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Geometrical and topological potentialities and restrictions in selective laser sintering of customized carbide precision tools

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Abstract

The joint research project PraeziGen is dedicated to achieve a technology leap by applying additive manufacturing (AM), respectively selective laser sintering (SLS) or melting (SLM), to fabricate customized carbide precision tools with complex inner and outer shape. A main objective during the project is the development of a process chain for AM of near-net-shape cutting tools and the qualification of carbide materials, especially tungsten carbide (WC-CO), for the SLS process. The increased design freedom inherent to AM processes offers significant benefits with respect to the development of cutting tools, such as a light-weight design and an increased degree of functionality. The ability to fabricate customized cooling channel systems inside the tool is of particular interest for industrial applications. Those applications are currently limited to the processing of steel alloys and have not been published for WC-Co so far. This is mainly caused by the intrinsic issues in SLS of tungsten carbide such as the formation of pores, cracks and brittle material phases, which were already identified in several studies. However, for the design of tools with complex shapes, not only the material microstructure and quality, but also the process-related geometrical and topological restrictions are of utmost importance. For example, the surface roughness inside the generated cooling channel has a significant impact on the pressure losses and the flow rate of the coolant. For SLM/SLS-qualified materials such as steel or aluminum alloys, appropriate design guidelines have already been established to consider the specific characteristics of the additively manufactured parts. Distinct guidelines for WC-Co are not yet existing and have to be elaborated. Hence, the proposed paper deals with the study of the geometric and topologic design aspects in SLS of WC-Co with regard to the characteristic design features of application optimized cutting tools.

Keywords: Selective Laser Sintering (SLS); Selective Laser Melting (SLM); Tungsten Carbide (WC-Co); Cutting Tools; PraeziGen; Design

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1. Introduction

The majority of modern cutting tools is made from carbides. In particular, tungsten carbide (WC) in combination with cobalt (Co) as a binding agent currently is the most common cutting tool material system. Due to the metastable characteristics of composite carbides, cutting tools are conventionally manufactured in a powder metallurgy sintering process. A specific powder composition is compressed into a green state and then sintered under defined temperatures to become a solid carbide blank. Dependent on the complexity of the tool geometry, a costly grinding treatment of the blank must subsequently be performed, to achieve the desired tool shape. Highly complex geometrical elements, such as branched internal cooling channel systems, honeycomb-like structures or optimized chip flute topologies, cannot be realized with the conventional manufacturing approach due to the restrictions given by the sintering and the grinding processes.

Additive manufacturing (AM) technologies can open up an enhanced degree of freedom in the design of application optimized cutting tools. Therefore, the joint research project “PraeziGen” is dedicated to exploit the potentialities of selective laser sintering (SLS) and to fabricate application optimized tungsten carbide precision tools with a minimum of geometrical restrictions. In a collaborative work of the iWFT and seven more partners from industry and research organisations, a process chain for the additive manufacturing of innovative cutting tools is developed. The qualification of composite carbide materials for the SLM process is the most challenging part of the process chain due to the formation of characteristic defects inside the material microstructure, already described by Laoui et al. 2000 at the University of Leuven, by Gläser 2010 at the Fraunhofer IPT Aachen, by Ott 2012 at the IWB in Munich, at the ISAF in Clausthal (N.N. et al. 2013), by Uhlmann et al. 2015 at the Fraunhofer IPK Berlin and at the iWFT in Cologne by Reuber et al. 2015 and Schwanekamp and Reuber 2016. The results of the studies indicate that a material quality, sufficient for the manufacturing of cutting tools, is not yet achieved.

However, for the design of tools with complex internal and external shapes, not only the material microstructure and quality, but also the process-related geometrical and topological restrictions are to be considered. One example is the surface roughness inside the generated cooling channel, which significantly takes influence on the pressure losses and the flow rate of the coolant.

For SLM/SLS-qualified materials such as steel or aluminum alloys, appropriate design guidelines have already been established to consider the specific characteristics of the parts additively manufactured on different AM equipment systems (VDI 2015). Ott 2012 published the evaluation of a benchmark geometry, additively manufactured from WC-Co 83/17 through SLS. However, only sparse information is given about the detailed results, distinct guidelines for the manufacturing of WC-Co cutting tools are not yet existing and must be elaborated. Hence, a study of the geometric and topologic design aspects in SLS of WC-Co with regard to the characteristic design features of application optimized cutting tools is conducted at the iWFT.

2. Process quality features and benchmark elements

For the development of appropriate benchmark elements both, the typical process-specific geometrical limitations of additive technologies as well as the typical geometrical elements of cutting tools must be taken into account. AM processes typically are evaluated by technological and economical quality features (Danjou 2010). For the initial purpose of the feasibility study, presented in this paper, a low priority is given to economic aspects. The considered technological features are dimensional and shape accuracy, roughness and surface quality, component curling and warping.

VDI 2015 gives a compendium of general design rules for part production using laser sintering and laser melting. A fundamental impact on the geometry and topology of the sintered or melted parts is exercised by the magnitude of the heat affected zone and hence by the induced laser energy. The dimensions of the melting pool have an influence on the accuracy, the roughness and the minimal resolution of details which can be realized. In addition, the roughness and the minimal resolution of details is affected by the particle size distribution of the powder and the thickness of the coated layers. The resulting drawbacks according to VDI 2015 are summarized below.

Local temperature gradients can cause shrinkage, residual stresses and local deformation of the manufactured part. It should be noted here, that the thermal conductivity of solidified material can significantly differ from the conductivity of the original powder material. If the shear strength of the material is exceeded by internal shear stresses between the layers, or if the connection between the layers is not sufficiently formed, delamination is the consequence. Fig. *1* (a) shows the problem of delamination for a WC-Co probe, additively manufactured through SLS. Furthermore, the internal thermal stresses can cause curling and warping phenomena (Fig. *1* (b)), which lead to an abort of the building process.

In addition to the thermal aspects, the layer-wise build-up of the parts results in a so called stair-step effect, which is illustrated in Fig. *1* (c) on the basis of a sintered sample and a sketch according to VDI 2015. The surface quality, respectively the roughness, is hence affected by the thickness of the layers. A particular emphasis must therefore be placed on deviations from form, dimensional and positional tolerances. A post-processing treatment is normally required for functional surfaces. The layer-wise build-up can also cause anisotropic material characteristics, which must be taken into account.

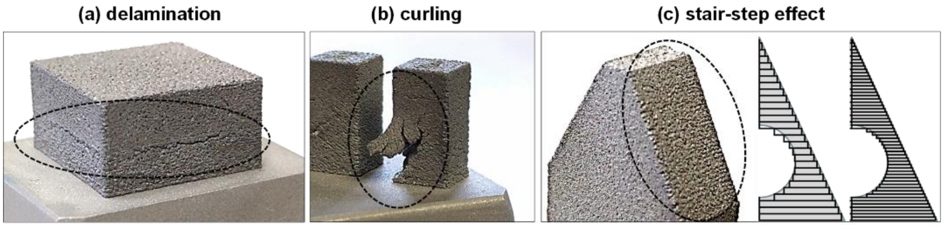

Fig. 1. Typical process-related problems shown by means of WC-Co specimens manufactured at the iWFT through SLS;
(a) delamination of layers, (b) curling defect and (c) stair-step effect (sketch according to VDI 2015)

In addition to the layer thickness, the inclination of the surface is of significant importance with respect to the dimensional accuracy, the roughness and the producibility (Adam 2015; Leutenecker-Twelsiek et al. 2016). Based on experimental results, Thomas 2009 elaborated an illustration showing the relationship between inclination and surface roughness (Fig. *2*). According to Thomas 2009, the best quality and lowest Ra-values can be achieved for vertically oriented surfaces ($\vartheta = \delta = 90°$), since the stair-step effect is less distinct. The quality of up-facing surfaces ($\vartheta < 90°$) degrades with the value of ϑ until it suddenly increases for $\vartheta = 0°$ since a stair-step effect does not occur anymore. For down-facing surfaces, the quality rapidly decreases with the value of δ, not only because of the stair-step-effect but also due to enhanced powder adhesion for parts manufactured by SLM/SLS. This is of particular importance for very small geometrical features, such as crevices, holes, channels and cavities, where allowance must always be made for powder removal (VDI 2015). Down-facing surface angles below $\delta < 45°$ need to be supported by additional structures to avoid curling defects and to safely be built. Support structures add an additional effort for removal and post-processing.

For SLM of stainless steel (316L), Thomas 2009 gives an average roughness Ra of 17 µm attainable for optimum orientation whereas a poor surface roughness is given with Ra = 34 µm for downfacing surfaces below $\delta = 45°$. It must be noted that the achievable surface roughness values of additively manufactured parts given by the literature are each determined under consideration of the specific AM technology, the processing parameters, the geometry and the material and are not universally valid though.

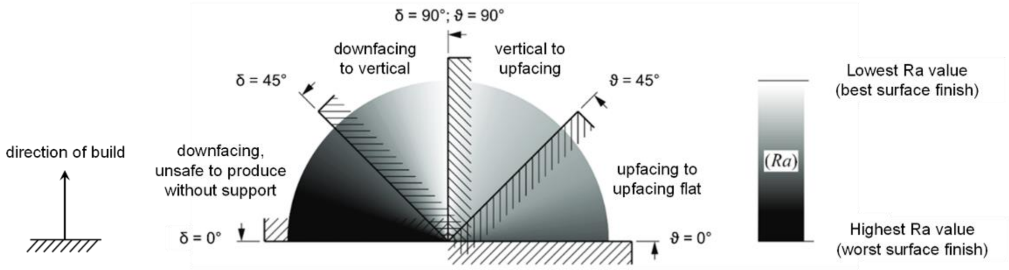

Fig. 2. Illustration of the relationship between inclination and quality of the surface according to Thomas 2009

Besides the orientation of a certain surface, the overall arrangement of critical elements inside the build space of the machine has an impact on the process stability, particularly with respect to the direction of the powder application system (wiper). VDI 2015 gives positioning and arrangement recommendations to minimize the frictional forces between the wiper and the elements to be built. Longitudinal elements should be arranged in the direction of the wiper to avoid recurvation. Downskin areas without support structures should not be built up against the direction of the powder application system since the downskin border can damage the wiper and hence corrupt the wiper accuracy. Multiple parts on the platform should laterally be displaced to ensure a constant coated powder level and to prevent undesired mutual interactions caused by weld spatters. Furthermore, the orientation of a part can significantly affect curling. Therefore the irradiated area per part and per layer should be minimized by means of an appropriate orientation.

Besides the geometrical characteristics, the application has to be taken into account, too. Fig. *3* shows the study logic for the deduction of appropriate benchmark elements and quality features to be assessed in this paper. Typical cutting tool geometries, particularly cutting inserts, drills and milling cutters, were analyzed, classified and systematically broken down into a set of recurring characteristic elements, such as the up- and downfacing slopes of the chip-flute or the circular holes of the coolant supply channels. In addition to the features of commercially available tools, the extended design options of additive manufacturing, like optimized internal structures, were also considered.

Based on the typical process-specific geometrical limitations of additive technologies and the typical geometrical elements of cutting tools, the benchmark elements were designed and manufactured from WC-Co through an SLS process. The features, which are assessed by means of the elements are also shown in Fig. *3*. It can be noted that the dimensional accuracy is not explicitly included, since this feature can be assessed for all the elements. The minimum width of crevices is mainly limited by the removal of the powder grains. The minimum thickness of walls is limited by the size of the melt pool and, particularly for WC-Co, by the mechanical stability of the material microstructure, which is the same for the minimum diameter of the cylinders. The circularity of cylinders, holes and radii mainly depends on the inclination with respect to the build direction whereas the straightness is mainly affected by thermal effects such as curling or warping. The quality features of up- and downskin surfaces are affected by many parameters such as the part orientation, the layer thickness, the laser parameters and the material characteristics. The minimum angle and the sharpness of the edges of peaks and corners mainly depend on the size of the melt pool.

Different concepts for benchmark elements are already existing and published e.g. by Köhler 2014; Kruth et al. 2005; Mahesh et al. 2004; Moylan et al. 2012; Vandenbroucke and Kruth 2007; Wegner and Witt 2012 with each concept covering a large variety of geometrical elements. However, in the present study it was decided to separately build up the different elements to reduce the consumption of material, to decrease the build time and the thermal stresses and to facilitate the measurability of the individual quality features.

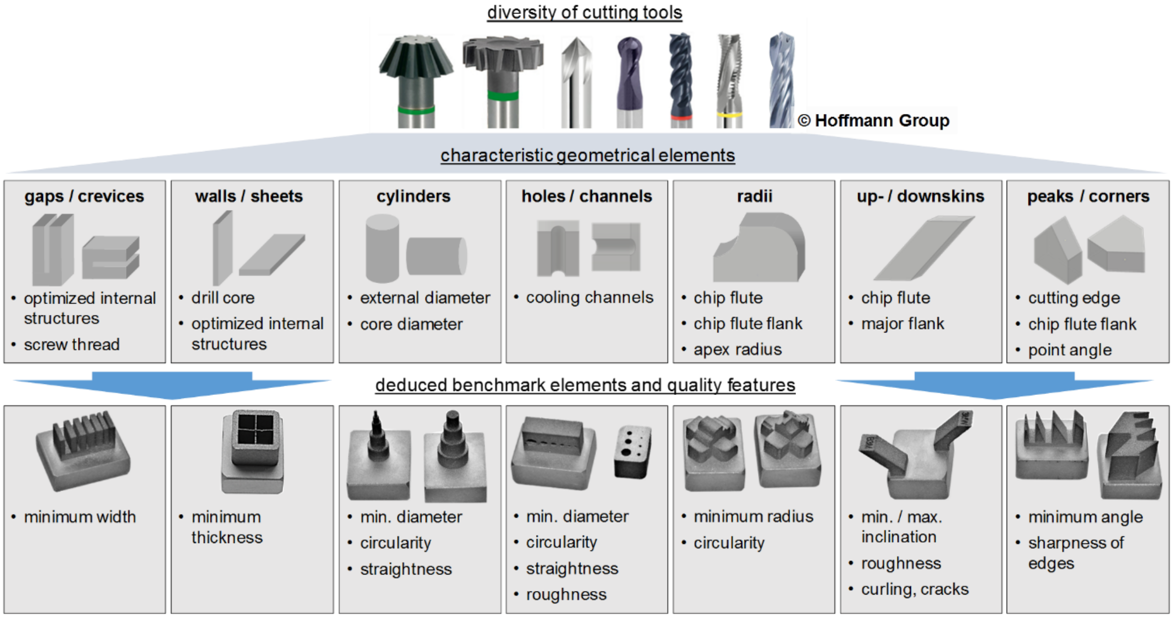

Fig. 3. Study logic for the evaluation of the geometrical and topological limits by means of appropriate benchmark elements

3. Optimization of surface quality

To partially compensate the process-specific surface roughness and dimensional accuracy and to avoid curling and warping, different scan strategies with individual sets of parameters should be applied for critical regions. Fig. *4* shows the different geometry zones, where the parameter sets can separately be selected for the Renishaw AM250 machinery. The process parameters such as laser power P, scan speed v and hatch distance h inside the fill hatch have an influence on the density of the solidified material, curling defects, thermal cracking and deformation. The investigation of adequate fill hatch scan strategies for the processing of WC-Co was performed, for instance, by Schwanekamp and Reuber 2016. Suitable process parameters for the fill hatch are adopted from this reference and not modified, since the focus of the study presented in this paper is on the optimization of the border scan as well as on upskin and downskin scan strategies. Hence, variations are focusing on the border, upskin and downskin parameters.

The contour of the part consists of one or several border scans. The number of border scans, the distance between the border scans and between the inner border scan and the fill hatch can be adjusted. A variation of the parameters P, v and h in the border zone affects the dimensional accuracy and the surface quality. The distance between the outermost border and the border of the CAD geometry is denominated the offset. The determination of an appropriate offset is essential for the dimensional accuracy and mainly depends on the size of the melting pool. Besides the standard fill hatch and border scan parameters, dedicated parameter sets can be chosen for upskin and downskin geometries to compensate the lower surface quality in these regions (Fig. *4*, right). The size of the up- and downskin areas highlighted in dark grey in Fig. *4* can be defined by the user. For upskin areas, an increased laser energy respectively a remelting is suggested by Yasa et al. 2011. For downskin regions Renishaw 2015 recommends a reduced laser energy.

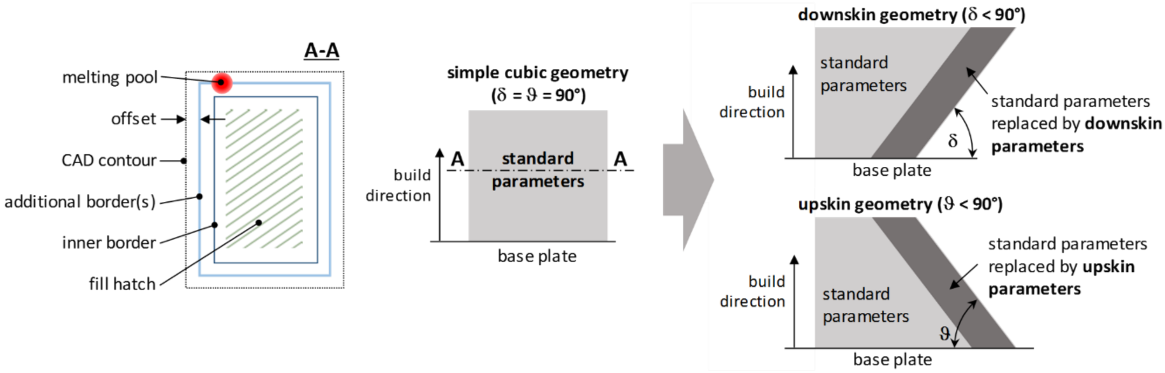

Fig. 4. Renishaw AM250 scan strategies for different zones of the part geometry

The results of the parameter optimization for SLS of WC-Co powder (DURMAT 111.015, WC/Co 88/12, grain size 10-25 µm) inside the different zones, shown in Fig. *4*, is summarized below.

In a first set of experiments, an optimization of vertically inclined surfaces ($\delta = \vartheta = 90°$) was conducted. In the beginning, it was found by means of simple cubic specimens, that the fill hatch should be scanned previously to the border. Otherwise the risk of thermal cracks and curling increases. This result fits to the general recommendations given by Renishaw 2015. Furthermore, it was shown that the utilization of the same parameter set for fill hatch and border scan does not improve the surface quality compared to a sole fill hatch exposure without any border scan. Hence, methods in the statistic design of experiments (DoE) were applied, to analyze and optimize the border parameters of vertically inclined surfaces with respect to a minimum roughness Ra. A Box-Behnken design was chosen with a number of 15 experiment points. The influence of the laser power P_{border}, scan speed v_{border}, and hatch distance h_{border} between the fill hatch and the border, on the averaged roughness Ra was determined. Absolute Ra values between 14.4 µm and 57.3 µm were detected. In the effect plots in Fig. *5* (DoE 1), the mean values of the averaged Ra are shown as a function of the factors P_{border}, v_{border}, and h_{border}. Significant influence was only detected for P_{border} and h_{border} whereas the influence of v_{border} was not found to be significant. The measured Ra values decrease with P_{border} and h_{border}, the optimum is reached for the minimum adjustable laser power of the AM250 machine.

Based on these results, a subsequent DoE was performed to further optimize the surface roughness with reduced hatch distances and under variation of the number of borders ($n_{border} = 1, 2, 3$), constantly keeping the laser power P_{border} on the minimum value instead. For each additional border, the same scan speed and hatch distance was set. The measured absolute Ra values are in the range of 14.4 µm to 33.9 µm. Major influence was detected for h_{border} and, particularly, for n_{border} (Fig. *5*, DoE 2). The impact of v_{border} was found to be even less significant than in DoE 1. The minimum Ra again is achieved for minimum hatch distance and border number $n_{border} = 1$. Finally, in comparison to a sole fill hatch scan, a reduction of the surface roughness Ra by more than 20% can be achieved through one subsequent border scan with the optimized parameters.

The dimensional accuracy of the part is mainly affected by the offset. Since the offset depends on the size of the melt pool, it must be adapted if process parameters are changed. In this study, the appropriate offset is determined for the previously optimized border scan parameters with the help of cubic and cylindric samples, sintered with zero offset. The average oversize in width and diameter is detected to be 340 µm (7 µm standard deviation). This corresponds to the diameter of the melt pool and results in an offset of 170 µm, which must be set to keep an optimum dimensional accuracy in lateral direction.

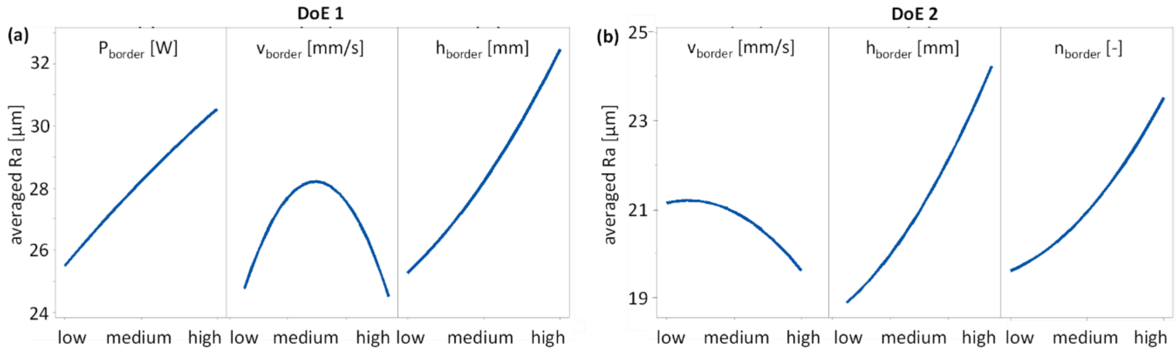

Fig. 5. Main effect plots of the averaged Ra, dependent on P_{border}, v_{border}, h_{border} (a) and v_{border}, h_{border}, n_{border} (b)

Based on the previous results of the vertical surfaces, a DoE parameter optimization was conducted for upskin ($\vartheta = 45°$) and downskin ($\delta = 45°$) areas. Upskin areas are less critical in terms of roughness and dimensional accuracy. The quality of the upskin surface was significantly improved by a triple remelting of the area with the same parameter set, used for the fill hatch. This corresponds to the results given by Yasa et al. 2011. However, for upskin areas between $0° < \vartheta < 90°$ the stair-step effect still leads to an increase of roughness compared to vertical or flat surfaces, as described by Thomas 2009 (Fig. *2*).

Downskin zones are more critical in terms of roughness and defects. A reduced energy input is recommended here by Renishaw 2015. However, to achieve a sufficient material microstructure and to avoid excessively high porosity inside the surface regions, it was found, that a certain minimum of energy input is required though. To solve this conflict, the downskin hatch was scanned with a low laser energy on the one hand but a multiple exposure on the other hand, keeping the scan speed and the laser power on constant values. During the DoE, the impact of the downskin fill and border hatch distance ($h_{downskin}$) and the number of fill hatch and border scans per layer ($n_{downskin}$) on the downskin Ra value was analyzed. A significant dependency on any of the varied parameters could not be detected. However, it was found that the orientation of the downskin areas with respect to the direction of the powder application system respectively the wiper movement is the key influence factor with respect to Ra.

The results of the surface roughness optimization are summarized in Fig. 6 for downskin (δ = 45°), vertical (δ = ϑ = 90°), upskin (ϑ = 45°) and upskin flat (ϑ = 0°) surfaces. The relationship between inclination and quality of the surface according to Thomas 2009 (Fig. 2) is reflected quite well by these results. The lowest initial and optimized Ra values are achieved for vertical and flat surfaces whereas Ra is much higher for upskin and, particularly, downskin surfaces. A reduction of Ra for δ = ϑ = 90° was mainly achieved by an optimization of the border parameters (P_{border}, h_{border}, n_{border}) and a reduction of Ra for ϑ = 45° and ϑ = 0°was achieved through a triple remelting of the upskin area. For δ = 45°, a significant optimization was only achieved by an appropriate orientation of the downskin areas into the direction of the wiper movement.

A lower surface roughness fairly corresponds to a lower required grinding allowance. For the investigation, the rough surfaces were subjected to a grinding process, until the maximum material density was reached. The lowest grinding allowance of less than 0.2 mm was detected for upskin flat (ϑ = 0°) surfaces. Grinding allowances for upskin (ϑ = 45°) and vertical (δ = ϑ = 90°) surfaces are in the range of 0.2 mm to 0.3 mm. The orientation of the downskin (δ = 45°) surface with respect to the wiper movement also affects the required grinding allowance. Minimum values of 0.35mm were detected for surfaces oriented into the wiper direction whereas a minimum grinding allowance of 0.45mm is required for surfaces oriented against the wiper direction.

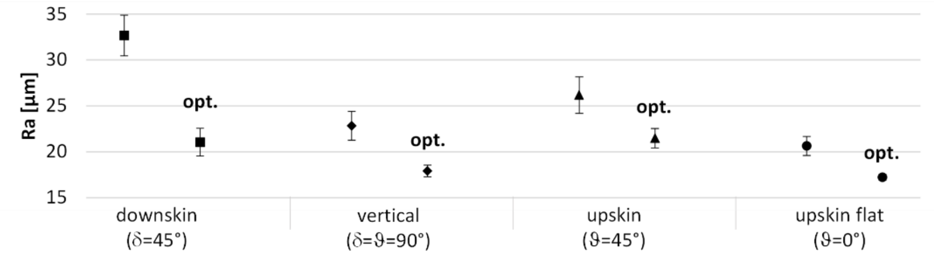

Fig. 6. Mean values and standard deviation of Ra for downskin (δ = 45°), vertical (δ = ϑ = 90°), upskin (ϑ = 45°) and upskin flat (ϑ = 0°) surfaces; shown for nominal and optimized (opt.) parameter sets

However, the orientation of the downskin surface does not only affect the roughness Ra and the required grinding allowances, but also the formation of cracks for downskin surfaces. All specimens, sintered without any specific downskin scan strategies, show enhanced cracking at the downskin surface if the orientation is aligned into the wiper direction (Fig. 7). A reduction of cracks was achieved by an optimization of the downskin fillhatch ($h_{downskin}$) and the number of downskin scans ($n_{downskin}$). Even if an influence on Ra was not detected for $h_{downskin}$ and $n_{downskin}$, these parameters were found to be significant for the formation of cracks.

The dimensional accuracy is also affected by the downskin orientation. For surfaces oriented into the direction of the wiper movement, deviations from the desired size between -16 µm and 38 µm were observed whereas the deviations against the direction of the wiper movement were between 60 µm and 136 µm.

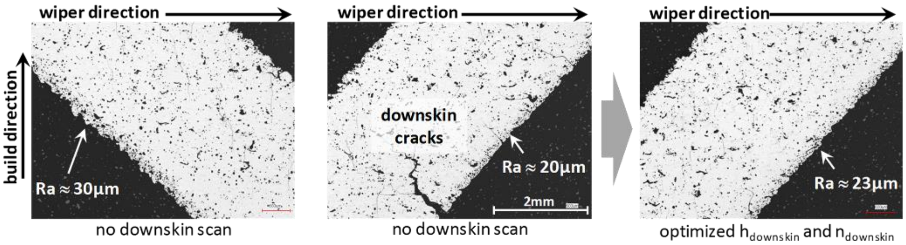

Fig. 7. Impact of the downskin orientation relative to the wiper direction on the formation of cracks

4. Geometrical limits

The determination of geometrical limits was performed by means of the benchmark elements, shown in Fig. *3*. Optimized parameter sets in terms of roughness and dimensional accuracy (see section 3) were applied for the different geometry zones. A selection of the results is summarized below.

Up- / downskin: A maximum or minimum producible upskin angle ϑ is not identified within the present study. Upskin areas from $\vartheta = 0°$ to $\vartheta = 90°$ can be built. For downskin angles, a significant dependence of the part orientation was already detected. Downskin angles against the wiper direction can safely be built down to angles lower than $\delta = 25°$ without curling or enhanced cracking. Downskin areas built in the direction of the wiper tend to an increase of curling defects for angles $\delta < 35°$.

Peaks / corners: For peak and corner angles, an accuracy of ±0.15° is achieved. The manufacturing of details is limited to the size of the melting pool. Hence, geometries of a width smaller than twice the offset (340 µm) are not scanned by the laser, regardless of the orientation. This effect can cause significant deviations between the desired and the manufactured geometry, in particular in the length of very sharp edges. Fig. *8* shows the top view on different sharp corners.

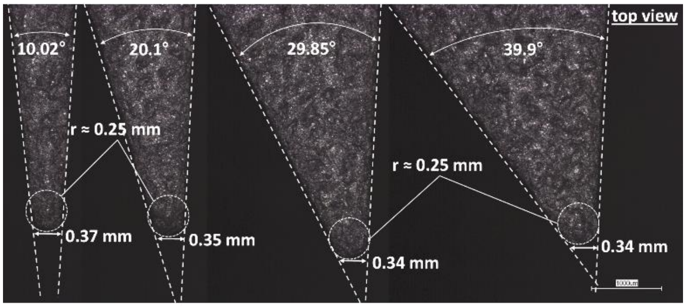

Fig. 8. Minimum edge resolution, edge radius and deviation from the desired length of sharp corners

Holes / channels: The minimum hole diameter and the dimensional accuracy that can be produced in SLS of WC-Co significantly depends on the inclination of the hole with respect to the build direction (Fig. *9*). Generally, the relative accuracy decreases with the diameter of the hole, due to the surface roughness and the adhesion of powder residuals. Vertical (A-A) and 45° inclined (B-B) holes are of sufficient accuracy and circularity down to 1 mm and penetrable down to 0.5 mm. An inclination of 45° leads to less adhesion of powder particles and therefore to a slightly better circularity compared to vertically oriented channels. This might be explained by the increased border area per layer for the inclined channel. The top of horizontally oriented channels (C-C) is subjected to sinking deformations if no support structures are existing. Without appropriate adaptions of the geometry, channels are penetrable only down to 0.75 mm. VDI 2015 proposes an adapted geometry of the channel cross section to avoid sinking deformation. This approach was successfully applied for WC-Co in the present study (Fig. 9, C-C optimized).

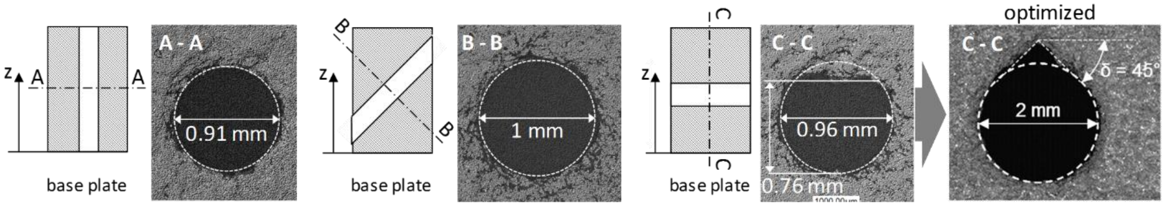

Fig. 9. Desired and actual diameters of circular channels, dependent on the orientation

5. Conclusion

A study of the geometric and topologic design aspects in SLS of WC-Co focusing on the characteristic design features of application optimized cutting tools is conducted at the iWFT. In a first step, relevant geometrical elements are deduced on the basis of typical cutting tool and cooling channel geometries. Furthermore, existing design guidelines and benchmark components for a wide range of metallic materials are classified, to extract the most important SLS process parameters with respect to the surface roughness, the dimensional accuracy and the geometrical feature characteristics. According to the results of the research, a set of benchmark elements is designed. In an experimental analysis, the benchmark elements are built up under systematic variation of the SLS process parameters using the Renishaw AM250 machinery to optimize the surface quality and to determine the geometrical and topological potentialities and limits of the process. The results are then summarized into a set of recommendations for the SLS of WC-Co. In conclusion it can be stated that, even if the fundamental material defects such as pores, cracks and embrittlement currently preclude an industrial application, the geometrical and topological limitations of the process are comparable to average limits for other qualified materials. The results are promising for realizing significant potential for AM of optimized cutting tool concepts.

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