# EFFECT OF TOOL WEAR ON SURFACE TOPOGRAPHY IN FINISH TURNING OF ABNT 1045 STEEL

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***Abstract.*** *The purpose of the present study is to investigate the relationship between tool wear and surface topography during tool running-in period in finish turning of carbon steel. The adopted workpiece material was normalized ABNT 1045 steel and the selected tools were commercial carbide inserts with two different post-coat treatments. Trials were carried out according to ISO 3685 standard. Cutting length was defined for a 270 mm long cylindrical part with a diameter ranging from 42 mm to 30 mm. The cutting process was interrupted periodically and the surface profile was acquired for three different regions of the workpiece using a portable roughness tester. Post-processing of the surface profile was done by filtering the acquired data and calculating several roughness parameters –Ra, Rq, Rt, Ry (JIS), Rz (DIN), R3z, and Rp (DIN). Statistical parameters such as skewness and kurtosis were also monitored. Tool wear was monitored at different stages of tool life. The evolution of roughness parameters and flank wear were compared for the adopted tools. Results indicate that the accommodation phase for both tools occur in a similar trend but the values of roughness parameters have a tendency to stabilize at different levels after the running-in period of each tool.*

***Keywords****: surface technology, roughness, tool wear, tool post-coat treatment*

## 1. INTRODUCTION

In manufacturing engineering, two issues are of main concern. The first one is selecting a process in order to achieve the desired quality on a manufactured part and the second one is maximizing productivity without affecting quality. In order to improve quality and productivity, tool technology is constantly advancing. Regardless of the process used and advances in manufacturing technology, deviations from the nominal surface will occur. These deviations are classified from first to sixth order according to DIN 4760 (1982), where the superposition of third and fourth order deviations is known as surface roughness. This so-called superposition is obtained by filtering the first and second order deviations with an appropriate computer algorithm or physical device. Figure 1 illustrates these surface deviations.

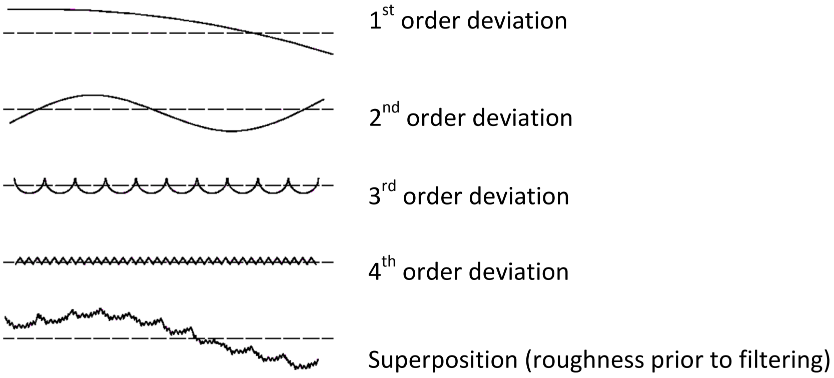

Figure 1. Surface form deviations (DIN 4760, 1982). The straight dotted line represents the nominal surface.

Several roughness parameters can be calculated from the acquired profile but it is well established that these 2-dimensional parameters are not enough to describe a real surface, working as mere indicators of surface features (Whitehouse, 1997; Bet, 1999).

Nonetheless, these two-dimensional roughness parameters have served the industry as indicators of functional performance of different components and, despite the advent of tri-dimensional parameters and other indicators, some authors believe that profile parameters will continue to be widely used in manufacturing engineering (Whitehouse, 1997).

It is well established that tool wear is related to the quality of surface finish (Field *et al.*, 1990). Notably, it has been widely confirmed that very sharp tools produce surfaces with better finish than worn out tools (Zhang and Li, 2010; Davim, 2010). The difference in roughness parameter values over time can be partially associated to the deterioration of the tool's geometry due to wear of the cutting edge. This loss of geometry is known to occur very rapidly at early life, reaching a steady state condition at mid-life, at which roughness parameters are known to be more constant (Davim, 2010). This rapid loss of the original geometry at early life contributes to the high variability of roughness parameters during this stage, as compared to tools at mid-life.

The tribological phenomenon that occurs between the tool and workpiece during early life is popularly known as the running-in process. It is believed that in this stage the tool surface is worn out to a certain extent, reaching a more stable edge configuration (Shaw, 2005). Some new tool grades developed by popular tool manufacturers advertise a significant reduction of this running-in stage, consequently producing lower friction and lower tool wear. The main idea behind these tool grades is relieving surface tension and polishing the outermost coating layer, removing the top TiN layer and exposing the alumina layer. This process produces a smoother tool surface (ISCAR Metalworking, 2010).

This study aims at analyzing tools of the same geometry but of different grades under the same cutting conditions in order to infer about the resulting surface finish while also monitoring tool wear.

The main objective of this study is to observe the evolution of 2-dimensional surface roughness parameters during the running-in process of two tools of different grades that differ by a post-coat treatment, while also monitoring tool wear.

## 2. DEFINITION AND SIGNIFICANCE OF ROUGHNESS PARAMETERS

This section defines the vertical roughness parameters used in this study since homonymous parameters exist in different standards. The absolute arithmetic average roughness (Ra) is defined by Eq. (1). The root-mean-square roughness (Rq) is defined by Eq. (2). In both equations $y_i$ (Fig. 2) is defined as the $i^{th}$ ordinate (height) of the roughness profile and $N$ is the number of ordinates in the profile.

$$Ra = \frac{1}{N}\sum_{i=1}^{N}|y_i| \tag{1}$$

$$Rq = \sqrt{\frac{1}{N}\sum_{i=1}^{N} y_i^2} \tag{2}$$

Rt is defined as the sum of the height of the highest peak and the depth of the deepest valley over the evaluation length, as shown in Eq. (3), and Ry is defined as the maximum distance from peak to valley among all five sampling lengths, as defined by Eq. (4) and Fig. 2. Ry is also denoted as Rmax in other standards (DAVIM, 2010).

$$Rt = \max\{y_i\} + |\min\{y_i\}| \tag{3}$$

$$Ry = \max\{Z_i\} \tag{4}$$

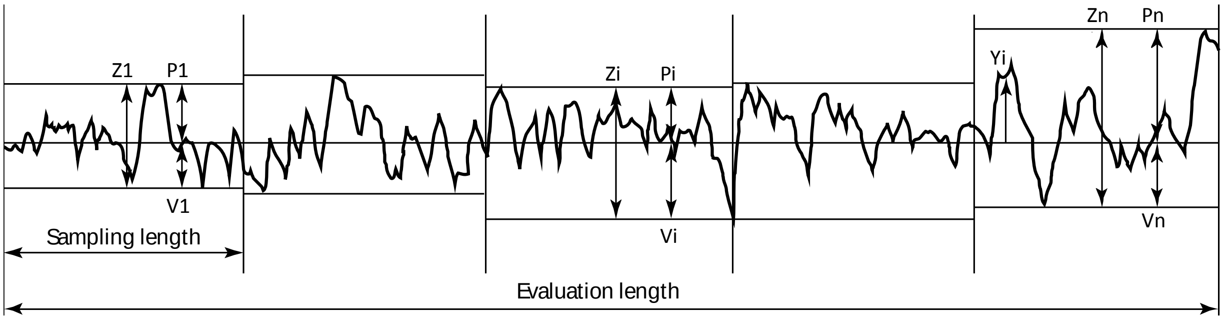

Figure 2. Roughness profile sections according to DIN 4768 (1990). Adapted from Bet (1999).

Rz is the mean average of the maximum distance from peak to valley within each sampling length, as defined by Eq. (5) and Fig. 2. R3z is a parameter similar to Rz, except that it considers the third longest distance from peak to valley within each sampling length, called $3Z_i$. A mathematical expression that defines R3z can be found in Eq. (6).

$$Rz = \frac{1}{5}\sum_{i=1}^{5} Z_i \tag{5}$$

$$R3z = \frac{1}{5}\sum_{i=1}^{5} 3Z_i \tag{6}$$

Rp is defined as the average of the maximum peak heights within each sampling length, as defined by Eq. (7) and Fig. 2.

$$Rp = \frac{1}{5}\sum_{i=1}^{5} P_i \qquad (7)$$

Statistical parameters such as kurtosis and skewness are also used to analyze a roughness profile. Skewness relates the distribution of peaks and valleys of the profile. A negative value of skewness (Rsk) indicates a predominance of valleys in the profile while a positive value indicates a predominance of peaks. The kurtosis coefficient (Rku) quantifies the asperity of a surface. A value of 3 for Rku indicates a normal distribution, therefore a value higher than 3 indicates a surface with narrower peaks and valleys while a value smaller than 3 indicates a smoother surface.

## 3. MATERIALS AND METHODS

### 3.1 Machine Tool, Workpiece, and Tool Materials

The experimental work comprised finish-turning ABNT 1045 steel using coated carbide tools of the same geometry but with different postcoat treatments. A CNC lathe machine was used (ROMI® Multiplic 35D) for all turning operations, as seen in Fig. 3. A three-jaw chuck was used along with a tailstock to support the workpiece. Details of the cutting tools used can be found in Tab. 1 and Fig. 4, and details of the steel bars adopted can be seen in Tab. 2.

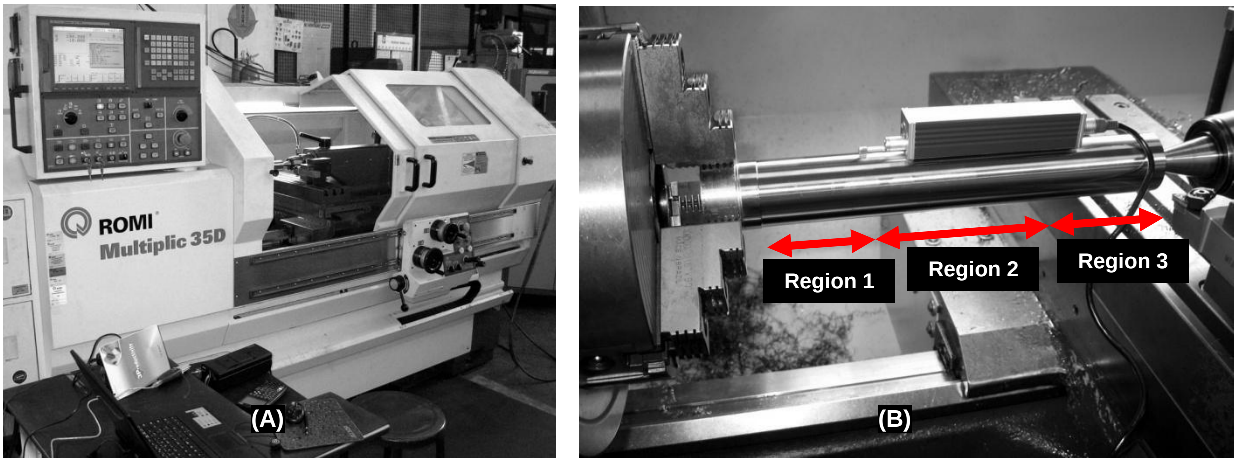

Figure 3. Lathe and data acquisition apparatus (A). Regions of profile acquisition and roughness measuring device (B).

Figure 4. Tool geometry assembled on tool holder (A) (dimensions in millimeters), IC9250 insert (B), and IC8250 insert (C).

The two tool types adopted consist of the same coating materials, being different only in regard to post-coat treatment. The IC9250 grade consists of a substrate with a cobalt enriched layer combined with MTCVD TiCN and a thick alpha $Al_2O_3$ CVD coating. The coating layers are, from inner to outer, TiCN, $\alpha Al_2O_3$, and TiN. No post-coat treatment is done on the IC9250 tool. Henceforth, this tool will be referred to as the reference tool. The IC8250 grade consists of the same coating materials as IC9250 except that the TiN outermost layer is smoothed out and has surface tension stresses reduced through proprietary post-coat polishing treatments. This polishing treatment is done on the tool surface and edge, exposing the $\alpha Al2O_3$ layer. Henceforth, this tool will be referred to as the polished tool.

Table 1. Description of the assembled tool geometry adopted in the experiments.

| Item | Description |
|---|---|
| Toolholder Designation | MTJNR 2525M-16W |
| Insert Designation | TNMG 160404-TF |
| Insert Clamping | Wedgelock |
| Cutting Edge Inclination ($\kappa_r$) | 93° |
| Rake Angle ($\gamma$): | -6° |
| Angle of Inclination ($\lambda$): | -6° |
| Included Angle ($\varepsilon$): | 60° |
| Nose Radius ($r_\varepsilon$): | 0.4 mm |

Table 2. Some relevant characteristics of the workpiece material.

| Work Material: ABNT 1045 hot-rolled steel | |
|---|---|
| Chemical composition (%wt)$^{(1)}$ | C: 0.460; Mn: 0.640; Si: 0.170; P: 0.017; S: 0.020; Cu: 0.140; Cr: 0.060; Ni: 0.040; Sn: 0.009; Mo: 0.007. |
| Tensile / Yield Strength (MPa)$^{(2)}$ | 570 / 310 |
| Hardness Brinell (HB) | 163 |
| Specific cutting pressure - $k_c$ (N/mm$^2$)$^{(3)}$ | 4200 for 0.1 mm/rev feed rate |
| Test specimen length / machined length (mm) | 300 / 270 |
| Diameter prior to machining (mm) | 44.5 |

$^{(1)}$: as certified by the material supplier; $^{(2)}$: usual values; $^{(3)}$: Stemmer, 2007.

### 3.2 Cutting Conditions

Cutting conditions were determined considering a finish operation (low feed rate and depth of cut) and a constant cutting speed ($v_c$) of 180 m/min according to the workpiece length to diameter ratio. Another factor in determining these conditions was chip formation, in order to ensure that the recently formed chip would not damage the workpiece surface. Details can be seen in Tab. 3.

Table 3. Cutting conditions adopted in the experiment.

| Cutting Conditions | |
|---|---|
| Cutting speed ($v_c$) (m/min) | 180 |
| Feed rate (f) (mm/rev) | 0.08 |
| Depth of cut ($a_p$) (mm) | 0.25 |

### 3.3 Wear and Roughness Measurements

Tool wear was measured using a stereo microscope (Olympus® SZ61). For each measurement, the tool was cleaned and maximum values of wear in the corner region (C zone as per ISO 3685 (1993)) were recorded.

The surface profile was acquired from three different regions of the workpiece periodically, as indicated by Fig. 3. A portable roughness measuring device was used (Mitutoyo® SJ-201P) connected to a portable computer with the data acquisition software. Cutoff and evaluation length were defined according to the mean width of the profile elements value (Sm), as recommended by product specifications. The acquired profile was filtered using a PC50 Gaussian filter and the roughness parameters were calculated from the obtained R-profile. The average roughness value for the three analyzed regions was calculated along with the standard error in order to be plotted in the time domain.

Accuracy of the instrument was verified by using a standard roughness specimen throughout the experiment and no significant changes from the expected roughness values were observed. After acquiring the surface profiles turning operations were resumed and the measuring procedure was repeated until the roughness parameters indicated some form of stability (end of the running-in process). Details of the roughness measuring apparatus can be found in Tab. 4.

Table 4. Details of the roughness measuring device (Mitutoyo® SJ-201P) and settings used.

| Item | Description |
|---|---|
| Detection method | Differential inductance |
| Stylus material / tip radius (μm) | Diamond / 5 |
| Cutoff length ($\lambda_c$) (mm) x Number of sampling lengths (n) | 0.8 x 5 |
| PC50 filter amplitude transmittance at $\lambda_c$ wavelength | 50% |

## 4. RESULTS AND DISCUSSION

### 4.1 Surface Roughness

As previously stated, the main goal of this study was acquiring surface roughness data in the time domain while periodically measuring tool wear for tools of different grades. Figures 5 through 8 show the evolution of several roughness parameters for both tools over a period of approximately 1 hour and 15 minutes. The data points shown in the figures are related to the end of each turning cycle. The end of the running-in stage for each tool can be observed through the evolution of roughness parameters over time. It is considered to be the instant of time corresponding to the first local roughness peak observed in the experiments, after which roughness values have a tendency to stabilize.

It can be seen from Fig. 5 that the Ra and Rq parameters show a similar evolution for both tools. Such a result is expected, since Ra and Rq are both average values that differ only in order. It can also be noticed that both tool grades have a similar behavior for the first 7 minutes of cutting time, when the polished tool seems to reach the peak of its running-in stage. Another difference that can be noticed is that the average roughness (Ra and Rq) produced by both tools at later times has a tendency to stabilize at different values. Rq values were above Ra values at an average of 18 ± 1%.

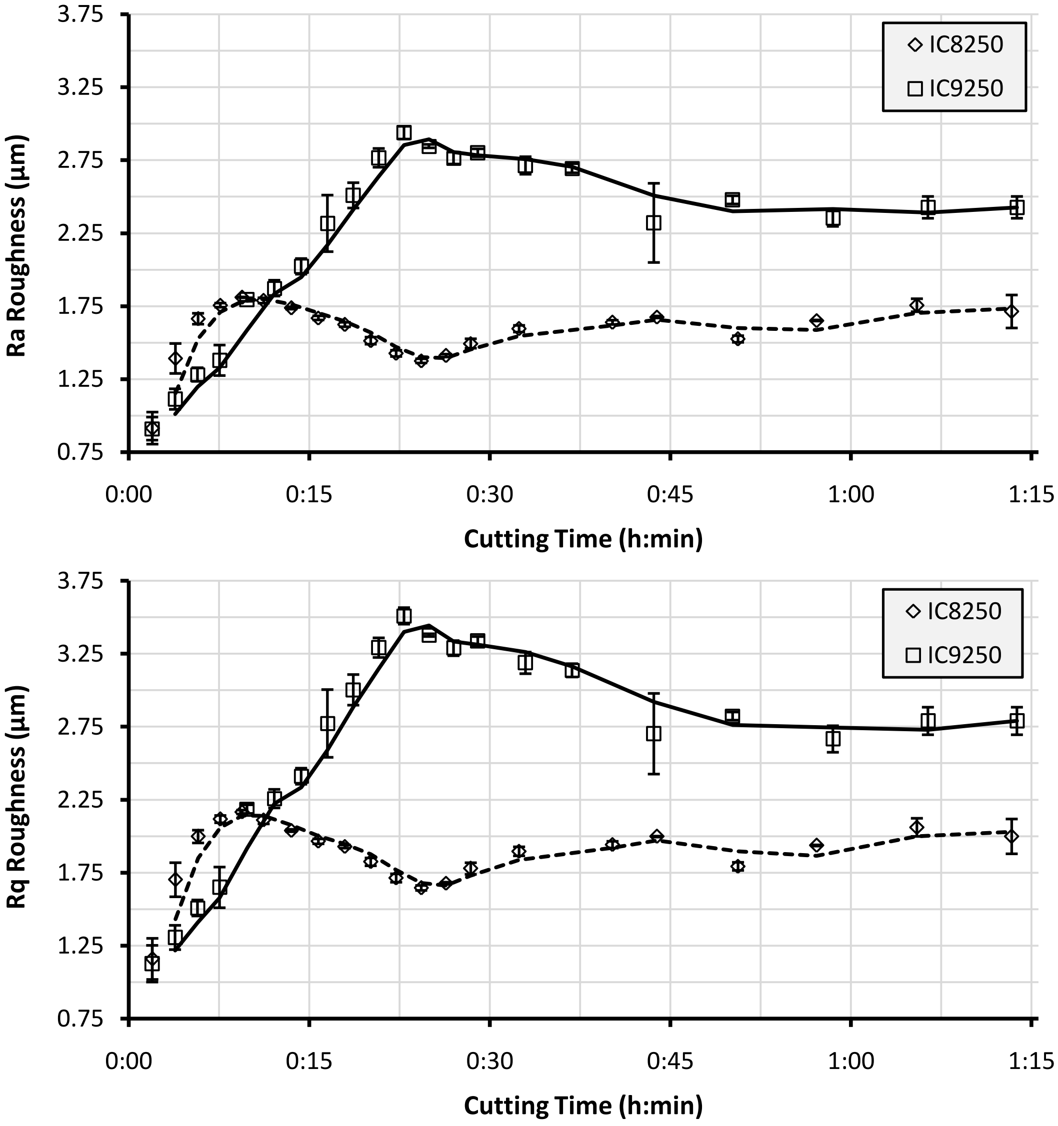

Figure 5. Absolute arithmetic average (Ra) (above) and Root Mean Squared Roughness (Rq) (below) over time for IC8250 (polished) and IC9250 (reference) grade tools. Error bars are based on standard error of three samples and trend lines are based on the moving average of two points.

Extreme parameters Rt and Ry also show a similar behavior. From Fig. 6 it can be seen that both tools produced overlapping values of Rt and Ry during the first 7 minutes of testing. It can also be noticed that the reference tool produced a surface with higher values of Rt and Ry than the polished tool after the running-in process came to an end.

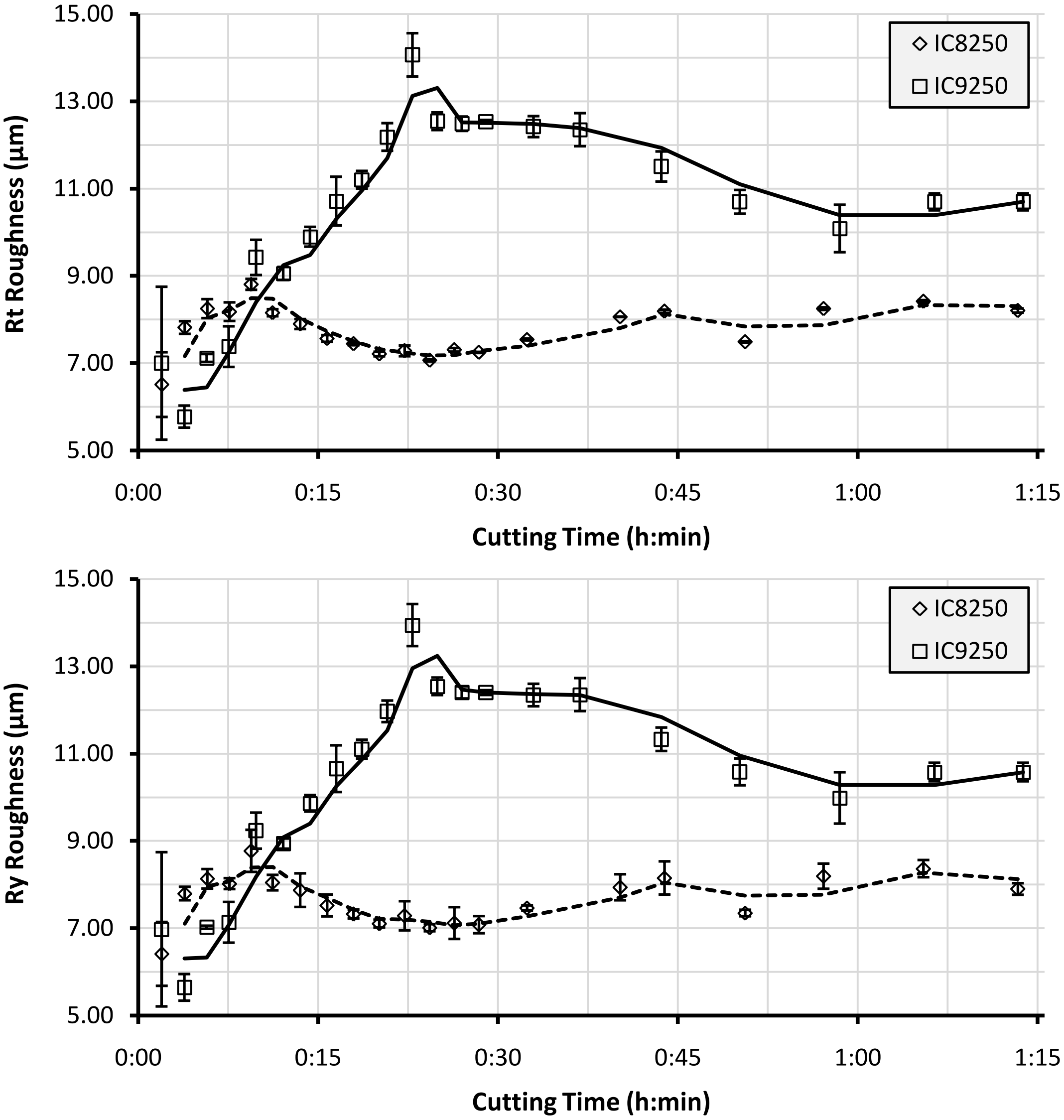

Figure 6. Total height of the profile (Rt) (above) and maximum height of the profile (Ry-JIS) (below) over time for IC8250 (polished) and IC9250 (reference) grade tools. Error bars are based on standard error of three samples and trend lines are based on the moving average of two points.

Rz and R3z values behaved similarly to the previous extreme parameters. Despite their great proximity, measuring these two parameters provides the user with more assertiveness over the real height of the profile, due to the relative instability of the Rz parameter as compared to R3z. In all measurements the Rz and R3z parameters did not show any significant difference, both numerically and in trendiness, therefore only the Rz data is plotted in Fig. 7.

The behavior of the maximum peak height of the profile (Rp) over time can also be seen in Fig. 7. It shows a similar evolution to the previously presented extreme values.

The behavior of these extreme parameters over time, specifically the local peak observed at 9 minutes for the polished tool and the one at around 25 minutes for the reference tool can be attributed to the transient cutting edge formed during the running-in process, as has been observed by Grzesik (2008). This transient cutting edge is believed to be formed by small grooves (not to be confused with notch wear) produced by tool wear which in turn generate irregular local surface peaks and contribute to the high variability of roughness parameters during the running-in process. These extreme parameters, as compared to the average parameters, revealed more clearly the end of the running-in stage due to the more evident curve peak.

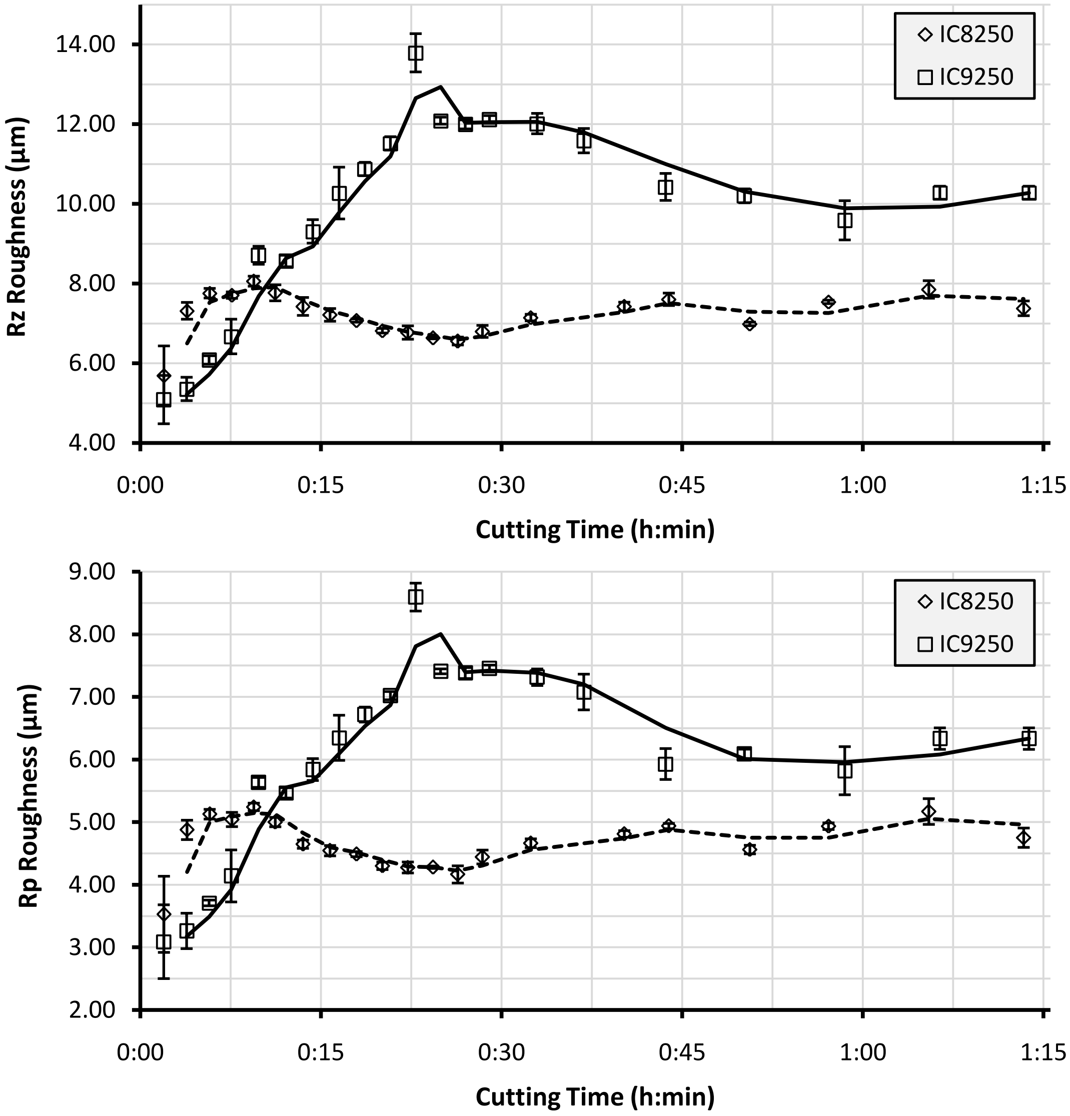

Figure 7. Maximum height of the profile (Rz-DIN) and maximum peak height of the profile (Rp) roughness over time for IC8250 (polished) and IC9250 (reference) grade tools. Error bars are based on standard error of three samples and trend lines are based on the moving average of two points.

Values for kurtosis and skewness can be seen in Fig. 8. The first recorded values of kurtosis for both tools vary significantly over the first 10 minutes and also show very high error values, indicating higher variability. It can also be noticed that after the running-in process ends, the reference tool produces a surface with slightly lower kurtosis values.

Skewness for both tools, when deviations are considered, show overlapping values for the first 30 minutes and a slight decrease in skewness is observed for the reference tool after this period. At the end of the running-in phase both tools produced surfaces with similar skewness values, with the reference tool showing lower values. Skewness values for both tools indicate a constant predominance of peaks. The surface profiles in Fig. 9 demonstrate the constant predominance of peaks. The acquired profiles for both tools at early life show more irregular peaks with varying height. At the end of the running-in process both tools produced profiles with more regular peaks. The lower variation of the skewness parameter during this later period correlates with the aforementioned profile characteristics.

As previously mentioned, kurtosis values higher than 3 indicate a surface with narrower peaks, while a value smaller than 3 indicates a smoother surface profile with softer curves. In this sense, results show that both tools have a tendency to produce surfaces with more asperities earlier in life. The surface profiles seen in Fig. 9 for one of the tools at different times show the characteristic surfaces produced at earlier times and at later times. These surface profiles show the presence of local peaks, which contribute to higher kurtosis values.

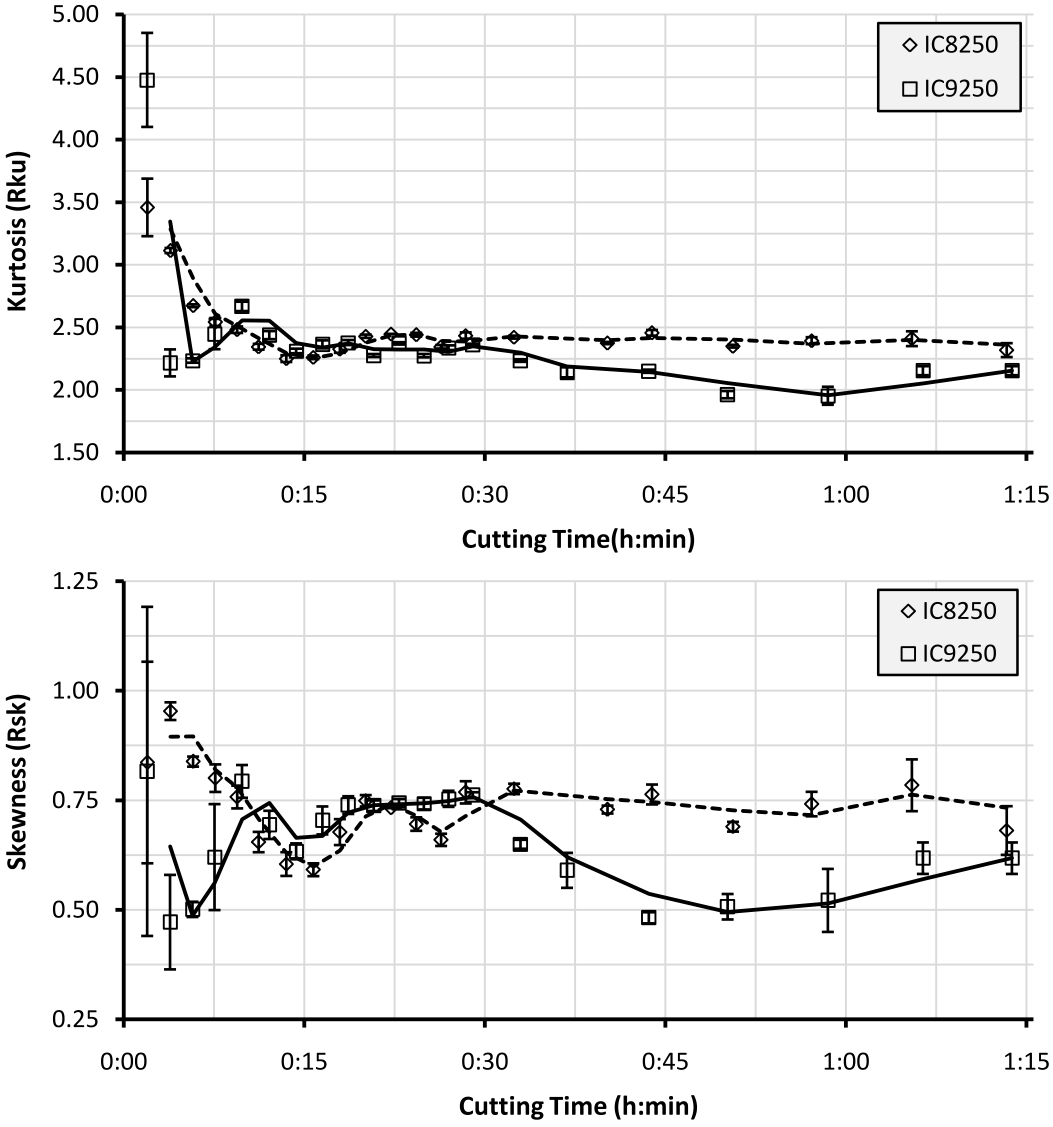

Figure 8. Kurtosis (above) and Skewness (below) over time for IC8250 (polished) and IC9250 (reference) grade tools. Error bars are based on standard error of three samples and trend lines are based on the moving average of two points.

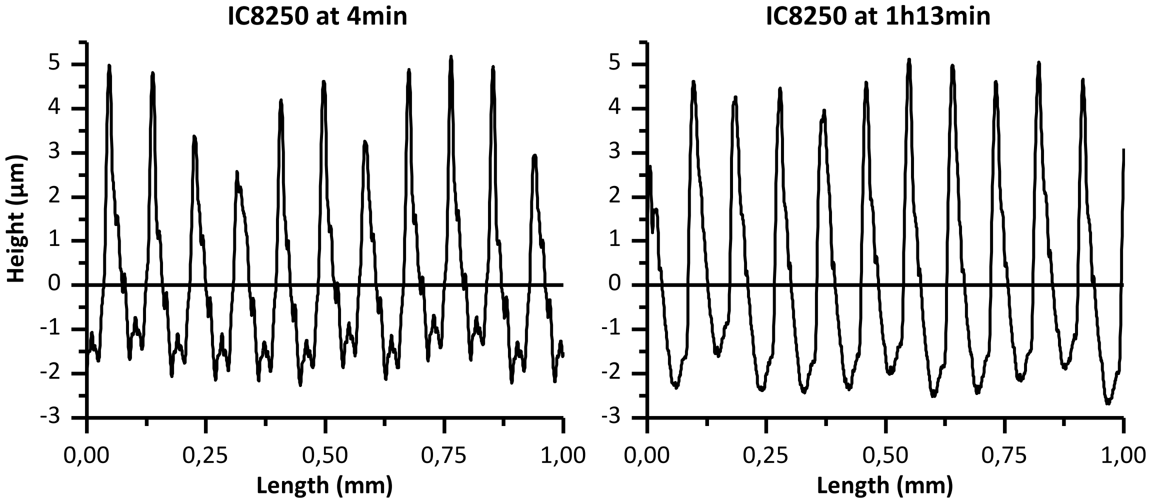

Figure 9. Characteristic roughness profiles produced by the polished tool during testing at different times. Only 1 mm of the 4 mm evaluation length is shown.

### 4.2 Chip Formation and Tool Wear

Tool wear was monitored in order to better understand the evolution of roughness parameters for both tools. Tool wear, as expected, occurred uniformly in the corner region, region C as per ISO 3685 (1993). Despite chip formation being affected by the chip breaker, no sign of notch wear or crater wear were detected. Chip form alternated between tubular snarled chips and short washer-type helical chips, as can be seen in Fig. 10. Chip flow occurred away from the workpiece and in the direction of feed motion at all times. All analyzed chips showed signs of being continuous type chips, as expected for the type of material and conditions adopted.

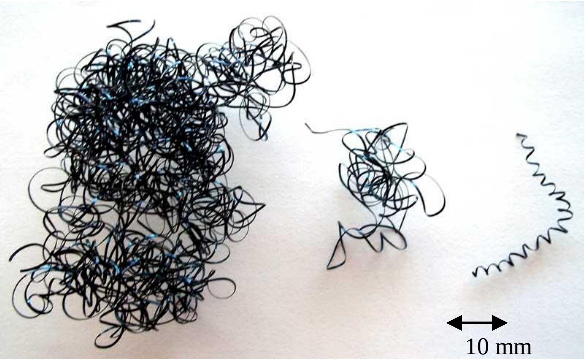

Figure 10 – Three samples of chips collected during testing. Snarled (left and middle) and short (right) washer-type helical chips.

Figure 11 shows the corner region of both tools at different times. Wear measurements indicate a similar loss of material during the running-in process for both tools. At 11 minutes of testing, wear on the polished tool reached a value of $VB_c = 70$ µm, close to the final measurement (73 minutes) at $VB_c = 85$ µm. Moreover, the reference tool at 14 minutes of testing reached a wear value of $VB_c = 66$ µm, farther away from the final measurement (73 minutes) at $VB_c = 89$ µm.

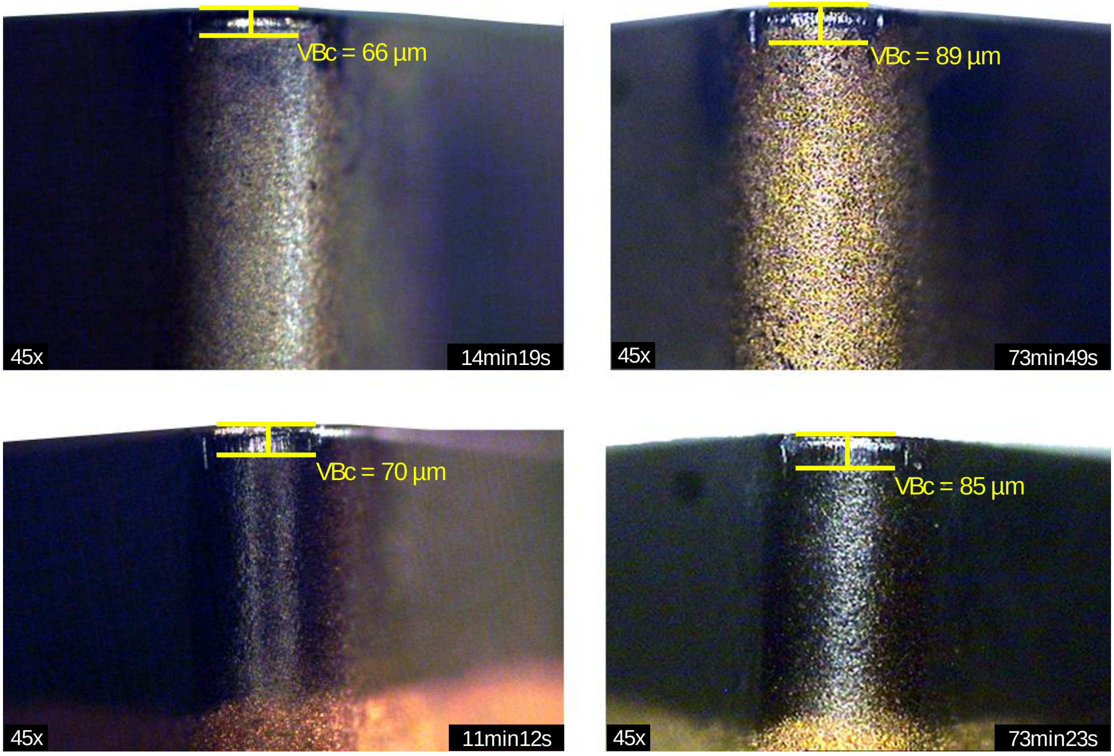

Figure 11. Corner region of IC9250 (above) and IC8250 (below) tools at different times of testing.

Figure 12 shows the flank of the polished tool at 50 minutes of testing. A slight loss of geometry can be noticed at the tool corner. Crater wear was not observed for both tools, but adhesion signs can be seen in all photographs.

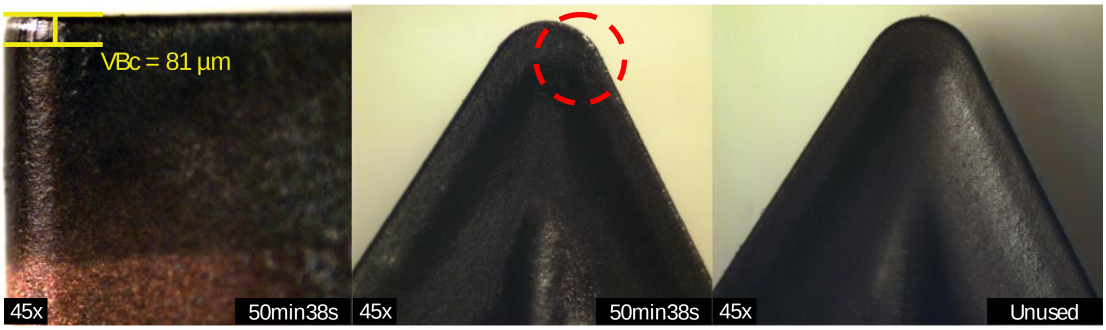

Figure 12. Flank during cutting (left) and rake surface (middle and right) during and prior to cutting of IC8250 tool.

## 5. CONCLUSIONS

The evolution of several surface roughness parameters and tool wear during the running-in process were investigated for tools of two different grades. Experiments revealed that the running-in process for the polished (IC8250) tool occurred more rapidly than for the reference (IC9250) tool. All vertical parameters calculated for the produced surfaces indicate that the polished tool has a tendency to produce surfaces with lower roughness values. Also, flank wear measurements indicate that both tools lose material at similar rates during the running-in process. Results indicate that the steady state condition is reached earlier for the polished tool as compared to the reference tool. This shorter running-in process can be attributed to lower friction while cutting with the polished tool. The analyzed roughness profiles along with skewness and kurtosis parameters indicate that both tools have a similar tendency to produce more irregular surfaces at early life.

As it is felt that all factors which may affect surface roughness and tool life were kept under a reasonable degree of control, it is justified to conclude that the IC8250 grade tool provided better results at producing less rough surfaces than the IC9250 grade tool. Also, results indicate that the IC8250 tool has a shorter running-in process than the IC9250 tool considering the test conditions adopted in the experiment.

## 6. ACKNOWLEDGEMENTS

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