Identification of the minimum chip thickness based on the two-dimensional wavelet analysis

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Abstract. In this paper, authors take attempt to adapt the two-dimensional wavelet transform to assess the value of the minimum chip thickness for the face milling process of C45 steel. The images of surface layer from selected measuring devices were analyzed using a mother wavelet bior6.8. The analysis based on the wavelet transform revealed in signals three characteristics zones of the impact of cutting insert on the workpiece during initiation of the cutting process. The obtained values allowed to determine the relative method accuracy and to evaluate the possibility of application the particular measuring machines to assess the value of $h_{\text{min}}$ parameter.

1. Introduction
The quality of the surface layer of the manufactured parts has significant influence on their mechanical properties [1,2]. The finishing process is the final step of the production process, which improve the surface texture of the manufactured parts. One of the most important parameters of milling process, during treatment with small depth of cut is the evaluation of the minimum chip thickness, which is the border value defining the beginning of machining process and the removal of material in chip form. Depending on the depth of cut it can be distinguished three zones of the impact of cutting insert on the workpiece.

In this case, the value of depth of cut is lowest than the value of material which can be removed in the process ($a_p < h_{\text{min}}$). In the next zone, elastic-plastic deformation of the partial cutting process of workpiece takes place ($a_p \approx h_{\text{min}}$). Material removal in form of the chip occurs in the last zone ($a_p > h_{\text{min}}$) [3].

Analyzing the current state of art it can be noted that it is possible to assess the $h_{\text{min}}$ value using analytical formulas [4-6] as well as using practical solutions, which allow to experimentally assess parameter value [7]. In analytical models are used relationship between cutting parameters, tool and workpiece. However, these models assume some simplification and idealization of process, which in real terms is not feasible. Empirical solutions are alternative to analytical approach. The $h_{\text{min}}$ value can be evaluate based on analysis of the characteristic contact zones during initiation of the cutting process using microhardness analysis or optical and contact profilometer.

2. Two-dimensional wavelet transform
Many optical devices can be employ to measure the surface topography of machine parts. However, not all of them provide proper resolution in the particular axes, so that it is not possible to determine the locus of the particular contact zones during initiation of the cutting process. There are many methods
which can be apply to analyze signal in order to detect in them the characteristic information. One of this method is wavelet analysis which was developed at the turn of the twentieth and twenty-first century. Wavelet transform is mainly used to analysis of non-stationary signals, that is, those which are characterized by non-periodic irregularities. The application of wavelet transform lead to removing background features. It allow to detect characteristic information such as drifts, trends or abrupt signal changes and determine the location of such information in the signal [8].

The wavelet transform can be apply to 2D and 3D signal processing in the field of mechanical engineering. Many researchers have used wavelet transform to analyze the GPS signals [9-16]. In the work [9] were used a engineering and biomedical surfaces to demonstrate the application of wavelet analysis in the assessment of surface topographical features. The application 2D continuous wavelet transform to study the effect of abrasive finishing were presented in [10]. In [11] authors applied wavelet transform to filtering of freeform surfaces. Multiscaler wavelets were used to analyze the surface topography of wear of orthopaedic implants in [12]. In the work [13] were analyzed the deviations of cylindrical surfaces. In order to assess the tool flank wear the turned surface images were analyzed in [14]. In the work [15] authors applied wavelet analysis for detecting low-contrast defects under various light conditions in magnetic tile images. The work [16] present results of the application of wavelet transform to assess nanotopography of crystal surfaces.

Discrete two dimensional wavelet decomposition is based on the application of two filters, high pass and low pass. Therefore, at each decomposition level, the input signal is divided into four different signals: horizontal, vertical, diagonal details and approximation. Thus, it is possible, on particular level of analysis to detect characteristic information, which is not visible at other decomposition level [17].

3. Methodology and research results

In order to evaluate the possibility of application the two-dimensional wavelet analysis to assess the value of the minimum chip thickness were prepared the cuboid samples. The key issue was to produce the samples which surface was as smooth as possible, therefore all samples were polished and then the flatness of surface was measured. The research was carried out on the Prismo Navigator measuring machine using the VAST GOLD S-ACC probe head. In table 1 are presented the research results of the surface flatness. Thereafter the samples were mounted on inclined prism and there were milled. The process was based on the flowing change of depth of cut. The vertical milling centre AVIA VMC 800 was employed to carry out cutting process. The scheme of milling process is shown in figure 1. The process was performed with specified milling parameters \( v_c = 250 \) m/min and \( f_z = 0,1 \) mm/tooth. In order to avoid axial and radial run-out, one cutting insert was used. In the research was used cutting insert SDMT 120508 SN-81. The cutting process was performed without the cooling and lubricating liquids.

| No. | surface flatness (μm) |
|-----|---------------------|
| 1   | 1.3                 |
| 2   | 1.3                 |
| 3   | 2                   |
| 4   | 2                   |
| 5   | 1.3                 |
Figure 1. View of milling process. 1- tool, 2- sample, 3- prism, 4- handle, 5- stopper, P- working surface of the sample, f- feed, n- rotation, α- angle of working surface.

Measurements were performed using the following measuring machines: optical profilometer Talysurf CCI, multisensor measuring machine O-Inspect 442 and workshop microscope MarVision MM320 using three levels of magnification (x0.7, x1, x2). The optical profilometer was adopted as a reference device. The selected images of surface for particular measuring devices are presented in figure 2.

Figure 2. View of the surfaces (a) Talysurf CCI, sample No. 3 (b) O-Inspect sample No. 3 (c) MarVision, magnification x0.7 sample No. 5 (d) MarVision, magnification x1 sample No. 5 (e) MarVision, magnification x2 sample No. 3.
On the assumed probability $P = 0.95$, the experimental, relative method accuracy values were calculated using formulas 1 and 2. According to the Student's t-distribution, the parameter $t$ value was determined. This value was equal 2.776.

$$w_h = \frac{h_i - h_{odn}}{h_{odn}} \times 100\% \quad (1)$$

$$DM = |\bar{w}_h \pm ts|_{\text{max}} \quad (2)$$

Where $h_i$ - calculated value of the minimum chip thickness, $h_{odn}$ - reference value of the minimum chip thickness, $s$ - mean deviation.

The presented method allows to evaluate the possibility to employ the selected measuring devices to assess the value of $h_{min}$ parameter. According to [18] the obtained values allow to quantitatively and qualitatively assess the relative method accuracy of evaluation the aforementioned parameter for selected devices.

**Table 2.** Ranges of relative method errors in surface texture measurement and the corresponding applications [18].

| Measurement accuracy range (%) | Type of application                                      |
|--------------------------------|----------------------------------------------------------|
| 2÷5                            | Measurement of standards: roughness, waviness, form profiles |
| 5÷15                           | Scientific research                                      |
| 10÷25                          | Measurement of surface texture under industrial condition |

In order to investigate the possibility of application the selected measuring machines there were prepared five samples. The first research phase involved the assessment of the $h_{min}$ value in directly manner. The value was calculated based on the measuring points from the optical profilometer and it was adopted as reference value. The prism draft angle and the length of the zone where the milling process was not regular were taken into account to assess this value. The minimum chip thickness was calculated using trigonometric function.

The analogous procedure of assessment the minimum chip thickness was used for all measuring devices. However, in order to precise evaluation the locus of zone of initiating of cutting process it was performed filtration process of the images of surface layer. In this research, two-dimensional wavelet transform (mother wavelet bior6.8) and thresholding method were applied to better visualize the characteristic cutting zones. The obtained signals are shown in figures 3-7, whereas the calculated values of the parameter $h_{min}$ are presented in table 3.

**Figure 3.** View of the wavelet decomposition coefficients on the surface, Talyurf CCI (a) sample No. 2 (b) sample No. 4
Figure 4. View of the wavelet decomposition coefficients on the surface, O-Inspect a) sample No. 3 b) sample No. 5

Figure 5. View of the wavelet decomposition coefficients on the surface, MarVision, magnification x0.7 a) sample No. 2 b) sample No. 3

Figure 6. View of the wavelet decomposition coefficients on the surface, MarVision, magnification x1 a) sample No. 2 b) sample No. 3
Analyzing the surface images obtained as a result of application two-dimensional wavelet transform, it can be noted that despite the performing the filtration process, in some cases there were not possible to clearly determine the cutting zones during the initiation of the cutting process. The evaluation of characteristic zones require significant skill from the person performing the analysis. However, the $h_{\text{min}}$ parameter values presented in the above table for particular measuring machines were only slightly differ than reference values.

Formulas 1 and 2 were used in order to comprehensive evaluation of the possibility to apply the selected measuring machines to assess the minimum chip thickness. The DM parameter values which indicate the relative method accuracy are presented in table 4.

Table 3. The values of the $h_{\text{min}}$ parameter

| No. | draft angle | Talysurf CCI (μm) reference | wavelet analysis | O-Inspect (μm) x0.7 | x1 | x2 | MarVision (μm) |
|-----|-------------|----------------------------|------------------|---------------------|----|----|----------------|
| 1   | 0°33'59''   | 2.64                       | 2.56             | 2.67                | 2.89 | 2.90 | 2.79          |
| 2   | 0°36'14''   | 2.23                       | 2.09             | 2.41                | 2.25 | 2.26 | 2.38          |
| 3   | 0°37'23''   | 2.22                       | 2.12             | 2.18                | 1.92 | 2.12 | 2.14          |
| 4   | 0°35'44''   | 2.43                       | 2.60             | 2.50                | 2.59 | 2.50 | 2.38          |
| 5   | 0°30'54''   | 2.27                       | 2.32             | 2.20                | 1.77 | 2.04 | 2.11          |

Table 4. Relative method accuracy, (%)

| Talysurf CCI | O-Inspect x0.7 | O-Inspect x1 | O-Inspect x2 | MarVision x0.7 | MarVision x1 | MarVision x2 |
|--------------|----------------|--------------|--------------|----------------|--------------|--------------|
| DM           | 12.49          | 12.53        | 29.8         | 18.58          | 14.94        |

Figure 7. View of the wavelet decomposition coefficients on the surface, MarVision, magnification x2 a) sample No. 1 b) sample No. 4
The research result shown that all above-mentioned measuring machines can be used to assess the value of the $h_{\text{min}}$ parameter. The obtained values were in range of 12.49% to 29.8%. According to table 2, it can be concluded that the method which based on two-dimensional wavelet analysis can be used for scientific research. The most favourable result was obtained for the signals obtained from the optical profilometer (12.49%). This fact was probably related with the density of the measurement points and the exact surface mapping. A slightly higher value was obtained for the O-Inspect multisensor measuring machine (12.53%). The least favourable result was obtained for the MarVision workshop microscope. For the two magnification level, i.e., x0.7 (29.8%) and x1 (18.58%), the DM values were higher than 15%. It can also be stated that with the increasing the magnification level the obtained values decreased. For magnification x2, the relative method accuracy value was obtained on a satisfactory level of parameter value equal 14.94%.

4. Conclusion
The assessment of the minimum chip thickness value is key issue during choosing machining allowance for finishing process or the depth of cut, especially for machining for which depth of cut value is lowest than the value of radius of cutting insert. The evaluation of the $h_{\text{min}}$ parameter value is a process which require experience to proper interpretation of characteristics zones of the impact of cutting insert on the workpiece during initiation of the cutting process. The application of devices with high vertical and horizontal resolution make possible to assess correctly the parameter value. The analysis of the possibility of application optical measuring machines which resolution in the particular axes were significantly lower than resolution of optical profilometer showed that application of wavelet transform allowed to proper detect characteristic cutting zones in images. For the particular measuring devices, the relative method accuracy values allow to conclude that the method based on two-dimensional wavelet analysis can be used for scientific research. The most favourable results were obtained for optical profilometer Talysurf CCI (12.49%) and the multisensory measuring machine O-Inspect (12.53%). The application of wavelet analysis enabled the correct identification of the characteristic zones during initiating a cutting process. Particular cutting zones were not visible on surface images prior to perform wavelet filtration.

The study also included the evaluation of the influence of the magnification of the MarVision MM320 workshop microscope on the possibility to correct identification of the above mentioned zones. According to table 4, with the increasing of the magnification, the DM parameter value decreased. Only for magnification x2 the parameter value indicated that the workshop microscope can be used to assess the value of the $h_{\text{min}}$ parameter.

The research can be extended to evaluate the possibility of application two-dimensional wavelet transform to analyze images of surface layer obtained from other measuring machines or digital camera. Research can be carried out on a wider range of mother wavelet and milling process parameters for different types of cutting insert, in particularly for inserts which performed a specified number of work cycles.

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