Study on Effect of Tool Nose Radius Wear on Hybrid Roughness Parameters during Turning Using Vision-Based Approach

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Abstract. In the past, most researchers have investigated the effect of tool flank wear on the average roughness parameter ($R_a$) during turning. The $R_a$ parameter, however, is sensitive only to the height variations of the machined workpiece profile and is insensitive to the spatial changes to the profile caused by gradual increase in tool wear. In this work, a non-contact vision-based method was used to investigate the effect of tool nose radius wear on the hybrid surface roughness parameters during finish turning. The roughness profile of the workpiece surface diametrically opposite the cutting tool was captured during turning of AISI 1035 steel using a digital camera. A high shutter speed (1/4000 s) was used to freeze the motion of the rotating spindle and obtain a blur-free image of the workpiece. The edge of the workpiece profile was extracted to sub-pixel accuracy using the grey level invariant moment method. The hybrid surface roughness parameters were determined from the workpiece profile. The effect on increased nose wear area on these parameters were investigated. Among these roughness parameters the mean wavelength ($R_\lambda$) parameter showed the best correlation with tool nose radius wear with coefficients of determination of 0.9734.

1.0 Introduction

Finish turning is used to produce precision parts whose quality is assessed mainly in terms of the surface roughness. The surface roughness of a finished product is affected by numerous machining factors among which the most critical is the wear of the cutting tool. Three types of wear are dominant during turning, namely flank wear, crater wear and nose wear. Notch wear, which occurs occasionally during the turning of hard materials, is a type of groove wear that appears at the flank where the edge of the cutting tool meets the workpiece. The flank of a cutting tool is divided into the major and minor flanks. The major flank area is involved in bulk material removal while the minor flank plays a greater role in shaping the surface profile of the workpiece. This is due to the direct contact of the minor flank with the freshly cut surface.

In finish turning, where the depth-of-cut is less than the tool nose radius, it is the nose wear that predominantly affects the surface roughness of the finished workpiece. Naiki and Mears [1] reported that tool flank wear does not necessarily have a significant effect on the surface roughness of the workpiece. Cantero et al. [2] found that although the flank wear increased significantly during the turning of Inconel 718 the surface roughness $R_a$ of the workpiece only showed a small variation. Kwon et al. [3] concluded that for small depths of cut, such as in finish turning, the flank wear provides little information on the tool wear condition because most of the wear occurs in the nose area of the tool. These findings suggest that the flank wear may not be the right wear parameter to measure when...
assessing the surface finish quality of the workpiece. Moreover, $R_a$ may not be the right roughness parameter to correlate with tool wear since the amplitude variation in the workpiece surface profile may be too small to be detected. This is evident also from the work of Shahabi and Ratnam [4] where the authors found that at low feed rates (0.2 to 0.3 mm/rev) the value of $R_a$ did not exhibit a significant variation.

Extensive research has been carried out in the past to monitor flank wear from the measured sensor signals but not much attention has been given to the tool nose wear [5-11]. In all these papers, the authors measured the roughness by using a stylus roughness tester, a 3-D optical profiler or a vision system and correlated the roughness parameters with tool flank wear. Coker and Shin [12] used an ultrasonic sensor to detect changes in surface roughness caused by tool wear. A good correlation between the mean sensor signal and average roughness ($R_a$) measured by a stylus roughness tester was obtained. However, the authors found that there was no straightforward linear correlation between the average roughness $R_a$ and tool wear. Several in-process roughness measurement methods have also been developed in the past. These include light scattering methods [13], ultrasonic sensing [14] and image processing method [15]. However, none of these methods has been applied to monitor the tool nose radius wear from the measured signal.

In a recent work [16] we developed an in-process surface roughness measurement method using machine vision. A digital single-lens-reflex (DSLR) camera was used to capture the image of the workpiece profile diametrically opposite the cutting tool during dry turning. The edge of the workpiece was located using sub-pixel edge location method. From the workpiece surface profile numerous amplitude, spacing, hybrid as well as functional roughness parameters as defined in the ISO 3685 (1993) standard were determined. In addition to the existing parameters three new parameters that are unique to the turning process were introduced. However, the correlation between the tool nose wear and the various roughness parameters was not investigated.

In this work, the previously developed in-process roughness measurement method was applied to investigate the effect of tool nose radius wear on the hybrid roughness parameters during finish turning. The tool nose radius wear occurs in the curved part of the tool and is related to the minor flank wear $V_c$ defined in the ISO 3685 (1993) standard. The nose wear can be determined by digitally subtracting the top (2D) views of the unworn and worn cutting tool and related to $V_c$ by the tool geometry and the cutting angle. In this work, the hybrid roughness parameters were extracted while the cutting was still in progress.

2.0 Methodology

2.1 Hardware setup

The experimental setup is shown schematically in Figure 1 and the actual setup is shown in Figure 2. The lathe used is a conventional lathe machine (Pinacho S90/200, Spain). A compressed air hose was provided to blow away chips and cutting fluid during the wet turning. A 10.2 megapixel DSLR camera (Sony α-230) mounted diametrically opposite the cutting tool was used to capture the profile of the workpiece during turning. The camera was triggered using a remote controller and the image was transferred to the personal computer via the universal serial bus (USB) cable. A CCD camera (JAI CV-AJ, Japan) with sensor resolution 1296×1024 pixels was used to capture the images of the cutting tool after each pass. The tool images were used to determine the tool nose wear area to be correlated with the roughness parameters.

Figure 3 shows a sample image captured using the setup during the wet turning and the zoomed-in view of the region-of-interest (ROI) for roughness measurement. The spindle speed used is 420 rpm. Distortions in the images were checked using a multi-frequency distortion target grid as detailed out in Ref. [16]. The scaling factors used for converting image coordinates in pixels to real-world coordinates in millimetres were obtained using a 1.35 mm diameter Mitutoyo pin gage. The horizontal and vertical scaling factors for the DSLR camera are 8.44 µm/pixel and 8.43 µm/pixel, respectively, while the corresponding scaling factors for the CCD camera are 1.87 µm/pixel and 2.12 µm/pixel, respectively.
Figure 1. Schematic illustration of in-process tool condition monitoring system.

Figure 2. Actual setup of in-process tool wear monitoring system.
2.2. Machining condition
Wet turning experiments were carried out on cylindrical bars of AISI 1035 steel of diameter 50 mm and length 250 mm using coated triangular carbide inserts (TNMG 160404R-ST) having nose radius of 0.4 mm. The lead angle is 0°. The feeds and depths-of-cut used were relatively small and are of the same order of magnitude as that of tool edge geometry. Thus, the cutting is confined to a small area on the nose radius of cutting tool and no premature tool insert breakage occurred during the turning tests. The positive cutting edge inclination disposes chips in the cutting direction and thus the chips do not interfere during imaging of the edge of the workpiece. It was found that the coolant initially fouled the Region-of-Interest (ROI) during wet turning. The jet of compressed air supply from nozzle cleared the field-of-view effectively thus producing a good quality image of the workpiece surface profile as seen in Figure 3.

2.3 Acquisition of workpiece surface image using DSLR camera
The DSLR camera was set to manual mode and the focusing ring was adjusted to obtain a sharp focus of the edge of the workpiece opposite the cutting side. The shutter speed of the camera was set to the maximum value of 1/4000 s and the backlight intensity was adjusted to obtain a good contrast image of the workpiece profile. At this high shutter speed blur-free images of the workpiece surface can be captured during the turning. Although the spindle speed used in the turning experiments was only 420 rpm relatively blur-free images can be captured at spindle speeds of up to 4000 rpm using the DSLR camera as demonstrated in our previous work [16]. Vibration of the workpiece did not introduce significant blurring in the image. A sequence of ten images of the rotating workpiece surface was captured remotely during a time interval of 2 s.

2.4. Acquisition of image of cutting tool insert using CCD camera
The contour of the cutting tool nose edge was captured with the aid of backlighting using the CCD camera in-between the cutting cycles without removing the cutting tool from the machine. The images were analysed and the progressive nose wear was calculated using the developed algorithm coded in MATLAB. The algorithm enables automatic correction of tool misalignment.

2.5. Sub-pixel edge location and roughness measurement
The step-edge model applying the concept of invariant moments for sub-pixel edge location proposed by Tabatabai and Mitchell [17] was applied to detect the edge of the workpiece image to sub-pixel accuracy. The details of the sub-pixel edge location method is explained in Ref. [16]. The grey level invariant moment method of sub-pixel edge detection enables accurate determination of the sub-pixel edge of the workpiece profile (Figure 4). The surface contour image was initially read into the MATLAB workspace and the edge image of workpiece was cropped automatically to the required evaluation length for roughness measurement. The threshold independent method of finding the edges with sub-pixel
accuracy was then applied. The algorithm starts to scan the surface profile from the first pixel in the first column to find the sub-pixel profile. The starting point of the scan line is taken to be at the upper-left corner point $O$. The interval $\Delta D$ along each pair of neighbouring scan lines $L(i)$ and $L(i+1)$ is one pixel. The variance between the maximum grey level and the minimum grey level data of the scan line $L(i)$ serves as a major characteristic in determining the sub-pixel roughness profile $k(i)$. Since the detected roughness is in pixels the scaling factors were used to convert the roughness to micrometres. Next, the best-fit line of the detected contour data, considered as a mean line, was determined using least-squares fitting. The distance of each pixel on the profile measured from the mean line was used in calculating the roughness parameters defined in Table 1. Detailed definition of the roughness parameters can be found elsewhere [18]. The roughness values obtained using the vision method at different intervals of machining time is shown in Table 2. Figures 5(a)-(d) show the images of workpiece profiles captured during the wet turning for different machining time and the corresponding roughness plots generated using the machine vision method. The deterioration in the surface quality of the workpiece after 30 minutes of machining can be seen from the roughness profiles.

![Orthogonal scanning of surface profile with sub-pixel edge location.](image)

Figure 4. Orthogonal scanning of surface profile with sub-pixel edge location.

### Table 1. Specifications of roughness parameters.

| Category        | Description                              | Symbol |
|-----------------|------------------------------------------|--------|
| Hybrid parameters | Mean slope of the profile                 | $R_{\Delta a}$ |
|                 | Quadratic mean of all local slopes        | $R_{\Delta q}$ |
|                 | Average wavelength                        | $R_{\lambda a}$ |
|                 | Root mean square wave length              | $R_{\lambda q}$ |

### Table 2. Roughness data obtained using the vision method at different intervals of machining time.

| Roughness Parameters | Machining time (min) |
|----------------------|----------------------|
|                      | 1.2 | 2.2 | 4.4 | 6.6 | 8.8 | 11 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| $R_{\Delta a}$       | 23.51 | 23.36 | 20.07 | 19.49 | 19.49 | 18.92 | 18.35 | 18.35 | 16.05 | 14.91 | 14.91 | 14.33 | 14.33 | 13.76 | 13.19 |
| $R_{\Delta q}$       | 32.39 | 29.24 | 28.67 | 28.09 | 26.92 | 25.23 | 24.14 | 23.57 | 22.26 | 21.66 | 21.02 | 20.38 | 19.81 | 19.72 | 17.20 |
| $\lambda a$ (\mu m)  | 198.77 | 201.86 | 211.38 | 232.01 | 241.51 | 254.27 | 268.46 | 276.74 | 279.73 | 280.31 | 284.42 | 287.91 | 284.82 | 296.57 | 297.67 |
| $\lambda q$ (\mu m)  | 179.55 | 264.23 | 291.69 | 377.38 | 380.15 | 358.36 | 273.16 | 274.21 | 263.14 | 263.84 | 258.65 | 253.22 | 247.47 | 251.40 | 260.31 |
3.0 Results and Discussion

3.1 Verification of roughness parameters determined using the vision method

The hybrid surface roughness data obtained using the wet turning process was verified using a portable stylus surface roughness tester (SurfTest SJ-210). Table 2 shows the roughness data measured using the vision method. The workpiece surface was also measured using a stylus method ten times at different regions using an evaluation length of 12.5 mm and a cut-off length of 2.5 mm. The averages of these values are tabulated in Table 3. Comparison between the vision and stylus method in measuring the hybrid roughness parameters are shown in Table 4. The maximum deviation for $R_{\Delta a}$, $R_{\Delta q}$, and $R_{\lambda a}$ between vision and stylus method are, respectively 7.69%, 9.68% and 8.74%.

Table 3. Roughness obtained using the stylus method at different intervals of machining time.

| Cutting time (min) | 1.2 | 12.2 | 24.4 | 36.6 | 48.8 | 61.0 | 73.2 | 85.4 | 97.6 | 109.8 | 134.2 | 158.6 | 183.0 | 207.4 | 244.0 |
|-------------------|-----|------|------|------|------|------|------|------|------|-------|-------|-------|-------|-------|-------|
| $R_{\Delta a}$    | 24.91 | 23.33 | 21.62 | 21.06 | 20.57 | 20.19 | 19.84 | 19.81 | 17.39 | 15.46 | 15.48 | 15.30 | 14.96 | 14.36 | 14.28 |
| $R_{\Delta q}$    | 33.45 | 30.65 | 29.58 | 29.03 | 28.13 | 26.71 | 25.59 | 24.28 | 23.74 | 22.93 | 23.06 | 21.58 | 20.47 | 21.86 | 18.31 |
| $\lambda_a$ (\mu m) | 211.73 | 215.82 | 220.70 | 247.91 | 251.17 | 276.88 | 278.27 | 289.72 | 302.64 | 303.85 | 308.64 | 313.51 | 291.16 | 316.56 | 310.49 |
| $\lambda_q$ (\mu m) | 191.26 | 270.60 | 307.73 | 281.41 | 281.05 | 267.79 | 296.46 | 287.27 | 281.95 | 277.01 | 262.52 | 262.45 | 250.33 | 259.86 | 272.43 |
Table 4. Comparison between hybrid roughness parameters obtained using vision method and stylus method.

| Cutting time (min) | $R_{\Delta a}(\sigma) - R_{\Delta a}(\bar{\sigma})$ | $R_{\Delta q}(\sigma) - R_{\Delta q}(\bar{\sigma})$ | $R_{\lambda a}(\sigma) - R_{\lambda a}(\bar{\sigma})$ | $R_{\lambda q}(\sigma) - R_{\lambda q}(\bar{\sigma})$ |
|-------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1.2               | 5.64 (× 100%)                  | 3.18 (× 100%)                  | 6.12 (× 100%)                  | 6.12 (× 100%)                  |
| 12.2              | 4.15 (× 100%)                  | 4.61 (× 100%)                  | 6.48 (× 100%)                  | 2.36 (× 100%)                  |
| 24.4              | 7.19 (× 100%)                  | 3.10 (× 100%)                  | 5.65 (× 100%)                  | 5.21 (× 100%)                  |
| 36.6              | 7.46 (× 100%)                  | 3.22 (× 100%)                  | 6.41 (× 100%)                  | 2.14 (× 100%)                  |
| 48.8              | 5.26 (× 100%)                  | 4.20 (× 100%)                  | 3.85 (× 100%)                  | 7.44 (× 100%)                  |
| 61.0              | 6.30 (× 100%)                  | 5.55 (× 100%)                  | 8.17 (× 100%)                  | 3.52 (× 100%)                  |
| 73.2              | 3.12 (× 100%)                  | 5.70 (× 100%)                  | 3.53 (× 100%)                  | 7.19 (× 100%)                  |
| 85.4              | 7.41 (× 100%)                  | 2.94 (× 100%)                  | 7.87 (× 100%)                  | 4.54 (× 100%)                  |
| 97.6              | 7.69 (× 100%)                  | 6.25 (× 100%)                  | 7.87 (× 100%)                  | 6.67 (× 100%)                  |
| 109.8             | 3.57 (× 100%)                  | 5.56 (× 100%)                  | 7.75 (× 100%)                  | 4.75 (× 100%)                  |
| 134.2             | 3.70 (× 100%)                  | 8.82 (× 100%)                  | 7.85 (× 100%)                  | 1.48 (× 100%)                  |
| 158.6             | 6.30 (× 100%)                  | 5.55 (× 100%)                  | 8.17 (× 100%)                  | 3.52 (× 100%)                  |
| 183.0             | 4.17 (× 100%)                  | 3.23 (× 100%)                  | 2.18 (× 100%)                  | 1.14 (× 100%)                  |
| 207.4             | 4.17 (× 100%)                  | 9.68 (× 100%)                  | 6.32 (× 100%)                  | 3.37 (× 100%)                  |
| 244.0             | 7.69 (× 100%)                  | 6.06 (× 100%)                  | 4.13 (× 100%)                  | 4.45 (× 100%)                  |
| 280.6             | 4.00 (× 100%)                  | 3.13 (× 100%)                  | 8.74 (× 100%)                  | 6.63 (× 100%)                  |
| Mean diff. (σ)    | 2.09                           | 2.32                           | 2.47                           | 2.24                           |
| Std. dev. (σ)     | 5.49                           | 5.05                           | 6.22                           | 4.41                           |

$R_{\Delta a}(\sigma), R_{\Delta q}(\sigma), R_{\lambda a}(\sigma), R_{\lambda q}(\sigma)$ Roughness measured using stylus method

$R_{\Delta a}(\bar{\sigma}), R_{\Delta q}(\bar{\sigma}), R_{\lambda a}(\bar{\sigma}), R_{\lambda q}(\bar{\sigma})$ Roughness measured using vision method

3.2 Assessment of tool nose wear from established roughness parameters

Progressive wear on the tool nose region constitutes a change in the edge geometry at the cutting tool-workpiece interface. Figure 6 shows sample images of cutting tools and the corresponding wear area at different machining times. The cutting tool images were captured in-between the turning passes in order to determine the nose wear area. The nose wear areas were later correlated with the surface roughness parameters determined by the vision method.

Figures 7(a)-(c) show the variation of nose wear area with the hybrid roughness parameters. The decrease in the mean slope $R_{\Delta a}$ and the quadratic mean slope $R_{\Delta q}$ as nose wear increases shows that slopes gradually become less steep as the nose becomes increasing worn. The average wavelength $R_{\lambda a}$, however, shows an increasing trend with increase in nose wear. The average wavelength parameter is a measure of the spacing between local peaks and valleys taking into account their relative amplitudes and individual spatial frequencies. There appears only a small increase in $R_{\lambda a}$ during the initial stages of machining when the tool is relatively new. Grooves produced by the feed motion of the tool are predominant when the tool is sharp resulting in small $R_{\lambda a}$ values. As the cutting edge is progressively worn the appearance of the machined surface tends to be smeared and localized peaks and valleys appear. The grooves corresponding to the feed marks become less dominant thus increasing $R_{\lambda a}$. For the mean slope parameter $R_{\Delta a}$ a reasonably good negative exponential fit with $R$-square value of 0.9588 can be obtained within the range of roughness investigated. On the other hand, a good positive exponential fit with $R$-squared value of 0.9734 was obtained for the $R_{\lambda a}$ parameter. Although such fits are only approximations they could provide a useful insight into monitoring of the tool nose wear during turning.
Figure 6. Sample image of cutting tool captured using CCD camera at various machining time and the corresponding nose wear areas: (a) after 36 minutes, (b) after 73.2 minutes and (d) after 158 minutes.

Figure 7. Correlation between tool nose wear with hybrid roughness parameter.
4.0 Conclusion

Among the hybrid parameters investigated the average wavelength ($\lambda_{av}$) showed the best correlation with the tool nose wear with $R$-squared values of 0.9734. The average wavelength increased rapidly with increase in nose radius wear due to the smearing effect of the worn tool nose. The mean slope of profile and quadratic mean of all local slopes decreased with increase in nose wear due to the same smearing effect. The fluctuation of the data in all three parameters is suspected to be due to the increased vibration caused by tool wear.

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