this softens the tool material and which in turn causes increased tool wear (VB). In addition, surface roughness also increases. The variation in the hardness of material and case depth are the other parameters affecting surface finish and tool wear. Machined surfaces with surface roughness(R_a) values above 6.3 μm are treated as highly rough surfaces and the surface roughness parameters (Ra) and corresponding flank wear(VB) can be derived from experimental data by using the following relations.

$$Ra = C_{Ra}.H^a.f^y.\gamma_n{}^n.d^p.v^x.t^z \ \mu m \quad (5)$$

$$R_q = (1.25)R_a \ \mu m \quad (6)$$

$$VB = C.H^a.\gamma_n{}^n.v^x.f^y.L^b \text{ in mm} \quad (7)$$

The face milling tests are continued till tool wear reaches the limiting criterion of flank wear of 0.3mm. where v is cutting speed (m/min), t machining time (min), L is the length of the cut (mm) and n, x, y, a, b, p, z are exponents.

3. Experimental Design and Methodology

The present work is planned to develop a base for on-line tool condition monitoring strategies and experimental plan is presented in figure 6. The block diagram for vision and acousto optic based tool condition monitoring in the present work is shown in figure 6. The objective of the present work is also to analyse the proposed methodology in face milling for tool condition monitoring. In the present work, data acquisition has been done in two ways, one of them is on-line continues data in the form of acousto optic emission signal and the other one is off line discrete mode of data acquisition through measurements and capturing of surface textures using machine vision systems. To achieve the objectives of the present work, a methodology has been developed and it is presented in the figure 7. An experimental setup is designed for face milling to validate this methodology.

Table .1 gives the various machining combinations and test conditions used in the work. The cutting parameters are selected according to the tool supplier's recommendation for tool and work piece combinations. Cutting tests are conducted at dry machining conditions. This condition decreases tool life and also experimental time. Cutting velocity and feed rates are selected based on the tool manufacturer's (Sandvik) recommendations for work-piece material and tool combination. During experimentation for every test condition cutting speed (V) and feed rate (h) are kept constant. The depth of cut value (b) varies in every chatter condition the same logic is applied in the face milling for validation of results. For evaluating the experimental results, AISI 1040 and AISI 4140 steels are used as workpiece materials. The vibration measuring equipment shown in figure .8 is kept at two meters away from the machine and an optic signal from laser doppler vibrometer is focused on to a rotating object (rotating milling cutter) and the way of mode conversion and reflection from the surfaces workpiece can lead to interference pattern during the machining. In case of face milling this is generally cutting direction and regarded as the direction in which most significant increase in vibration amplitude is observed. This signal is amplified and fed to the FFT analyser which is connected to computer for analysis.

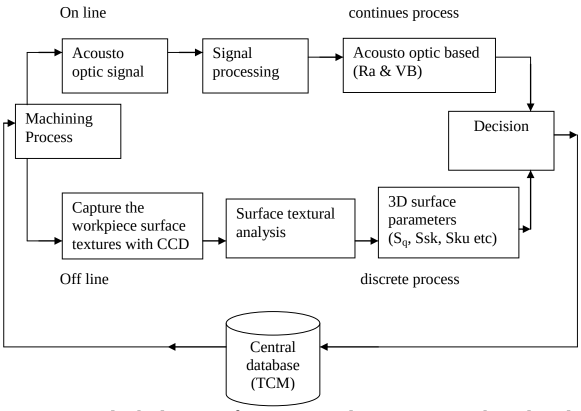


Figure 6: Block diagram for vision and acousto optic based tool condition monitoring.

When all instruments are ready, a CNC program is executed to perform face milling operation. With this designed experimental setup the following procedural steps have been implemented to carry out experimental investigation in face milling. In the analysis of acousto optic signature in experimental data, a time domain is converted into frequency domain to obtain output in the specified range of frequency. In the present work the problem of overlapping of the modes is made for force calculation there by determination surface roughness (R_a) and flank wear (VB). Experimental setup developed in the work is used for acousto optic pulse generation with different workpiece materials at different conditions (sharp, semi sharp & dull) of tool state are tested in their stable, chatter and severe chatter vibratory conditions on the test setup. When all instruments are ready, a CNC program is executed to perform facing operation, with this designed experimental setup the following procedural steps have been implemented to carry out experimental investigation.

Step 1. Each test started with a fresh insert tip , experiment has been started with test conditions 1 and machining is stopped at the end of every 4^{th} pass of cut. The workpiece has been machined four times (with depth of cut) and this process continued up to 40 passes of cut.

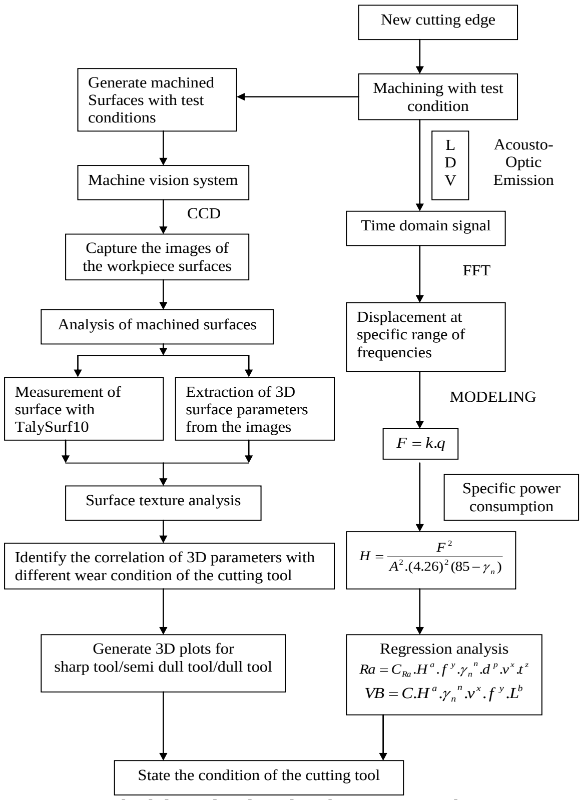


Figure 7: Methodology developed in the present work.

Step 2. Vibration signals are measured just before the machining is stopped.

Step 3. Surface textures are captured under CCD using rapid vision inspection system.

Step 4. A new workpiece is loaded on to the machine and machining is initiated with next test condition and step 3 and step 4 are repeated for this test condition.

Step 5. For remaining test condition also the same procedure has been implemented.

Step 6. In the experiment, besides measuring the surface roughness and vibration, the tool was removed from the machine after a given cutting time to have its flank wear measured and to be photographed under rapid vision inspection system.

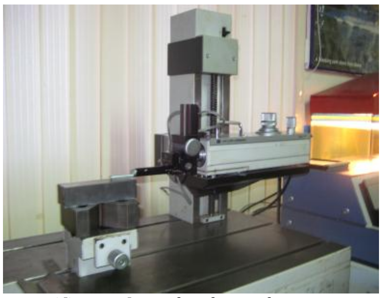
4. Experimental setup and procedure for face milling

Schematic diagram for face milling is shown in figure .9. In a milling process, the cutting parameters are the cutting speed, feed rate, axial and radial depth of cut. Table .1 gives the details of test conditions. The axial depth of cut depends on the vibration displacement.

(a) Laser doppler vibrometer

(b) Workpieces used in experiment

(c) Tool maker's microscope for flank wear.



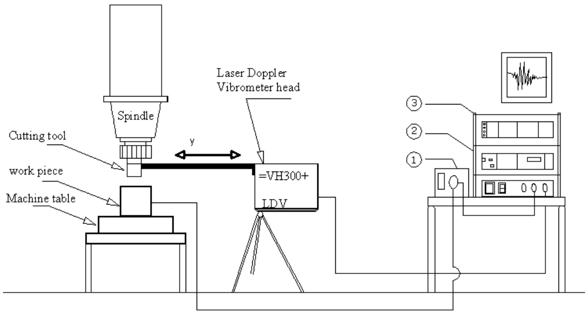
(d) TalySurf10 for surface roughness.

Figure 8: Data acquisition systems used in the experiment.

Tables 1: Test conditions selected for face milling.

Face milling	Carbide insert tip
Cutting speed(m/min)	92,115, 138
Feed rate(mm/tooth)	0.254, 0.381, 0.508
Depth of cut(mm)	0.5, 0.8,1.5

The cutting is a dry cutting process with no coolant. This condition decreases tool life and also experimental time. The metallurgical properties and cutting parameters of AISI 1040 and AISI 4140 presented in table 1. The workpieces used in the experiment are shown in figure 8(b). The feed rate was kept constant during machining and depth of cut values 0.5, 0.8 and 1.2 mm are varied for stable to severe vibratory conditions respectively. The cutting tool has four teeth in order to distribute the wear among four different teeth.



1. Piezoelectric accelelrometer (Bruel & Kjaer)
2. Pre-amplifier (Bruel & Kjaer)
3. FFT analyser (Bruel & Kjaer)

Figure 9: Schematic diagram for experimental setup in face milling.

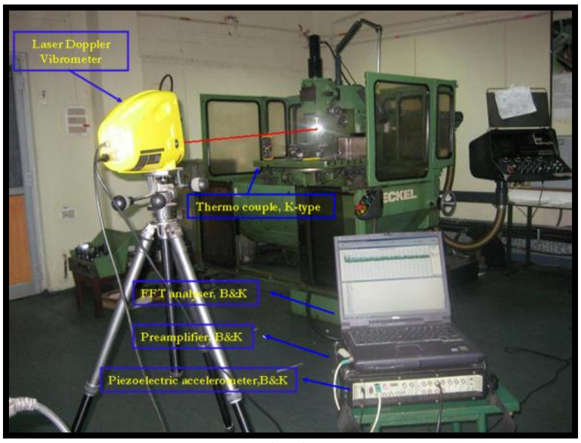


Figure 10: Experimental setup for face milling.

The cutting tool is clamped to the holder with a torque about 35 Nm for both tool lengths. With this designed setup, ISO recommended machining conditions are tested on AISI 1040 and AISI 4140 steels with common face milling cutter with four carbide tip flutes has been used. Based on the ISO standards, three conditions of the tool are considered; sharp tool (0 m of the flank wear), semi dull tool (0.3mm of tool flank wear), dull tool (0.6mm of tool flank wear) in face milling. Tool maker's microscope is used for flank wear is measurement and it is shown in figure 8(c).

5. Surface textural analysis for tool condition monitoring using machine vision system

In recent years surface texture has been recognized as being significant in many fields. In particular the surface roughness is an important factor in determining the satisfactory performance of the workpiece and cutting tool combination. Second part of the proposed methodology is that analyzes images of workpiece surfaces that have been subjected to machining operations and investigates the correlation between tool wear and quantities characterizing machined surfaces.

The machine vision system consists of CCD camera and frame grabber it is shown in figure.11 is used to process the image data. The CCD camera operates at 768 x 574 pixels. The images were analysed in the surface metrology software TRUEMAP and the values of different surface amplitude parameters were obtained. A sub image of the original image, of size 100 × 100, used for further processing with image metrology software. Then the comparison is made between Ra and 3D parameter values extracted from images of the machined surfaces. This system provides sufficient information about a machined surface and is much faster than a stylus based system. The following 3D parameters used in the analysis. Figure 8(d) shows the conventional measurement of surface roughness with TalySurf10.

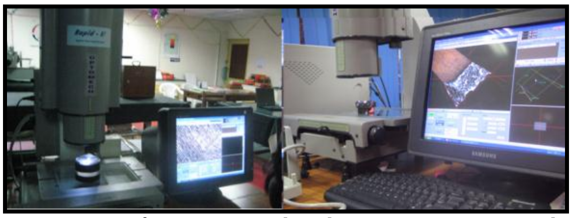


Figure 11: Surface texture and tool wear measurement under machine vision system.

5.1. Surface texture parameters used for cutting tool condition monitoring:

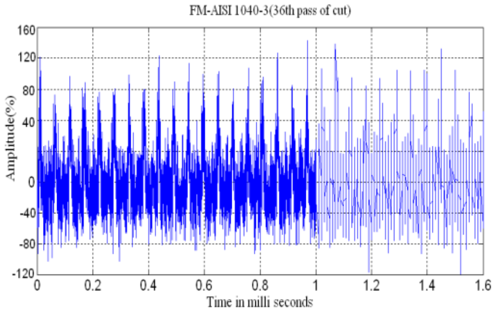
The following 3D parameters are used for surface textural analysis of workpiece surface. Root mean square roughness (S_q) parameter is assumed to provide an estimate of the average asperity height measured from datum, Skewness of surface height distribution(S_{sk}) to measure the asymmetry of surface deviations about the mean plane, Kurtosis of surface height distribution, (S_{ku}) to measure peakedness or sharpness of the surface height distribution, Texture aspect ratio (S_{tr}) is used to identify texture pattern, i.e., isotropy or anisotropy.

6. Results and Discussion

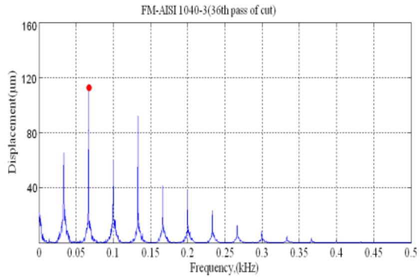
In the present work, identification of changes in displacement characteristics due to tool wear condition for worn tool with respect to its fresh tool state is used for on line tool condition monitoring. All the time domain signals in these experiments were filtered using a 100-1000 kHz band-pass filter. The sampling frequency was 4MHz and signal processing using blocks of 8000 data points collected over a period of sampling interval 1ms. Time and frequency domain spectrographs for face tuning and face milling are presented in figure 7. Flank wear value of 0.3mm is considered as tool life rejection criterion as per ISO 3685 throughout the present study.

6.1. Correlation between tool wear and displacement:

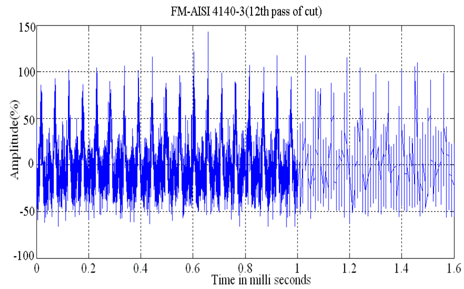
When a tool is new there is relatively little friction between the tool and the workpiece, therefore the amplitude of vibration will naturally be lower.



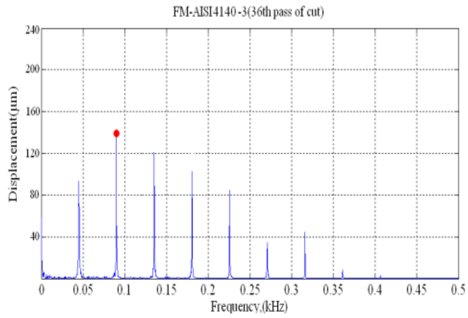
(a) FM-AISI 1040-3-Time.



(b) FM-AISI 1040-3-FFT.



(c) FM-AISI 4140-3-Time.



(d) FM-AISI 4140-3-FFT.

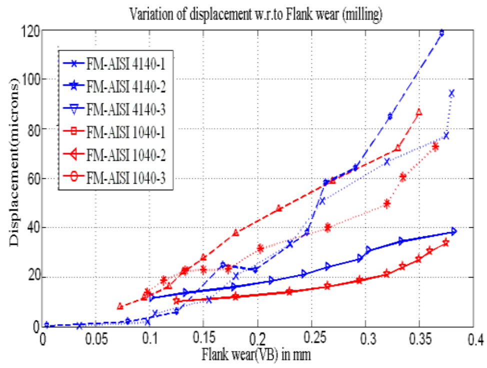
Figure 12: Time and frequency domain spectrograph in face milling.

Further, as the workpiece has a heavier mass during the early cutting stage, there will be an increase in vibration spectra can be considered to represent the system characteristics. As the increase in stiffness of the workpiece increases, a corresponding increase in vibration amplitude is recorded. Further increase in vibration spectra is due to the increasing friction between the workpiece and cutting tool as the tool wear increases. Therefore, second peak is taken as the indicator for tool state and its wear limits.

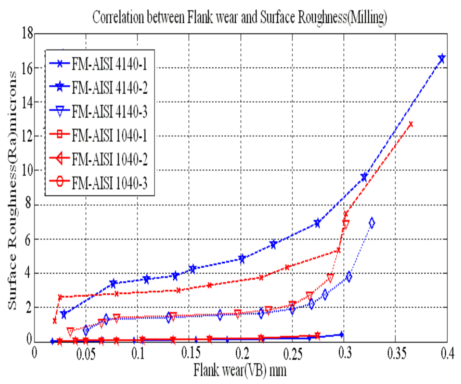
The vibration is measured in the feed direction since this direction has more dominant signals than other two directions. In this work, vibration parameter considered for the experimental analysis is displacement. The peak amplitude varies from $5\mu m$ to 150 μm depending on the severity of the chatter and cutting speed as shown in figure 12. As per ISO 2372(10816) for vibration severity standards, displacements in rotating cutter up to 20 μm do not have any effect on tool flank wear. Tool flank wear is found to be effected by the measured displacements in the range between 20 μm to 60 μm. A displacement value beyond 60 μm is not a acceptable as per ISO 10816. The results plotted in figure 13(a) justify this standard. All the test condition in each curve indicates the same. Any displacement beyond this value is showing excessive vibration which deteriorating the work piece surface and reducing the tool life. In figure.12 the correlation between tool wear and vibration amplitude is presented for test condition FM AISI 4140-3 and FM AISI 1040-3.

6.2. Surface roughness and tool flank wear:

The graphs in figure.13 (b) exhibits a correlation between surface roughness and flank wear in all test conditions with different workpiece materials. The rate of the tool wear increases as the number of passes increases. The effect of cutting speed on tool life is pronounced but it becomes less descent for higher speeds. Surface roughness is almost remains constant when tool is sharp irrespective of workpiece material. It can be seen that the growth in surface roughness is similar to the increase with flank wear in figure 13(b). From results table .2, it is clear that the severe chatter (dull tool) results in surface quality nearly two times worse than the stable cutting(sharp tool). Surface roughness values remained almost constant although flank wear increases with feed rate, depth of cut and cutting speed. However the magnitude of surface roughness (Ra) is higher for higher feed rates and depths o cuts.



(a)



(b)

Figure 13: Variations of displacement and surface roughness with respect to wear.

The test results for face milling are summarized in table 2. If red and blue colored curves are compared, it can be seen that the variation in tool life at stable condition for two different workpiece materials is more regular and the slopes are very similar to each other. The same result is not valid for test conditions with excessive displacements due to vibration because the variation between tool life and vibratory conditions for different stiffnesses in workpiece is much higher and irregular. That difference of displacement is more obvious at higher cutting speeds.

From results tables 2 it is found that hardness of the specimen and its stiffness at different test conditions is influencing the displacement in cutter during the machining. Because of this variations tool life at vibratory conditions is much higher and irregular. The effects of displacement variation on tool life in milling are shown in figure 13(a).

Figure 14 is the carbide insert tip after 38 minutes. The flank wear under vibration is obviously greater than the results of stable cutting condition. The cutting forces in feed direction only derived from displacements measured with LDV this can be done many times throughout the total experimentation i.e,. up to 40 pass of cuts with a test condition. The time interval between two displacement measurements varies 16 sec to 19 minutes.

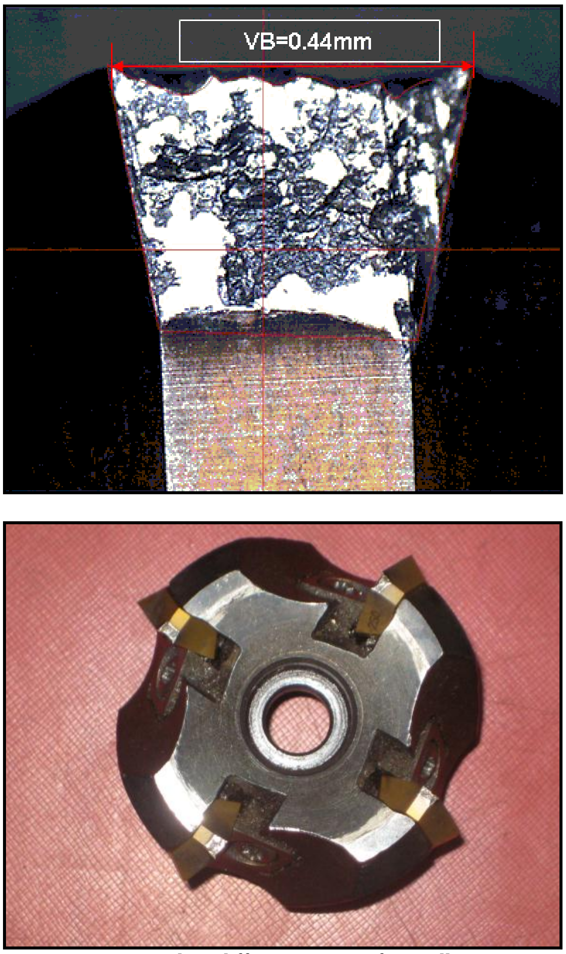


Figure 14: Worn tools at different stages in face milling.

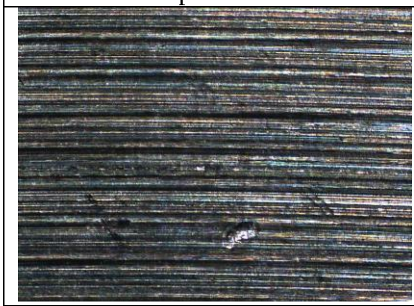
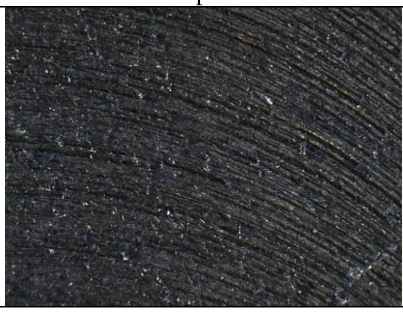
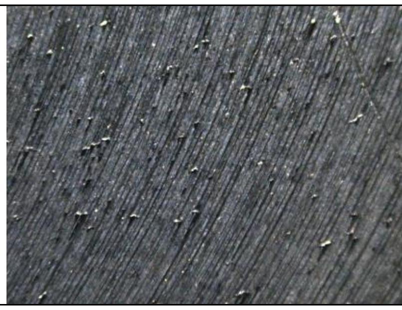
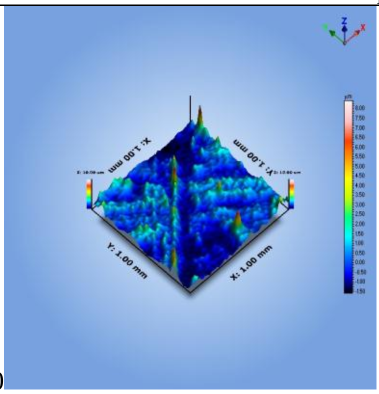
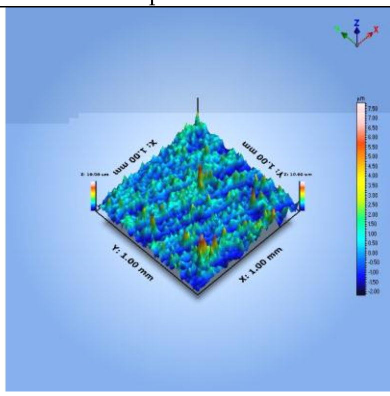
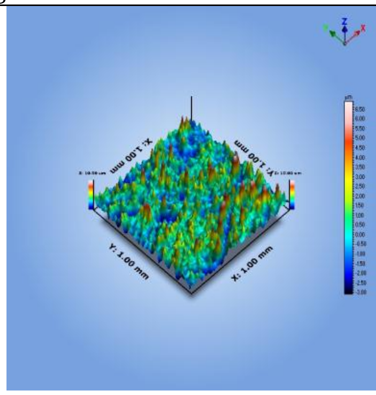
6.3. Analysis of machined surfaces:

When the tool is worn, the texture distribution strength in feed direction is weakened. With the increasing tool wear the effect of randomly occurring deeper furrows along the feed direction on the machined surface is more apparent. This is indicated in the figures in table .3 shows the 3D plot of machined surface when tool is in semi dull condition. Table 2 also compares the traces of the work piece surfaces. It is observed that the surface topography has good texture in the feed direction, the surface is very flat, and it has low levels of waviness when tool is new; with increasing tool wear the regular texture loses "strength" with scuffs and furrows appearing, with further tool wear, the surface appears very irregular having alternate rough and smooth zones.

6.3.1. 3D RMS roughness (Sq) and flank wear:

S_q, the 3D root mean square roughness, increases with tool wear increase, with the amplitude of the roughness rising with the increasing tool wear i.e., between test condition1 and test condition 2 for two machined surfaces with two cutting tool. A good understanding is found between 3D rms roughness with flank wear in the results table 3.

Table 2: Images of the machined surfaces in face milling.

Traces of workpiece surfaces in face milling		
Sharp condition	Semi sharp condition	Dull condition
		
3D plots for anisotropic surfaces in face milling		
0 		

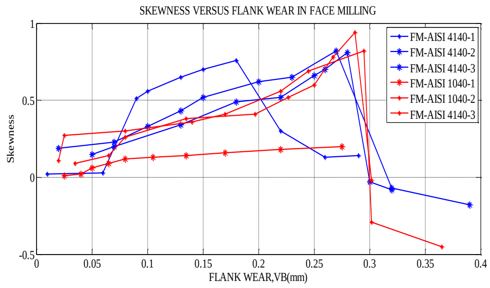
6.3.2. Skewness and tool wear:

Skewness (S_{sk})is the measurement of asymmetry of surface deviations about the mean/reference plane. From the figure 10(a), S_{sk} is near zero when the cutting tool is in good condition, which means that the surface height distribution curve is very like a standard normal distribution and a symmetrical distribution. When the tool is worn, Ssk becomes increasingly negative, due to the fact that the height distribution curve is changed to an asymmetrical distribution with a negative skew, which shows that the height of the surface is mainly above the mean plane with the surface tending towards having a "flatter top" with some deep valleys below the mean surface plane.

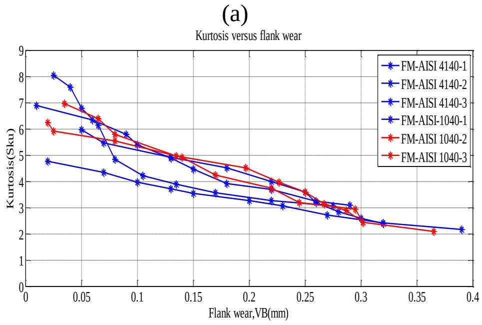
6.3.3. Kurtosis and tool condition:

Graphs developed for kurtosis parameters are presented in figure 10(b). Kurtosis ( ) characterises the spread of the height distribution. These curves indicate that the Sku is near 3 when cutter in good conditions, which shows that the surface surface height distribution is very close to a Gaussian distribution. When tool is worn, the machined surface has greater "peakedness", with the Sku will lee than 3.

Variation in hardness of the samples with progress in machining time is more in case of AISI 4140 steels compared to AISI 1040 steel, the reason being higher tool tip temperatures generated in carbide tool. However in both cases, samples machined using different test conditions vary significantly in terms of hardness. The observations of milling tests bring some conclusions. Chatter results significant reduction on tool life about 30% when the tool in semi dull state and more than 50 % in when tool reaches to dull state are presented in results table 3. Displacement has direct influence on tool life. Higher vibration amplitude means lower the tool life and all the results indicate the same.



(a)



(b)

Figure 15:Variation skewness and kurtosis with tool flank wear.

Cutting time, derived cutting force, displacements and hardness are given. The cutting force data also presented in tables for all tests. It is easily seen that the displacement due to vibrations generally increase cutting forces. The increase of cutting forces is directly proportional with the severity of vibration. It is clearly seen in the milling tests with carbide tipped cutter that chatter vibration increases tool wear.

A logarithmic transformation is applied to convert the non linear form equations 4.15 and 4.17 into the following linear from:

$$\ln R_a = \ln C_{Ra} + a\ln H + y\ln f + n\ln\gamma_n + p\ln d + x\ln v + z\ln t \qquad (9)$$

$$\ln VB = \ln C + a\ln H + n\ln\gamma_n + x\ln v + y\ln f + b\ln L \qquad (10)$$

This most popularly used data transformation method as per literature review [16]. Table 4 gives the new functions for flank wear and surface roughness after processing extensive experimental data of the present work. From the results table 3, texture aspect ratio parameter, Str is found to be greater than 0.5 it indicates the texture strength of isotropic face milled surface this trend confirms ISO 25178 standards .

Table 3. Experimental results for test condition FM AISI-4140-3.

No.of passes	Cutting force (N)	Displacement (μm)	Time (min)	Hardness	Sq (µm)	Ssk	Sku	Sds	Str	VB (mm)	Ra (μm)	Rq (μm)
4	281.36	3	0.67	197	1.60	0.19	4.77	1235	0.63	0.02	1.54	1.92
8	282.29	6	1.21	198.7	3.94	0.23	4.33	1249	0.62	0.07	3.25	4.06
12	283.69	8	2.10	199	4.23	0.33	3.97	1256	0.61	0.10	3.49	4.36
16	286.09	24	2.42	201	4.65	0.43	3.72	1269	0.59	0.13	3.79	4.73
20	287.37	30	3.22	203	5.04	0.52	3.54	1277	0.57	0.15	4.15	5.18
24	288.95	38	4.31	205	5.67	0.62	3.27	1285	0.55	0.20	4.67	5.83
28	290.70	58	4.53	209	6.6	0.70	3.07	1309	0.52	0.23	5.44	6.8
32	292.36	65	5.32	210	8.16	0.82	2.71	1325	0.50	0.27	6.72	8.4
36	293.71	85	6.43	213	13.27	- 0.07	2.42	1339	0.47	0.32	9.35	11.6
40	295.49	117	6.59	215	22.65	- 0.18	2.17	1350	0.41	0.39	15.95	19.9

Table 4. Experimentally derived function for surface roughness and tool wear.

Test condition	New developed functions for surface roughness(R_a) and flank wear(VB) based experimental data
FM-AISI 4140 -1	$Ra = 0.7571.H^{0.393}.f^{0.733}.\gamma^{0.0988}.d^{0.507}.v^{-0.063}.t^{0.245}$ $VB = 2.433.x10^{-8}.H^{2.8173}.\gamma^{0.1020}.v^{-0.0533}.f^{-0.2487}.L^{0.514}$
FM-AISI 4140 -2	$Ra = 0.946.H^{0.4972}.f^{0.9162}.\gamma^{0.1235}.d^{0.633}.v^{-0.078}.t^{0.3062}$ $VB = 3.406.x10^{-8}.H^{3.944}.\gamma^{0.1428}.v^{-0.0742}.f^{-0.3481}.L^{0.7196}$
FM-AISI 4140 -3	$Ra = 1.3244.H^{0.6960}.f^{1.282}.\gamma^{0.1729}.d^{0.886}.v^{-0.1092}.t^{0.4286}$ $VB = 4.768.x10^{-8}.H^{4.5216}.\gamma^{0.1999}.v^{-0.1038}.f^{-0.4873}.L^{0.986}$
FM-AISI 1040 -1	$Ra = 0.605.H^{0.314}.f^{0.586}.\gamma^{0.079}.d^{0.4058}.v^{-0.0509}.t^{0.195}$ $VB = 1.946.x10^{-8}.H^{2.2534}.\gamma^{0.0807}.v^{-0.042}.f^{-0.1989}.L^{0.4113}$
FM-AISI 1040 -2	$Ra = 0.726.H^{0.3977}.f^{0.7032}.\gamma^{0.0948}.d^{0.4869}.v^{-0.0610}.t^{0.234}$ $VB = 2.432.x10^{-8}.H^{2.8167}.\gamma^{0.1008}.v^{-0.0525}.f^{-0.2486}.L^{0.5141}$
FM-AISI 1040 -3	$Ra = 0.980.H^{0.596}.f^{0.9493}.\gamma^{0.1279}.d^{0.6573}.v^{-0.0823}.t^{0.3159}$ $VB = 3.404.x10^{-8}.H^{3.9433}.\gamma^{0.14112}.v^{-0.0735}.f^{-0.3480}.L^{0.7197}$

7. Conclusion

In this study, relationship between the surface textural analysis, vibration and tool wear is investigated during face milling. Vibration signature analysis during face milling appears to be a promising method for tool flank wear detection. Measurements have shown that the analysis of vibration displacement amplitudes are used to assess tool wear in face milling. Vibration displacement in the feed direction consistently produces two peak amplitudes just prior to rapid tool degradation. Throughout the experimentation the vibration amplitudes are found to be increases as the progression of tool wear. As expected, with increase of speed, feed rate, depth of cut tool life became shorter. It is demonstrated that the AOE signal can be used successfully to distinguish between new and worn tools. The non contact monitoring capability of laser doppler vibrometer allows automatic tool wear classification with minimum human interaction.

Face milled surfaces with isotropy are extensively analysed in the present work. The level of isotropy in face milled surfaces is clearly revealed by texture aspect ratio parameter Str. Tool wear influences almost all the 3D surface parameters. The surface textural analysis of machined surfaces is very effective in tool condition monitoring. Thus, combined analysis of 3D surface topography of workpiece surface textures and acousto optic emission method for vibration displacement during the machining can be a choice for on line monitoring the tool wear state and can be used to monitor the machine states; therefore, it could provide a means to optimise the machining process. The encouraging results of the work paves the way for the development of a real-time, low-cost, and reliable tool-condition-monitoring system. A high degree of correlation is established between the results of the AOE signal and vision based surface textural analysis in identification of tool wear state.

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