Definition of 3-D Surface Parameters

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Objective:

In order to improve the tribological properties of sheet metal when deep drawing, the surface is roughened with a structured surface when dressing by means of work rolling. The two-dimensional surface parameters available today are no longer sufficient for describing the primary features of surface structures for the tribological requirements in the forming process. Surfaces with deterministic structures in particular, as they are created with laser texturing or electron beam texturing, for example, make the development of more informative 3-D parameters necessary. Based on the research work of the Lehrstuhl für Fertigungstechnologie (LFT) [Chair of Manufacturing Technology], the Institut für Produktionstechnik und Umformmaschinen (PtU) [Institute for Production Engineering and Forming Machines] and the Institut für Umformtechnik (IFU) [Institute for Metal Forming Technology], parameters are defined that describe the primary features of the topology for tribology.

Abstract:

Three-dimensional surface parameters are defined based on a mechanical/rheological model for theoretical description of the frictional state in forming and molding engineering. These are both the material area ratio and the open and closed void area ratios of the surface topography. The area ratios, the volumes and the number of area ratios are described and defined for the three area ratios.

1 Initial situation

In modern-day practice, the surfaces of fine steel sheet exhibit numerous structures that are custom made for specific requirements of the forming processes,

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subsequent production steps or applications. During the forming process, the topography has an effect on the friction and wear characteristics and thus on the quality of the components. After forming, the topography must facilitate high-quality paint finishing with a corresponding luster. In addition, there are various requirements with regard to isolation of the blanks from the sheet metal stack, cleaning and welding and bonding capability. In order to satisfy these requirements, several methods have been developed for the roughening of dressing rollers (**Figure 1**) [1]. Random structures are generated with the Shot Blast Texturing (SBT), Electro Discharge Texturing (EDT) and Electro Chromium Deposit (ECD) methods. Regular crater structures are manufactured with the Laser Texturing (LT) and Electron Beam Texturing (EBT) methods, whereby so-called pseudo-deterministic surfaces can also be created in particular with the EBT method.

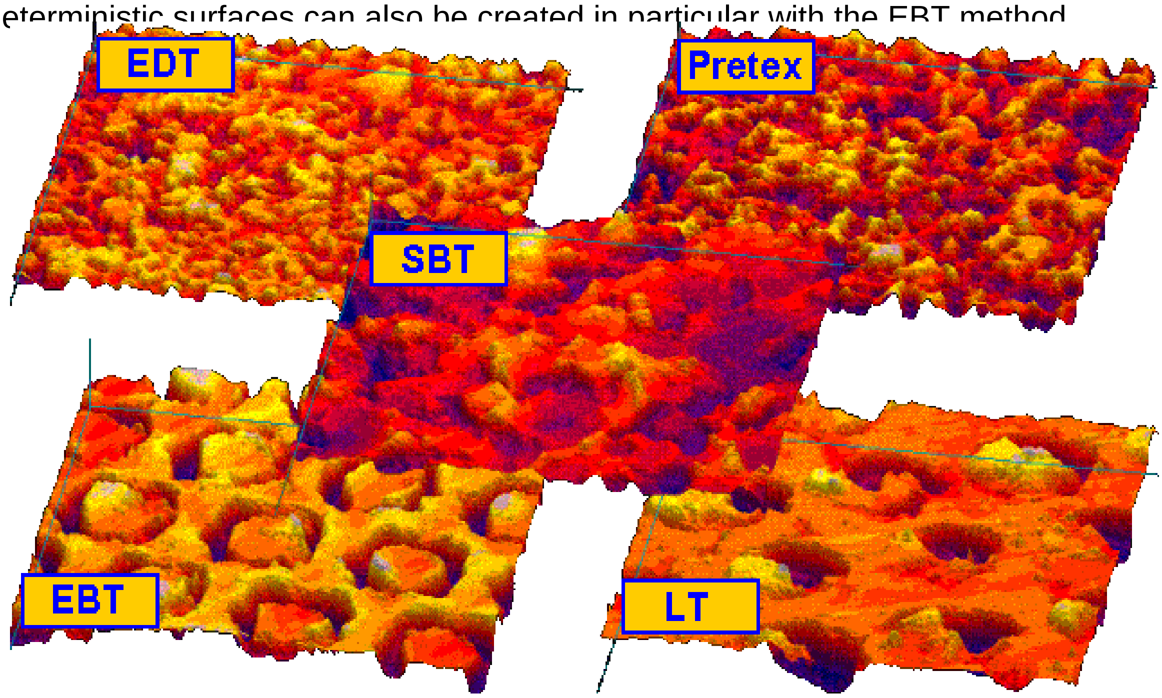

Figure 1: *Representation of various surface structures of fine steel sheet [2]*

2 Meaning of the surface structure in the process chain from semi-finished product to the finished part

In order to illustrate the meaning of the topography for tribology in sheet metal forming, the results of various tribological examinations of recent years were compared at PtU [2]. In individual test series (**Figure 2**), the sheet metal coating, additives, topography and lubricants were varied in each case and all other parameters were kept constant. The lubricants vary both with regard to their additives and also in terms of their viscosity. Differences in the evaluation of the additives and lubricant groups are therefore to be explained by the influence of the viscosity. As a measure for the effect of each group, the difference between the best and the worst test results were related to the average value. Each group contains the results of at least five tests. In order to keep the results for the applications of sheet metal forming as representative as possible, sheet metal and lubricants were evaluated exclusively within the framework of industrial orders.

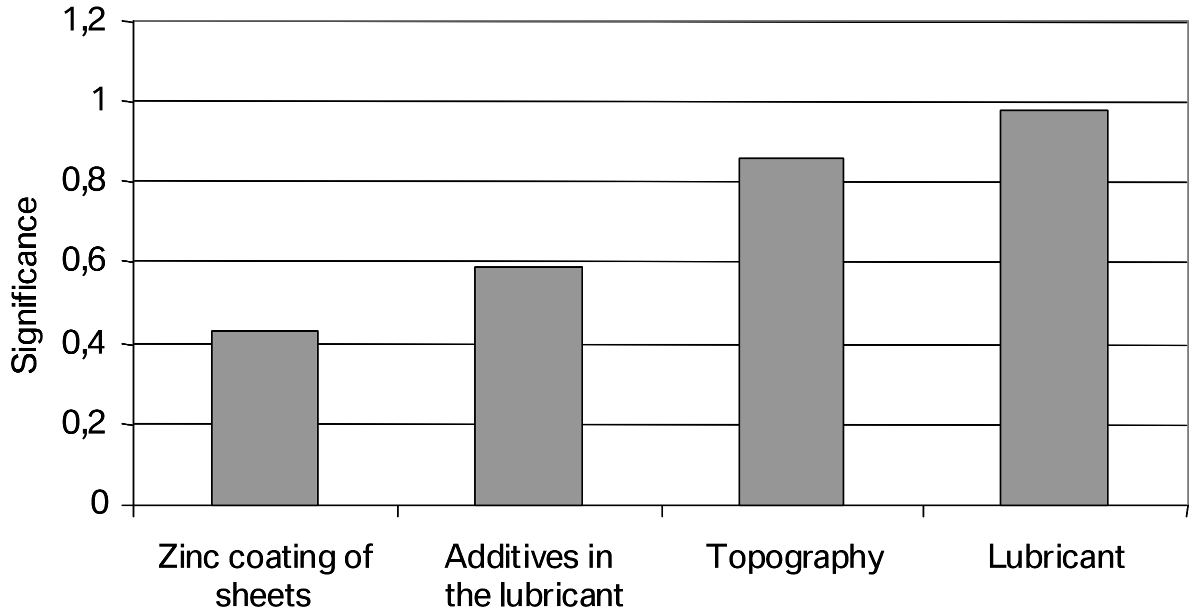

Figure 2: *Evaluation of influencing factors on friction in the forming process according to examinations at PtU Darmstadt*

It was distinctly shown that the topography, in addition to the lubricant, was of decisive importance. If one takes into account in the case of the lubricant that the viscosity is the decisive factor and that this cannot be increased arbitrarily from the requirements of the overall process sequence (application on the sheet metal surface, washing capability), the meaning of the topography for the tribological conditions when deep drawing becomes that much clearer.

Not only for the assessment of the tribological characteristics of a sheet metal surface, but rather for the entire production process from the manufacturing of the sheet metal to the end product, possibilities are required for describing the topography and thus for assuring quality in the production process. Additional relevant items in the process chain from rolling to the paint finishing of the finished parts are discussed below:

Creation of the rolling texture

The methods for the texturing of the rollers offer a multitude of parameters and possible settings. In order to ascertain a constant quality level of the rollers and in order to utilize the potential of the procedures, suitable measurement and evaluation techniques are required for evaluation of the rolling texture.

Transfer of the rolling structure onto the sheet metal

The transferring characteristics of the structure of the rollers onto the sheet metal are dependent on multiple process parameters. In order to examine whether the texture has been transferred in a homogeneous manner onto both sides of the sheet metal, and both over the length and also over the width of the coil, the topography must be measured.

Roller wear

The high level of loading on the roller surface during dressing leads to wear. Suitable surface parameters that characterize the state of wear of the rollers allow the time for replacement of the rollers to be determined or for adaptation of the rolling parameters on a timely basis.

Painting capability

The quality and the luster characteristics of the paint finished on the end product are influenced by the topography of the sheet metal and the structure of the paint layers. In order to determine the influence of the sheet metal surface on the degree of luster, measuring procedures are needed that, in addition to roughness, also register the amount of waviness of the topography before and after painting.

It is known that the standardized parameters derived from two-dimensional measurement can only describe the newer deterministic surfaces to an insufficient extent, especially those that exhibit a three-dimensional structure due to the individual lubricant craters [3].

For this reason, three-dimensional surface parameters have been developed independently of one another within the framework of multiple research projects at the institutes IFU [4, 5], LFT and PtU (**Figure 3**).

Chair of manufacturing technology
- Basic research on tribology in metal forming processes
- Roller wear

Institute for production engineering and forming machines
- Assessment of tribological systems with model tests
- Tribological mechanisms of topography

Institute for metal forming technology
- Experimental setups for tribology
- Deep drawing of panels
- Development of surface measurement equipment

Figure 3: *Focal points of the work of the institutes LFT, PtU and IFU in the area of surface analysis*

In order to use the same terminology in the future in the area of the three-dimensional measurement of sheet metal surfaces, uniform designations have been established at those three institutes. These are introduced below.

3 Derivation of surface parameters from a friction model

The surface parameters can be derived according to **Figure 4** from a mechanical/rheological model whose foundation is based on the physical examination of the processes in the surface pair between the tool and the workpiece [6]. The model is based on the premise that transfer of the contact force in forming-related processes takes place via the three bearing area ratios of solid body contact and static and dynamic lubricating pockets. Dynamic lubricating pockets are those areas from which the lubricant can flow out during the forming process. The pressure formed in the dynamic lubricating pockets is thus hydrodynamic in nature. Static lubricating pockets, in contrast, are understood to be those areas from which lubricant cannot flow out during the transforming process [7]. They do not form on real surfaces until there is a certain amount of deformation of the surface. With this assumption taken into account, the parameters summarized in **Figure 5** can be derived for description of the surface.

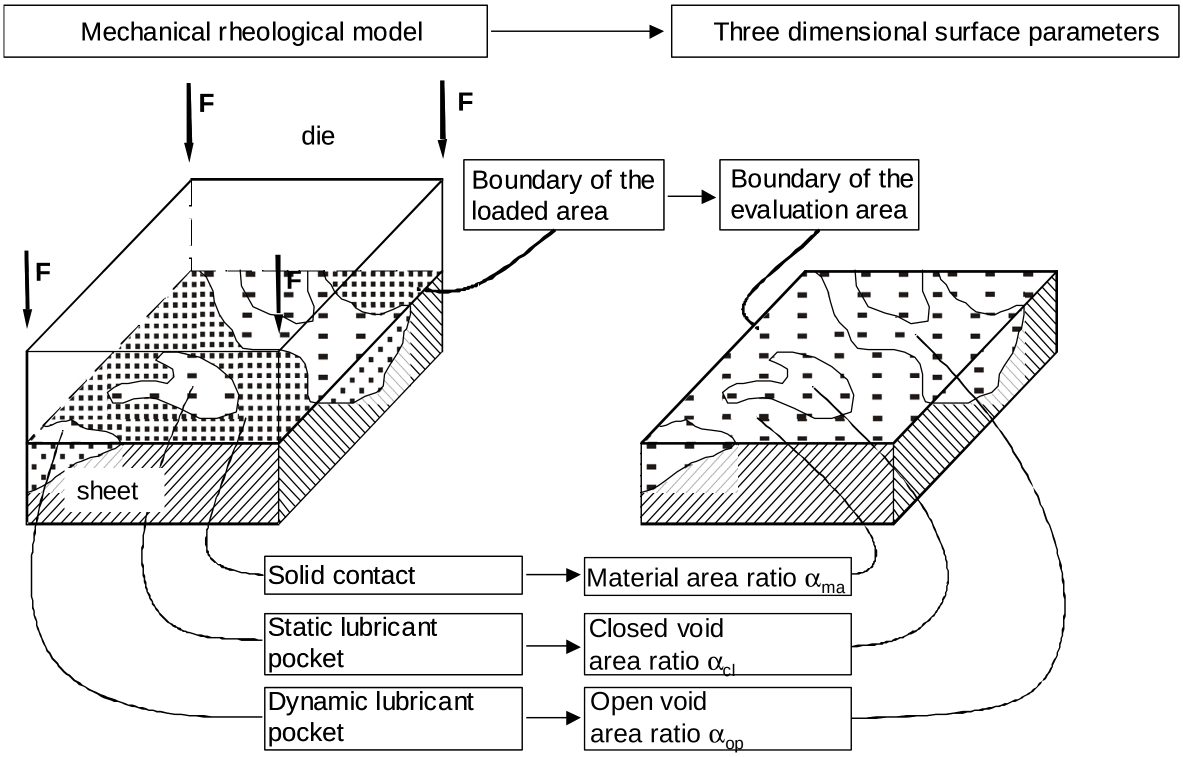

Figure 4: *Derivation of three-dimensional surface parameters from the mechanical/rheological model [6, 12]*

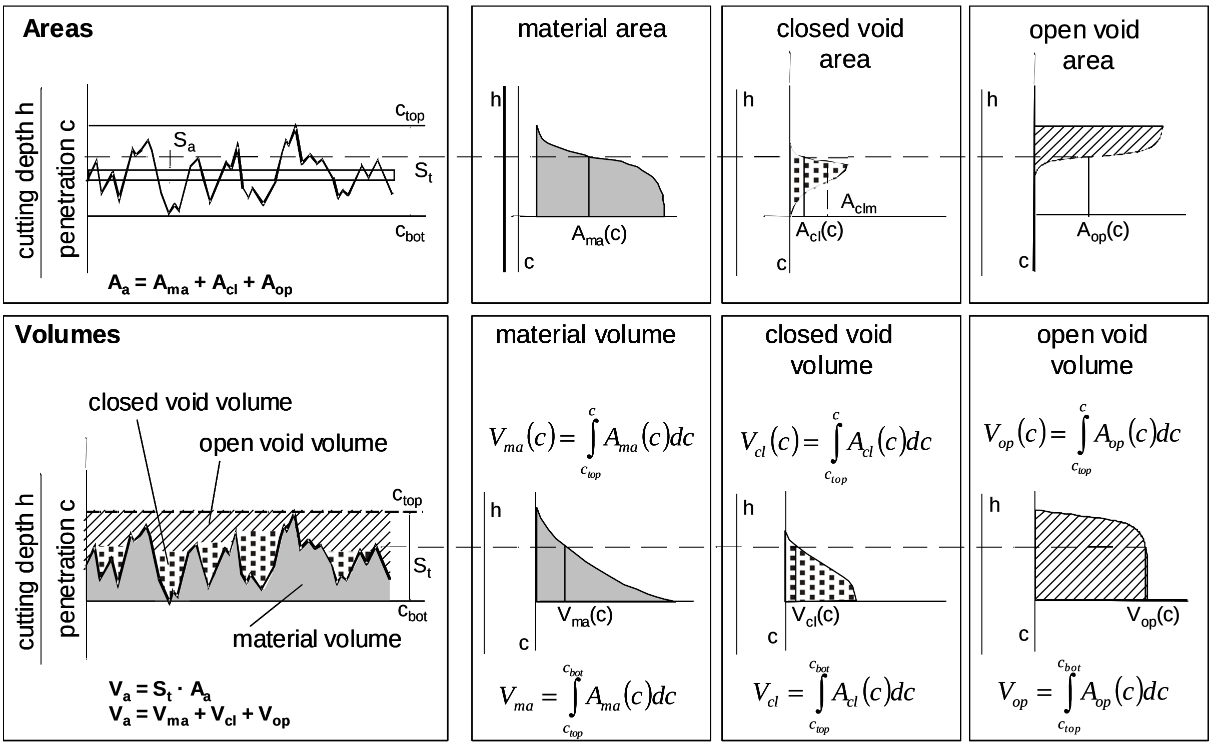

Figure 5: *Definition of the three-dimensional surface parameters of area ratios and volume ratios*

The thought behind the calculation of the new parameters is to evaluate the cross-sectional area patterns of the surface topography. In this regard, the sheet metal surface is first registered three-dimensionally with the aid of a suitable measuring procedure (**Table 1**) and stored in a suitable format. Thereafter, computational steps are taken in equidistant intervals through the topography of the surface. Due to the possibility of quantitatively evaluating the individual sections, the parameters for description of the spatial characteristics of the surface can be calculated.

Table 1: *Presentation of the measuring techniques predominantly used at the three institutes for registering the surface topography (the RM 600, also present at LFT, is also implemented at IFU).*

Measuring technique	LFT	PtU	IFU
Model	Rodenstock RM 600	Hommeltester T20 S	Self-developed item
Principle	Optical	Mechanical	Strip projection
Maximum area	100 x 100 mm²	25 x 25 mm²	1.4 x 1.8 mm²
Resolution	At least 2 µm x 2 µm	At least 4 µm x 4 µm	2 µm x 2 µm

4 Definition of the surface parameters

The evaluation area A_a necessary for three-dimensional measuring corresponds to the evaluation length l_m according to DIN 4768 that is familiar from two-dimensional realms. The overall sampled area is designated as A_t analogous to tracing length l_t. Evaluation takes place between the highest point of the topography c_{top} (top) and the lowest point of the topography c_{bot} (bottom). This definition takes place from forming-related points of view as contact of the frictional partners always begins first in the area of the peaks of roughness, which are at the highest point of the topography. A change of direction, as can be necessary in the calculation of the volume of lubricant necessary for forming, must be indicated separately. In this second case, the surface parameters are calculated as a function of the sectional height h. The limits for the sectional height are defined in accordance with the limits of penetration by h_{top} and h_{bot}.

4.1 Size of sectional areas and area ratios

The material ratio, which is already known according to DIN 4776 as the Abbott Tp curve, is derived from the solid body contact in the forming process. For the areas of the static lubricating pockets of the rheological model, the parameter “closed void area“ A_{cl} (**cl**osed) and for the areas of the dynamic lubricating pockets the parameter “open void area“ A_{op} (**op**en) are introduced. From this standpoint, there are four curve progressions for each surface as a function of the penetration c:

- **Material area A_{ma}(c):** Material area curve
- **Void area A_{vo}(c):** Void area curve
- **Closed void area A_{cl}(c):** Curve of the closed void area
- **Open void area A_{op}(c):** Curve of the open void area

Table 2 contains the designations for the areas. A distinction is made as to whether the values describe the absolute size of the areas (Column 2) or whether they are relative to the base area (Column 3).

Table 2: *Designations of surface parameters for areas*

	Areas		Number of areas	
	Absolute [mm^2]	Overall area ratio [%]	Absolute [-]	Number of areas [1/mm²]
		Curves		
Material ratio	A_{ma}	α_{ma}	N_{ma}	n_{ma}
	Material area	Material area ratio	Number of material areas	Number of material areas
Void ratio	A_{vo}	α_{vo}	N_{vo}	n_{vo}
	Void area	Void area ratio	Number of void areas	Number of void areas per mm²
Open void ratio	A_{op}	α_{op}	N_{op}	n_{op}
	Open void area	Open void area ratio	Number of open void areas	Number of open void areas
Closed void ratio	A_{cl}	α_{cl}	N_{cl}	n_{cl}
	Closed void area	Closed void area ratio	Number of closed void areas	Number of closed void areas
		Characteristic parameters:		
Maxima of the material ratios	-	-	N_{mam}	n_{mam}
			Maximum number of material areas	Maximum number of material areas per mm²
Maxima of the void ratios			N_{vom}	n_{vom}
			Maximum number of void areas	Maximum number of void areas
Maxima of the closed void ratios	A_{clm}	α_{clm}	N_{clm}	n_{clm}
	Maximum closed void areas	Maximum closed void area ratios	Maximum number of closed void areas	Maximum number of closed void areas

The void area is comprised of the open and closed void area and, together with the material area, results in the overall evaluation area A_a.

4.2 Number of sectional areas

No information with regard to the size and quantity of the individual areas is contained in the 3-D material ratio curve and the parameters derived from it. The opportunity thus exists to count the material areas and the void areas in various penetrations and to calculate the average size. The quantity and size of the material and void areas are schematically portrayed in **Figure 6** as a function of the penetration. Columns 4 and 5 of **Table 2** contain the designations for the quantity of areas. Among other things, the maximum quantity of material and void areas can be read from these curves as characteristic variables.

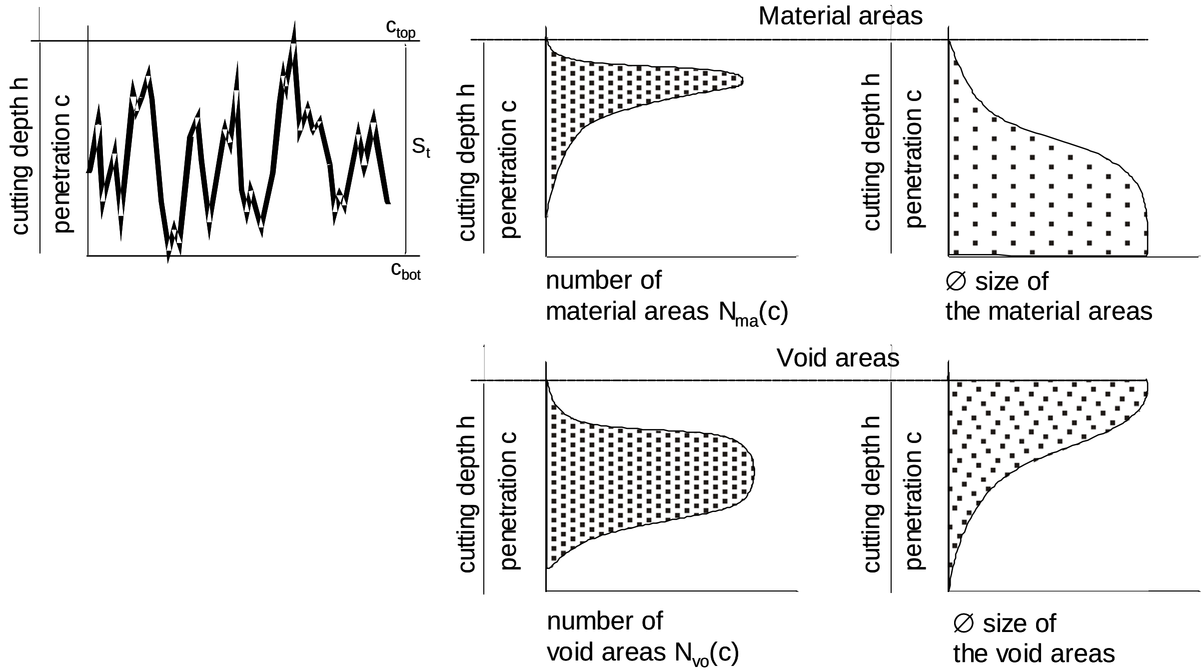

Figure 6: *Definition of the number and size of area ratios*

4.3 Volumes

In addition to the areas, the corresponding volumes below or above the individual sectional areas can be derived from the mechanical/rheological model. The volume V is calculated through integration of the respective area as a function of the penetration. When calculating the volumes, integration of the area ratios takes place in the limits from c_{top} to c_{bot}. The volume parameters in **Table 3**, a function of penetration, result as a supplement to the area parameters shown in **Table 2**. Calculation of the volumes through integration of the areas is illustrated using the example of closed void areas.

$$V_{cl}(c) = \int_{c=top}^{c} A_{cl}(c)\,dc$$

$$V_{cl} = \int_{c=top}^{c=bot} A_{cl}(c)\,dc$$

The value V_{cl} corresponds thereby to the overall closed void volume and $V_{cl}(c)$ to the void volume present between c_{top} until penetration c. In the calculation of the parameters as a function of penetration, the volume of material can be of importance, for example, if the volume of the smoothed or abrasively stripped peaks is to be calculated. Calculation of the open and closed void volumes as a function of the sectional height h can provide information with regard to oil absorption capability and thus with regard to the necessary amount of oiling. The sum of the three complete volume ratios V_{cl}, V_{op} and V_{ma} result in the overall volume V_a of the surface topography that is calculated from the profile depth S_t of the topography and the measuring area A_a:

$$V_a = S_t \cdot A_a$$

4.4 Parameters

Several possibilities are available for deriving numerical values for the parameters from these curves.

- The penetration or the sectional height for which the value has been determined is to be specified. Example: α_{ma} (c=5%). This method is suggested in [8].
- Points of reference are defined, as in the case of determination of the R_k parameters according to DIN 4776, for example. Via the slightest rise of the material ratio curve, characteristic sections are determined there on which the material ratios M_{r1} and M_{r2} are calculated.
- Characteristic points of the curve such as the maximum values can be evaluated. The designations for these values are specified in the lower portion of **Table 2**.

5 Application of the parameters

The results of a measurement on a single lubricant crater of a **L**aser-**T**ex surface (LT surface) are used (**Figure 7**) in order to explain the surface parameters using an illustrative practical example. The curves of the area ratios are portrayed in the graph as a function of penetration. Penetration of the topography begins with the highest roughness peak of the topography so that an area ratio of the open void areas of 100% is present. As penetration of the topography increases, the area ratio of the material increases and the open void area ratio decreases. From a certain amount of penetration onward, the closed void area ratios occur as can be clearly seen in the third 3-D representation. As penetration continues to progress, the curve of the closed void area ratios reaches its maximum. This value is a characteristic variable for every surface and is designated as the maximum of the closed void area ratio α_{clm} (**cl**osed, **m**aximum). At this level of penetration of the surface, there are nearly no open void areas. At a penetration of 100%, which is at the lowest point of the profile, a material area ratio of 100% is present. Resulting from the illustration in Figure 7 are two significant vertical parameters that identify the position of the maximum of the closed void area ratios within the topology. These are, on the one hand, the penetration c_{clm} and, on the other hand, the height h_{clm}. With the depth of the topography S_t taken into account, the following relationship applies to the two vertical parameters:

$$S_t = c_{clm} + h_{clm}$$

The characteristic value S_t according to [8] is defined as a synonym for the profile depth P_t according to DIN 4771 as the depth of the topography. S_t is thus the vertical difference from c_{top} to c_{bot}. The example discussed shows, however, that reliable calculation of the parameters is dependent on the size of the evaluated area. If one displaces the evaluated area for the lubricant crater of the Lasertex surface by 50% in one direction, for example, an open void area ratio results from the closed void area ratio of the lubricant crater. It can be shown, however, that the parameters converge upon a constant value when the evaluated area is sufficiently large [9, 10].

6 Outlook

Which of these parameters are to be selected for evaluation of the functional characteristics of the topography is a current topic in various research projects. In addition to the tribological properties, wear of the dressing rollers, embossing characteristics and the degree of luster are assessed based on these parameters.

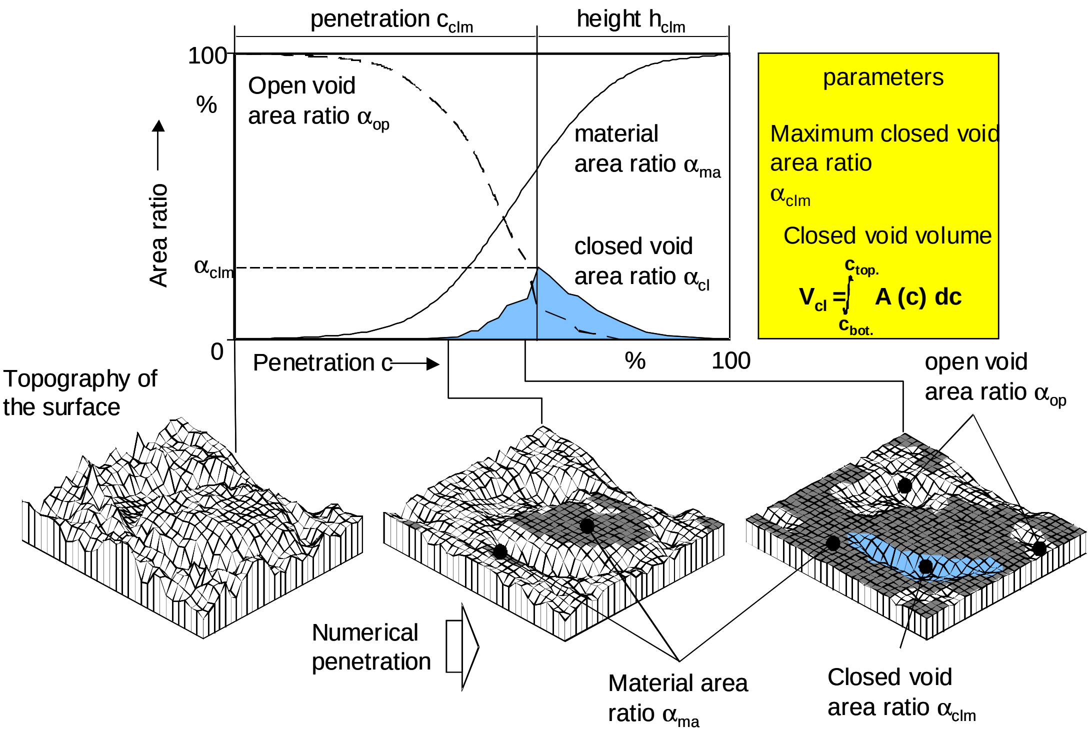

Figure 7: *Material ratio, as well as the open and closed void ratio using the example of the lubricant crater of a Lasertex surface and definition of vertical parameters according to [12].*

The correlations to the tribological characteristics of sheet metal of a dressing procedure can be shown to date for the parameters α_{clm}, n_{mam} and the closed void volumes V_{cl} [11, 12]. The comparison of topographies of varying manufacturing procedures is currently still difficult, especially when deterministic and random structures are concerned. The objective of development of three-dimensional parameters must therefore be the description of all topographies with a uniform set of parameters. They must facilitate unambiguous distinction of deterministic structures from random structures. The parameters, 3-D filtering procedures and rapid measuring methods with regard to the temporal requirements of current series production are to be further developed and optimized in the future for this application.

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