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Evaluation of tool performance and wear through vibration signature analysis in drilling of IS3048 steel

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Abstract

In this paper, a connection between vibration amplitude and tool wear when drilling of IS3048 steel utilizing different dimensioned tools is dissected through tests. Discriminant features, which are sensitive to drill wear and breakage, were developed. These were discovered to be somewhat impervious toward sensor location and cutting conditions. In the process, the vibration amplitude features a checking highlight dependent on ascertaining both the tools and their performance over vibrations, which was discovered to be somewhat powerful for on-line identification of drill tool breakage in both frequency and time domains. These vibrational amplitude signal features are directly affected, related to the tool geometry, which give higher chances of tool selection criteria during the drilling process. The experiments were carried out using solid carbide tool with change in tool geometry under dry conditions where the vibration amplitude for both is evaluated. The results revealed that cutting tool vibrational amplitude and tool wear were relatively dependent showing the tool selection of suitable tool geometry.

Keywords: Vibration measurement, Drilling process, Tool wear, Tool condition, SEM-EDA

Introduction

A significant explanation for the incidence of damage is accelerated wear of the instrument due to the abrasive workpiece materials. Drill geometry is an important aspect that defines the consistency of the hole being drilled. Recommendations are given to assist in the selection of the appropriate drill for the desired criterion of hole quality. Drilling, generally utilized machining process, is addressed roughly 60% of all material removal tasks performed in an industry. Ordinarily, turn drill tools are utilized within a breadth ranging from 1 to 20 mm. One of the disappointments of drilling happens by one of the two ways, either by causing crack in tool or by wear [1]. It was evident that under typical cutting conditions, failure because of tool breakage was seen with smaller drills which are < 3 mm diameter, while unnecessary wear was the prevailing failure approach with bigger drills that are > 3 mm diameter. Drill tool wear and failure impact the dynamic qualities of the drilling cyclic process [2]. Worn-out drill tool produces vibration signal characteristic of the drill tool conditions during machining [3]. The



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vibrations produced can make the drill “wander” from its actual axis center which causes improper holes tolerances. These imperfections are of specific significance for high-speed machining with accuracy. Such a cycle is normal in the aeronautical and automotive industry and for machining of aluminum parts and cast-iron. Computerization of these tasks require the turn of events of dependable strategies for on-line detection of tool damage and tool wear. A few detecting strategies have been accounted for in the writing by different investigators who managed the issues of recognizing crack in the tool, edge chipping, wear, and poor manufacturing quality. These methods incorporate acoustic discharge, touch sensors, power, vibration, forces, and vision systems with respect to torque. Insights identified with the utilization of different monitoring methods in machining are touch probes tests which are regularly used to identify drill cause failures. Despite the fact that these sorts of tests are for the most part solid, their scope of utilization is somewhat restricted in a few regards [5]. Condition monitoring power was accounted for and has been roughly 80% fruitful in distinguishing drill environments [4]. This sort of checking involves measurement of voltage and the current of the shaft armature. Estimation of the axle speed is additionally needed to figure out the relating torque. Trial contemplates performed by a few examiners [5] demonstrate that various combinations of cutting conditions bring about various amounts and measures of drill wear. Various drill tool wear patterns might change the subsequent vibration features in the frequency spectrum. Thus, it is important to examine and study the impact of each sort of wear [6] on the vibration spectrum generated during drilling process.

Vibration monitoring [7] methods applied in practical to the inspection of tool failure have been accounted for by a few specialists. The upsides of these procedures incorporate simplicity of execution and the way that no alterations to the machine [8] apparatus or the workpiece installation are required, notwithstanding the drawbacks revealed in the writing incorporate reliance of the vibration signals [9] on workpiece material, machine structure and, cutting conditions. Obviously, extra examination is needed to foster reasonable vibration monitoring procedures which are sensitive to tool [10] state yet generally insensitive toward cutting conditions [11], sensor area, and so on. The current work manages the advancement of vibration-based monitoring techniques for recognizing breakage of smaller size drills having < 3 mm diameter and tool wear of bigger drills that are having diameter > 3 mm. The qualities of the vibration signature analysis [12] were analyzed in time domain as well as frequency displacement spectrum. Vibrations signal feature highlights were advanced and were demonstrated to be compelling in detection of drill tool failure [13] and wear [14] while being insensitive toward disparities in cutting conditions. The viability of the proposed tool monitoring features was confirmed from experiments on drilling cast-iron workpieces utilizing solid carbide drills.

Methods

For the dry drilling process, tools of Ø7 mm solid carbide drill bit and Ø3 mm were used to analyze the vibrations which occurred at various diameters while drilling hole. The workpieces of IS3048 steel having chemical and mechanical properties and tool specifications are given in Table 1, which were drilled on a BFW –BMV 60 CNC vertical machining center as shown in Fig. 1. The experiments were carried at changing

Table 1 Chemical composition and mechanical properties of IS3048 workpiece (IS:3048-1965: UDC 621-514.59 Indian Standard Dimensions for Handwheels)

Designation	Chemical composition					Mechanical properties			
	Posco	C	Cr	Ni		Yield strength (N/mm ²)	Tensile strength (N/mm ²)	Elongation (%)	Hardness (Hv)
IS3048		≤ 0.08	18.0	20.0	80.00 10.50	≥ 205	≥ 520	≥ 40	≥ 200

Tools specifications: solid carbide tool

Parameters	Tool A	Tool B
Diameter	7 mm	3 mm
Shank diameter	8 mm	5 mm
Cutting edge length	38 mm	35 mm
Overall length	165 mm	100 mm

cutting speed using the Taguchi L9 orthogonal array method. The experimentation setup is shown in Fig. 1, and the study was performed on a VB7 GE vibration analyzer (LDV) to analyze the vibrations intended during drilling with solid carbide cutting tools. The details of the experimentation are given in Table 2, and the setup rig is shown in Fig. 1.

The drill tools of Ø7 mm and Ø3 mm solid carbides are set for machining of IS3048 steel as per conditions designed using the Taguchi L9 orthogonal array method. The experimentation was carried out with nine test conditions (TC1 to TC9) of feed rate (f), rotational speed (N), and depth of cut (d).

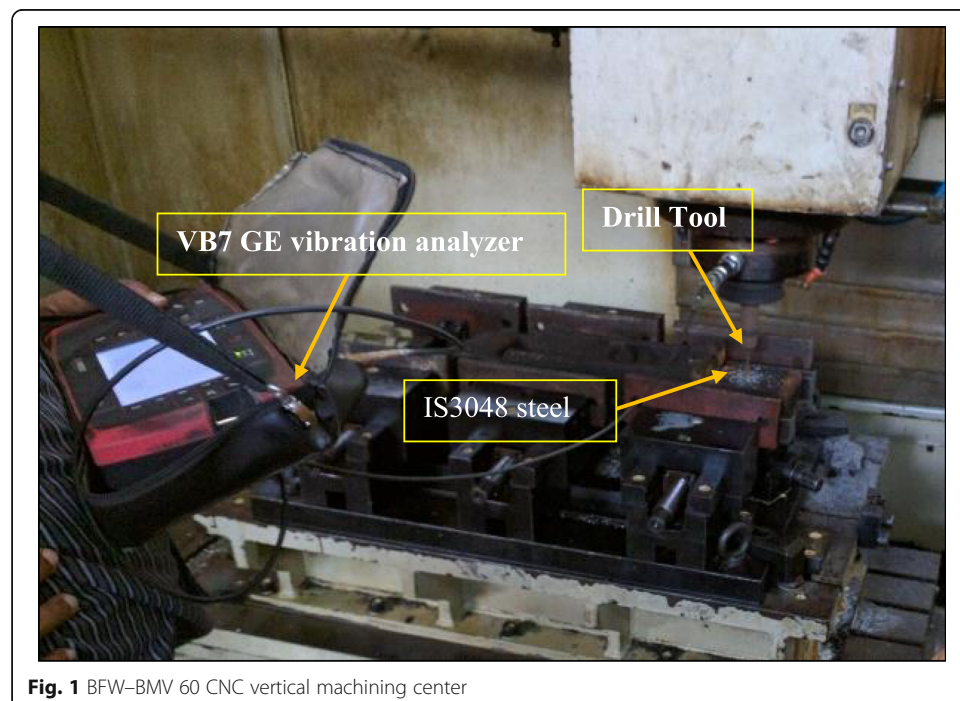
**Fig. 1** BFW-BMV 60 CNC vertical machining center

Table 2 Proposed experimental test setup

CNC drilling operation	
Equipments used in the experiemnt	BFW–BMV 60 CNC vertical machining center
Sensors used (DAQ)	VB7 GE vibration analyzer (LDV)
Workpiece materials (%C is similar)	IS3048 steel 150 × 150 × 10mm
Cutting tools	Ø7 mm solid carbide drill bit, Ø3 mm solid carbide drill bit

Cutting tool vibrations

The vibration information created during cutting were estimated utilizing the VibSoft software, and the equipment hardware accelerometer mounted on the drill tool holder at Z-axis and vibrations of the tool were plotted as shown in Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig.7, and Fig. 8. Subsequently, the vibration information gathered by the Type 8762A accelerometer were studied using VibSoft Console, and the amplitude values of Z-axis taking average for each tool were plotted. Type 8762A accelerometer is a special shear sensor component that highlights very low vibrational amplitude transient reaction, a high insusceptibility to base strain, and crossover speed increase. A high-level advanced configuration gives remarkable signal response, just as a wide frequency working range. The lightweight, aluminum lodging is epoxied and anodized covered to give ground isolation. VB7 GE vibration analyzer (LDV) is used for measuring the vibrations. Tests were expected to distinguish the presence of vibration parameters all through the experimentations utilizing a LDV as feedback device gadget for non-contact vibration inspection. During machining, vibrations brought about by unexpected conflict of a cutting tool against a work material as an outside excitation will influence the machining quality. To acquire the exact information about the reasons for such vibrations, this attainability study estimated the vibrations and tool conditions in symmetrical cutting utilizing a vibration analyzer. A lot of information were directly measured or post-processed. Some comparisons between the collected data were made.

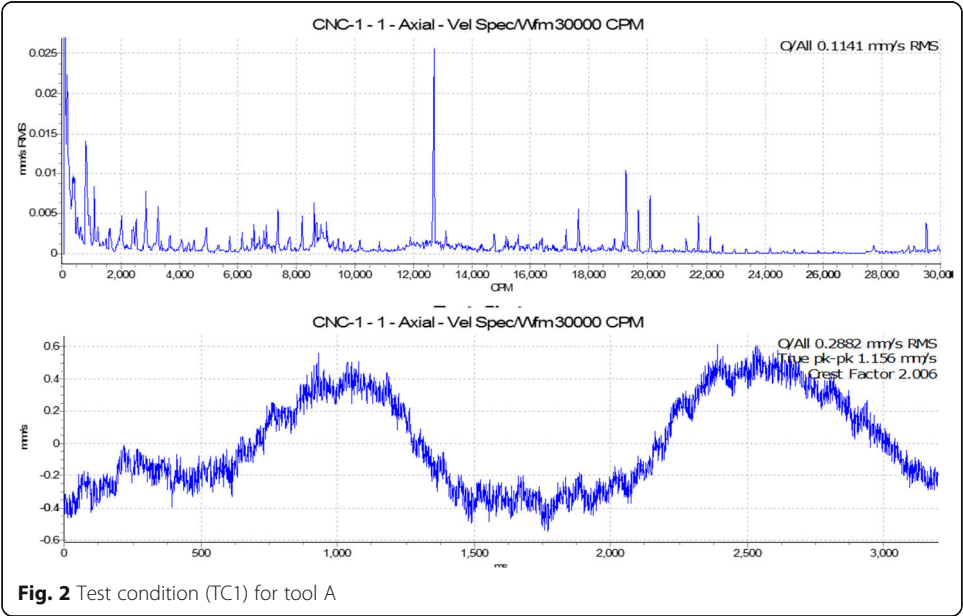
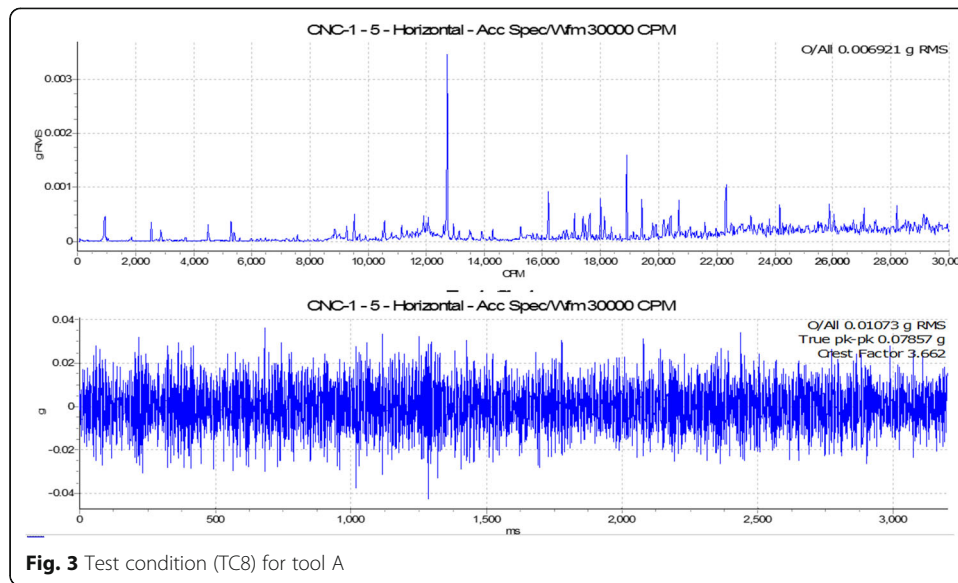


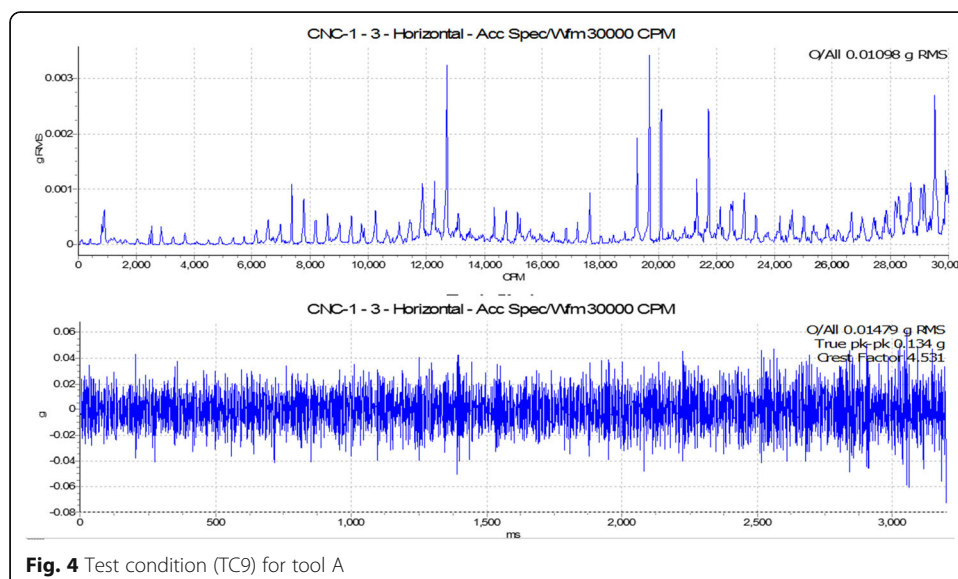
Fig. 2 Test condition (TC1) for tool A

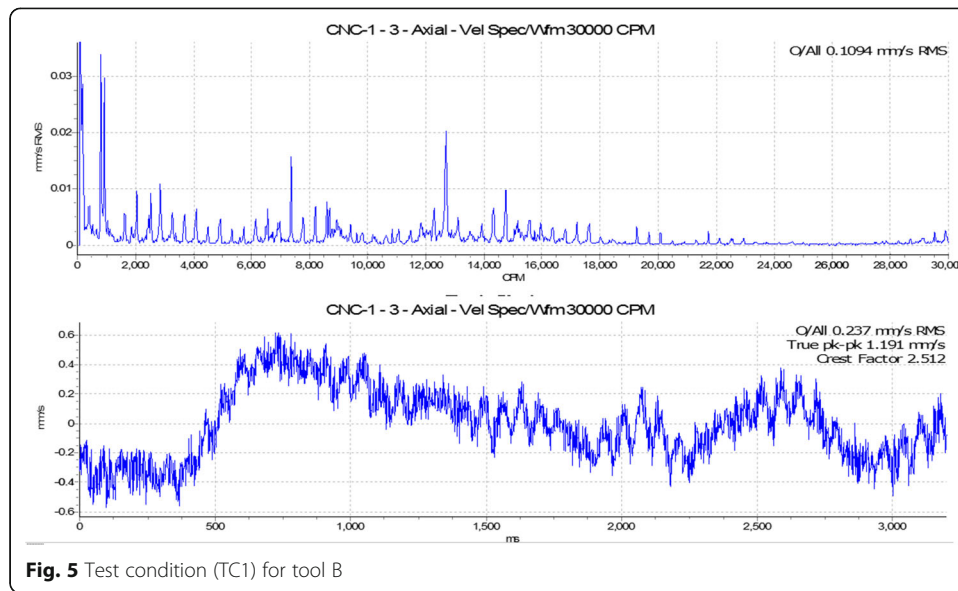


The main focus is on the vibrations which occurred among the tools which are observed to be with change in diameter affecting the machining quality with respect to the tool wear caused. The vibration amplitudes of the drill tools with varied geometries increased with cutting speed at z -axis. The point of this work is to create exploratory information base for the advancement of another, easy to utilize and solid reliable technique for locating and observing wear on the cutting drill tool through vibration signature analysis among varied tool geometries.

Tool rejection adopted for in the current study

Drill tool exclusion requirements have been tested using both ISO 3685 and ISO 10816 in the current report. With ISO 3685 normal deliberations, three tool wear (VB)

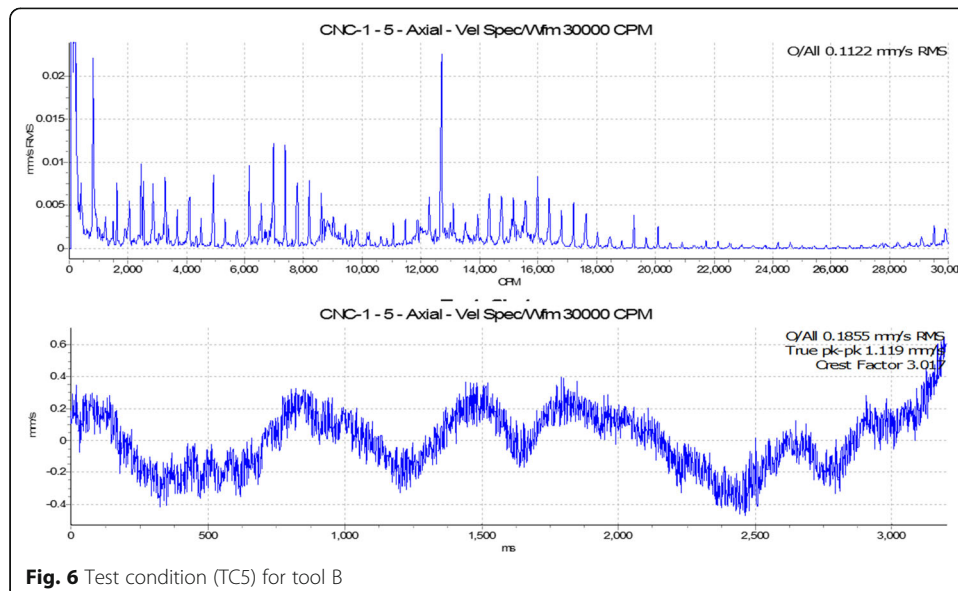




restrictions are well thought out, and VB 0.3 mm is treated as a cutoff value for drilling activity. To determine the state of the tool-based vibration frequency, the displacement parameter value $\leq 60 \mu\text{m}$ and RMS velocity of the spinning object $\leq 4.5 \text{ mm/s}$ along with acceleration are used in compliance with ISO 10816-3 requirements for vibration intensity.

Results and discussion

The results obtained in real-time analysis during machining are studied and analyzed to determine the tool performance based on vibrations and tool wear with respect to the cutting tool conditions. The tool vibrations were measured for horizontal and axial directions as shown in Table 3. The drill tool was analyzed for vibrations with respect to the optimized test conditions (TC1, TC₂..TC₉) with the L9 orthogonal array method.



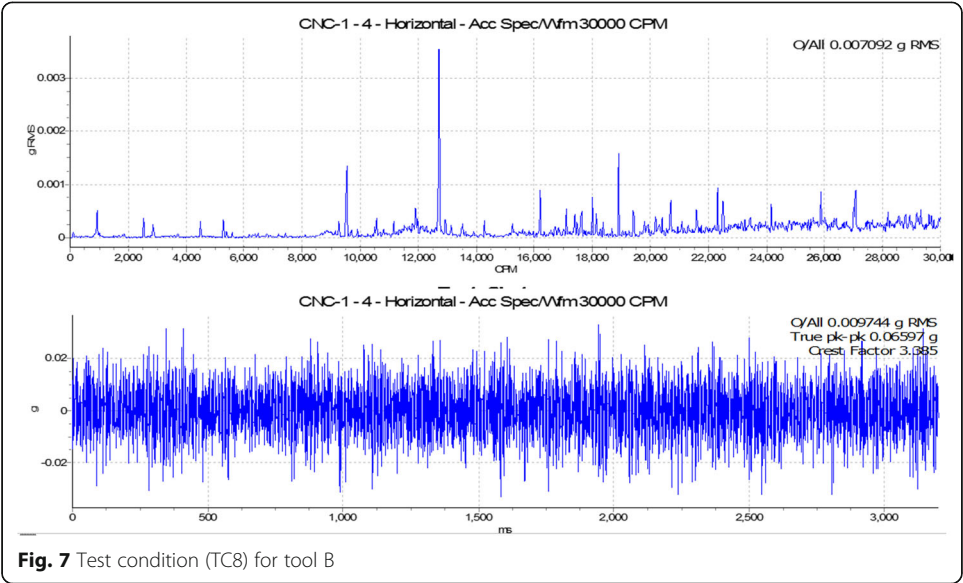


Fig. 7 Test condition (TC8) for tool B

The depth of cut, feed, and speed are varied for both the tools and measuring velocity at horizontal and axial alongside with horizontal and axial accelerations, since for measuring, the vibrations generated accurately the horizontal vibrations, which are considered for better understanding. The vibrations recorded are in Table 3 and Table 4 for tool A and tool B, respectively.

From Table 3, the experiments from TC1 (test condition 1) to TC9 (test condition 1) are conducted with optimized parameters, and the horizontal acceleration is recorded with increased speed which is shown in Table 3. Similarly, the observations are tabulated for tool B which is shown in Table 4.

Table 3 and Table 4 represent the real-time vibrations results obtained during machining with tool A and tool B.

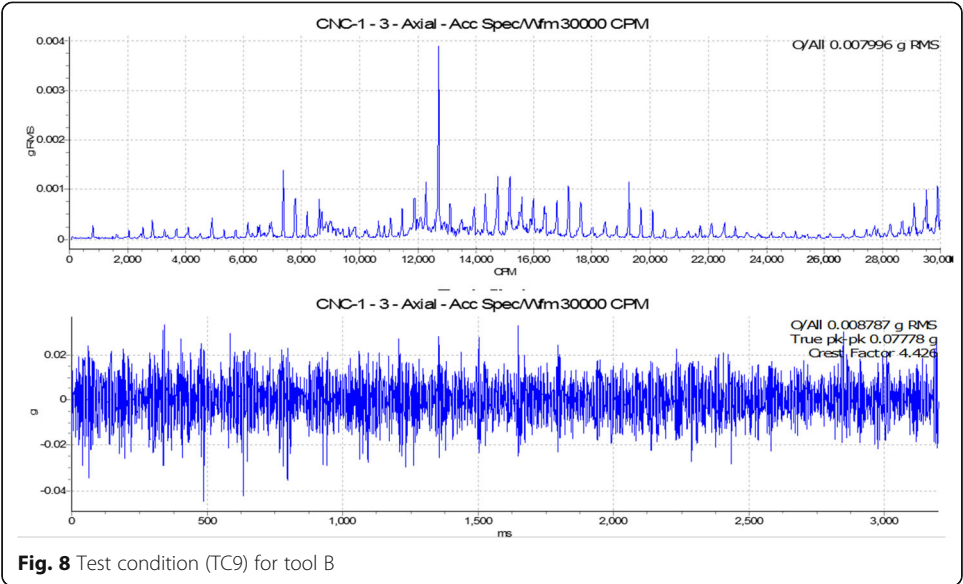


Fig. 8 Test condition (TC9) for tool B

Table 3 Vibrational data of tool A

Test condition	Feed rate, mm/rev (<i>f</i>)	Rotational speed, rpm (<i>N</i>)	Depth of cut, mm (<i>d</i>)	Horizontal velocity <i>V</i>	Axial velocity <i>V</i>	Horizontal acceleration m/s ²	Axial acceleration m/s ²
TC1	0.5	600	8	1.7392	1.6420	0.8228	0.6136
TC2	0.1	600	10	1.9538	1.1190	0.8258	0.6062
TC3	0.2	600	12	1.8427	2.9375	2.1817	1.9839
TC4	0.5	900	10	1.7212	1.6350	1.793	0.7548
TC5	0.1	900	12	1.7301	1.7859	1.4823	1.2356
TC6	0.2	900	8	1.8122	1.6589	2.6585	0.2546
TC7	0.5	1200	12	1.7985	1.5685	2.952	1.7985
TC8	0.1	1200	8	1.7785	1.2356	3.0156	1.5898
TC9	0.2	1200	10	1.8919	1.2485	2.9982	1.5656

Tool vibration analysis

From the results obtained during real-time observations of drilling of work materials with different tool geometries, the vibrations are analyzed for tool A and tool B.

Tool A

The recorded plots of spectrographs are shown in Fig. 2, Fig. 3, and Fig. 4, in which the time-domain to frequency-displacement is observed.

From the plots of tool A as shown in Fig. 2, the amplitude of vibrations is obtained by converting the time-domain to frequency-displacement with the help of FFT (fast Fourier transforms) where the vibrations induced are minimal at TC1 (test condition 1) and Fig. 3, which observed that the amplitudinal frequency of vibrations is 3.0156 Hz at TC8 which is the highest horizontal acceleration generated during drilling of the IS3048 steel. The minimal horizontal acceleration is observed to be 0.8228 Hz which can be told as the initial cutting operations at TC1 performed which is presented in Fig. 4. Similarly, the vibrational amplitude is observed higher at TC9 in tool B, i.e., 1.8562 Hz which is shown in Fig. 8. The minimal vibrations are observed at TC1 as plotted in Fig. 5, and moderate vibrations induced at TC5 and TC6 are as shown in Fig. 6 and Fig. 7. The plots generated for tool B with test conditions of TC1, TC5, TC8, and TC9 are shown in Fig. 5, Fig. 6, Fig. 7, and Fig. 8, respectively.

Table 4 Vibrational data of tool B

Test condition	Feed rate, mm/rev (<i>f</i>)	Rotational speed, rpm (<i>N</i>)	Depth of cut, mm (<i>d</i>)	Horizontal velocity <i>V</i>	Axial velocity <i>V</i>	Horizontal acceleration m/s ²	Axial acceleration m/s ²
TC1	0.5	600	8	1.2426	1.1910	1.0309	0.7630
TC2	0.1	600	10	1.6177	1.5565	1.417	0.4372
TC3	0.2	600	12	1.3862	1.2897	0.6472	1.2106
TC4	0.5	900	10	1.4154	1.2758	1.321	0.2456
TC5	0.1	900	12	1.5626	1.2565	1.6895	1.5689
TC6	0.2	900	8	1.6589	1.2855	1.6258	0.2565
TC7	0.5	1200	12	1.2565	1.4565	1.8452	1.5265
TC8	0.1	1200	8	1.5689	1.6252	1.0548	0.254
TC9	0.2	1200	10	1.7899	1.7895	1.8562	1.2356

Tool B

The recorded plots of spectrographs are shown in Fig. 4, Fig. 5, Fig. 6, Fig. 7, and Fig. 8 in which the time-domain to frequency-displacement is observed.

The plots are obtained and recorded during drilling process with tool A and tool B as shown in Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig. 7, and Fig. 8. High peaks are observed in the frequency-displacement curves where it is considered as the highest vibrations generated. Based on the data, data is plotted as shown in Table 3 and Table 4; so as to clearly understand the vibrations generated, individually, the tools are analyzed for vibrations as shown in Fig. 2, Fig. 3, and Fig. 4 for tool A.

Comparative vibrational analysis in tools

Figure 9 shows the comparative vibrational analysis in tool A and tool B. During machining, enormous amounts of vibrations are generated, since so as to clearly analyze the vibrations, the varied tools are comparatively studied as shown in Fig. 9. Since the diameter of tool A is more when compared to that of tool B, higher amounts of vibrations are generated.

From Fig. 9, it was clearly understood that the test condition of TC8 generated the highest vibrations, i.e., 3.0156 Hz for tool A and TC7, i.e., 1.8452 Hz for tool B. The finding of the change in parameters with respect to the change in tool dimensions affects the tool performance. The lowest vibrations are generated at TC1 having 0.8228 HZ for tool A and 0.6472 Hz for tool B at TC3. The cutting parameters of TC1 for tool A is observed with speed (N) having 600, feed (f) having 0.5 mm, and depth of cut (d) having 8 mm. In the same way, the lowest vibrations were generated at the initial state of machining where the cutting parameters of TC3 (test condition 3) for tool B having speed (N) having 600, feed (f) having 0.2 mm, and depth of cut (d) 12 mm.

Tool wear analysis

In this examination, the connection among vibration and the tool wear and furthermore impact of sensor location in monitoring the tool condition were explored during

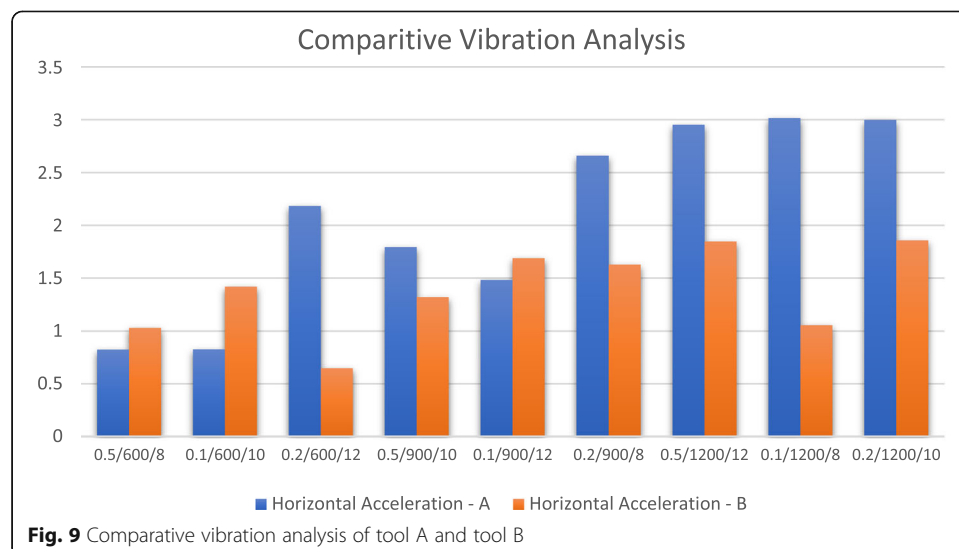


Fig. 9 Comparative vibration analysis of tool A and tool B

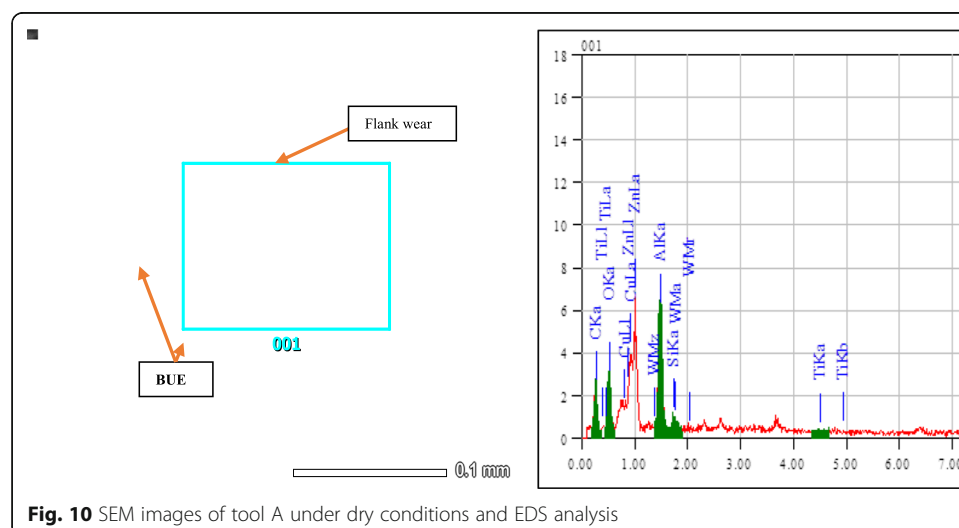
machining process. For this reason, a progression of experiments led in a CNC vertical drill machine. Tools of $\varnothing 7$ mm and $\varnothing 3$ mm solid carbide drills along with an IS3048 steel for machining were used for experiments, notwithstanding, in reasonable reality, the arrangement of the sensor in a consistent situation from a drill zone is not possible, where it is made exactly high amplified to capture the features required for examination. From the experimentation post examinations of the tools, the wear of the flank was observed using SEM at highest peak of frequency displacement plots for tool A and tool B which is as shown in Fig. 10 and Fig. 11.

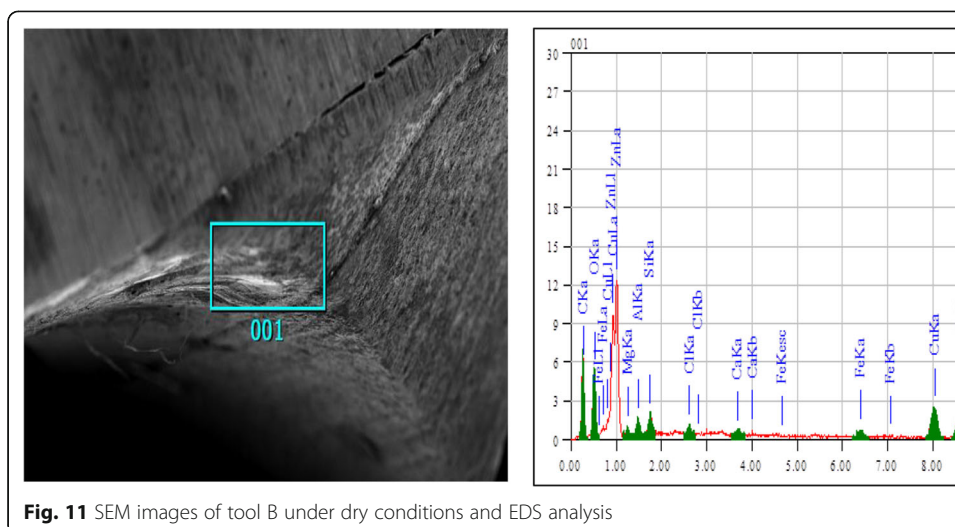
At the cutting zone conditioned with high pressure inducing vibrations, the wear at the material removal zone is increased thereby forming debris of the tool and resulting in the foundation of built-up-edges (BUE) at in tool A. This is observed as shown in the SEM images magnified at various resolutions for the experiments conducted as shown in Fig. 10. The EDS analysis for the wear observed clearly showed the embedding of foreign materials at the BUEs formed. Similarly, when tool B wear is observed as shown in Fig. 11 along with the EDS analysis with less composition when compared to tool A, it resulted in the highest wear recorded when compared to tool B. This results in reducing of tool life with the formation of tool debris in the cutting edge. Thus, tool life is observed extended for machining operations with smaller diameter when compared with larger diameter in tools.

This work provides a varied amplitude from the vibrational signal features obtained for the real monitoring of the tool state, which is the most delicate statistical parameter than other measurable parameters such as exponential, standard deviation, root mean square (RMS), max-min, peak, and mean. The findings revealed that the vibration amplitude of the variation did not increase dramatically until a 0.30-mm flank wear value is achieved, over which the amplitude of vibration increased considerably.

Conclusions

The finding of the change in parameters with respect to the change in tool dimensions affects the tool performance.





- The lowest vibrations are generated at TC1 (test condition 1) having 0.8228 Hz for tool A and 0.6472 Hz for tool B at TC3.
- The cutting parameters of TC1 for tool A is observed with speed (N) having 600, feed (f) having 0.5 mm, and depth of cut (d) having 8 mm.
- The cutting parameters of TC3 for tool B having speed (N) having 600, feed (f) having 0.2 mm, and depth of cut (d) 12 mm where the lowest vibrations were generated at the initial state of machining.
- The tool wear of the tool A is observed higher when compared to tool -B of its lesser diameter.

The intensity of the vibration has been shown to increase with the development of tool wear. This paper explains the direct relationship between tool flank wear and the vibrational amplitude. For both solid carbide drills, the variance amplitude flank wear up to 0.3 mm is 10 times greater than the amplitude of the worn-out tool. Shift in amplitude due to distance between the sensor and the drill hole was observed for specific cutting conditions and wear state. It can be inferred that the models of tool wear established in previous studies are restricted to the constant position of the sensor. In the future, the tool wear model-nullifying technique will be established to compensate for the difference in amplitude due to distance variation from the sensor position.

Abbreviations

TC1, TC2,...TC9: Test condition 1, test condition 2,...test condition 9; TCM: Tool condition monitoring; LDV: Laser Doppler vibrometer; BUE: Built-up-edge

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Authors' contributions

Mr. AVS, presently working as Assoc. Prof in Mechanical Engineering Department at GIET Engineering College Rajahmundry, India. Presently, i am pursuing my part-time Ph.D. at GITAM University, Visakhapatnam, in mechanical engineering under the guidance of Dr. Balla Srinivasa Prasad. I have 14 years of teaching experience and 6 years of industrial experience.**Dr. BSP**, presently working as Associate Professor in Mechanical Engineering, GIT, GITAM, Visakhapatnam, India, since 2003. He graduated in B.E (Mechanical Engg) from Andhra University—Visakhapatnam, Master's degree in Production Engineering from S V University, Tirupati. He was awarded Ph.D. from Andhra University in 2010. Dr. Balla so far published 30 peer-reviewed publications and actively engaged in research in fields of additive manufacturing, tool condition monitoring, and multi-sensor fusion.**Mr. KVNRCM** is a research scholar in GITAM

Deemed to be University, Visakhapatnam, India, under the guidance of Dr. Balla Srinivasa Prasad. He is presently working as an assistant professor in one of the reputed colleges in mechanical department, affiliated to JNTU Kakinada, India. He had done his master's in CAD/CAM from GITAM and graduated from B.Tech. (Mechanical Engg) from JNTU Kakinada. His research interests include additive manufacturing and multi-sensor fusion techniques. All authors have read and approved the manuscript.

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Availability of data and materials

The dataset on which this paper is based is too large to be retained or publicly archived with available resources. Documentation and methods used to support this study are available from Dr. Balla Srinivasa Prasad at GITAM University, Visakhapatnam

Declarations

Competing interests

The authors declare that they have no competing interests.

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