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Real Time Tool Wear Condition Monitoring in Hard Turning of Inconel 718 Using Sensor Fusion System

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Abstract

The work presented here is an attempt to introduce a sensor based tool wear monitoring system for hard turning of Inconel718 material. Tool wear is a significant factor which influences surface finish, production time and economy of tooling. Hence, an online tool wear monitoring system has been developed using a sensor fusion system, consisting of a vibration sensor and a force based measurement system. Nine experimental runs based on L_9 orthogonal array of Taguchi method are performed and analysis of variance (ANOVA) is carried out to identify the significant parameters. The second part of the study include extended period turning operation performed till the tool is worn out completely. Both vibration and force signals are captured by a data acquisition system. The study shows that force data is quite useful to establish a strong correlation between the cutting force and tool wear. Cutting forces establishes a uniform correlation with tool wear which can effectively be used for online tool wear measurement. The effectiveness of these signals to predict tool wear has been established with a MATLAB based GUI that directly displays the real time tool wear.

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*Keywords:*Vibration, Force, Tool Wear, Sensor Fusion System, MATLAB.

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1. Introduction

The developments in machining of larger and complicated shapes made of expensive material lead to the development of a tool condition monitoring system. The contact between the cutting tool, workpiece and the chip causes the tool shape to change. The phenomenon known as tool wear, has a major influence in machining economics, final workpiece dimensions and surface finish. Current shop floor practice is to use the life expectancy of a cutting tool to formulate replacement strategy and is changed by the machine operator. The judgment of operator is often based on the visual inspection of the tool and surface finish of the work piece, both requiring a certain degree of skill. Tool change based on operators experience and skill may cause either earlier or delayed tool replacement. This leads to additional expenses for cutting tool and/or higher surface roughness and subsequent rejection of the component. The frequent tool changes cause higher machine downtime, thereby decreasing the system productivity and increasing production costs [1]. For these reasons, quality and productivity requirements through international competition have forced many manufacturers to use automated monitoring systems.

There are several tool wear monitoring techniques being used at present namely, direct and indirect sensing methods. Direct sensing methods use direct measurement of the wear, like optical scanning, electrical resistance, and radioactive techniques, measurement of tool geometry, change in work piece size and distance between the work piece and cutting tool. Indirect techniques involve keeping track of one or more parameters of the cutting process and correlate the change with tool wear. These includes measurement of Acoustic Emission, spindle motor current, vibrations, cutting forces, energy input to the system, surface finish, and cutting temperature [2-5].

It is well established that flank wear influences more on tolerances and surface finish. Hence, the work presented here is an attempt to characterize flank wear with continuous sensory signals or data. The successful implementation of an on-line tool-monitoring system depends on two factors (a) quality of the data acquired and (b) diagnosis technique to analyze the data [6]. However, as a single sensing technique does not appear reliable in practice, indirect sensing techniques are adopted together in a sensor fusion system. This system/method which uses more than one sensor is attractive since the loss of sensitivity in one sensor domain can be offset by information from the other sensor ensuring more accurate and reliable results [2]. Hence, on-line tool monitoring system with sensor fusion system can be used effectively to estimate the state of tool in real time more accurately and reliably.

Nomenclature

S	Cutting velocity (m/min)
F	Feed rate (mm/rev)
D	Depth of cut (mm)
CNC	Computer Numerical Control
FFT	Fast Fourier Transform
GUI	Graphical User Interface
RMS	Root mean square

2. Experimental details

In the present work, turning tests are carried on Inconel 718 (Ni based alloy) using a CNC turning Centre (PMT make). Inconel 718 is a high-strength; corrosion-resistant material having very high hardness and difficult to cut primarily used for high temperature and pressure applications. Typical properties of the material are given in Table 1 [7]. A round bar of 40 mm diameter size work piece is considered for turning operation and coated carbide CNMG 120408 SM 1105 inserts from Sandvik are used for conducting experimentss [7, 8]. L_9 orthogonal array of Taguchi method has been formulated to conduct the tests [9, 10]. A Mitutoyo toolmakers microscope is used for the measurement of tool wear at equal intervals of 15 seconds till the tool is worn out completely. Further, a MATLAB based GUI has been developed to display the on line tool wear [5, 11].

Table 1: Inconel718 Properties

Inconel 718 chemical composition (values in %)

Ni	Cr	Fe	Cb	Mb	Co	Al	Ti	Si	Mn
52.82	19	17	5	3	1	0.8	0.6	0.35	0.35

Inconel 718 Mechanical Properties

Hardness (HRC)	Yield strength, (MPa)	Ultimate strength	Elongation (%)	Density (g cm^{-3})
40 - 45	1041 – 1160	1260 - 1390	14 - 19	8.19

2.1. Vibration measurement system

Experimental setup for measuring both vibration and forces is shown in Fig. 1(a) and (b). Vibration measurement system (Fig. 1(a)) is used to acquire the time and frequency domain data during experimentation [12, 13].

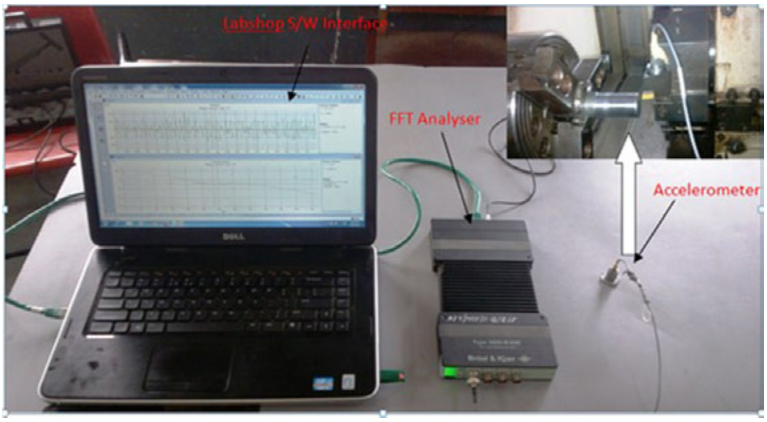

Fig. 1. (a) Vibration Measurement System

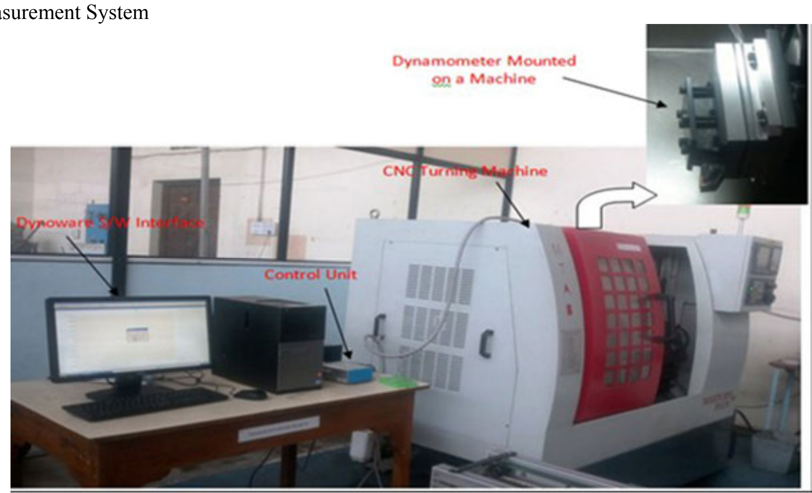

Fig. 1. (b) Force Measurement System

An accelerometer (Delta Tron accelerometer of type 451457125 from Bruel & Kjaer) is placed on the tool holder using a magnetic clamp to capture the vibration data through FFT analyzer (Fig. 1(a)). Four channel FFT analyzer (make Bruel & Kjaer of type 3050-B-040) is used for the experiments. FFT analyzer amplifies and modifies the incoming signal to make it measurable. Hence, pure waves representing the metal deformation or tool wear are allowed to pass though this unit [14].

2.2. Force Measurement System

Metal cutting operation requires certain amount of force to cut or remove the material from the work piece. It has been widely published that variation in the cutting force can be correlated to tool wear. It is one of the commonly used technique for monitoring tool wear. Force can be easily measured either directly from a dynamometer (strain gauge or piezoelectric type), or indirectly by evaluating the motor current, torque, vibration or sound during metal cutting [6, 15]. The dynamometer consists of three-component force sensors; sensitive to pressure in the z direction and the other two responding to shear in the x and y directions respectively. The force measurement system as shown in Fig. 1(b) is capable of measuring radial force (F_r), thrust force (F_t) and cutting force (F_c) which occurs during machining [16, 17]. However, only feed or cutting force is considered for further analysis [18].The overall system performance enhances as two sensors are coupled in the sensor fusion system to ensure reliability and accuracy of tool wear prediction [19].

3. Experimental results and analysis

3. 1.Taguchi Design of Experiments

The effect of three major parameters i.e. speed, feed and depth of cut that significantly affect the turning operation are studied using Taguchi method. In this study, all three parameters are considered at three levels. Therefore, nine combinations were tested for a constant time period to know their effect on tool wear. Results obtained by Taguchi L_9arrays are shown in Table 2.

Table 2: Tool Wear data.

Experiment No.	S	F	D	Wear (μm)
1.	40	0.05	0.4	40
2.	40	0.10	0.8	50
3.	40	0.15	1.2	85
4.	80	0.05	0.8	65
5.	80	0.10	1.2	100
6.	80	0.15	0.4	45
7.	120	0.05	1.2	155
8.	120	0.10	0.4	110
9.	120	0.15	0.8	140

Statistical ANOVA is a technique which gives quantitative contribution of each parameter on a response variable. ANOVA summary for tool wear obtained from MINITAB16 showed that speed is influencing the most with 73.3% contribution, followed by depth of cut with 25.4% contribution, while feed has negligible effect on the tool wear.

3.2. Extended Period Tests

Once these parameters and their significance on tool wear are studied, their combinations (Table 3) were selected for extended period tests. For extended period tests turning operation is carried till the tool is worn out completely i.e. up to 0.3 mm flank wear (as per ISO 3685:1993). However in 3rd trial (9th experiment) chipping off of the tool took place. This failure is because of fracture due to high thermal and mechanical loading at the interface.

Table 3: Extended Period Tests.

Sr. No.	S	F	D
1. (2nd Expt.)	40	0.1	0.8
2. (6th Expt.)	80	0.15	0.4
3. (9th Expt.)	120	0.15	0.8

Hence, results from two trials i.e. for 2nd and 6th experiments were used for further analysis. During extended period tests, tool wear is checked for every 15 seconds until the insert is worn out. Simultaneously force and vibration data are captured as given in Table 4 are used to correlate with tool wear. It is understood from the data that tool wear rate increases with time. Three distinct phases of tool wear namely initial wear, gradual wear and rapid wear are observed during machining.

3.3. Analysis of Vibration Signals

The time domain data of acceleration is used to analyze the tool wear with time. The RMS values of the signals are considered in the present study. Both vibration data and tool wear are recorded for every 15 sec. till the insert is worn out completely. In the present work, 2nd and 6th experiments are run for nearly 120 seconds so that the insert is failed. The vibration and tool wear data acquired for 2nd experiment, is plotted as shown in Fig. 2 (a) and (b). Similarly, variations in vibration data and progressive tool wear with time are studied for 6th experiment.

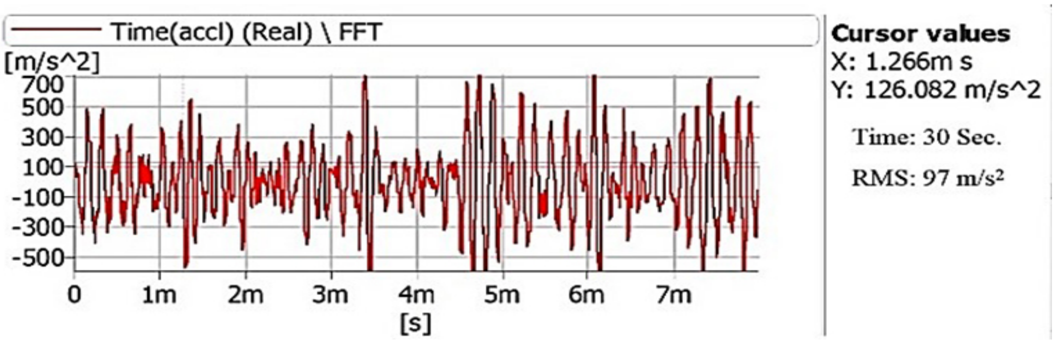

Fig. 2 (a): Variations of acceleration with Time (for 2nd Expt.)

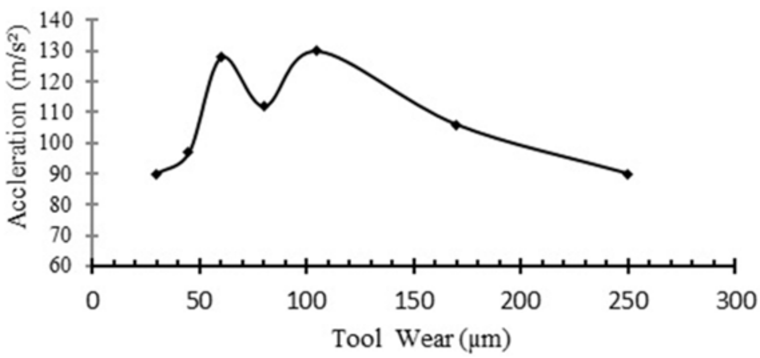

Fig. 2 (b): RMS of acceleration with progressive tool wear

Fig. 2(b) shows that initially acceleration increases with increase in tool wear. Local fluctuations are observed during gradual wear phase and acceleration settles down smoothly with time during last phase of tool wear. Hence by referring this correlation and observing the variation in acceleration tool wear state can be predicted. Hence the vibration data is useful to predict the tool wear state; however, it cannot quantify the actual tool wear. It is clear from the observations made that the vibration in general shows the non-linear trend with the actual tool wear. Hence, either advanced approaches like artificial neural network, genetic algorithm and/or fuzzy logic etc. is to be used for establishing the relation between tool wear and vibration signal or some other approach like force data acquisition in combination with vibrations to overcome these limitations.

3.4. Analysis of Cutting Forces

To overcome these limitations inherent to vibration data, force data are coupled or integrated with the vibration data. Such integration leads to enriched sensory data that ensures strong correlation with tool wear and reliable results. Similar to vibrations, force data during the cutting operation are measured till the insert is worn out. Force values are measured and stored in Dynoware software for about 120 sec. An average of these values are used for further analysis. The force data along with tool wear are given in Table 4.

Table 4: Vibration and Force data with Time.

Expt. No.	Time	For 2nd Experiment			For 6th Experiment		
		Wear	Acceleration	Force (N)	Wear	Acceleration	Force (N)
1.	15	30	90	695	10	190	237
2.	30	45	97	724	25	260	255
3.	45	60	128	774	55	331	278
4.	60	80	112	843	90	254	332
5.	75	105	130	860	140	345	412
6.	90	170	106	873	220	283	460
7.	105	250	90	982	325	235	485
8.	120	Break	--	---	Break	--	---

Fig. 3(a) shows the variation in all three types of forces (F_x, F_y and F_z) with time. The cutting force data are plotted against respective tool wear as shown in Fig. 3(b). This implies that cutting forces varies linearly with tool wear. Hence, by knowing the force values, tool wear can be calculated accurately by using the equation of the line. All such correlations for different combinations of input parameters (i.e. speed, feed and depth of cut) i.e. for other set of experiments can be obtained and stored in the software. Once such strong correlation is established between the force and tool wear, cutting forces can be used very reliably and accurately to calculate the online tool wear.

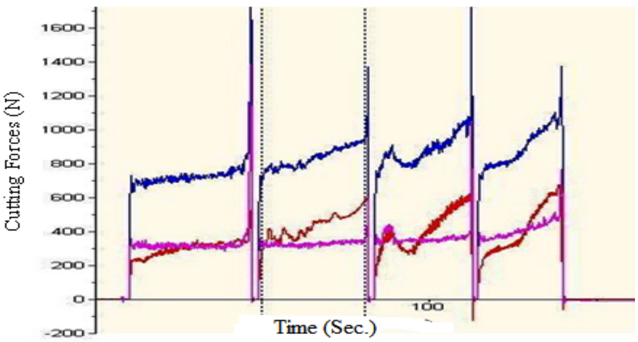

Fig. 3 (a):Real time variation of cutting force with Time

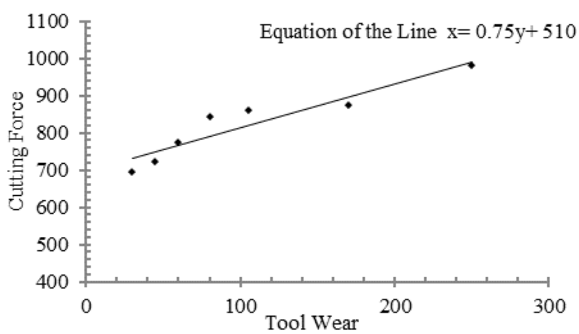

Fig. 3 (b):Variation of cutting force with progressive tool wear

For online tool wear monitoring, a MATLAB based program is developed to read the force data. Then average of the forces for last 15 sec. period are evaluated to substitute in the equation (Fig. 3(b)) and corresponding tool wear value is displayed. Results (calculated wear) obtained in real time using MATLAB based GUI and measured tool wear values using Tool maker's microscope are listed in Table 5.

Table 5: Measured and calculated tool wear.

Time (sec.)	for 2nd Experiment			for 6th Experiment		
	Forces (N)	Measured wear	Calculated wear	Force (N)	Measured wear	Calculated wear
15	695	30	12	237	10	10
30	724	45	33	255	25	11
45	774	60	70	278	55	38
60	843	80	122	332	90	101
75	860	105	135	412	140	196
90	873	170	145	460	220	252
105	982	250	227	485	325	282

It is evident from these values that evaluating tool wear using this method is quite accurate. However, unlike a vibration measurement system which can predict only tool wear state and not the actual tool wear values; measurement of forces during the metal cutting operation can predict the actual tool wear. Hence, by formulating the sensor fusion system, the strong linear correlation obtained from force measurement can offset the limitations of the vibration system which are discussed earlier. Once the relation is established between cutting forces, vibrations and tool wear; cutting force and vibration signals can be an accurate source to predict the tool wear. Hence, an effective online tool wear monitoring for turning process was ensured only through measurement of vibrations and cutting forces.

4. Conclusion

In the present work use of vibration and force data together as a single system to detect cutting tool wear condition has been proposed and its feasibility is investigated. Both vibration and force data are plotted against the progressive tool wear to ensure the correlation existing between them. However, vibrations showed the non-linear trend towards the tool wear and any simple or generalize mathematical model is not much useful for accurate tool state prediction. The study also showed that the combination of farce and vibrations enhances the accuracy of tool wear prediction. The results obtained from MATLAB based GUI are used to represent the tool wear accurately and reliably. However, this study also emphases on the need to add more sensors with existing dual sensing method to ensure the highest accuracy in online tool wear monitoring system.

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