Research Article

Measurements of Tool Wear Parameters Using Machine Vision System

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Monitoring tool wear is very important in machining industry as it may result in loss of dimensional accuracy and quality of finished product. This work includes the development of machine vision system for the direct measurement of flank wear of carbide cutting tool inserts. This system consists of a digital camera to capture the tool wear image, a good light source to illuminate the tool, and a computer for image processing. A new approach of inline automatic calibration of a pixel is proposed in this work. The captured images of carbide inserts are processed, and the segmented tool wear zone has been obtained by image processing. The vision system extracts tool wear parameters such as average tool wear width, tool wear area, and tool wear perimeter. The results of the average tool wear width obtained from the vision system are experimentally validated with those obtained from the digital microscope. An average error of 3% was found for measurements of all 12 carbide inserts. Scanning electron micrographs of the wear zone indicate the severe abrasion marks and damage to the cutting edge for higher machining time. This study indicates that the efficient and reliable vision system can be developed to measure the tool wear parameters.

1. Introduction

Measurement of tool wear is extremely important to predict the useful life of tool inserts. This will be helpful to monitor and to study the effects of the tool wear on quality of machined workpiece and economy of manufacturing process. There are two main methods to measure tool wear: indirect and direct methods. In the indirect method, tool wear is estimated with the signals coming from different types of sensors such as surface texture of machined workpiece, acoustics, vibration, feed forces, and current consumption [1–5]. The tool wear prediction model is prepared based on the magnitude of collected signals. Other method for the measurement of tool wear is the direct measurement over the tool wear zone. There are two main tool wear types: flank wear and crater wear. The flank wear is widely used to quantify the severity of tool wear. Characteristics of qualitative and quantitative morphology of tool wear are of great concern for researchers nowadays. More morphological features other than commonly considered parameter,

i.e., average tool wear width, are required for better evaluation of the actual condition of tool which can affect machining process and quality of machined workpieces [2, 5]. The study shows that there is prominent effect of these new tool wear parameters on producing quality workpieces and also has an economic advantage by making strategies for timely changing tool inserts.

Tool wear generally results in loss in dimensional accuracy of finished products, possible damage to workpiece, and decrease in surface integrity and amplification of chatter. Detailed review for the tool condition monitoring indicates that the machine vision system can be extremely useful for the direct measurement of various types of tool wear [6]. Some statistical approaches are also useful in conjunction with machine vision system to find tool wear [1, 2, 5, 7, 8]. Some researchers developed their own algorithm for the edge detection and segmentation of tool zone [1, 8]. White light interferometry [9–11] and stereo vision technique [12] are used for the measurement of volumetric wear in crater as well as flank wear region. Teti et al.

presented detailed review of the sensor technologies, signal processing, and decision-making strategies for the efficient machining systems [13].

Various methods are suggested for the online and offline condition monitoring of the machining tool. Danesh and Khalili measured tool wear in terms of surface texture of the workpiece during the turning process using undecimated wavelet transform and statistical features of the surface irregularities [5]. Yu et al. used morphological component analysis and edge detection techniques to detect the wear edges under carrying working conditions [7]. D'Addona and Teti used artificial neural network for the automatic and real-time evaluation of the crater wear depth during quasi-orthogonal cutting tests on AISI 1045 steel using tungsten carbide insert [8]. Xiong et al. developed an image processing algorithm using Matlab to measure the tool wear area. The image acquisition system consists of high-resolution CCD camera, fluorescent high-frequency linear lights, and data acquisition module [11]. Schmitt et al. developed an automatic tool wear monitoring system based on the active contour algorithm and neural networks for the flank wear measurement [14]. Fernández-Robles et al. developed an algorithm to measure the defects in cutting edges of milling inserts online without disturbing the machining operation. A three-stage algorithm consists of edge preserving smoothing filter, computation of image gradient, and assessment of damage of cutting edge using geometrical properties [15].

Some assumptions are also made to quantify the volume of wear region approximately. The wear at the tool nose was measured by assuming the part of cutting edge as a disk of radius equal to a tool nose radius [9]. Various geometrical parameters are determined for flank wear region by standardizing the wear region as an ellipse [2]. Researchers suggested various tool wear parameters such as maximum wear land width, wear land area, wear land perimeter [16] and compactness [3], length of major axis, length of minor axis, eccentricity, orientation, equivalent diameter, solidity and extent [2, 4], end wear length [17], and nose radius and flank wear width [18].

Current work is focused on the measurement of flank wear using the machine vision system. A new approach of inline automatic calibration is proposed here. Average tool wear width, tool wear area, and tool wear perimeter are measured using the machine vision system. All these tool wear parameters are correlated with the machining time.

2. Methodology

A schematic diagram of the tool wear measurement system is shown in Figure 1. The digital camera (SONY Cyber-shot DSC-HX400 V) was used for capturing the image of worn out tool inserts. LED was used for illumination purpose of tool insert and calibration square. "Image processing toolbox" of the software MATLAB® was used for the image processing. The worn out carbide tool inserts (SEMT 1304 PETR-M TT8020, TagueTec) were used for conducting the experiments in this work.

The fixture has been developed for proper positioning of tool insert and the calibration square. Figure 2(a) shows the designed fixture for this purpose. The calibration square ($10 \times 10 \, mm^2$ radium paper) was pasted on a vertical plate of fixture. The fixture was covered with a black paper to avoid the reflection of light. This square is also used for defining the origin of the virtual coordinate system developed for the measurement of tool wear volume. The vertical plate has provision to move forward and backward so that the plane of calibration square and tip of tool insert remains same. The position of the camera, light source, fixture, and insert is indicated in Figure 2(b). The image has been captured such that it contains both the calibration square and tool insert as indicated in Figure 3(a). Figure 3(b) shows the processed image of the calibration square. Equations (1) and (2) give the calibration factor of pixel in horizontal and vertical directions. Figure 4 shows a flowchart of an algorithm for image processing to calculate tool wear parameters. The images of calibration square and tool wear zone are cropped and processed separately:

horizontal calibration distance of a pixel,

$$P_x \, (mm) = \frac{\text{side of the square (mm)}}{\text{number of pixels in the } x \text{ direction}}, \quad (1)$$

vertical calibration distance of a pixel,

$$P_y \, (mm) = \frac{\text{side of the square (mm)}}{\text{number of pixels in the } y \text{ direction}}. \quad (2)$$

Figure 5 indicates the results of various stages of the image processing algorithm. Figure 5(a) indicates the grayscale image of the tool wear zone. Figure 5(b) indicates the binary image of the segmented tool wear zone obtained by using Otsu's thresholding method. A threshold value of 0.5216 has been computed by using the inbuilt function of software Matlab. Noises from the image are removed using the median filter. Figure 5(c) indicates the image of the wear zone obtained after applying the median filter. Figures 5(d) and 5(e) are the images of the wear zone obtained after the application of dilation and erosion operations. Finally, the canny edge detection algorithm is used to characterize the boundary of the wear zone. Figure 5(f) is finally used to measure the various tool wear parameters.

The algorithm is used to calculate three tool wear parameters, i.e., average tool wear width, tool wear area, and wear perimeter.

(1) *Average tool wear width*. At different locations in the segmented tool wear zone, the pixels were counted vertically. The average of these readings was multiplied by vertical calibration factor to get average tool wear width.

(2) *Tool wear area*. The number of pixels in segmented tool wear zone was counted. The counted number of pixels was multiplied by the area of single pixel to get the tool wear area.

(3) *Tool wear perimeter*. After skeletonization operation, only one pixel remains at the boundary of the tool
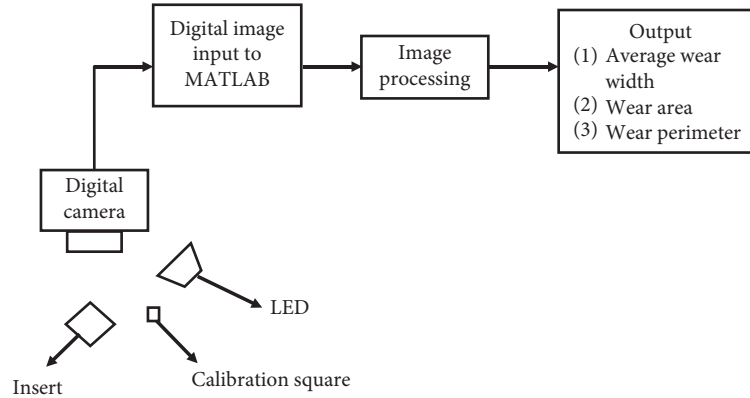
FIGURE 1: Schematic diagram of the tool wear measurement system.

FIGURE 2: (a) Fixture for positioning of the tool insert and calibration square; (b) set up for the vision system.
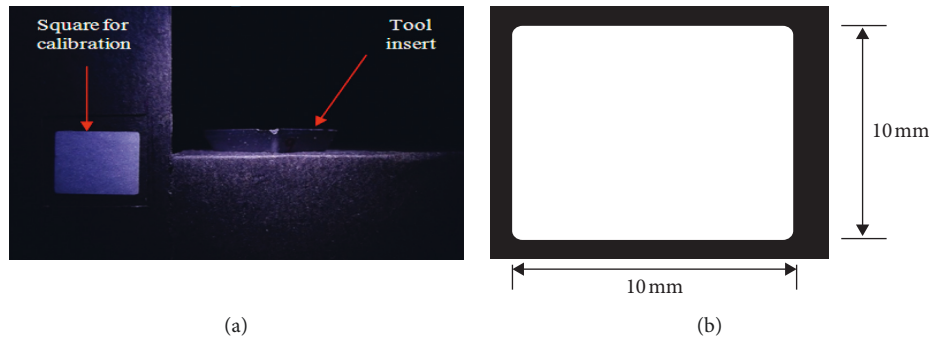

FIGURE 3: (a) Captured image of the worn out insert; (b) processed image of the calibration square.

wear zone. These pixels were counted and multiplied by the horizontal calibrating factor to get the tool wear perimeter.

3. Results

In this section, the final results of measurements of three tool wear parameters measured by the vision system have been presented. For the measurement of the wear of tool insert, the turning experiments are conducted on low alloy steel which is widely used for the production of bearing cover of an IC (internal combustion) engine. Turning operations are conducted on a CNC turning machine (Seimens control; DX200, Jyothi Company) using carbide inserts (TNMG-16-04-04-QM J13 A) for the machining of internal diameter.

The details of the machining parameters are indicated in Table 1.

For every turning operation, fresh carbide insert was used in which the machining and machining parameters were kept same. Machining time required for every specimen was around 5 minutes. Table 2 indicates the details of machining times for all the inserts. After the machining operation, the tool wear parameters of all the inserts were measured by the vision system. In order to validate the accuracy of the developed system, the average tool wear width for all inserts was also measured using a digital microscope (ViTiny UM05).

Table 3 indicates the images of the wear zones of all the carbide inserts. These images are obtained after the processing of actual images of tool wear by the machine vision
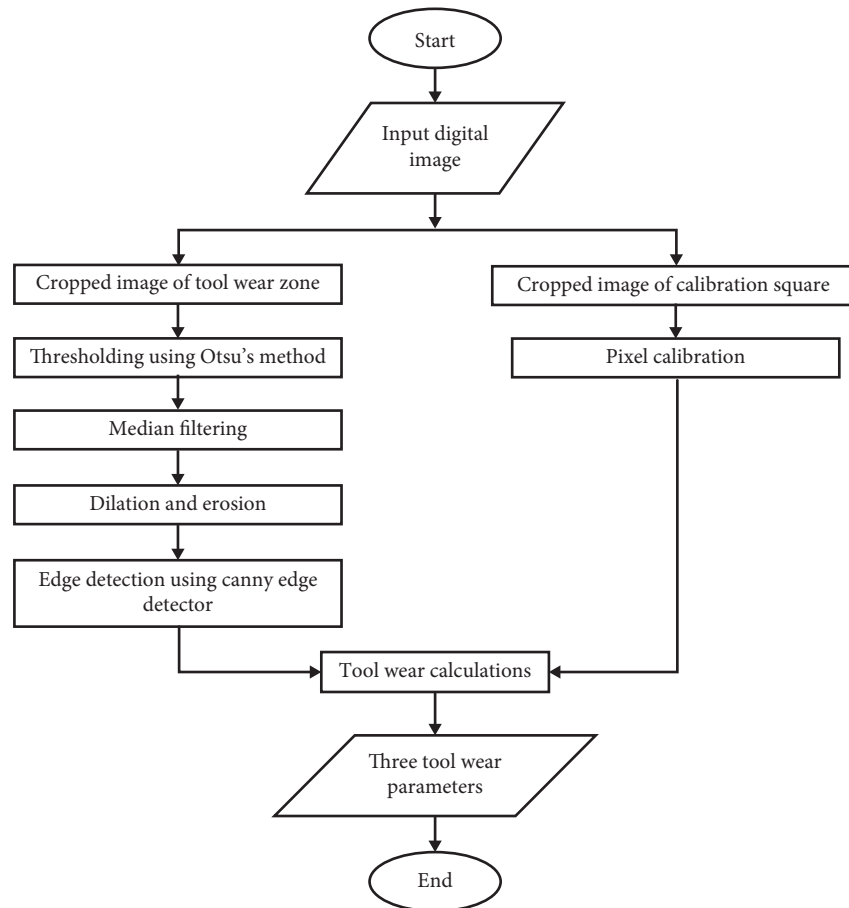
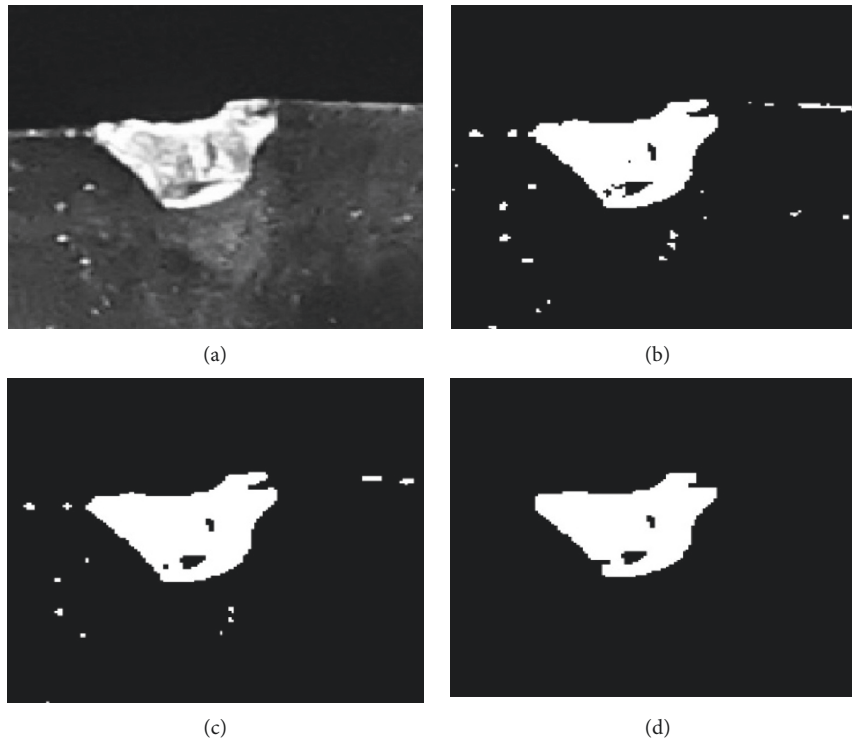FIGURE 4: Flowchart of the algorithm for image processing.

(a)

(b)

(c)

(d)

FIGURE 5: Continued.

(e)

(f)

FIGURE 5: Results of various stages of the image processing algorithm indicating (a) actual grayscale image and images (b–f) obtained after thresholding, filtering, dilation, erosion, and edge detection, respectively.

TABLE 1: Details of the machining parameters.

Workpiece outer diameter	240 mm
Workpiece inside diameter	97 mm
Spindle speed	300 rpm
Feed rate	0.3 mm/revolution
Depth of cut	2 mm
Machining duration	5 minutes

system. These images are used to automatically determine the wear width of the carbide inserts. Wear width is measured at five locations, and the average value of the wear width is determined and compared with the readings of the digital microscope. The magnitudes of average wear width obtained by the vision system and the digital microscope are fairly close for all the inserts. An average error of approximately 3% between both the readings indicates that the machine vision system can correctly estimate the magnitude of tool wear. Figure 6 indicates the comparison of the average wear width obtained by both the techniques. Tool wear width is seen increasing with the machining time in almost linear fashion. When the insert is used for the machining of multiple workpieces, it undergoes the abrasion marks due to friction between the workpiece surface and the cutting edge. And it increases with the number of machined workpieces or machining time. Figure 7 indicates the scanning electron micrographs of the wear zone of carbide inserts.

Figures 7(a) and 7(b) indicate the scanning electron micrographs (SEMs) of the wear zone of carbide inserts 2 and 12, respectively. Machining time of inserts 2 and 12 are 10 and 60 minutes, respectively. Images indicate the abrasion marks on the cutting edges during the machining of workpieces. The image of insert 2 indicates the mild wear of the cutting edge. On the contrary, the image of insert 12 indicates the thick abrasion marks and severe wear of the cutting edge. The machine vision system estimates the average wear width of inserts 2 and 12 as 0.103 and 0.515 mm, respectively.

The magnitudes of other tool wear parameters determined by the vision system for all twelve inserts are indicated in Table 4. Similarly, Figures 8(a)–8(c) indicate the variation of wear width, wear area, and wear perimeter,

respectively, with the machining time. It indicates almost linear increase of wear parameters with the machining time. Interestingly the cutting speed, feed rate, and depth of cut were kept constant during the turning process.

The study indicates the application of the machine vision system for the measurement of flank wear in terms of average wear width, wear area, and wear perimeter. The machine vision system can be preferred over the conventional approach of measurement of only one parameter such as average wear width. The machine vision system can give exhaustive picture of the wear zone and thus can indicate the severity of tool wear more efficiently. Scanning electron micrographs indicate severe abrasion marks and damage to the cutting edge in the case of higher machining time. Previous researchers also indicate the more exhaustive approach for the measurement of tool wear and its effect on the machining accuracy. Three geometric descriptors, i.e., eccentricity, extent, and solidity, were found to contribute significantly to characterize the tool wear severity [2]. A new feature of flank wear, i.e., end wear length, was proposed in addition to flank wear area, average wear width, and maximum wear width for microdrill to predict the tool life [12]. This indicates that the use of only one parameter is inadequate to decide the extent of tool wear qualitatively and quantitatively. Hence, this vision system is designed to measure tool wear parameters such as tool wear area and tool wear perimeter in addition to the commonly used tool wear parameter, i.e., average tool wear width.

4. Conclusion

The inline automatic calibration system was successfully implemented for the measurement of tool wear parameters. With this calibration system, there is no need for separate calibration of the vision system. The measurements of an average tool wear width with the present vision system are found to be in close agreement with that with the digital microscope. The average absolute error in measuring average tool wear width for all the twelve inserts was found to be 3.08%. Average wear width, wear area, and wear perimeter were seen increasing with the machining time. The scanning electron micrographs indicate severe abrasion

TABLE 2: Machining time of all carbide inserts.

Insert number	1	2	3	4	5	6	7	8	9	10	11	12
Number of workpieces machined	1	2	3	4	5	6	7	8	9	10	11	12
Machining time (min)	5	10	15	20	25	30	35	40	45	50	55	60

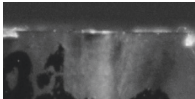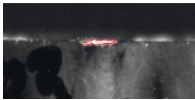TABLE 3: Comparison between the average wear width measured by the vision system and the digital microscope.
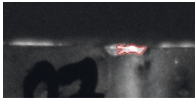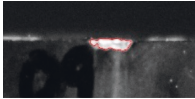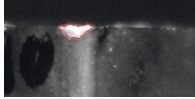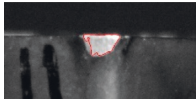
Insert number	Wear zone image	Wear zone captured by vision system	Average wear width of inserts (mm)		Error (%)
			Machine vision system	Digital microscope	
1		Negligible tool wear	—	—	
2			0.108	0.103	4.6
3			0.155	0.149	3.9
4			0.169	0.162	4.1
5			0.183	0.178	2.7
6			0.206	0.199	3.4
7			0.208	0.201	3.4
8			0.278	0.274	1.4
9			0.286	0.273	4.5
10			0.35	0.339	3.1

TABLE 3: Continued.

Insert number	Wear zone image	Wear zone captured by vision system	Average wear width of inserts (mm)		Error (%)
			Machine vision system	Digital microscope	
11			0.46	0.438	4.8
12			0.521	0.515	1.2

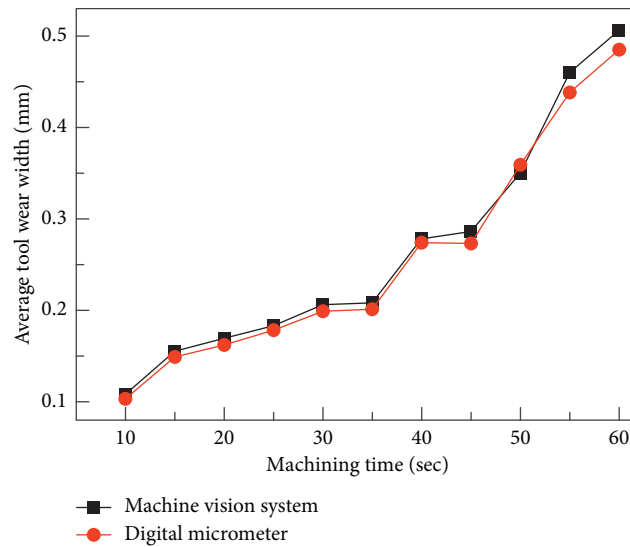FIGURE 6: Graph comparing the digital microscope and the vision system measurements of average tool wear width.
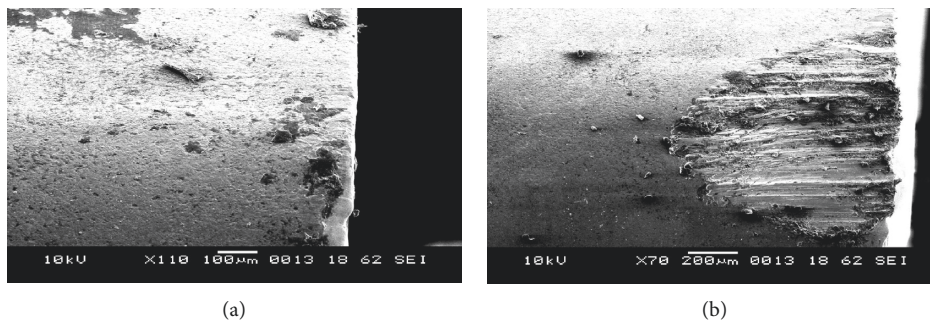

(a)

(b)

FIGURE 7: Scanning electron micrographs of the wear zone of carbide inserts (a) 2 and (b) 12.

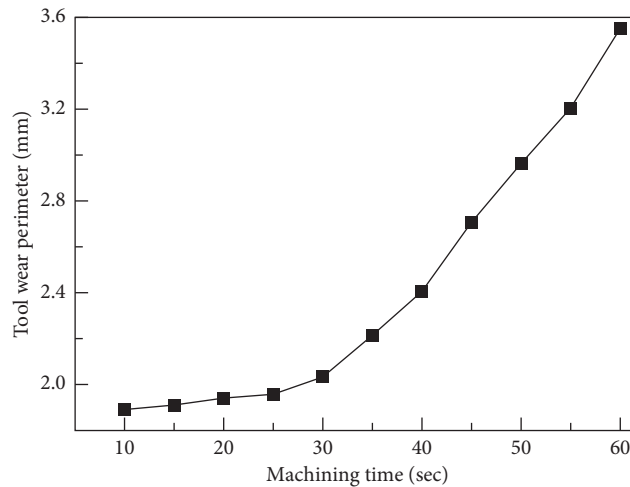TABLE 4: Measured parameters of the tool wear with the vision system.

Insert number	Average tool wear width (mm)	Tool wear area (mm^2)	Tool wear perimeter (mm)
1	5	—	—
2	10	0.169	0.160
3	15	0.108	0.126
4	20	0.155	0.170
5	25	0.183	0.178
6	30	0.206	0.198
7	35	0.208	0.194
8	40	0.278	0.322
9	45	0.286	0.327
10	50	0.290	0.331
11	55	0.460	0.589
12	60	0.506	0.644
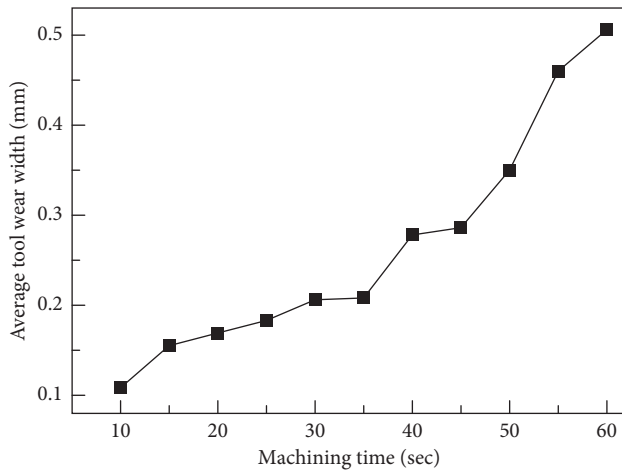
(a)
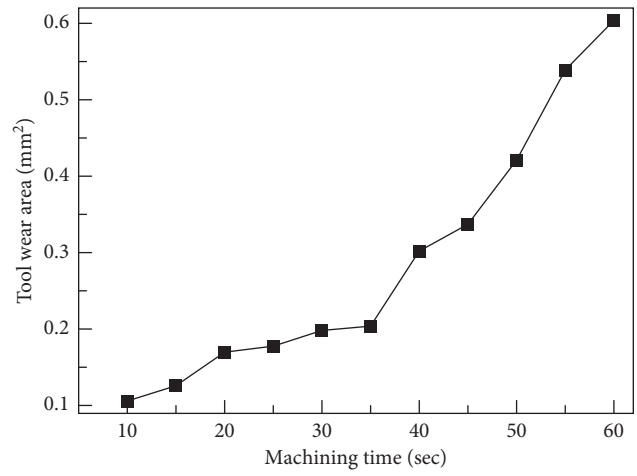
(b)

(c)

FIGURE 8: Variation of (a) average wear width; (b) wear area; (c) wear perimeter of the carbide insert with the machining time.

marks and damage to the cutting edge in the case of higher machining time.

This study shows that the machine vision system can be effectively used to measure all tool wear parameters and thus presents the correct and exhaustive picture of the tool wear.

This methodology will be extremely useful for manufacturing industry to monitor tool wear effectively rather than relying only one parameter. This will be extremely useful to study the effects of tool wear on quality of machined surface and economy of machining process.

Data Availability

Required data are already provided in the manuscript.

Disclosure

The work is carried out in V. N. I. T, Nagpur, as a part of dissertation work carried out by for the postgraduate students in Mechanical Engineering department under the guidance of Dr. A. A. Thakre.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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