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ORIGINAL ARTICLE

Surface characterisation in forming processes by functional 3D parameters

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Abstract Tribology in metal forming plays a significant role for process feasibility and process quality. Especially in micro forming the influence of the tribological condition is very essential due to an extensive increase in friction which is observed while scaling processes from macro to micro. As friction depends considerably on the surface topography of tool and workpiece, functional surface characterisation concerning the tribological properties becomes even more relevant. Standardised 2D roughness-measurements and -parameters are not able to fulfil this task satisfactorily. Hence the surface has to be measured three dimensionally. An appropriate method is given by confocal white light microscopy. New 3D parameters are defined with respect to the functional behaviour of the surface. These parameters are derived from a mechanical-rheological model which describes the transmission of the forming load from the tool to the workpiece. In order to calculate these parameters, the software WinSAM has been developed. Especially the maximum closed void area ratio and the volume of closed lubricant pockets have already proven their capability of characterising the tribological behaviour of the surfaces in the macro world. It is expected that these parameters are a basis for a functional characterisation of the topography in micro-forming applications as well.

Keywords Metal forming · Surface characterisation · Tribology

1 Introduction

As friction in forming processes depends extensively on the surface topographies of the tool and the workpiece, an optimisation of the surface concerning its tribological behaviour is advisable. In sheet metal forming it is a common technique to apply a defined texture to the sheets by a skin pass rolling process with textured rolls in order to create additional lubricant pockets [1]. Nowadays there are several commercial methods for texturing the rolls available, e.g. shot blast texturing (SBT), laser texturing (LT) or precise texturing (Pretex). In bulk metal forming it is the state of research to texture, e.g. cold forging punches in order to improve tool life [2].

For the specific adjustment of the surface topography concerning its functional behaviour, the significant and comparable characterisation of the surface is obligatory. Standardised 2D roughness-measurements and -parameters are barely able to fulfil this task satisfactorily. Especially deterministic surfaces like LT textured surfaces can hardly be characterised by 2D parameters. For example - concerning a measured profile - a pit is indistinguishable from a scratch as both features appear as valleys. Additionally, a functional description of the surface concerning its tribological behaviour during the forming process is almost impossible [3]. Major efforts are made for the definition of 3D surface parameters, e.g. within the EU sponsored project called "SURFSTAND" (cf. [4]). Atthe Chair of Manufacturing Technology, functional 3D surface parameters have been derived from a mechanical-rheological model, which have already shown their applicability for a description of the surface concerning its tribological behaviour in deep drawing processes in the press shop.

Concerning micro forming, tribology, thus the surface topography, plays an even more important role due to size

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effects which cause a massive increase in friction when scaling down forming processes to smallest dimensions [5]. Performing surface characterisation in micro applications, difficulties occur in all three phases of surface characterisation - measurement, processing and evaluation [6]. During the measurement phase which samples the topography in a digital map, non-contact measurement systems are preferred for micro applications due to difficulties in fixing the samples. Additionally, the minimum measuring length which is demanded by national and international standards cannot be maintained in many cases due to the small specimen dimensions. In the processing phase the measured data is filtered in order to separate the roughness from the waviness and roughness parameters are computed. As the available assessment length or area is restricted on microparts, adequate filtering techniques have to be selected. For example, the application of filters has to be standardised which have no running-in and running-out length, e.g. Gaussian regression filters [7], in order to use the whole measuring length for the evaluation. Concerning the evaluation phase, the significance of already defined roughness parameters, 2D as well as 3D, has to be reviewed. Possibly, new parameters have to be defined for a dedicated surface characterisation in micro applications.

In this paper, methods and tools for functional surface characterisation are presented which have already shown their potential in the macro world. It is expected that they are a basis for the surface characterisation concerning tribological behaviour in micro applications as well.

2 Surface measurement

Due to the time consuming procedure of measuring surfaces three dimensionally by tactile measuring systems, their application is less advisable. In order to measure the topography of a surface, optical measuring systems are more suitable. At the Chair of Manufacturing Technology a confocal white light microscope μSurf (company NanoFocus) is used whose main advantages are the short measuring time and the non-contact measurement. Difficulties may occur at steep edges due to insufficient reflection of light to the detector. For the 10× and 100× objectives the maximum allowable surface slope is 8.7 and 35.9°, respectively. As the geometry of the surface features may cause problems, the optical properties of the surface may influence the measurement results as well. When measuring translucent materials or coatings for example problems may occur.

The confocal white light microscope (Fig. 1) utilises the restricted depth of focus of an objective in order to determine whether certain parts of the measured area are in focus or not. The application of pinholes leads to a further reduction of the depth of focus [8]. The degree of the accordance between the reflected plane and the focus plane can be described by a characteristic distribution of intensity. The maximum intensity of light which is reflected to the detector is reached when the measured area is in focus. The intensity distribution and the maximum intensity for each point in the measuring area are detected by moving the measurement head vertically along the whole measurement range. Thus the individual height of every point can be calculated.

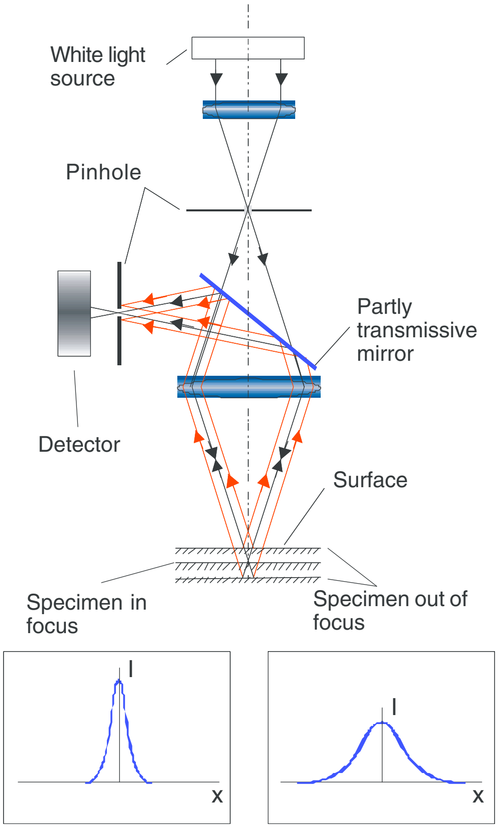


Fig. 1 Principle of confocal white light microscopy

The measurement area for a single measurement varies depending on the objective used. Table 1 gives an overview of the measurement area as well as the lateral and vertical resolution. The measurement area can be extended by stitching algorithms.

Table 1 Measurement area and resolution according to the objective as specified by the manufacturer

Objective	Measurement area (μm × μm)	Lateral resolution (μm)	Vertical resolution (nm)
10×	1600 ×1500	3	50
100×	160 ×150	0.3	5–20

3 Functional parameters

In order to derive functional 3D parameters the mechanical-rheological model introduced by [9, 10] is used. In this model, the load on a surface is transmitted by three different kinds of bearing ratios. These are the ratios of the regions of solid contact as well as the ones of open and closed lubricant pockets (Fig. 2). When a forming load is applied to a lubricated workpiece surface, the asperities deform plastically. Therefore the roughness valleys which entrap lubricant between the tool surface and the workpiece surface act as lubricant pockets. Closed lubricant pockets have no connection to the edge of the surface. Thus the lubricant is trapped in these pockets and pressurised while the forming load is applied. The developing hydrostatic pressure takes a part of the external forming load, reducing the normal pressure on the asperities which leads to lower friction. In contrast, lubricant pockets which have a connection to the edge of the surface are called open lubricant pockets. Due to this link to the edge lubricant is squeezed out during the forming process resulting in a hydrodynamic pressure. The transmission of external load by open lubricant pockets is dependant on process velocity and viscosity of the lubricant but in general negligible compared to the load transmitted by closed lubricant pockets. Hence, the forming load acts mainly on the asperities which results in a higher contact stress, a higher degree of surface flattening and thus a higher fraction of real contact area and increased friction. The ratio of the material area as well as the open and closed void area are determined numerically by several equidistant penetrations of a plane between the highest and the lowest point of the topography. Typical courses for the bearing ratios are shown in Fig. 3. Two characteristic parameters can be derived from the closed void area ratio: the maximum ratio of the closed void area (α_{clm}) and by integrating the curve, the normalised closed void volume (v_{cl}). Additional parameters like the maximum number of closed lubricant pockets N_{clm} or the maximum of the average size of closed void areas A_{clm} can be determined.

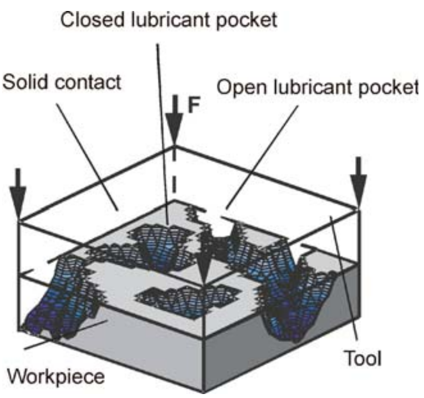


Fig. 2 Mechanical-rheological model

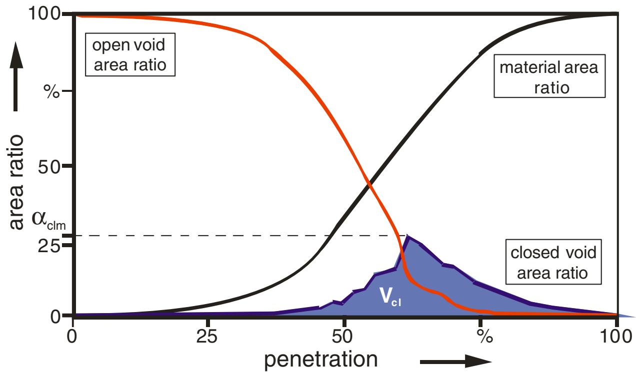


Fig. 3 Area ratio diagram

For the characterisation of sheet metal, α_{clm} and v_{cl} are the most promising 3D parameters as former investigations have shown [11].The parameter v_{cl} specifies the amount of lubricant which is trapped in the roughness valleys of the surface. Thus this parameter indicates the ability of the surface to store and transport lubricant. As this is a main requirement of the topography with respect to optimum lubrication, surfaces with high v_{cl} values are favourable.

In order to characterise the tribological behaviour of a surface, an additional parameter - the maximum ratio of closed void areas α_{clm} - has to be considered. α_{clm} provides precise information about the area where hydrostatic pressure can be built up. In order to transmit as much forming load as possible by pressurised lubricant, a high value of α_{clm} is desired for a good tribological behaviour.

The normalised closed void volume v_{cl} and the maximum ratio of closed void area α_{clm} have shown their capability for the tribological characterisation of sheet metal in various experiments carried out in the press shop in cooperation with automobile manufacturers [1, 11].

4 WinSAM

In order to calculate the above mentioned parameters, the software WinSAM - Surface Analysis Module for Windows - has been developed at the Chair of Manufacturing Technology. Subsequent to the measurement of the surface the topography data is imported to WinSAM. The most important data file formats of various measuring device manufacturers are implemented. In order to prepare the measured surface for the parameter calculation, it can be modified in manifold ways: data sets can be turned or merged. The resolution can be modified and artefacts can be removed by various substitution strategies.

For the separation of the waviness from the roughness a wide range of 2D as well as 3D filters are implemented. In addition to Gaussian filters for filtering each profile two dimensionally, moving-average filters, regression filters as well as a Fourier filter for 3D filtering are available.

In addition to the above mentioned 3D parameters resulting from the calculation of the area ratios as a function of the penetration (Fig. 3), a wide range of 3D parameters derived from conventional 2D parameters can be calculated, e.g. the arithmetic mean value S_a, the kurtosis S_{ku} or the core roughness depth S_k.

The detection of regular features of the surface is performed by the Fourier transformation. Besides the presentation of the topography in terms of height values at discrete points, the surface can be interpreted as the superposition of various frequencies with different amplitudes. If the topography is transferred to the frequency domain by Fourier transformation, regular elements are easier to detect, as they cause high amplitudes at a small frequency band. Another tool for the detection of regularities, especially their direction and their distance, is the calculation of the plane auto-correlation-function. Further tools for surface characterisation which are implemented in WinSAM are the calculation of flank angles and flank angle distribution as well as the calculation of the fractal dimension. Additionally, various ways of visualisation, e.g. 3D (Fig. 4) or pseudo colour representation of the topography, are available.

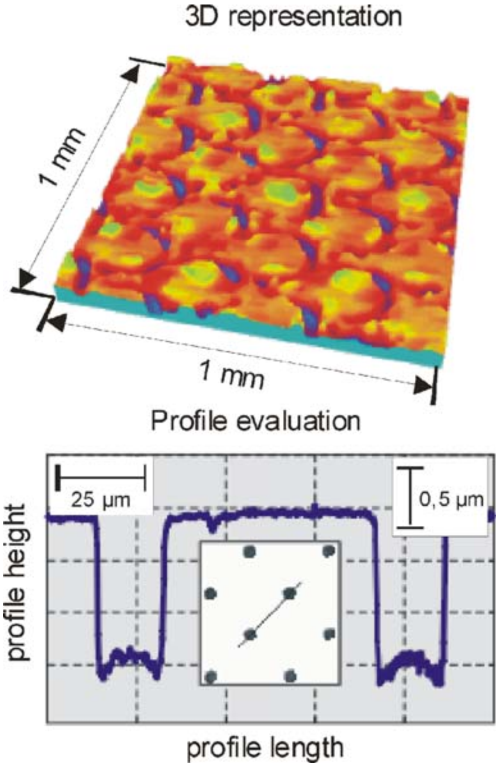


Fig. 4 Topography evaluation in WinSAM

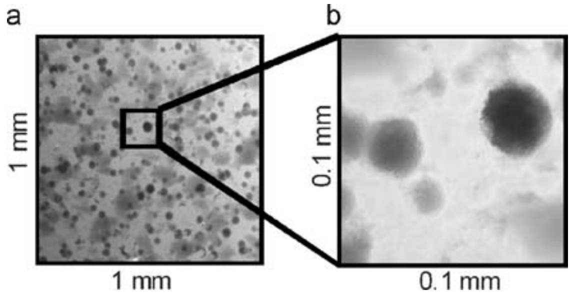


Fig. 5 Influence of the measurement area on the stochastic distribution of surface features

For the quantification of wear volumes, the original topography and the worn topography can be aligned and subsequently subtracted from each other. The resulting topography represents the worn volume and can be quantified by the calculation of the material volume.

If the topography is interpreted as a row of profiles, a 2D evaluation of arbitrary profiles (Fig. 4) according to standardised roughness parameters like the quadratic mean value Rq or the core roughness depth Rk is possible. Due to the consideration of all profiles of the topography a statistical evaluation of the surface can be performed. Additionally, WinSAM provides the possibility for the evaluation of the geometry of single profiles: the width, the height, radii and angles of profile elements are calculated.

5 Roughness measurement and evaluation at micro scale

When measuring the roughness in micro applications, several specifics have to be taken into account. While the surface features are approximately invariant to the dimensions of the parts, the assessment areas have to be drastically reduced for surface roughness measurements of micro parts. Consequently, the evaluation area is no longer representative for the whole surface. Figure 5a shows the measurement of a steel sheet with a measurement area of 1 ×1 mm^2. By reducing the measurement area to 0.1 ×0.1 mm^2 (Fig. 5b), one single surface feature becomes

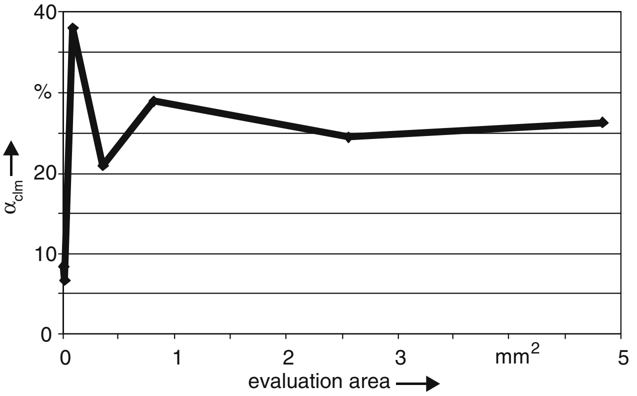
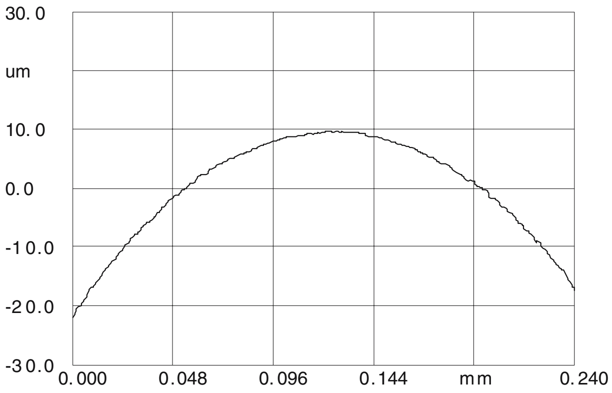
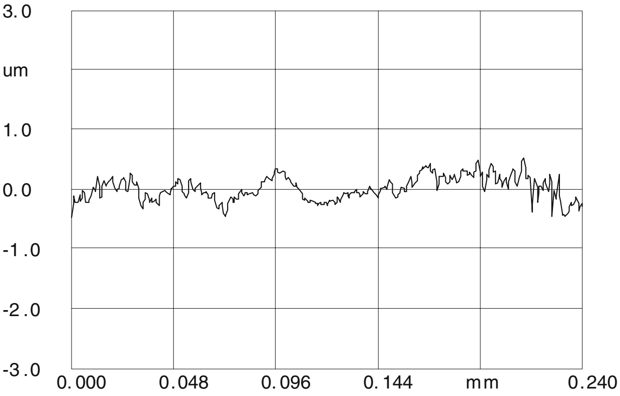


Fig. 6 α_{clm} as a function of the evaluation area

a measured profile



b regression filter with polynomial 2nd degree, Ra = 0.16 μm



c gauss filter, cutoff 0.08 mm, Ra = 0.07 μm

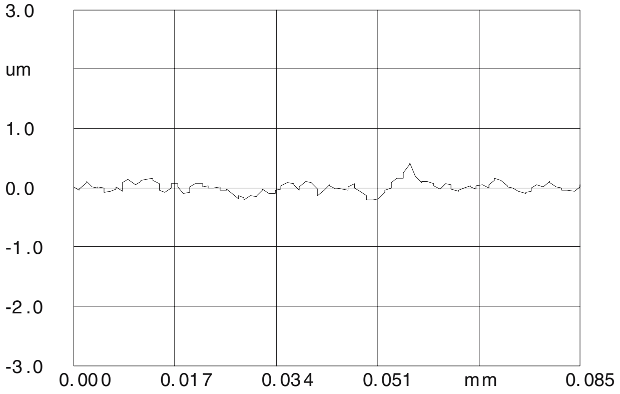
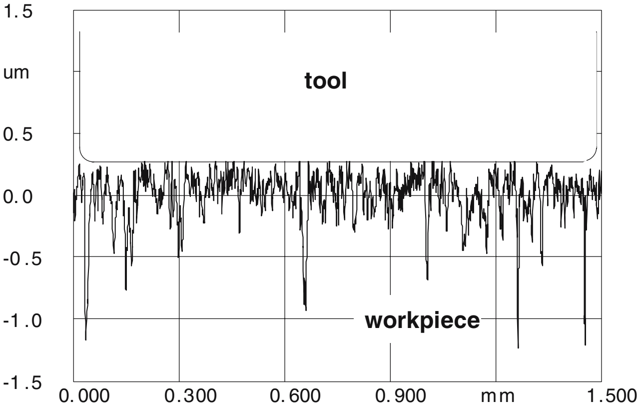


Fig. 7 Influence of filter on the roughness profile

much more decisive for the calculation of surface parameters. Thus, Fig. 5b is no longer a representative section of the surface shown in Fig. 5a. Hence, the surface parameters are varying heavily depending on the specific measurement area which is selected by the user. The influence of the measurement area on surface parameters is shown in Fig. 6 exemplarily for α_{clm}. For large evaluation areas, the parameter converges to a constant value [12]. By reducing the evaluation area, α_{clm} begins to scatter in a very wide range.

a ground surface on a conventional workpiece - many asperities contacting the tool



b ground surface on a micro workpiece - few asperities contacting the tool

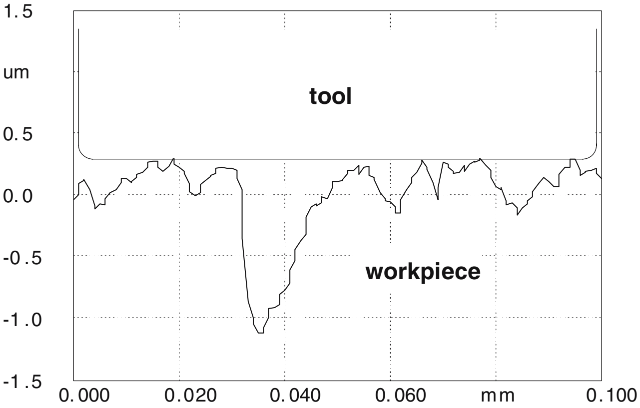


Fig. 8 Asperities in contact on a workpiece in conventional length scale and on a micro part

Due to the small dimensions of microparts, the minimum tracing length demanded by national and international standards for filtering and calculation of surface parameters is often not available. Hence, the separation of form, waviness and roughness is heavily dependant on the filter parameter selected by the user and is not yet standardised in the micro world leading to difficulties in comparing the calculated parameters with other measurements. Figure 7a displays a profile in circumferential direction of the shell of a combined full forwards cup backwards extrusion part (material CuZn15) with a diameter of 0.5 mm and a length of 1 mm measured by confocal white light microscopy. The use of a regression filter with a polynomial of 2nd order results in a R_a value of 0.16 μm (Fig. 7b). If the original profile is filtered by a Gaussian filter with a cutoff of 0.08 mm, the R_a value is 0.07 μm (Fig. 7c). According to the German standard DIN 4768 a cutoff of 0.8 mm and a measurement length of 5.6 mm has to be used for R_a values between 0.1 μm and 2 μm.

Concerning the characterisation of the tribological behaviour of the surface by 3D parameters in the micro

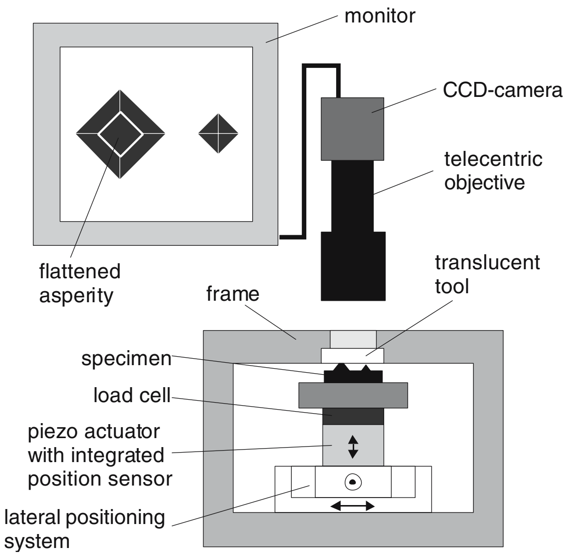


Fig. 9 Experimental setup for the evaluation of the flattening behaviour and formation of submicron cavities

case, the significance of these parameters has to be reconsidered. Figure 8a shows the contact zone between a ground workpiece and a tool in conventional length scale: many asperities on the workpiece surface are in contact with the tool surface which is assumed to be ideally planar. Concerning micro parts only a small number of asperities are in contact with the tool (Fig. 8b). Hence, the properties and the behaviour of single asperities under load are much more important for the flattening of the surface and thus for the tribological behaviour of micro parts. For the derivation of functional parameters for micro applications describing the tribological behaviour of the surface, the behaviour of a single asperity under load has to be evaluated. In order to determine the properties and the flattening behaviour of a single asperity which may vary intensely from the macroscopic case due to the existence of only a few grains in the asperity resulting amongst others in a different plastic behaviour and a bigger influence of surface layers, a micro upsetting test with a translucent tool has been designed. The experimental setup (Fig. 9) consists of a piezo actuator with an integrated position sensor for the vertical movement of the specimen in 10 nm steps. The required force for flattening the asperities is measured by a load cell with a responsivity smaller than 1 mN. The upper tool is made out of quartz glass.Thus, the flattening of the asperities and the developing real contact area can be observed in-situ by a telecentric objective and a CCD camera with a resolution of about 1 µm. The specimens (OFHC copper) are designed as an array of pyramids with a base of $120 \times 120\ \mu m^2$ and a height of 35 µm representing idealised asperities. In order to ensure that there is no interaction between the topography elements, there is a distance of 1 mm between each other. The specimens have been produced by micromachining at the Laboratory for Precision Machining at the University of Bremen. Starting from the analysis of single idealised asperities, the flattening of real topographies produced by turning, grinding, etc. will be investigated in order to gain better insight into the interaction of adjacent surface features under load and finally the tribological behaviour of the surface of the micro part in microforming processes.

As the real contact area plays the significant role in tribological processes [13], in micro applications single asperities cannot be assumed to be flattened completely. Due to the existence of only a few asperities in contact, micro asperities on asperities - as they have been already proposed by [14] - have to be taken into account for characterising the tribological conditions. Preliminary investigations indicate the existence of such a sub - topography on flattened contact areas [5]. Figure 10 shows the surface of a cylindrical specimen (diameter: 0.5 mm, CuZn15) upset by an almost ideally plane glass plate with a normal pressure of about 2.5 k_f and no lubrication. The original surface was produced by turning which results in an asperity distance of approximately 50 µm. After flattening there are still many non-flattened, submicron cavities within a single asperity which cannot be explained completely by the elastic redeformation of the material after unloading. For measuring this sub-topography, the resolution of common surface measurement systems is

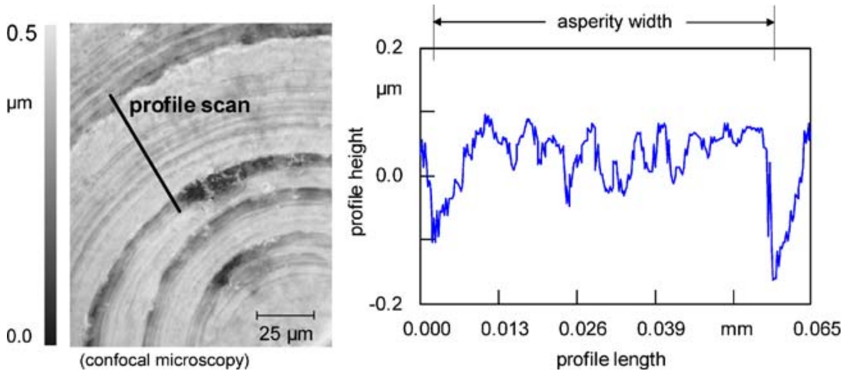


Fig. 10 Sub-micron cavities on a flattened asperity

insufficient. Therefore, high resolution surface measurement devices, e.g. atomic force microscopes will be used.

The extended knowledge about the flattening behaviour of the workpiece surface at the interface tool/workpiece and the characterisation of the submicron cavities on single asperities represent the presupposition for deriving new significant functional surface parameters characterising the tribological behaviour of the surface in micro forming processes.

6 Conclusion

This contribution gives an overview over the methods and tools for the functional characterisation of surfaces in metal forming as they are used at the Chair of Manufacturing Technology. The main advantages of the confocal white light microscope are the short measuring time and the non-contact measurement.

According to the introduced mechanical-rheological model, the forming load is transmitted from the tool to the workpiece by solid contact, open and closed lubricant pockets. Functional parameters like the normalised closed void volume v_{cl} and the maximum ratio of the closed void area α_{clm} are derived from this model. These parameters have already shown their potential in macro applications in the press shop.

For the calculation of the introduced 3D surface parameters, the software WinSAM - Surface Analysis Module- has been developed. WinSAM offers a variety of tools and parameters for surface characterisation like filtering methods, fourier transformation, areal auto correlation and functional parameters.

Finally, the particularities and challenges are presented which occur when characterising surfaces on the micro scale. The influence of the assessment area on surface parameters has been demonstrated exemplarily for α_{clm} and the need for standardisation of the evaluation of surface parameters in the micro scale has been shown. As there are only a few asperities in contact with the tool in micro forming processes, the knowledge of the behaviour of a single asperity under load is fundamental for the definition of functional surface parameters. Thus, an upsetting test with a translucent tool for the determination of the properties and the flattening behaviour of single asperities made out of materials relevant for micro forming applications (OFHC copper in a first step) has been set up, which will enable the in-situ observation of the flattening behaviour of asperities. Additionally, the emerging submicron cavities on single asperities during flattening can be measured, e.g. by atomic force microscopes and evaluated.

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