ON THE COMPARISON OF CONTACT AND NON-CONTACT EVALUATIONS OF A MACHINED SURFACE

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Surface integrity of machined parts plays a crucial role in their use, efficiency, comfort and safety. The trend of more effective and low-consumption products forces the producers to reduce weight and dimensions of the industrial parts so the requirements on the machined surface quality evaluation is more important from many aspects. The booming trend in optical non-contact techniques seems to be a serious challenge to the traditional tactile methods. The paper deals with selected contact and non-contact evaluation methods of machined surface (Form Talysurf Intra, Taylor Hobson and IFM G4, Alicona) and relations between profile and 3Dsurface parameters when finishing face turning of AlCu4MgSi in a variety of feed rates. A good correlation for many amplitude and functional surface parameters has been found. Nevertheless, the paper reveals a big power of the optical focus variation technique for quality and functional predictions assessments.

Keywords:
surface roughness, surface metrology, stylus measurement, 3D optical methods, comparative study, statistical analysis.

Introduction

Manufactured components and their functional properties are heavily influenced by the material quality and the surface integrity of the machined surfaces [M'Saoubi 2008, Davim 2010]. Surface of a machined part can be inspected with many techniques with a wide range of shape and quality parameters in 2D or 3D. The trend of more effective and low-consumption products forces the producers to reduce weight and dimensions of the industrial parts so the requirements on the machined surface quality evaluation is more important from many aspects like wear, leakage of oils, etc. The booming trend in optical non-contact techniques seems to be a serious challenge to the traditional tactile methods, esp. in the 3D surface assessments, but the problem of correlation and reliability should be studied urgently due to many reasons. However, the comfort and new parameters open new view on the quality and competiveness of producers.

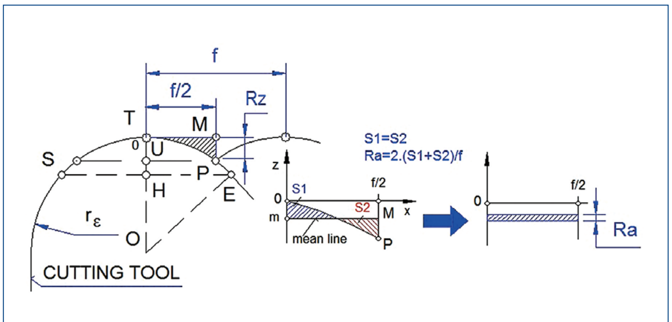

***Figure 1.** A scheme of longitudinal turning – residual machined surface and a model for the Ra roughness prediction.*

Theory

Surface roughness in engineering industry is traditionally defined by two profile parameters – arithmetical mean deviation of the assessed profile Ra and average maximum height of assessed profile Rz [De Chiffre 1999,Petersa 2001]. These profile parameters are the most commonly used and accepted by researchers and production engineersbecause of the simplicity of their geometrical meaning – Fig. 1. In the figure the residual surface after two cutting paths made by a tool with tip radius r_e with a feed per rotation f is showed. The roughness average represents the area between the roughness profile and its central (mean) line marked as m, or the integral of the absolute value of the roughness profile height over the sampling length.

According to the [ISO 4287:1997] the integral formula of Ra can be expressed as

$$Ra = \frac{1}{l_r}\int_0^{l_r}|z(x)|\,dx, \tag{1}$$

where is z(x) is the height profile deviation from the mean line and lr is the sampling length. Nowadays, the simplified equation computing Ra from the data file of z_i by the software can be approximately calculated as:

$$Ra = \frac{1}{n}\sum_1^n|z_i|. \tag{2}$$

A theoretical value of Ra for the longitudinal turning can be predicted according to the equation [Davim 2010]:

$$Ra = \frac{1000f^2}{18\sqrt{3}r_\varepsilon} \tag{3}$$

where f [mm] is a feed per rotation and r_ε [mm] is the corner radius of a cutting tool. The theoretical function of Ra for selected range of variables can be seen in Fig. 2.

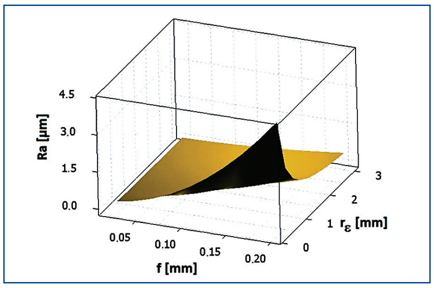

***Figure 2.** A prediction of the Ra theoretical value for a longitudinal turning as a function of feed and corner radius.*

The partial derivatives with respect to the continuous variables lead to the general forms

$$\frac{\partial Ra}{\partial f} = C_1.p, \quad resp. \quad \frac{\partial Ra}{\partial r_\varepsilon} = C_2.p^2, \tag{4}$$

where C1, C2 are computational constants and p = f/r_ε. A deeper analysis for standard cutting conditions and geometry confirms the prevailing role of the feed compared to effect of the cutting edge radius. Conventionally, surface roughness measurement has been performed by using a stylus instrument in the perpendicular orientation of the stylus to the cutting tool path. When a stylus traverses the surface, the vertical motion of the stylus is converted into an electrical signal that is processed. However, this method has two disadvantages:

- it is a measurement in one direction to the surface of a workpiece,
- it is a contact loading of the analysed place, so the contact pressures can plastically deform or scratch the surface being measured, especially speaking of soft materials.

New progress in the measuring techniques have been made in last two decades,so that a 3D surface structure of the precisely machined surfaces with by means of optical and non-optical methodscan be acquired and analysed and compared [Ohlidal 1999, Lonardo 2002, De Chiffre 2000,Valicek 2001, Demircioglu 2011, Nwaogu 2013]. Moreover, an isotropy and anisotropy of machined surfaces is also considered and volumetric parameters can be quantified.

In this experimental study, both surface measuring systems have been examinedand some other useful data have been estimated.

The profile parameters Ra, Rq and the bearing curve/material ratio parameters (Rk, Rpk, Rvk, Rmr1, Rmr2) have been assessed and compared. The reason for a study of Rq parameter is its higher sensitivity to the profile peaks and valleys compared to Ra because of the square function of the height deviations z(x). Rq is widely used for finished and optical surfaces.

$$Rq = \sqrt{\frac{1}{l_r}\int_0^{l_r} Z^2(x)\,dx} \tag{5}$$

The analogical surface parameters according to the standard are the arithmetical mean height of the scale-limited surface Sa

$$Sa = \frac{1}{A}\iint_A |z(x,y)|dx\,dy, \tag{6}$$

and the root mean square height of the scale-limited surface Sq as

$$Sq = \sqrt{\frac{1}{A}\iint_A z^2(x,y)dx\,dy}. \tag{7}$$

From many surface parameters (height, spatial, hybrid and miscellaneous) the 3D variance of the Abbott-Firestone curve emerges with analogical parameters: Vmp (peak material volume of the scale-limited surface), Vmc (core material volume of the scale-limited surface), Vvc (dale void volume of the scale-limited surface) and Vvv (core void volume of the scale-limited surface)– Fig. 3.

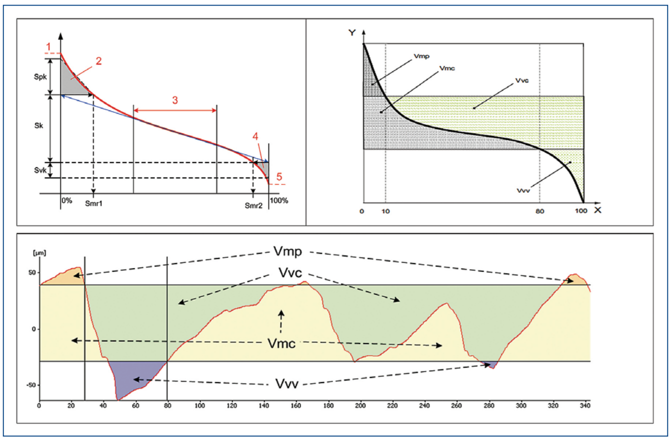

Figure 3. *The Abbott-Firestone curves - significant areas, limitations and the surface (left) and volume (right and at the bottom) parameters [Alicona].*

Objective

The goal of this research work is to obtain mathematical models of Ra and Rq estimating the coefficients of the linear equation, involving the feed as the independent variable.The main goal of the research was focused on comparison of the contact and non-contact methods, comparisons and analyses of some selected 2D/3D parameters.

The aluminium alloy AlCu4MgSi in a blank of ϕ 202/1000 mm and the chemical composition according to the Tables 1,2 and material structure (Fig. 4) was used. Two discs of 40 mm in length were cut-off and pre-machined for the finishing turning.

Ultimate tensile strength Rm [MPa]	360-400
Yield strength $R_{p0,2}$ [MPa]	220-270
Minimal failure elongation A [%]	8-10
Brinell hardness [HB]	105

Table 2. *Mechanical properties of the AlCu4MgSi (according to the Rio Tinto Group Material Certificate).*

The twin-spindle turning centre SPY280 CNC/Sinumerik 840DSl with Shop Turn integrated system was used (Kovosvit, a.s., Sezimovo Usti). The tool holder SGBTU 25-6G with the tool blade CGHN 32-5D, and uncoated indexable insert GIPA-6.00-3.00 (grade ISO 513 N05-N25) with corner radius r_ε=3.001 mm and cutting edge r_n=2.884 µm were selected (ISCAR CR, s. r. o., Plzen). A face turning of 9 surfaces, each of 10 mm width (apart of the central surface close to the rotational axis) was done. The constant cutting speed v_c=200 m/min and axial depth ofcut a_p=0.1 mm was set. Feed per rotation was variable in the arithmetical range 0.02-0.18 mm. External turning and cooling with Cimstar 597 HD emulsion (6%, cooling rate 20 l/min) was set.

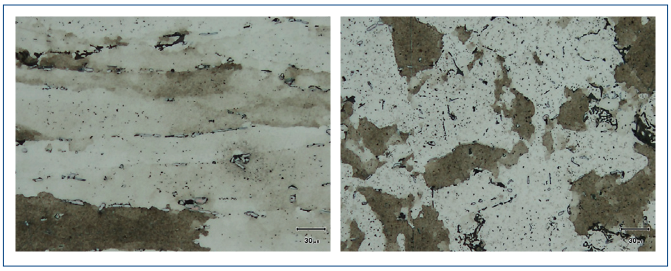

Figure 4. *Longitudinal (left) and cross-sections (right) of the blank rod material (Fuss 2%) – α-Al(f.c.c.), binary eutectic of α+$CuAl_2$ on the grain borders, tiny crushed particles of ternary eutectic α+$CuAl_2$+$Cu_2Mg_2A_5$ and some tiny particles of Mg_2Si,$FeAl_3$, AlFeMnSi, AlCuFeMn.*

A standard Form Talysurf Intra 50,Taylor Hobson GmbH (as "Taylor Hobson" in the graphs) with the stylus tip radius 2 mm was used for the contact surface measurements – Fig. 5. A new measuringmicroscope IFM G4, Alicona, GmbH, Graz, Austria (as "Alicona" in the graphs) based on a new non-contact optical surface characterization technique called "focus variation" was used. This technique enables the device to build true 3D images of macroscopic surfaces and microscopic structures as well. Its operating system combines the small depth of focus of a classical optical systemwith vertical scanning to provide 3D topographical and true colour information from the variation of the focus [ISO/DIS 25178-606]. This non-destructive technique uses a coaxial white light (common or polarized) or the ring light. The system provides dense measurements over large areas with a density of 2 Mio – 25 Mio measurement points. For IFM G4 (Alicona, 2014) the best vertical resolution (for the lens 100x) was 10nm, and minimal measurable roughness (Ra) was 30 nm. Accuracy for roughness measurement of the microscope in term of uncertainty was U = 25nm at Ra =100nm. For Form Talysurf Intra 50 the vertical resolution was 16 nm in 1 mm range and height uncertainty parameter for peak parameters was within 2% + 6nm (Taylor Hobson 2014).

Each measurement with both devices was redone five times in four places at the 90° quadrants, but similar values for the same techniques were found within each quadrant. The graphs in the paper represent the average values and range of the minimal and maximal values (apart of the 3D parameters, where the data matrices were much higher). The measurements were taken with commercially

Fe	Si	Mn	Cr	Cu	Mg	Zn	others	–
0.7 max.	0.2-0.8	0.4-1.0	0.1 max.	3.5-4.5	0.4-1.0	0.25 max.	each 0.05; 0.15 in total	Zr+Ti< 0.25; Al – rest

Table 1. *Chemical composition of the alloy AlCu4MgSi (wt. %).*

Figure 5. *The compared contact (Form Talysurf Intra 50, Taylor Hobson GmbH – left) a and non-contact (IFM G4, Alicona – right) devices, examples of the workpiece measurement.*

available instruments with no special adjustment according to the standards [ISO 25178-2:2012, ISO 25178-3:2012] and [ISO 25178-601:2010]. The analysis of variance (ANOVA)and regression analysis (Minitab® 17) were used as the statistical tools.

Experimental Results

Parameter Ra

Due to short time of machining any significant wear of cutting tool or a built-up-edge production were found. The chip was continuous, short, not affecting the machined surface or interfering with cooling fluid. Furthermore – a very good correlation of the average and pooled Ra values for both techniques has been found – Fig. 6. However, the theoretically predicted Ra values including the real trend were in contrast, esp. in the range of feeds 0.02-0.06 mm, resp. 0.16-0.18 mm.

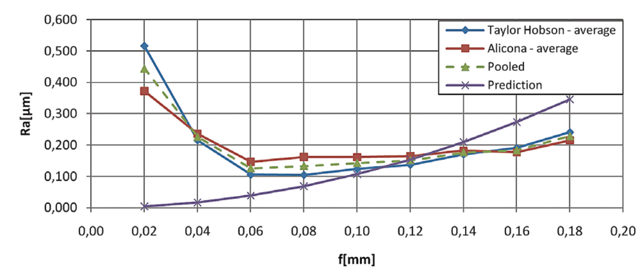

Figure 6. *A comparison of the arithmetical mean deviations of the assessed profiles by different methods.*

A detailed analysis of the surfaces confirmed statistically significant (α=0.05) aperiodic waviness of the surfaces at the outer disc border– caused by vibrations. The chattering marks and sound effect could also be easily found in the audible sound spectrum, but the waviness was very evident at the surface analysis of affected surfaces – Fig. 7. For these reasons surfaces machined with feeds 0.02 and 0.04 mm were excluded from following studies.

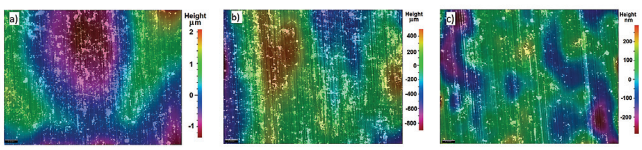

Figure 7. *Waviness for surfaces with feeds per rotation: a) f=0.02 mm, b) f=0.04 mm, c) f=0.06 mm.*

Fig. 8 confirms a general parabolic trend of the Ra parameter for all measured data with acceptable statistical coefficient of determination R^2=0,975:

$$Ra = 0,0025.f^2 - 0,0042.f + 0,13. \tag{8}$$

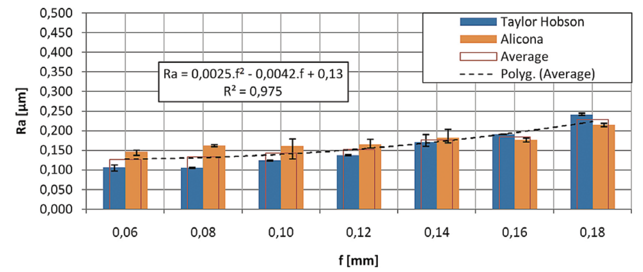

Figure 8. *Thestatistically evaluated arithmetical mean deviations of the assessed profiles.*

Parameter Rq

The individual measurements can be seen in Fig. 9,10 (the dotted lines represent the regression models). On the base of the datasome differences for the values dependent on the techniques have been found, but a very significant linear relation for Rq have been found with the same multiplicative constant for the contact and the non-contact method of the measurements:

$$Rq = 1{,}23 \cdot Ra \quad [\mu m] \tag{9}$$

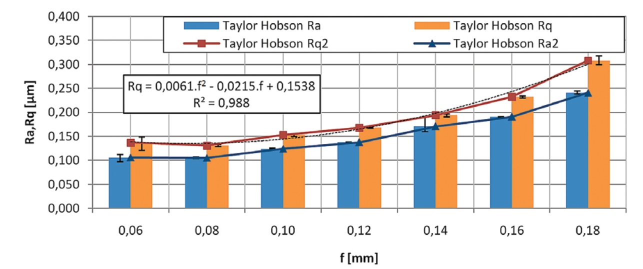

Figure 9. *The measured values of Ra and Rq for the machined surfaces – the contact method.*

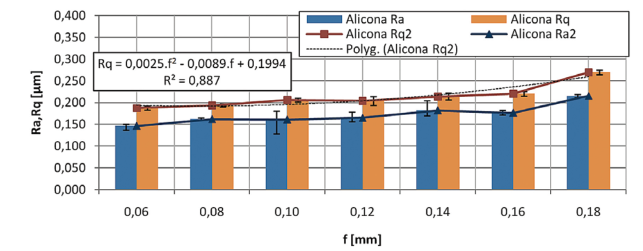

Figure 10. *The measured values of Ra and Rq for the machined surfaces – the non-contact method.*

Bearing (Abbott-Firestone) curve parameters

A very good correlation for the core roughness depth Rk as a function of feed for the contact method of measurement can be seen in Fig. 11. The values of Rk and Sa acquired by contactless (non-contact) technique oscillate along the feed values – in a similar way. For a better comparison of the amplitude parameters some surface parameters Sa, Sk, Spk, Svk, Smr1, Smr2 have been added – Fig. 11-15.

The reduced peak height Rpk is analysed in the Fig. 12. This parameter is used to characterize protruding peaks that might be eliminated during function and a very good correlation was found for the contact Taylor-Hobson measurements. Similarly, the parameter Rvk (that quantifies the reduced valley depth) is analysed in the Fig. 13. This parameter is used to characterize the valleys that will

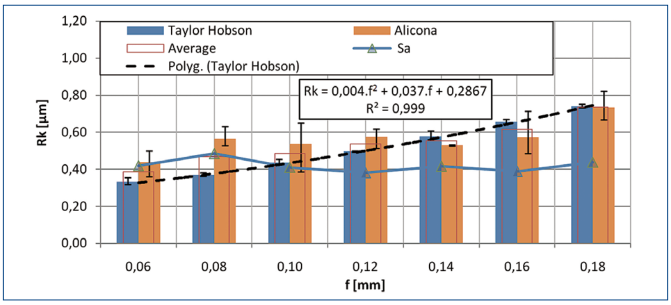

Figure 11. *The core roughness depth Rk as a function of feed for the contact and non-contact measurement method (the regression model belongs to the contact method of measurement).*

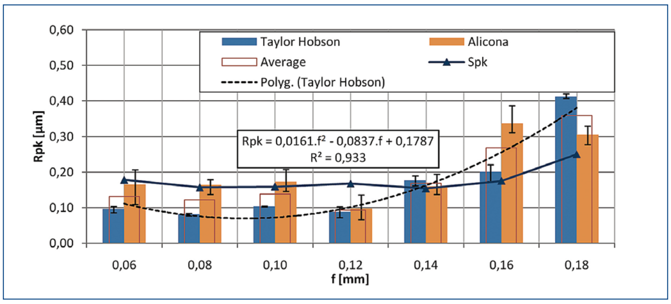

Figure 12. *The reduced peak height Rpk as a function of feed (the regression model belongs to the contact method of measurement).*

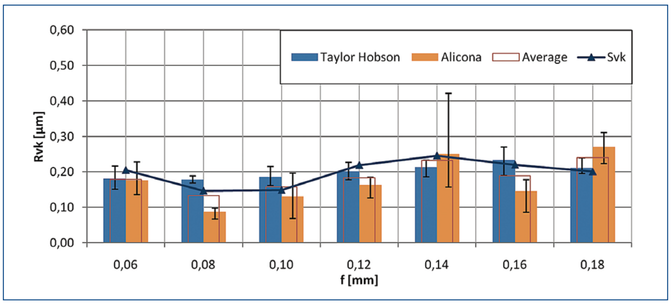

Figure 13. *The parameter Rvk (reduced valley depth) as a function of feed.*

retain lubricant or worn-out materials and a good correlation can be found for the contact measurements. For both parameters the surface parameters Spk and Svk follows the trends in the studied range of feeds, but only a slight increase Rpk for the feeds 0,16-0,18 mm has been found.

The analyses of material ratio delimiting the core area are shown in Fig. 14, 15.

Due to a bigger dispersion of Sa data – Fig. 16 – the relation for Sq can be expressed in the statistical mean interval regression (confidence 95%, for Alicona):

$$Sq = (1.254\text{-}1.310)\cdot Sa \quad [\mu m], \tag{10}$$

and the relations between the surface and amplitude means as the linear function of feed can be expressed as

$$Sa = (1.038-2.285.f)\cdot Ra \quad [\mu m], \tag{11}$$

and

$$Sq = (1.054\text{-}2.231.f)\cdot Rq \quad [\mu m]. \tag{12}$$

Finally, the volume parameters Vmp, Vmc, Vvc, Vvv were studied – Fig. 17, but it seems that no significant relation to the variable

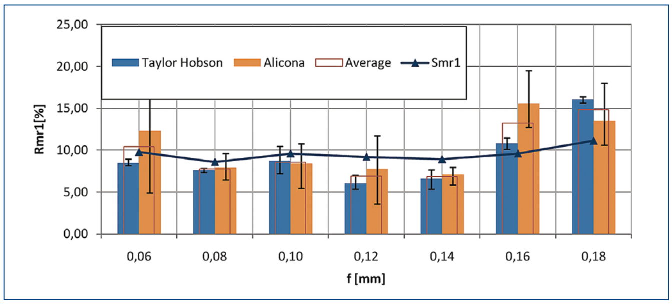

Figure 14. *The material ratio parameter R_{mr1} delimiting the core area.*

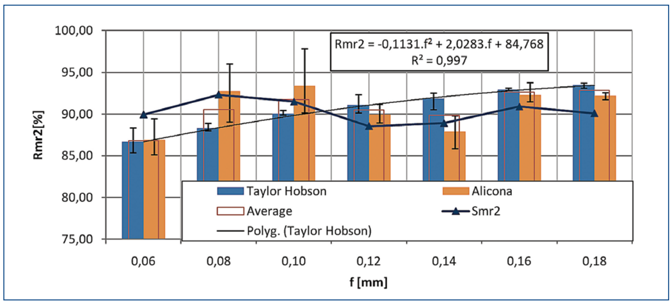

Figure 15. *The material ratio parameter Rmr2 delimiting the core area.*

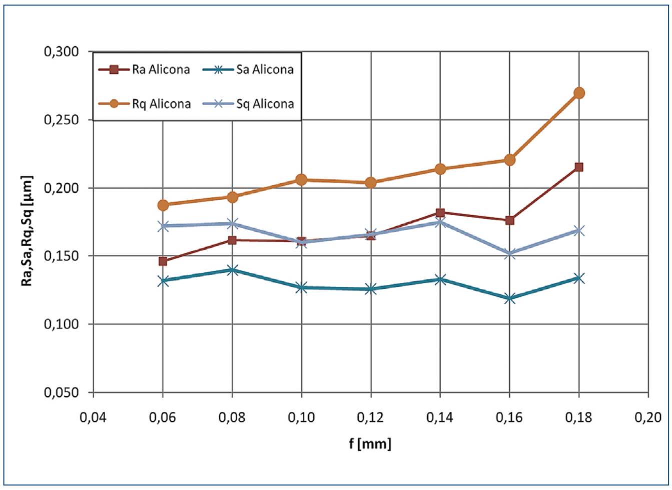

Figure 16. *The analyses of the amplitude parameter Ra and its 3D surface analogy – the parameter Sa.*

feed can be derived from the experiments and the material core and void volume ratios for such machining were approximately constant, confirming just a good quality of the surface because of high share of bearing material, and Vmp (resp. Vvv) corresponding with the Spk (resp. Svk) trends against the feed.

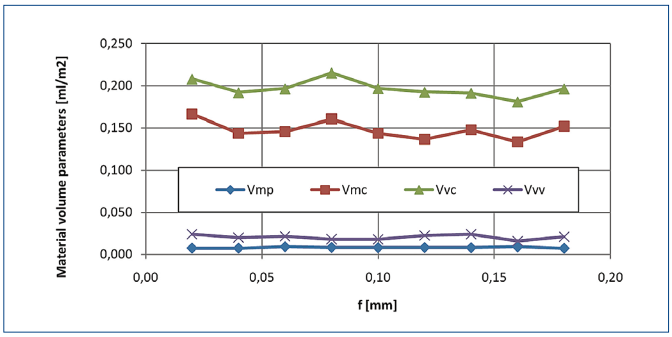

Figure 17. *The material volume parameters.*

Discussion

The main goal of the research was focused on the Ra parameters measured by the contact and non-contact methods, but some selected surface and volumes parameters have been analysed as well.

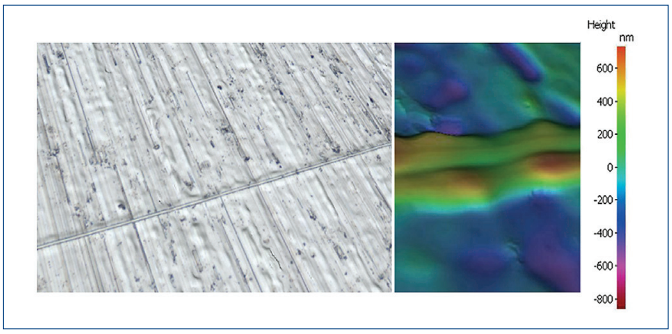

Figure 18. *A ploughed furrow of the stylus in the measured surface.*

The capabilities of the two measurement systems have been tested successfully. The main focus of the paper was focused on the Ra parameters measured by the contact and non-contact evaluations. This research presents an experimental study of the roughness analyses of the conventionally turned sample with CNC and flat surfaces in order to compare the data obtained from the contact stylus measurement device with anon-contact optical surface measurement instruments.

Both devices confirmed very good and similar results in the comparable measured variables, however, the predicted theoretical values e.g. of Ra were higher. The explanation can be seen in the reduced plastic flow of the machined material and its structural anisotropy. The major disadvantage of using a stylus instrument is that it requires direct physical contact, which limits the measuring speed and can course some micro-scratches – Fig. 18. Also the data could be possibly affected.It is observed that the two devices give very comparable results if the surface has a good reflection value, is not very fine machined surface with a periodic profile and not damaged, contaminated or scratched. A lot of spatial, hybrid and miscellaneous 3D parameters are being under statistical assessment now.

Conclusions

The results from the measurements can´t be overestimated, because of the high reflexivity of the machined surfaces and relatively soft machined material. However, some good correlations for a very typical surface parameters used in nowadays practice have been found. The industry will use both of the techniques because each of them has many advantages. The trend today shows the non-contact methods as very powerful, but also more expensive ones. The relation between the surface parameters and functional impacts should be studied as well in a continuing research.

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