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## 3D SURFACE ANALYSIS OF MILLING SURFACES: STATISTICAL EVALUATION AND APPLICATION OF THE ABBOT CURVE

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**Abstract:** This study analyses milled surfaces using Alicona measurements with various lenses, focusing on area-based surface evaluation. The analysis uses Alicona software, comparing different parameters and performing statistical evaluations. A key aspect is to assess the added value of area-based evaluation using Abbott curves, as well as the influence of the sampling interval on the parameters, in accordance with ISO 25178 standards. In addition, the study examines different surface regions to derive meaningful interpretations of surface functionality. The results provide insight into the practical application of 3D surface parameters and their relevance in the characterization of engineering components.

**Key words:** Surface measurement, Abbott curve, ISO 25178, milling inserts, statistical evaluation, 3D surface analysis.

### 1. INTRODUCTION:

The surface roughness of a workpiece is influenced by the manufacturing process, including machine vibrations, plastic deformation of the material and friction between the tool and the material [1]. Surface topography analysis is a crucial aspect of quality assurance [2]. The surface finish has a direct effect on functional properties such as friction, wear resistance, tightness, corrosion behavior and the visual appearance of the workpiece [3]. Traditionally, the characterization of technical surfaces has been based on profile measurements in accordance with the DIN EN ISO 21920-2 standard ([4]). However, with the increasing availability of optical 3D measuring systems, area-based parameters in accordance with DIN EN ISO 25178-2 are becoming more important ([5]). The complexity of the surface can be captured much better without replacing the profile-based methods. Rather, they represent a useful addition [3] [6]. It is recommended that the measured values of the surface parameters are not directly compared with the tolerance requirements of the profile parameters. Although the values correlate with each other, they are not directly comparable. Larger values are assumed for surface

parameters that characterize the extreme values on the surface. The reason for this is that the “peaks and troughs” shown in the profile do not represent the actual extreme values. In contrast to the stylus method, which is based on a contact method, non-contact methods are used for the areal measurement of surface parameters. This also offers potential for deviations between profile and surface measurement values [6]. An overview of the parameters of the areal- and profile surface parameters and their use can be found, for example, in the work by Baofeng He et. al. ([3]). The functional properties can be described using the Abbott-Firestone curve. This material proportion curve was originally developed in Germany to analyze the tribological properties of cylinder liners and provides information on the load-bearing capacity and wear resistance of components [7]. The manufacturing process influences the shape of the material ratio curve [8]. Since then, it has proven itself in numerous industrial and even medical applications.

This article examines how different measurement conditions, in particular the choice of lens, resolution and evaluation area, affect the parameters of the Abbott-Firestone curve. The aim is to develop practical recommendations for the robust application of this method.

## THEORETICAL BACKGROUND:

The Abbott-Firestone curve provides important information on the tribological properties of the surface. It divides the surface into three functional zones. The peak zone, which is relevant for running-in wear, the core zone, which is stressed throughout the entire service life of the component, and the valley zone, which is decisive for lubricant retention under severe conditions [9]. A practical and industrially relevant application is the assessment of the oil retention capacity of cylinder liners. If the oil retention volume is too large, the oil consumption increases; if the oil retention volume is too small, the tendency of the pistons to seize increases. Sufficient lubricant retention capacity is also crucial for the service life of other machine components, such as plain or roller bearings [8]. In addition to automotive technology, the material content curve is also increasingly being used in medical technology. Examples include the determination of tooth enamel wear [10], and the surface changes to the tooth structure [11]. It is also used in the evaluation of complex, laser-hardened and ultrasonically peened surfaces [12].

The Abbott-Firestone curve is formed by determining the ratio of the area  $A_c$  to the area of the evaluation range  $A$ . The determination of the material proportion curve is shown schematically in Fig. 1. [5].  $A_c$  corresponds to the surface area that is intersected by a plane at height  $c$ . The height  $c$  is determined against a reference height  $c_0$ . By default,  $c_0$  is at the highest point of the surface, but can also be set to a different height. The material percentage is plotted on the abscissa with the axis designation  $X$  and is specified either as a percentage or as a value in the interval  $[0,1]$ . The position of the cutting plane is specified on the ordinate with the axis label  $Y$ . The parameter  $d$  shown in Fig. 1. indicates the proportion of material at height  $c$  [5] [13].

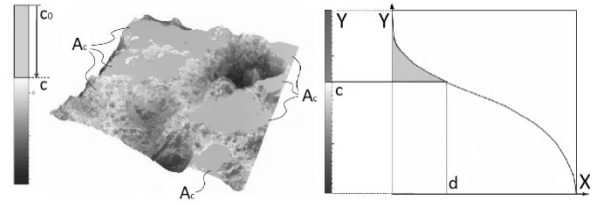


**Fig. 1.** Determination of the material proportion curve [5]

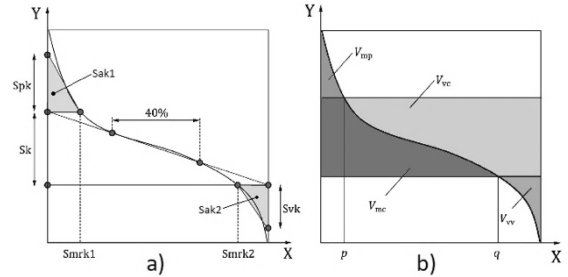


**Fig. 2.** Calculation of the parameters [5]

This curve is analyzed using standardized parameters such as  $Sk$  (core height),  $Spk$  (reduced peak height),  $Svk$  (reduced valley height) as well as  $Smrk1$  and  $Smrk2$  (material proportions). They allow a functional evaluation of the load-bearing capacity, wear resistance and lubrication behavior of a surface. However, these parameters are only meaningful if the material content curve has a typical S-shape - a criterion that is particularly fulfilled for ground, honed or finely machined surfaces [5].

The determination of the surface parameters  $V_{mp}$ ,  $V_{mc}$ ,  $V_{vv}$ , and  $V_{vc}$ , is shown schematically in Fig. 2. b). The positions  $p$  and  $q$  marked on the abscissa assume the default values  $p = 10\%$  and  $q = 80\%$  for the specified parameters.  $V_{mp}$  indicates the peak material volume,  $V_{mc}$  the material volume of the core,  $V_{vv}$  the empty volume of the valleys and  $V_{vc}$  the empty volume of the core [5] [6].

## 2. TEST EXECUTION:

Two series of tests were carried out to investigate the influence of different measuring conditions. The basis was a block made of stainless steel 316L (1.4404), which was applied to a carrier plate using plasma welding and then milled flat. A face milling cutter M3024-063-B22-06-04 and indexable insert type XNGU0705ANN-F57 WSM35G from Walter were used for the machining. The selected cutting values are listed in Table 1.

**Table 1: Cutting parameters**

|           | $v_c$<br>[m/min] | $f_z$<br>[mm] | $Z$<br>[-] | $a_p$<br>[mm] | $a_c$<br>[mm] |
|-----------|------------------|---------------|------------|---------------|---------------|
| Roughing  | 120              | 0,12          | 6          | 1,5           | 50            |
| Finishing | 120              | 0,08          | 6          | 0,2           | 50            |

**Test series 1:** The influence of lens selection, lateral / vertical resolution and data reduction was investigated here. Three lenses (20x, 50x, 100x) were used, with five identical positions on the surface being measured in each case. The parameters are listed in Table 2. Care was taken to ensure that overlapping areas could be evaluated comparably. The maximum possible number of data points of the software used was approx. 30 million, which in some cases requires data reduction. The evaluation was always carried out with a nesting index  $L_c = 800 \mu\text{m}$ . The selection of the lateral and vertical resolution as well as the evaluation range was based on the specifications of DIN EN ISO 25178-3 ([6]), which defines a maximum permissible sampling interval as a function of the refinement index. This enabled standard-compliant evaluation of the surfaces.

**Table 2: Measurement parameters for Fig. 3 - 14**

| x-Axis | Lens | Resolution             |                        | Lateral data reduction |
|--------|------|------------------------|------------------------|------------------------|
|        |      | L<br>[ $\mu\text{m}$ ] | V<br>[ $\mu\text{m}$ ] |                        |
| a      | 100x | 0,5                    | 20                     | 1x                     |
| b      | 100x | 1                      | 20                     | 1x                     |
| c      | 100x | 1,5                    | 20                     | 1x                     |
| d      | 50x  | 1,5                    | 20                     | 1x                     |
| e      | 50x  | 2                      | 20                     | 1x                     |
| f      | 50x  | 2,5                    | 20                     | 1x                     |
| g      | 50x  | 2                      | 50                     | 1x                     |
| h      | 50x  | 2,5                    | 50                     | 1x                     |
| i      | 20x  | 2                      | 50                     | 0x                     |
| j      | 20x  | 2                      | 50                     | 1x                     |
| k      | 20x  | 2,5                    | 50                     | 0x                     |
| l      | 20x  | 2,5                    | 50                     | 1x                     |

The results of the evaluations are shown as box plots in Fig. 3 - 11. Fig. 12 - 14 provides an overview of the mean values of the measurement series. Even at first glance, the 20x lens provides significantly different values compared to the 50x and 100x lenses, while there is broad agreement between 50x and 100x except for the  $\text{Smrk2}$  parameter.

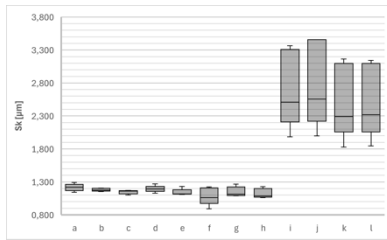


**Fig. 3.  $S_k$**

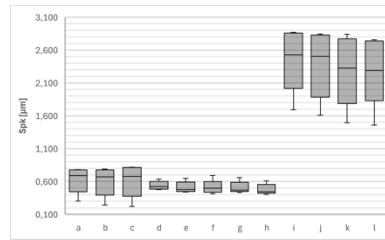


**Fig. 4.  $S_{pk}$**

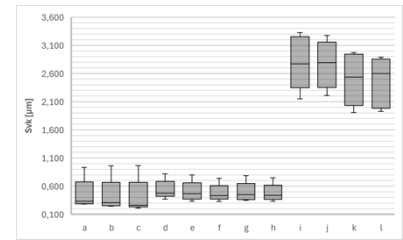


**Fig. 5.  $S_{vk}$**

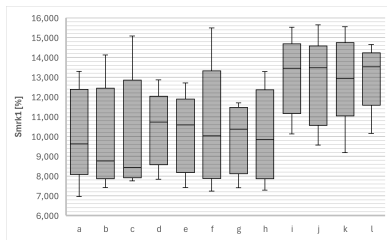


**Fig. 6.  $\text{Smrk1}$**

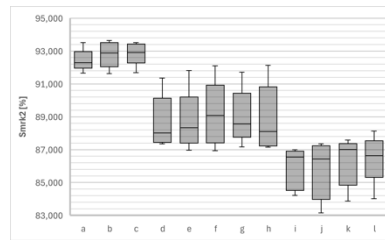


**Fig. 7.  $\text{Smrk2}$**

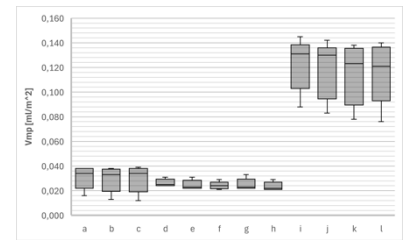


**Fig. 8.  $V_{mp}$**

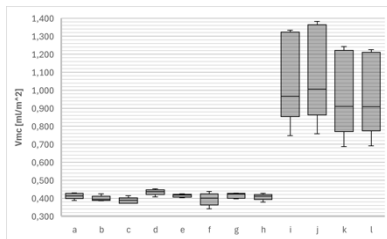


**Fig. 9.  $V_{mc}$**

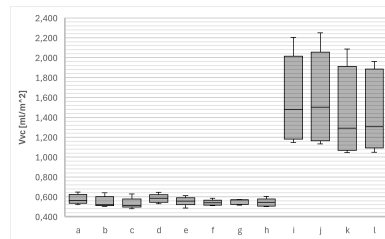


**Fig. 10.  $V_{vc}$**

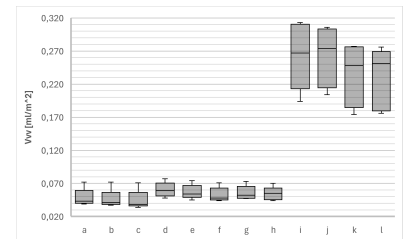


**Fig. 11.  $V_{vv}$**

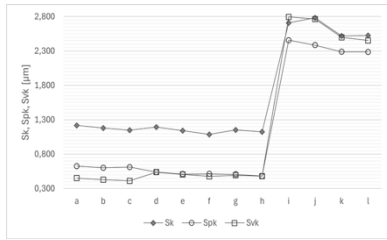


**Fig. 12.** Mean values of  $Sk$ ,  $Spk$ ,  $SvK$

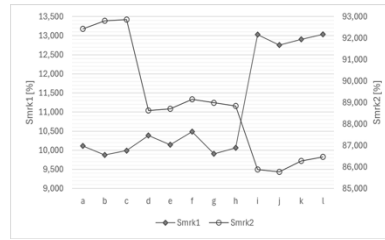


**Fig. 13.** Mean values of  $Smrk1$ ,  $Smrk2$

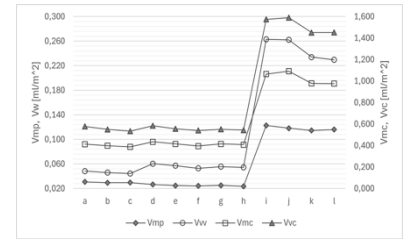


**Fig. 14.** Mean values of  $Vmp$ ,  $Vvv$ ,  $Vmc$ ,  $Vvc$

**Test series 2:** In accordance with DIN EN ISO 25178-1 ([13]), the possibility of adapting the evaluation range to the respective measurement task via the [OR(n)] parameter was considered in this test series. The aim was to analyze the influence of the size of the evaluation area. For this purpose, an area of 4.8 x 4.8 mm was measured and then segmented into seven squares of different sizes

(400 – 4800  $\mu\text{m}$ ). The measurement parameters are given in Table 3. Triple lateral data reduction was used for the acquisition. This resulted in around 50 million data points. During the evaluation, a further lateral data reduction to around 30 million data points was necessary in order not to exceed the limit of the evaluation software in the version used. The nesting index  $Lc = 800 \mu\text{m}$  was also used here.

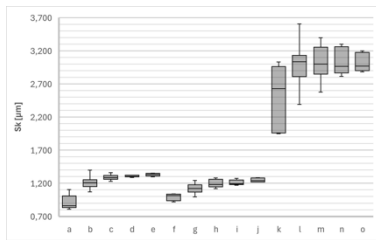


**Fig. 15.**  $Sk$

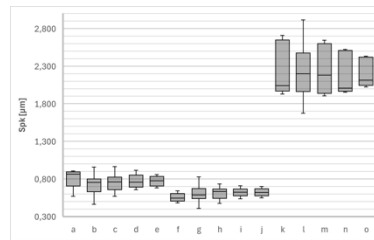


**Fig. 16.**  $Spk$

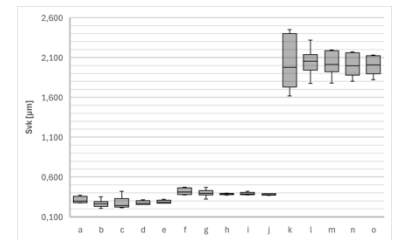


**Fig. 17.**  $SvK$

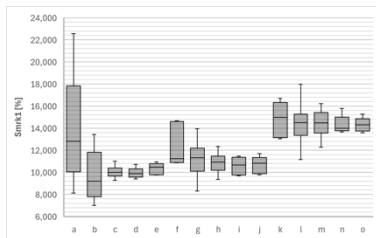


**Fig. 18.**  $Smrk1$

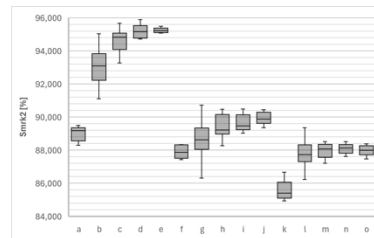


**Fig. 19.**  $Smrk2$

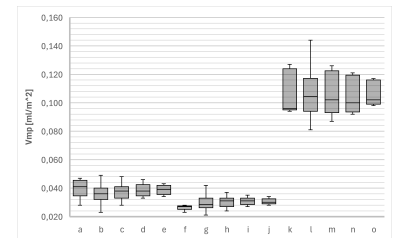


**Fig. 20.**  $Vmp$

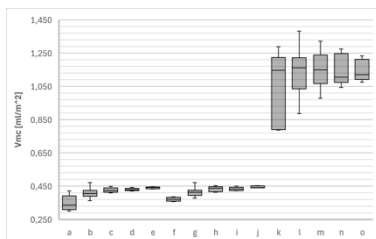


**Fig. 21.**  $Vmc$

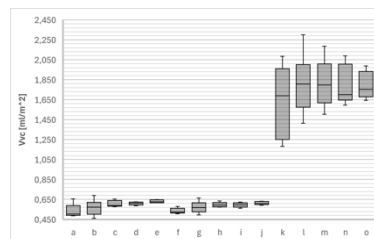


**Fig. 22.**  $Vvc$

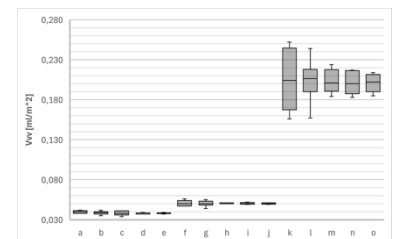


**Fig. 23.**  $Vvv$

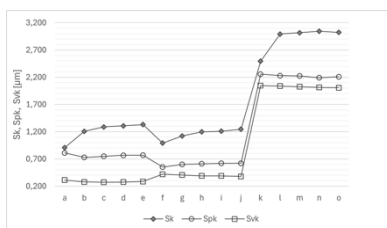


**Fig. 24.** Mean values of  $Sk$ ,  $Spk$ ,  $SvK$

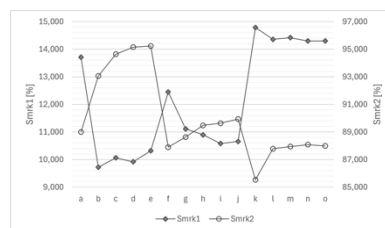


**Fig. 25.** Mean values of  $Smrk1$ ,  $Smrk2$

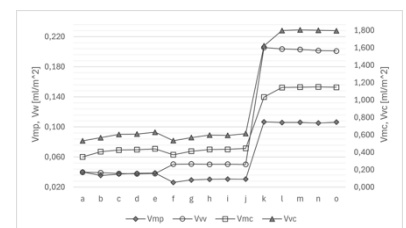


**Fig. 26.** Mean values of  $Vmp$ ,  $Vvv$ ,  $Vmc$ ,  $Vvc$

**Table 3: Measurement parameters for Fig. 3 - 14**

| Lens | Resolution     |                 | Nesting Index |
|------|----------------|-----------------|---------------|
|      | Lateral L [μm] | Vertical V [nm] | Lc [μm]       |
| 20x  | 2,5            | 100             | 800           |
| 50x  | 2              | 50              | 800           |
| 100x | 1              | 20              | 800           |

To ensure comparability, identical surface areas were examined for all three lenses. Due to the large amount of data, the reduction was applied evenly to all segments. In this series of tests, the resulting parameter values were also displayed in box plots (Fig. 15 - 23) and their mean value comparisons (Fig. 24 - 26). The measurement parameters are shown in Table 4.

**Table 4: Measurement area and lens**

| x-Axis | Lens | Measurement area | Number of measurements |
|--------|------|------------------|------------------------|
| a      | 100x | 0,4 x 0,4 mm     | 5                      |
| b      | 100x | 0,8 x 0,8 mm     | 36                     |
| c      | 100x | 1,6 x 1,6 mm     | 9                      |
| d      | 100x | 2,4 x 2,4 mm     | 5                      |
| e      | 100x | 3,2 x 3,2 mm     | 5                      |
| f      | 50x  | 0,4 x 0,4 mm     | 5                      |
| g      | 50x  | 0,8 x 0,8 mm     | 36                     |
| h      | 50x  | 1,6 x 1,6 mm     | 9                      |
| i      | 50x  | 2,4 x 2,4 mm     | 5                      |
| j      | 50x  | 3,2 x 3,2 mm     | 5                      |
| k      | 20x  | 0,4 x 0,4 mm     | 5                      |
| l      | 20x  | 0,8 x 0,8 mm     | 36                     |
| m      | 20x  | 1,6 x 1,6 mm     | 9                      |
| n      | 20x  | 2,4 x 2,4 mm     | 5                      |
| o      | 20x  | 3,2 x 3,2 mm     | 5                      |

### 3. INTERPRETATION AND RESULTS

The results show that the lens choice and the setting of the lateral and vertical resolution have a significant influence on the determined area parameters of the material fraction curve. The 20x lens in particular delivers significantly different values for almost all parameters (Sk, Spk, Svk, Smrk1, Smrk2, Vmp, Vmc, Vvc and Vvv) compared to the 50x and 100x lenses. These deviations are due to the lower resolution and the associated data reduction.

In contrast, the 50x and 100x lenses show largely comparable results. Only the Smrk2 parameter, which describes the proportion of material in the valleys, shows noticeable differences - an indication of the sensitivity of this value to the measurement conditions.

The investigation of different evaluation areas shows that larger areas lead to more stable mean values. Small evaluation areas are more susceptible to local topographical fluctuations, while areas that are too large can be distorted by macrostructures. An evaluation range of around 800 μm therefore represents a practicable compromise.

The results underline the suitability of the Abbott-Firestone curve for the functional characterization of technical surfaces. At the same time, they show the necessity of a coordinated measurement strategy to enable reproducible and reliable statements.

### 4. CONCLUSIONS AND OUTLOOK

The study emphasizes the relevance of areal surface analyses according to DIN EN ISO 25178 for the evaluation of milled surfaces. The Abbott-Firestone curve allows a targeted functional classification regarding load-bearing capacity, wear behavior and lubricant retention. This shows that insufficient resolution, for example due to low magnification or excessive data reduction, can significantly impair the informative value of the parameters. A stable measurement configuration, consisting of at least 50x magnification, a constant data structure and an evaluation range close to the nesting index, provides reliable results. For further work, the analysis of additional materials and machining processes such as grinding, honing or laser treatment is recommended. In addition, an in-depth investigation into the influence of software filters and AI-supported evaluation methods would be of interest. In the future, these could contribute to automated, robust quality assessment in industrial production.

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## ANALIZA 3D A SUPRAFETELOR DE FREZARE: EVALUARE STATISTICĂ ȘI APLICARE A CURBEI ABBOT

**Rezumat:** Acest studiu analizează suprafețele frezate folosind măsurători Alicona cu diferite obiective, concentrându-se pe evaluarea suprafețelor pe bază de suprafață. Analiza este efectuată utilizând software-ul Alicona, comparand diferiți parametri și efectuând evaluări statistice. Un aspect cheie este evaluarea valorii adăugate a evaluării bazate pe suprafață utilizând curbele Abbott, precum și influența intervalului de eșantionare asupra parametrilor, în conformitate cu standardele ISO 25178. În plus, studiul examinează diferite regiuni de suprafață pentru a obține interpretări semnificative ale funcționalității suprafeței. Rezultatele oferă o perspectivă asupra aplicării practice a parametrilor de suprafață 3D și a relevanței acestora în caracterizarea componentelor tehnice.

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