Study on the Effect of Nose Wear and Groove Wear on Surface Roughness on Turned Parts Using a Machine Vision

H.H. Shahabi and M.M. Ratnam

School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia
Department of Industrial Engineering, Amirkabir University of Technology, Tehran, Iran

Abstract: The surface roughness of turned parts and the nose wear of cutting tools used in the lathe operation were measured using a machine vision method. The measurement was carried out in-cycle on a conventional lathe machine. Although the literature on monitoring of flank and crater wear using machine vision is well documented, monitoring of nose wear and groove wear using this technique is relatively unexplored. The system developed was used to assess the effect of nose and groove wear on the surface roughness of the workpiece. The study showed that increasing flank wear causes a smearing effect on the workpiece surface and thus decreases the surface roughness. However, growing groove wear increases the roughness value after a certain machining time.

Key words: Machine vision • Nose wear • Groove wear • Surface roughness

INTRODUCTION

Tool wear monitoring has been studied extensively in the past [1-4] due to the complex effects of different parameters of the machining process on the cutting tool and the effect of wear on the surface quality of the machined part. Tool wear is a random phenomenon, complicated by the combination of abrasive, adhesive and diffusive types of wear and the condition of the machine tool. Several types of wear pattern can occur on the cutting tool, such as flank wear, crater wear, nose wear and groove wear. An exhaustive classification of tool wear morphologies was given by Lanzetta [5]. Among these, flank wear and crater wear have been most frequently studied in the past [6-9]. Flank wear is created on the flank face of the cutting tool due to the rubbing action of the tool with the workpiece, while crater wear occurs on the rake face.

Nose wear is a type of wear that occurs on the nose area of the cutting tool and is caused by the loss of material from the tool. Groove wear is a small notch that appears at the nose area of the cutting tool, which can change the shape of nose area. Nose wear can be determined from a 2-D profile of the tool tip [10]. Unlike flank and crater wear, nose wear has received less attention in the past from the research community. This could be partly because flank wear and crater wear has been identified in the ISO 3685 [11] standard with definitive wear criteria that can be used to decide when a tool must be changed. Another reason for the wide use of $V_B$ in studying tool wear is due to the ease of measuring this parameter using a standard toolmaker’s microscope. However, in some machining operations the surface finish of the workpiece was found to be almost unaffected by the increase in flank wear [12]. This finding suggests that flank wear may not be a reliable parameter to determine the tool condition. Kwon and Fisheer [13] proposed a new tool wear indicator (TWI) that incorporates both flank wear and nose wear. Unlike $V_B$, TWI was able to predict the surface roughness extremely well. The loss of material in the nose area was also shown to have significant effect on the surface roughness, depending on the feed. The effect of notch wear on average surface roughness $R_\mathrm{q}$ was investigated by Pavel et al. [14]. They attributed the increase in $R_\mathrm{q}$ in continuous cutting to the rapid increase in notch wear to a steep groove, though the actual notch wear area was not measured. In interrupted cutting, flattening of the nose area decreased the roughness value.

The study carried out by Kwon and Fischer [13] and Pavel et al. [14] verifies the importance of wear that occurs in the nose area of the cutting tool. Since the
machined surface is mainly formed by the tool nose in finishing turning, the geometry of the nose area will have great effect on the surface quality of the workpiece. Also, the profile of the machined surface is the negative of the cutting edge profile, thus the loss of nose material is only an approximate parameter that influences the surface roughness. Thus, the shape of nose area of cutting tool, which affected by the nose wear and groove wear, can change the surface roughness of workpiece.

In this work, a machine vision system that is able to measure both tool wear and workpiece surface roughness intermittently during the machining operation, i.e. in-cycle, has been developed to demonstrate the effect of nose wear and groove wear on surface roughness of workpiece.

System Configuration: Figure 1 shows a photograph of the system employed to measure tool nose wear and surface roughness of workpiece. The system consists of a high-resolution (1296x1024 pixels) CCD camera (model: JAI CV-41), 25 mm lens, a 110 mm lens extension tube, Data Translation (DT3162) frame grabber and a personal computer. A diffused back light was used to highlight the contour of the specimen. The scaling factors for the output images were determined using standard pin gauges of dimension 0.22 mm (Mitutoyo). The horizontal and vertical scaling factors are 1 μm and 1.06 μm respectively.

In order to study the effect of nose and groove wear on the surface roughness of the turned parts the worn cutting tool was rotated between +1 to -4 degree from its original location. Rotation of the tool changes the contact geometry between the tool and the workpiece. The rotation angle was verified using a laser system comprising a low-power laser, a reflector and a scale. The parameters used for shaping the wear area of cutting tool and surface roughness of specimen are given in results and discussion.

MATERIALS AND METHODS

Wear Measurement Algorithm: The wear area of cutting tool was measured using the algorithm that is briefly described in this section. A complete description of the algorithm was published in Ref. [10]. In the first stage, the CCD camera was interfaced to the computer using the frame grabber to capture an image of the specimen. The image was improved using Wiener filtering method in the second stage. In the third stage, the opening and closing morphological operations were used to smooth the image using a 3x3 structuring element. This method can remove pixels due to microdust particles from the specimen. In the forth stage, thresholding method was used to segment the image into two regions: Cutting tool tip and its background.

In Stage 5 of the algorithm, a conforming method was used to decrease the misalignment of cutting tool. Machine parts clearance can cause a slight rotational and translational misalignment when the cutting tool moves to machine the specimen. The misalignment decreases the accuracy of the system because the vision method in this study is based on subtraction of worn cutting tool image from the unworn image. The effect of the clearance was assessed by subtracting two images of one cutting tool captured before and after movement of the tool. The subtraction result is shown in Figure 2 (a) where the effect of the tool misalignment is clearly visible. The conforming method was used to decrease the misalignment [10]. Figure 2 (b) shows the result of subtracting two images after conforming where the error due to misalignment has been reduced significantly. Since the images captured using back lighting show the cutting tool contours and their background, the material lost in the nose area during machining can be determined simply by subtraction of the unworn and worn tool. Figures 3(a)-(c) show the nose wear area of cutting tool obtained by the subtraction method.

Workpiece Roughness Measurement Algorithm: The first and second stages of surface roughness measurement algorithm are the same as first and second stages of tool wear measurement algorithm and the third stage is the same as the forth stage of wear measurement algorithm. The surface profile was obtained using the parameters given in Subsection 4.2.2. The images
Fig. 2: Result of subtraction of two images: (a) Before applying the conforming method (b) after applying the conforming method

Fig. 3: (a) Unworn cutting tool tip, (b) worn cutting tool tip and (c) wear area obtained by subtraction

Fig. 4: Workpiece surface profile after (a) 50 minutes (b) 100 minutes of machining

Fig. 5: Surface roughness profiles for: (a) Feed rate 0.2 mm/rev and (b) feed rate 0.4 mm/rev captured using backlight show the surface contour and the roughness value can be determined using the algorithm developed in this study. Figure 4(a)-(b) show sample images of workpiece surface after 50 minutes and 100 minutes of machining. In Stage 4, the contour of surface roughness was detected. Each captured image was saved as a matrix consisting of X rows and Y columns. Since the binary images obtained from Stage 3 consist of background (white pixels with a value of 1) and contour of surface profile (black pixels with a value 0),
the algorithm searches the first row to locate the first black (0) pixel. The algorithm then searches the second row to detect the second black pixel. This procedure continues until all the first black pixels in each of the row is detected. The black pixels show the contour of surface profile of the workpiece (Figure 5(a)-(b)). In the fifth stage, the least-squares method was used to determine the best-fit line of the contour that represents the mean height of the profile. The roughness value was determined by subtracting each point on the profile from the mean. In Stage 6, the average roughness value $R_a$ was calculated after applying the scaling factors. The cut-off distance for roughness measurement is 0.8 mm [15].

RESULTS AND DISCUSSION

Tool Wear Measurement
System Error Evaluation: The clearance between machine parts can affect the results of wear area measurement due to movement of the cutting tool between image captured. The algorithm developed in Ref. [10] was used to decrease the error due to clearance between the machine parts. The maximum and minimum remaining errors were $0.99 \times 10^{-7}$ mm$^2$ and $1.78 \times 10^{-7}$ mm$^2$ respectively. The error is possibly due to the resolution limitation of CCD camera and vibration in the system. The effect of ambient lighting on system error was studied under different light intensity levels using algorithm in Ref. [10]. The effect of environmental vibration on system error was also studied under the same lighting condition using algorithm in Ref. [10]. The system error under different environmental light intensity was $1.54 \times 10^{-3}$ mm$^2$ and the error due to vibration was $2.84 \times 10^{-3}$ mm$^2$. The results show that the system error due to variation in ambient light intensity and vibration is negligible.

Determination of Nose Wear Area of Cutting Tool: To study the cutting tool wear area, an alloyed steel rod (AISI 304) was machined using an uncoated cutting tool insert. Other machining conditions are shown in the next subsection. Although the use of CNC machine is common to study tool wear, in our work a conventional lathe machine was used so that the applicability of the system can be assessed in a regular workshop environment. The image of cutting tool was captured in-cycle by moving the cutting tool away from the workpiece. Figure 6 shows that the nose wear area increased continuously with machining time as expected. This trend shows that material is being lost continuously from the nose area during machining, thus changing the nose-workpiece contact geometry.

<table>
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<th>Table 1: Machining parameters</th>
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<tr>
<td>Machine tool</td>
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Surface Roughness Measurement
System error evaluation: To study the surface roughness, the workpiece was machined using an uncoated cutting tool insert. Four feed rates (0.2, 0.25, 0.3 and 0.4 mm/rev) and three cutting speeds (25.5, 37.7, 56.5 m/min) were used to shape twelve surface profiles using other machining conditions shown in Table 1. Ten images of one area of workpiece were grabbed using the CCD camera. The mean values of average roughness $R_a$ for ten different images were determined. This method was repeated to measure the roughness value of all twelve specimens. The roughness values obtained from the machine vision method were verified using a mechanical roughness tester (SJ-201P, Mitutoyo). The mean deviation of $R_a$ between mechanical method and vision method was 3.2%. The effect of ambient intensity and vibration on surface roughness measurement was also investigated. The deviation of $R_a$ between mechanical method and vision method in the presence of different ambient lighting was found to be 2.1% and the deviation of $R_a$ due to ambient vibration was 1.99%.

Nose Wear and its Effect on Surface Roughness: An uncoated cutting tool insert was used to machine an alloyed steel rod (AISI 304). The machining time was between 3 min and 175 min. The cutting speed and feed rate were fixed at 56 m/min and 0.1 mm/rev respectively for each machining cycle. The cutting tool was then used to prepare the specimen for surface roughness measurement using alloyed steel rods to study the effect of tool wear on surface roughness. The rod was machined using four different feed rates: 0.2, 0.25, 0.3 and 0.4 mm/rev and cutting speed 56 m/min. Other parameters of machining condition are shown in Table 1. Figures 5 a, b show the roughness profiles machined using feed rates 0.2 and 0.4 mm/rev respectively. These figures indicate that increase in feed rate increases the surface roughness value. Ten images of each workpiece were captured at different locations on the surface in order to determine the average value of $R_a$ for various feed rates and machining time. The results are shown in Fig. 7 where the surface roughness initially decreased, but when the
Fig. 6: Nose wear area of cutting tools for various machining time

Fig. 7: Effect of feed rate and time of machining on $R_a$.

Fig. 8: Effect of cutting tool rotation and feed rate on roughness value
machining time is increased beyond a certain value the roughness increased. This trend was similar for all feed rates tested. A close study of the workpiece surface images showed that flank wear increases gradually and flattens the nose area of the cutting tool. The flattened tool causes a smearing effect on the workpiece surface and decreased its roughness value, similar to that observed by Pavel et al. [14]. Beyond a certain time, the groove wear increased and this in turn increased the average distance between the peak and valley of the machined surface profile, thus increasing the roughness value. The results of this study agree with the results of Pavel et al. [14], where the increase in $R_a$ in continuous machining was attributed to increase in grooves occurred on the tool nose area.

**Effect of Groove Wear on Surface Roughness:** To study the effect of groove wear on the surface roughness, the cutting tool used (175 min) in lst Subsection was rotated between -1 and 4 degrees from its original position and the machining was repeated. Ten images of one region of the workpiece were captured and the mean value of $R_a$ was calculated. This was repeated for four different feeds. Figure 8 shows the results of surface roughness for different feed rates when the cutting tool was rotated. For feed rates 0.2, 0.25 and 0.3 mm/rev the roughness value increased when the cutting tool was rotated counter-clockwise (-1 degree). In contrary, the surface roughness decreased when the cutting tool was rotated clockwise (between +1 to +4 degree). In the original position, the groove, which occurred on the nose area of cutting tool, causes a high roughness value. However, rotation of the tool between +1 to +4 degree causes the effect of nose wear to flatten the profile and decrease the roughness. This is because at these rotation angles, the groove is not directly in contact with the specimen. Although this result clearly shows that the roughness value of the machined surface can be controlled by rotating the cutting tool, the cutting tool cannot be rotated because it can change the cutting process geometry. Figure 8 also shows that the effect of cutting tool rotation on roughness value at a higher feed (0.4 mm/rev) is not the same as at lower feeds. This is due to the relatively small groove wear area compared to the roughness profile.

**CONCLUSION**

A machine vision method was developed to measure both cutting tool nose wear area and surface roughness of turned parts using the same setup. The results of the study showed that increasing the machining time of the tool decreased the surface roughness in the first stage of machining due to increased nose wear. However, in the second stage of machining, the roughness value increased due to increased groove wear. A close correlation was found to exist between the shape of wear area of cutting tool nose and the roughness profile.

The effect of nose and groove wear on the surface roughness of workpiece was demonstrated by rotating the cutting tool. Counter-clockwise rotation of the cutting tool increased the effect of groove wear on the surface roughness, while clockwise rotation decreased the effect. Images of workpiece showed that machining using the area of cutting tool where groove wear is predominant increased the surface roughness, whereas machining using the area where flank wear is predominant decreased the roughness due to a smearing effect.

The system and algorithm developed in this study is applicable for the in-cycle monitoring of tool wear and surface roughness of the workpiece. Compared to conventional off-line measuring methods, this method is fast because capturing the images and determining surface roughness and wear area can be done in-cycle within the workshop environment.

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