PROCESS DESIGN FOR MICROMILLING OF STOCHASTICALLY DISTRIBUTED BIONIC SURFACE STRUCTURES

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The process design for the manufacturing of surface structures with functional tribological properties is a major challenge when machining workpieces with freeform surfaces. Distortion effects of the structures and limitation of CAD/CAM-systems require the development of novel technological solutions. The paper presents a new approach for designing the machining processes of functional textures on freeform surfaces. Within the approach, a new bionic motivated type of micromilled surface structures is presented. By stochastically distributing sampling points for the replication of machining commands of individual structure elements, a stochastic surface structure can be produced while simplifying the process design. In this paper, the procedure for generating NC paths on the free-form surfaces of using Poisson-Disk sampling as well as transferring this to a machine-compatible machining program is illustrated. The basic approach as well as the resulting surface structures are further compared with the method of NC-projection and the potentials of the new approach are discussed.

KEYWORDS

Bionic surface structures, micromilling, design of NC-programs, free-form machining, Poisson-Disk sampling

1 INTRODUCTION

In many areas of production technology, the tribological contact situation of functional surfaces represents an important factor for adjusting the process performance. With respect to forming technology, the frictional behavior between the mold and the workpiece is of great importance for the outcome of the process. With respect to the functionality of the contact, it can be advantageous to have both high and low friction between the active pairs. On the one hand, the material flow can be enhanced by a low friction or, on the other hand, hindered by a higher friction [Vierzigmann et al. 2011]. By locally adapting the friction properties of the functional surfaces, material flows can thus be optimized in the forming process, which improves the shaping of filigree mold elements [Löffler et al. 2016]. This is particularly advantageous for complex and demanding forming processes, such as sheet-bulk metal forming (SBMF) [Merklein et al. 2015; Merklein et al.21]. By applying bulk forming processes to the sheet metal, the manufacturing of complex components with filigree secondary shape elements can be achieved. However, forming filigree shape elements out of thin sheet metal results in high forming degrees in certain areas. In addition, these processes exhibited a high contact area in relation to the workpiece volume, giving great importance to the friction situation in the processes [Vierzigmann et al. 2011]. In this context, filigree surface structures on the functional surfaces of the forming tools have proven to be a target-oriented approach for improving the material flow, respectively the shape filling [Kersting et al. 2016; Merklein et al.21]. In addition to the direction-independent influencing of friction between the active pairs, direction-dependent surface structures also offer the possibility of favoring the flow of material in a specific direction [Behrens et al. 2020a; Meijer et al. 2021a]. Furthermore, surface textures can also be combined with lubricants to achieve different effects [Sulaiman et al. 2017; Tillmann et al. 2017]. Structure elements can also serve as a reservoir for lubricants, i.e. lubrication pockets [Henneberg et al. 2019]. On the one hand, this can provide sufficient reserves of lubricant during the process or even make use of hydrodynamic effects in the forming process [Behrens et al. 2020b]. Various application tests of different structure types and classes revealed potentials for influencing the shaping, the resulting process force, the tool load and the tribological wear behavior [Behrens et al. 2020a; Meijer et al. 2021a; Sieczkarek et al. 2012]. Thus, the approach of surface structuring can be attributed great potential.

In manufacturing the structures, it must be considered that, on the one hand, a high manufacturing quality of the structure elements must be ensured. On the other hand, regarding the forming technology, mostly high-hardness tool steels have to be machined. Furthermore, the resulting influence on the sub-surface must be taken into account as it is considered of great relevance for the wear resistance. Especially thermal machining processes, for example electronic discharge machining (EDM) can cause unfavorable effects e.g., tensile residual stresses that reduce the service life of mechanically stressed components. Technological achievements in the field of laser material processing enable such effects to be avoided, making the process also suitable for structuring [Primus et al. 2023]. In particular, the flexibility of the manufacturing process as well as wear-free machining are fundamental advantages. Likewise, very filigree and versatile surface structures can be produced [Wang et al. 2021]. However, only minor ablation rates can be achieved compared to mechanical machining processes and the impact on the fatigue performance of highly-stress components is not entirely grasped. For reasons of removal rates, achievable surface properties as well as sub-surface constitution, mechanical machining processes still offer the potential to improve the structure and the properties of a tribological surface [Keitel et al. 2021; Tillmann et al. 2021]. In addition to other machining processes, such as grinding or high-feed milling, micromachining has proven to be a versatile method for manufacturing filigree structures [Baumann et al. 2021; Biermann et al. 2011; Siebrecht et al. 2019]. It has already been shown that the micromilling of tool steels enhances the fatigue behavior, which was attributed to the induction of high residual compressive stresses in the sub-surface [Wild et al. 21]. This has additionally a positive effect on the coatability of the machined surfaces [Tillmann et al. 2021]. In contrast, micromilling poses challenges in terms of tool wear and process design especially regarding size effects and ploughing. Furthermore, static and dynamic tool deflections can impair the manufacturing quality.

Within the framework of the TCRC 73, surface structures occurring in nature were analyzed and derived for application in forming technology [Tillmann et al. 2015]. Surface structures of beetles and leaves, which can be found in nature, served as templates. The honeycomb surface structure observed in the analyses can be traced back to the head shell of the scarab beetle (lat. *heliocopris gigas linnaeus*). In contrast to the natural surface structures, these machined structures exhibited rigid geometric arrangements, which were necessary to duplicate the structure elements in the CAD/CAM environment, see Figure 1.

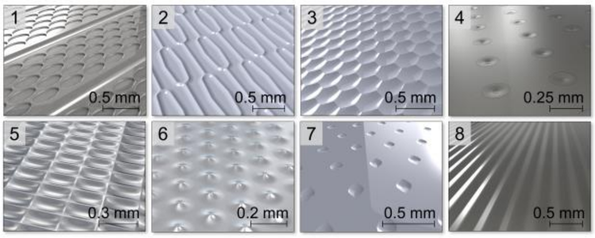

Figure 1. Selection of bionic motivated deterministic surface structures – according to [Meijer et al. 2021a]

Apart from the potentials of surface structures or micromilling the design of the machining process, however, represents a major challenge. Due to the free-form shape of the structure elements as well as the sheer number of elements, the process design is difficult to achieve with conventional CAD/CAM-software. For most bionic surface structures, a large number of NC commands is necessary to ensure a defined engagement of the tool as well as high manufacturing quality [Biermann et al. 2011]. For small areas, the machining programs can be designed comparatively efficiently in a CAD/CAM environment. However, calculation problems occur already above an area of about 8 x 8 mm or approx. 6000 structure elements [Meijer et al. 2021a; Meijer et al. 2021b]. For example, the construction of the model and calculation of NC-paths for an area of 10 x 10 mm for structure 3 (Figure 1) already took about 30 min. For structure 6, already 4.75 h were required [Meijer et al. 2021b]. In addition to the extremely high calculation time, however, the uniform machining of the individual structure elements also poses a problem [Meijer et al. 2021b]. Common process cycles in CAM software offer only limited possibilities to design the structure manufacturing in an expedient way. Because of this, previous efforts have already focused on the efficient design of the machining programs. A first approach has already been presented in the past in which the NC paths of a single structure element are reproduced [Krebs 2017; Meijer et al. 2021a]. By replicating the machining paths, the computational effort in the CAD/CAM environment can be minimized while ensuring uniform machining of each individual element. In addition, machining strategies can thus be strategically adapted and transferred to the entire surface. Furthermore, the approach of projection of planar machining programs onto free-formed surfaces was implemented [Meijer et al. 2021a]. Based on a projection calculation, the NC-points are shifted to the surface of a designed component. By additional compensation of the tool engagement, it was already possible to structure free-formed surfaces of forging tools regardless of the area size and shape complexity [Meijer et al. 2021b]. By calculation on graphics cards, an efficient process chain for the generation of large machine programs with several million NC-points was realized [Meijer et al. 2021b]. However, it was found that the projection results in an impairment of the structural design depending on the flank angles of the surfaces. This effects the contact situation to such an extent that the tribological contact properties will differ from the originally designed shape. To overcome these limitations, a new approach for the process design of micromilling is required that enables the homogeneous and comprehensive structuring of free-form surfaces.

Based on the detected constraint, a new approach is presented in this paper, which favors the efficient and homogeneous machining of free-formed structural surfaces. Contrary to previous approaches, the replication of the NC-points of a single structural element is not based on fixed geometric parameters, but on a stochastic distribution, which is more comparable to naturally occurring surface structures. This is achieved by Poisson-Disk sampling on the desired surface of the constructed component [Wang et al. 2018]. By replicating the NC-Points for each element at the respective sampling point a machining program for a stochastic surface structure can be generated. In the following, the schematic approach is described, and the potentials are analyzed based on the application in the production of a demonstrator. Furthermore, a comparison is made between a projected deterministic and a stochastic structure based on free-form demonstration components.

2 MATERIALS AND METHODS

2.1 Methods for generating NC-programs

The following section describes the method for generating NC programs for free-form surface structuring. First, the projection approach is briefly described. This is followed by a more comprehensive explanation of the developed approach based on a stochastic structure distribution. The basis of the computer-assisted replication of surface structures of both approaches are machine commands (NC-points), which are necessary to manufacture a single structural element or a partial segment of the entire surface structure. The generation of the partial segments is done in the conventional method via CAD/CAM.

Projection of planar NC-programs

The projection of structuring programs is based on planar machining programs, which lateral dimension corresponds to the geometry of the component to be machined. For this, the partial segments of the machining program are first duplicated to the required area. This was done with a software developed at the Institute of Machining Technology called *NC-Code-Generator* [Krebs 2017; Meijer et al. 2021a]. This program rasterizes the partial segments to a defined area (e.g., rectangles, circular areas or partial sections) on the basis of geometric reference parameters, which have to be set for the respective structure (see Figure 2). Linkages between the individual structure elements are inserted in the NC-program as traversing movements of the machine. Due to the simplified generation of coordinates independent of the design of the workpiece, large-scale machine programs can be created very efficiently. When the calculation is complete, a machine-readable NC-program is generated, which, in addition to the movement commands, also contains information such as function commands, tool changes, and feed commands.

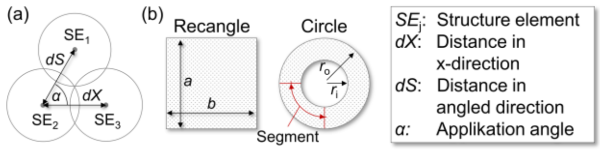

Figure 2. Geometrical arrangement of structure elements and replication in the NC-Code-Generator - according to [Meijer et al. 2021a]

In a further step, a projection onto a more complex workpiece surface can be performed. The schematic process chain and individual steps are illustrated in Figure 3. Before projection of the planar structuring program onto a free-form surface, it may be necessary to subdivide longer linear sections of the machine program due to varying point distances. This is particularly important for linear structures to achieve sufficient NC point density for homogeneous projection onto a curved surface. In a further step, the projection of the planar machining program is performed. For this purpose, the workpiece geometry can be extracted from the CAD design as a high-resolution triangle mesh representation. The individual point coordinates of the planar NC-program are then analyzed in the following step. First, a ray calculation is performed which runs along the Z-axis through the

NC point under consideration. Subsequently, all triangular surfaces are tested for an intersection point with this ray [Möller et al. 1997]. Once an intersection point is found, the NC point is projected along the Z-axis onto the intersection point and is thus located on the desired surface. To compensate for the tooling engagement, the calculated point is transformed along the surface normal of the intersected triangle, taking into account the tool radius. The information on the desired depth of cut respectively the initial Z-component of the NC point is considered in this calculation, so that a constant structure depth is achieved regardless of the slope of the surface. The calculated NC-points are then output as a machine-readable program. For an efficient generation of large machining programs with a high-resolution representation of the workpieces, the projection calculation is performed on the graphics card (GPU), since this allows a high degree of parallelization of the calculations.

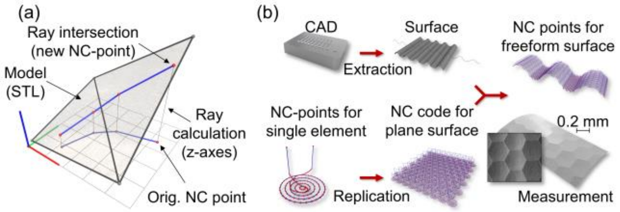

Figure 3. **(a)** NC-to-STL projection and **(b)** schematic process chain for structuring free-form surfaces - according to [Meijer et al. 2021a]

Stochastic distribution based on Poisson-Disk sampling

The simple projection of plane structural programs leads to a considerable stretching of the structural elements on surfaces with a strong inclination. This is due to the difference in area between the free-form surface and the projected outline. In the region of steep flanks, individual structural elements cover a larger area on the free-form surface, which leads to a distortion of the structural shape. Due to the fixed geometric arrangement of the structures as well as their defined size, this problem cannot be solved geometrically without affecting the arrangement or size of each structure element. Looking at surface textures of various kinds occurring in nature, it is noticeable that these mostly exhibit a greater variance [Arzt et al. 2021; Parker et al. 2001; Wen et al. 2014]. Most surface structures show a certain variation in the size as well as the arrangement, which allows the coverage of non-uniform surfaces. Bionic motivated but technical constructed structures, however, are often design in fixed arrangements, which complicates the area coverage. Consequently, regarding the superior design of nature, an avoidance of the problem described can be achieved by a more random arrangement.

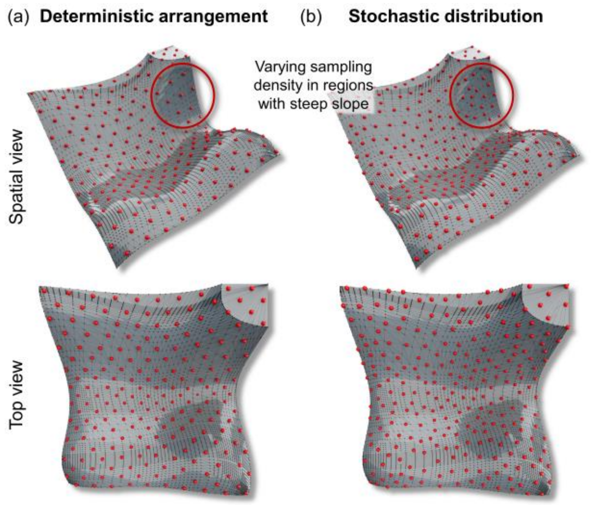

Figure 4. Comparison of **(a)** deterministic arrangement and **(b)** stochastic distribution

In the presented approach, this is achieved by a stochastic distribution of the structural elements. Since the structural elements are no longer arranged in a defined geometric order, deviating surface areas respectively steep flanks can be uniformly patterned. This results in a random structural shape, which is more uniform over a free-formed workpiece surface. Contrary to the original approach using the *NC-Code-Generator*, sampling points of the structural elements are determined first on the surface of the workpiece. For this purpose, Poisson-Disk sampling is performed on the triangle mesh representation of the workpiece surface [Wang et al. 2018]. The density of the structure elements ρ_{ST}, respectively the number of sampling points that are used in the calculation, determines the number of structural elements and thus the resulting structure topography. As the density increases, a higher number of structural elements are placed in a certain area, resulting in a finer structure with less roughness. The result is a random distribution of points on the surface, which have distances between each other in a stochastic range. This is illustrated exemplary in Figure 4 (b). Recognizable is a simplified triangle mesh representation as well as a random arrangement of sampled points on the surface. Due to minor tolerances regarding the distances between the individual points, an approximately uniform coverage of the surface can be achieved. In a following step, at each point of the sampling and considering the respective surface normal, a replication of partial segments of the structure program can be performed. Comparable to the previous approach, the tool engagement is compensated further based on the tool diameter.

2.2 Machining process, materials and tools

The machining experiments were carried out on a machine tool of type HSPC 2522 - KERN Microtechnik (Eschenlohe, Germany). The kinematic capabilities as well as the high working accuracy make this machine very suitable for surface structuring in the field of micromilling. Due to the climate-controlled and vibration-decoupled installation, external influences can be minimized, ensuring a reliable experimental setup.

Milling tools

The demonstrators have been structured with double fluted ball end mills of solid carbide with a diameter of d = 2 mm. The ball end mills of type 551.0200.100.060 by Zecha GmbH (Königsbach-Stein, Germany) are designed for high-speed machining of non-ferrous metals and do not feature a wear protection coating.

Workpiece

The demonstrators were machined from aluminum EN AW-7075 allowing an illustration of the methodical approach and an evaluation of the manufactured surface structures. In addition, this initially enables an analysis regardless the increased tool wear that is to be expected when machining forming tools made of tool steel. The chemical composition of the alloying elements of EN AW-7075 are shown in Table 1. The specimens were available in the dimensions 50 x 50 x 30 mm (L x W x H).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
≤ 0.4	≤ 0.5	1.2 - 2.0	≤ 0.3	2.1 - 2.9	0.18 - 0.28	5.1 - 6.1	≤ 0.2

Table 1. Alloy elements of aluminum EN AW-7075 in wt. %

Process: Design, parameters and software

The design of the free-form surface and the process design of the process steps for the production of the surface to be structured were carried out in the CAD/CAM software Siemens NX (Munich, Germany). The NC-paths for individual structural elements were designed in this software as well. The honeycomb surface structure chosen has been the subject of a previous series of scientific studies [Behrens et al. 2020b; Löffler et al.

2016; Meijer et al. 2021a]. This structure has been successfully used in different application scenarios in the field von sheet-bulk metal forming. For initial consideration, however, the structure was scaled up by a factor of 2. The structure elements have a depth of 10 – 40 µm and a diameter of 0.9 mm. Each structure element was manufactured in a 3-axis machining process in a spiral path, (see Figure 3). Machining was performed at a rotational tool speed of n = 20,000 min^{-1} (v_c = 125.7 m/min) and a feed per tooth of f_z = 8 µm. Furthermore, the structure was machined using a flyover lubrication system. The lubricant used was a water-miscible cooling lubricant of type Avantin 404 hm by Carl Bechem GmbH (Hagen, Germany).

2.3 Surface characterization

The surface analysis and evaluation of the structural topography was performed using both a confocal microscope and a focus variation microscope. The high-resolution analysis of machining quality was carried out on the confocal 3D microscope DuoVario by Confovis GmbH (Jena, Germany) equipped with a 20x lens by Olympus Corporation (Tokyo, Japan). In addition, the optical focus variation microscope Infinite Focus G5 by Alicona Imaging GmbH (Graz, Austria) was used to analyze hard-to-reach areas of the structured surface. Specific areas of the demonstrator with different shape elements of the free-form surface are measured to evaluate the structure arrangement.

The determination of roughness parameters was performed on simulated as well as measured areas of 10 x 10 mm. The calculation was done in MoutainsMap 7 by Digital surf (Besançon, France) in accordance with DIN EN ISO 21920-3 with a cutoff wavelength of λ_c = 2.5 mm. In order to discuss directional dependences of the topography, the surface structures were analyzed in in two directions. The demonstrators were evaluated at selected points on the surfaces, as described below. The profile parameters were determined based on 500 profiles.

3 RESULTS AND DISCUSSION

In the context of the results, a discussion of the stochastic approach as well as a comparison to the deterministic variant is conducted. This is first based on simulated topographies in order to consider in particular the parameter of the structure density ρ_{ST}. In the following, specific areas of demonstrators are discussed and the potentials of the new approach are evaluated based on the deviations of the NC trajectories, roughness parameters and the manufacturing quality of the structures.

3.1 Influence of the density on the surface characteristics

The topography of the stochastic surface structure depends strongly on the density selected for the sampling. This parameter presents the number of structure elements in relation to the area. To consider the effect of varying structure density, a variation of the parameter was performed in a range of ρ_{ST} = 1.0 - 5.0 SE/mm^2. The influence on the topography was first determined simulatively using a geometric process simulation developed at the Institute of Machining Technology [Freiburg et al. 2018; Meijer et al. 2019]. Due to the high degree of accuracy of predicted topographies already shown in the past, it was thus possible to carry out an efficient structure analysis. The change in the structure topography can be seen in Figure 5. For comparison purposes, the deterministic honeycomb structure (Figure 1) was also considered.

A comparison of the stochastically distributed structure with the deterministically arranged structures reveals a considerably different topography. The more random distribution of the structural elements results in varying distances as well as different arrangements between the structure elements. Thus, a regular honeycomb shape does not always occur. These deviations in the arrangement also lead to considerable deviation in the height of each structure element, which distinguishes the contact situation of the stochastic surface structure from the deterministic variant. Considering the variation of the structure density, the strong scaling of the entire structure is also evident. In addition to the influencing of the lateral dimensions of the structural elements, the scaling also leads to a change in the height of the structure peaks. However, especially at very low structure density, geometric deviations are noticeable. Furthermore, it was found, that with low structure densities, a complete shaping of the structure design could only be achieved with sufficient depth of the NC-paths. If this is not the case, it leads to the formation of unstructured areas, which appear as islands of the initial surface. This can be attributed to the uniform replication of the NC paths. In this approach, the NC-paths of a single structural element are not scaled nor distorted. Thus, the entire surface structure results from the intersection of the machining paths of different structure elements. A low structure density therefor results in an inadequate overlap of NC-paths, respectively insufficient coverage of the surface to be machined. Considering the deterministic structure, which has a density of ρ_{ST} = 2.7 SE/mm^2, the stochastic structure could be scaled up with sufficient machining depth to a structure density of 2.0 before significant degradation of the structure design occurred. Furthermore, the density can be increased very flexibly. However, due to the strong overlapping of the NC-paths, an increasing share of the machining movements do not achieve a material removal anymore. Therefore, the machining program becomes more inefficient. In summary, a certain flexibility with regard to the structure density can be determined for the stochastic approach, which allows an adaptation of the structure design, e.g. the roughness. In perspective, the density of the structure could also be varied locally in order to realize a local modification of the tribological properties.

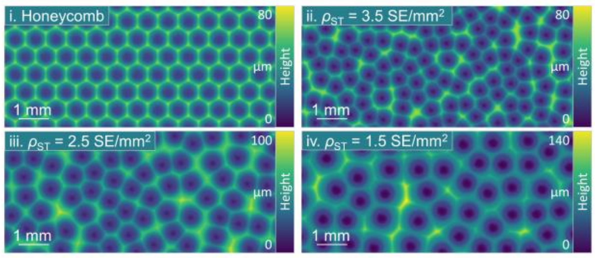

Figure 5. Topographies of stochastic structures with varying structure density compared to the deterministic honeycomb surface structure

Furthermore, the topographies were evaluated with respect to resulting roughness parameters. As can be seen in Figure 6, a substantial reduction in roughness is evident with increasing structure density. These trends can be determined in the areal parameters as well as in the profile roughness parameters regardless of the evaluation direction. In general, this can be linked to the downsizing of the structural elements due to the increasing overlapping of the machining paths with higher density. Slight deviations from the trends were attributed to the random occurrence of higher peaks between structural elements with greater spacing. It is expected that further optimization of the sampling, taking into account the distances, will result in a more uniform structural topography. Due to the stochastic arrangement, the structures also exhibit a lower directional dependence. While the deterministic structure in fact shows three predominant directions, the stochastic arrangement results in a roughness profile that is directional independent. This is particularly evident from the high agreement of the profile parameters in different evaluation directions. However, the direct comparison of the roughness characteristics of the stochastic structures with the deterministic arrangement shows that the stochastic approach results in a higher roughness at comparable structure density. This was justified by the more random arrangement as well as the varying height of the structure peaks. Therefore, in order to obtain a structure with comparable roughness, a high structure density must be selected for the stochastic distribution than it is the case with deterministic arrangement. This can be seen in Figure 5 as well as in Figure 6.

The classic honeycomb structure (i) with a structure density of ρ_{ST} = 2.7 SE/mm^2 and the stochastic structure (ii) with a density of ρ_{ST} = 3.5 SE/mm^2 showed comparable roughness values in the arithmetic mean roughness *Ra* as well as arithmetic mean height *Sa*. Nevertheless, the higher number of structural elements in (ii) is evident. Still a higher roughness of the stochastic structure is, however, certainly identifiable in the values maximum profile height *Rz* as well as the areal maximum height *Sz* in this comparison. Moreover, the overall level of the maximum peak height *Sp* indicates an stronger formation of the structural peaks with the approach of the stochastic distribution, see Figure 6. As previously described based on the topographies shown in Figure 5, the roughness characteristics presented indicate a very flexible adaptation of the contact properties by varying the structure density.

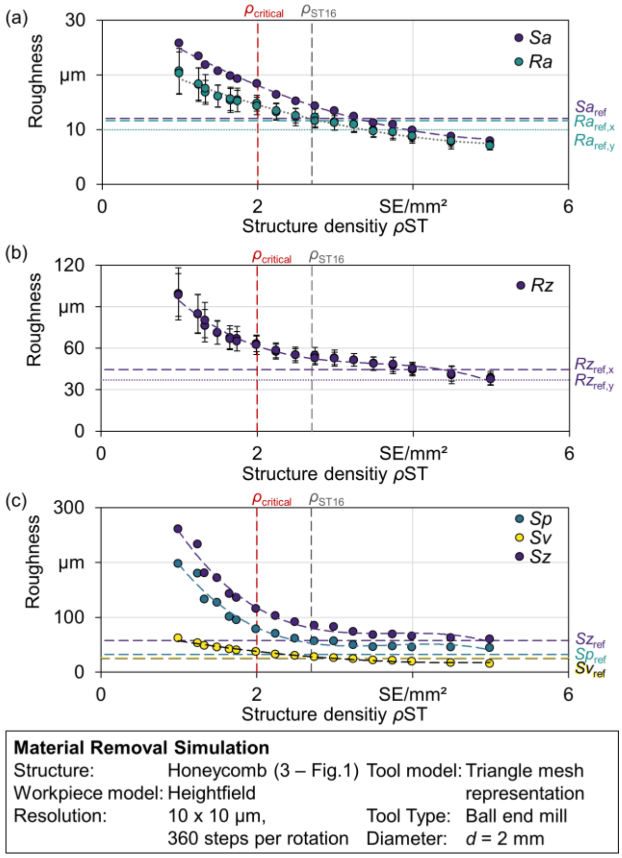

Figure 6. Influence of the structure density on the surface roughness: **(a)** arithmetic mean roughness *Ra* and arithmetic mean height *Sa*; **(b)** maximum profile height Rz; **(c)** maximum height *Sz*, maximum peak height *Sp*, and maximum pit height *Sv*

3.2 Comparison of deterministic and stochastic approaches

The potential of the presented techniques will be discussed in the following based on specific regions of the demonstrators machined. These are simple shape elements, which result from the surface inclination or curvature. More specifically, the four regions of i. *plane*, ii. *flank* (45°), iii. *concave*, and iv. *convex* are assessed. First, the deterministic structuring is examined based on projected NC-paths, see Figure 7. Based on the measurement in the region of the plane surface (i), the structure design can be seen without any distortions. The deterministic arrangement of the structure elements results in a uniform and homogeneous surface structure. However, considering the inclined flank (ii), a strong distortion of the surface structure is evident, as it was already determined in previous investigations [Meijer et al. 2021a; Meijer et al. 2021b]. The distortion can be related to the approach of NC-projection, described in section 2.1. Due to the simple projection along the Z-axis, a distortion of the NC-paths, i.e. the structure elements, results, which depends on the inclination angle of the surface. With increasing inclination a stronger distortion results, which impairs the tribological contact properties. This is already evident from the measurement in the strong directional dependence of the surface structure, which can no longer be considered isotropic. The convex and concave areas, however, do not show substantial change in the structure design. Nevertheless, based on the superimposed curvatures in two spatial directions, a certain influence on the size ratios can be assumed, which depends on the curvature of the surface.

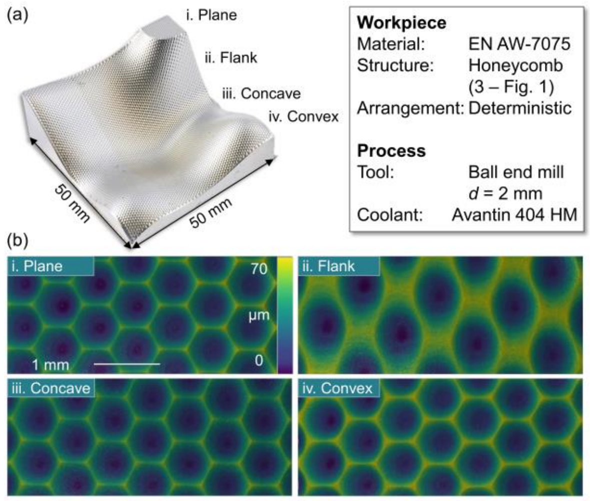

Figure 7. Structured demonstrator - arrangement of the bionically inspired structural variant according to a deterministic approach, which leads to a distortion of NC trajectories in critical areas such as the flank, and thus in reduced shape accuracy.

Furthermore, Figure 8 shows the manufacturing result of the demonstrator with a stochastic distribution of the structure elements. On the plane surface, the manufactured surface structure can be seen with a structure density of ρ_{ST} = 2 SE/mm^2, regardless of any influence of the shape of the components surface. As described above, random arrangements of the structural elements result, which feature varying heights and shapes in a certain range. However, these tolerated shape deviations enable a structure distribution in demanding regions of a free-form surface, e.g. cavities or surfaces with a steep slope (II). For this reason, the surfaces generally show a comparable density with a similar number of structure elements resulting in directional independent topographies for areas of consideration. An examination of the inclined flank (ii) revealed a more regular distribution of structural elements compared to the projected deterministic surface structure shown in Figure 7.

With the approach presented, the application of surface structures in these steep regions shows the potential of the stochastic distribution. Furthermore, the measurements of all regions show similar arrangements of the structure elements independent from the characteristics of the surface. However, when comparing the measurements in convex as well as concave areas, a certain variation in the structure height is evident. For a further characterization of the tribological behavior will be necessary, which focus on the friction conditions, as for example a ring compression tests [Merklein et al.21].

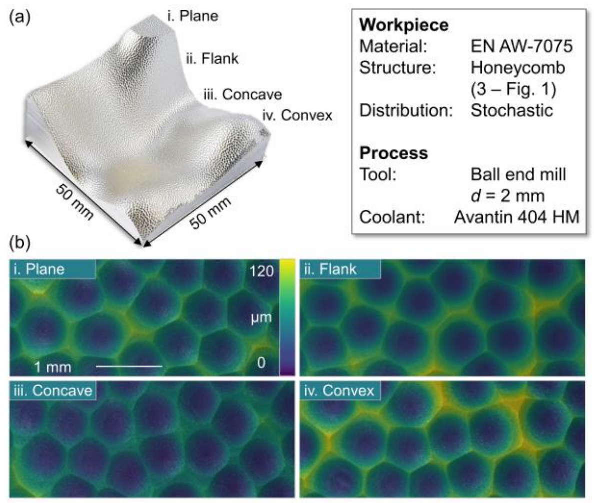

Figure 8. Structured demonstrator - arrangement of the bionically inspired structural variant according to a stochastic approach that leads to a quasi-homogeneous structuring even in critical areas such as steep flanks by allowing slight shape inaccuracies of the structure elements.

In addition to the qualitative structural analysis, a determination of areal roughness parameters as well as profile parameters was conducted. Figure 9 shows the values determined of the maximum profile height *Rz* and the arithmetic mean roughness *Ra* for the two approaches with respect to the region of analysis. Over all the approach of a deterministically distributed structure for the maximum profile height contains values in the range of 45.6 < *Rz* < 55.9 µm for the investigated areas. In comparison, the stochastic surface structure result in a higher level for the roughness values of 56 < *Rz* < 71.1 µm, which was attributed to structure density as well as the deviating structure composition. As can be seen in Figure 9, the values of maximum profile height vary between the regions of analyses for both structuring approaches. However, it is noticeable that despite the higher roughness of the stochastic structure, a smaller deviation was recorded between the plane surface and the steep flank. The deterministic structure showed a more deviating roughness value complementary to the already shown stretching of the structural shape at steep flanks. However, when considering the roughness in the curved regions, the stronger scattering of the stochastic structural distribution becomes apparent.

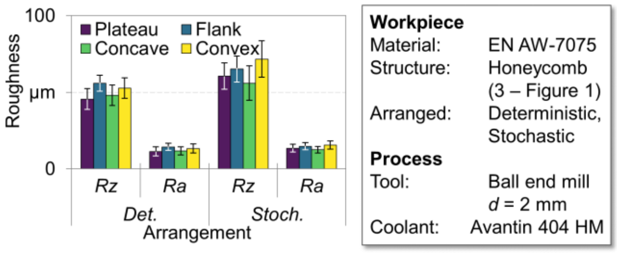

Figure 9. Structured demonstrator – Profile roughness parameters.

Furthermore, areal roughness parameters of the material ratio were determined in order to show deviations between the two approaches as well as the regions of interest, see Figure 10. As can be seen from the characteristic values, the trends are comparable to those described above. The stochastic structure showed a considerable higher roughness level, which is due to the lower density as well as the randomized distribution. Furthermore, the approach seems to be more sensitive to convex or concave curvature of the freeform surfaces. Since no distortion of the NC paths is performed in stochastic approach so far, this motivates to introduce a slight distortion of the NC-paths in addition to the random distribution. It is to be expected that advantages of both approaches can thus be combined.

In contrast, the significant deviation of the reduced valley depth *Svk* with the deterministic structure is evident, which the stretching of the structure elements shown in the region of the flank. This represents the strongest deviation determined on structured surfaces analysed. With such a significant change in the structure characteristics, a distinct influence on the contact situation is to be expected. Thus, in steep, challenging regions, the stochastic distribution-based approach provides a more homogeneous areal coverage. However, associated variation in structure geometry can be debilitating, so incorporating rules into the approach are necessary to improve overall roughness and limit the variety of structure element shapes, which reduces variation between structure peaks.

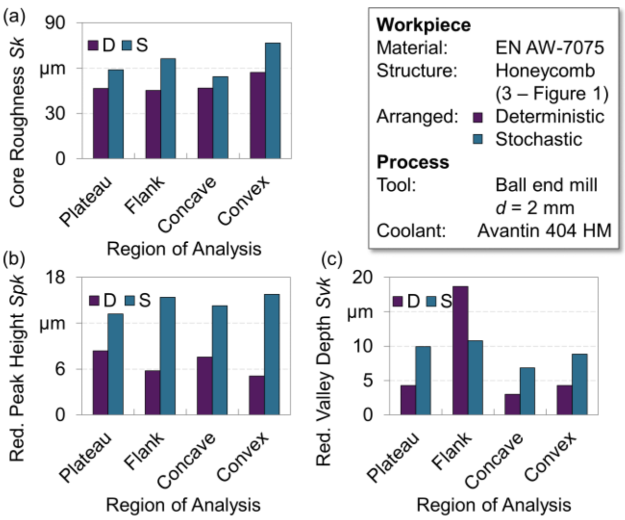

Figure 10. Structured demonstrator - volume ratios

4 CONCLUSIONS

In the paper, an approach for the generation of machining programs for micromilling of stochastic distributed surface structures on free-formed workpieces was introduced. In addition to the established deterministic surface structures, a distribution approach by Poisson-Disk sampling was presented. First, the schematic method was described. Further, it was compared with the previously used technique of projecting planar machining programs of deterministic surface structures. In the context of a simulative analysis of the surface structures, a comparison of both approaches as well as a consideration of the structure density was conducted. Here, suitable scaling limits for the structure density have been identified for the setup considered. Furthermore, the stochastic distribution resulted in a lower directional dependence of the resulting structure roughness and a scalability of dimensioning by adjustment of the structure density was identified. Due to the random distribution of the structure elements, however, higher values of certain roughness parameters were determined. This was attributed to the more irregular shape of the individual structure elements, which resulted not only in the lateral dimensions of structure elements but also in the height of the structure peaks. Moreover, the manufacturing result of demonstrators was considered, which were processed using the previous approach of NC-projection of deterministic structuring programs and the stochastic distribution by Poisson-Disk sampling. It could be shown that a homogenous structure design could be achieved on the entire free-form surface by the approach presented. This also applied to steep flanks, which previously led to a significant stretching of the structural elements and thus a local deviation of the contact situation. Based on the quantitative analysis, however, certain deviations of roughness parameters were still evident for different analysis regions of the stochastic structure. This was particularly evident in areas of convex or concave curvature. Therefore, further development steps are necessary to improve the overall approach of stochastic distributed surface structures. Thus, an optimization of the sampling is aimed at to reduce the non-uniform distribution of the structure peaks and to achieve a more uniform roughness texture. Furthermore, an additional distortion of replicated NC paths is seen as an advantage in order to better adapt the structural elements to the shape characteristics of the free-form surface of the component. Local adjustments of the sampling density are also conceivable in order to achieve adjacent structure areas of the same design but with different roughness characteristics.

Future investigations will transfer the approach described above to workpieces made of tool steel. In addition to tribological analyses of the contact situation, application tests in forming processes are also pending in order to be able to better evaluate the potential of stochastically distributed structures. In this context, other structuring approaches and processes also need to be compared. In addition to the original focus of the development, the approach also offers the possibility of being extended to other manufacturing processes, such as laser material processing. Furthermore, the use of complex surface structures on medical products, such as in the field of prosthetics, should also be evaluated independently of forming technology. This approach offers promising possibilities, particularly in the manufacture of complex prostheses with complex free-form geometries.

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