# How to control the surface qualities in AM channels?

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## Abstract

Design for Additive Manufacturing maximizes the potential of Additive Manufacturing (AM) through design guidelines and tools. However, a methodological gap remains in integrating hollow structures to enable new functionalities, which is address in this contribution. The quantitative working space model (qWSM) is introduced as a tool to enable the examination of surface characteristics and their impact on channel functionalities in AM. The qWSM's dynamic representation of design embodiment supports updates for new design solutions, thus enhancing digital product development efficacy. Utilizing the qWSM, the relationship between surface roughness and state variables like pressure drop are explored. The objective is to refine the AM process and improve functionality through design guidelines.

## Keywords

*DFAM, design for X, qWSM, maschine elements, sensing machine elements, channels, fluidflow*

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## 1. Introduction

Additive Manufacturing (AM), a cornerstone of the Fourth Industrial Revolution, is rapidly transforming the manufacturing sector [1]. With its ability to create complex geometries and customized parts, AM has opened new frontiers in design and production. To fully exploit these capabilities, Design for Additive Manufacturing (DfAM) approaches have appeared, employing process-specific design guidelines and advanced software automation. Despite these advancements, challenges persist for the successful exploitation of all DfAM potential, such as the systematic integration of hollow structures [2]. These structures, which can supply functionalities like thermal regulation or fluidic conduction, lack comprehensive methodological support for their incorporation. This study addresses this deficit by using the qWSM for the design of additive manufactured channel structures. The aim of using the qWSM is to investigate the manufacturability of intricate internal channel structures in AM. It primarily focuses on understanding how design and process parameters affect the morphology and quality of embedded channels. The pursuit of high-caliber channel structures is central to their best performance. Factors such as printing orientation, support strategy, and process parameters can significantly influence the cross-sectional shape of these structures [3]. The surface quality, a factor contingent on geometry and the manufacturing process, is also crucial for the functional integrity of the channels. The qWSM supplies a robust schema for deriving the relationships between functional properties, design parameters, and process parameters. It enables designers to understand the correlation between the quality of the structure's surface and fluid flow state variables such as temperature, particle velocity, and pressure drop. The investigation aims to formulate design guidelines that detail the embodiment and orientation of channel-like structures [3] within AM part-volumes. By examining the relationship between surface quality and the embodiment of hollow structures, the authors intend to provide a foundation for this relationship, which will offer valuable insights for refining the manufacturing process and enhancing functionality of the manufacturable products.

## 2. State of the Art

The current body of research in AM, focused on the production of embedded channel-like structures, has seen a noticeable uptick in novel methodologies [4]. These methodologies intend to enhance both the design and manufacturing processes and aim for improved functionality and reliability. This trend underscores the growing understanding of the inherent challenges in this field and the pressing need for robust solutions [5]. One of the primary hurdles in this domain is the ambiguity surrounding the quality of the channels. This uncertainty stems from several influencing factors, with notable significance given to those affecting the configuration of the cross-sectional areas [6]. For instance, studies have shown that factors like printing orientation, support strategy, and process parameters significantly impact channel geometry, highlighting the need for careful consideration of these aspects to optimize channel performance [8]. Surface quality is another critical aspect influencing the functionality of the embedded channels. In this context, geometric quality and surface roughness prove to be key determinants of fluid flow dynamics and the overall performance of the channels. Current research efforts are concentrated on adjusting the manufacturing process parameters and refining post-processing techniques to control these attributes [9]. However, a distinct gap in research exists in identifying advanced methodologies for accurately determining surface quality, particularly where traditional optical analysis techniques are not applicable [9]. To address these challenges, researchers have turned to quantitative frameworks such as the qWSM [10]. The qWSM provides a systematic methodology to understand the relationship between functional properties, design parameters [8], and process parameters. It quantifies surface quality and links it with fluid flow state variables - temperature, particle velocity, and pressure drop - allowing for the prediction of these variables based on the structure's geometry, fluid properties, and surface quality. Recent research efforts, involving computational fluid dynamics (CFD) simulations, have focused on the further development of the qWSM. These studies have demonstrated the effectiveness of the qWSM in accurately predicting state variables and determining the influence of design and process parameters on channel performance.

Despite significant advancements, gaps in literature persist, specifically about the precise correlation between ideal geometry, process parameters, printing orientation, and the resulting real geometry for specific AM processes. There is also a need to refine the qWSM methodology for accurately quantifying surface roughness in embedded channel-like structures [11]. Addressing these gaps will significantly contribute to the development of design guidelines and optimization strategies for achieving high-quality channels with predictable functional properties in additive manufacturing.

## 3. Research Problem and Objectives

The integration of multifunctional capabilities into a single entity through the application of embedded channel-like structures is a promising potential of AM [12]. However, the successful realization of these structures is often impeded by uncertainties related to channel quality. Numerous variables, including printing orientation, support strategy, and process parameters, have the potential to significantly alter the cross-sectional shape of the channels, thereby directly influencing their performance. Surface quality, encompassing aspects such as geometric accuracy and surface roughness, is a pivotal determinant of channel functionality [13]. Despite its importance, achieving consistent control over these factors remains a formidable challenge. Current post-processing methods frequently lack the capacity to provide exhaustive data on surface quality, especially in regions outside the reach of optical analysis [14]. The link between surface roughness and state variables of fluid flow within the channels is insufficiently explored [15]. In an endeavor to bridge the existing knowledge chasm, this manuscript aims to devise a rigorous and comprehensive methodology for evaluating the manufacturability and surface integrity of embedded channel-like structures fabricated via additive manufacturing. To accomplish this, we delineate the following specific research objectives:

1. Conduct an in-depth investigation of the correllation between ideal geometry, process parameters, printing orientation, and the resultant surface finish, in conjunction with the actual geometry, within a specific AM process. This objective fosters a quantitative understanding of the influence of design and process parameters on surface integrity and geometry providing the basis for the optimization of channel structures.
2. Propose a methodology employing the qWSM to assess the resultant surface roughness of test specimens. By characterizing surface roughness and scrutinizing its correlation with state variables of fluid flow within the embedded channels, we aim to illuminate the relationship between surface integrity and channel functionality. This objective strives to decipher the complex interplay between surface integrity and the operational efficiency of the channels.

## 4. Methodology:

This study adopts a rigorous methodological approach that combines DfAM principles, the qWSM, and CFD simulations. DfAM principles inform the design of the test components, optimizing the channel structures for AM processes and considering the challenges associated with integrating functional elements. The qWSM, as a volume-based model, establishes a quantitative relationship between the functional properties (state variables) and the corresponding design or process parameters of the observed system [16]. By characterizing surface quality and investigating the correlation between surface roughness and state variables of fluid flow, the qWSM enables the prediction of state variables such as temperature, particle velocity, and pressure drop. CFD simulations of the designed part provide a comprehensive fluid flow analysis, verifying the design and qWSM predictions, while identifying opportunities for improvement. This iterative design approach, encompassing both digital engineering and DfAM, offers a comprehensive methodology to evaluate design variations and optimize the functional impact of AM-produced channel-like structures [2]. In conclusion, this research aims to address the research gap in understanding the manufacturability and surface quality of embedded channel-like structures in AM. By investigating the correlation between surface quality, geometry, and state variables of fluid flow, the study intends to develop design guidelines and optimization strategies for achieving high-quality channel structures [17].

### 4.1 QWSM

The quantitative Working Space Model (qWSM) provides the foundation for our prototype representations. The model uses finite volumes, known as 'working spaces', which permeate the system under analysis and can incorporate fluids in liquid or gaseous states, and solids. Figure 1 depicts a qWSM of the prototype, including a more detailed description of the inlet section, shown in the detailed view. The need for the iterative increasing degree of detail is informed by the experimental results discussed in section 5.

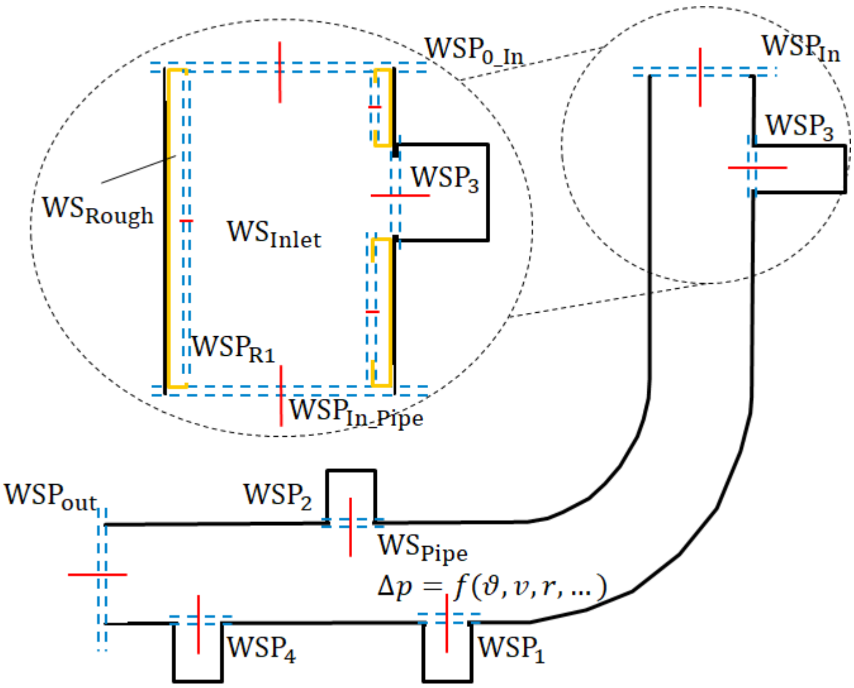


Figure 1 qWSM

In the first iteration, the geometry of the working spaces (WS) can resemble the geometry of the individual parts and therefore give an insight into the inherent structure of the modeled technical system [18]. The qWSM embeds a methodology for constructing the system representation in a systematic way, adopting an iterative strategy of gradually adding detail to the model. This approach allows for the inclusion of more specific knowledge into the representation when necessary. In later iterations, using smaller volumes can enhance resolution through subdivided working spaces if needed [19]. The interaction between each working space results in working space surfaces that create working surface pairs (WSP). This interaction is characterized by any type of energy flow that can be electrical, mechanical, thermal, or volumetric. Essentially, each working space can be viewed as a subsystem of the larger system, demarcated by a subsystem boundary. The overall system can be analyzed by analyzing the energy flow via the WSPs and identifying intended flows, unintended flows and intended but absent flows. These different categories of energy flow result in intend functions, malfunctions and so-called ”non-functions“, while the detection of non-functions by identifying unintended energy flow is a unique mechanism of the qWSM in the context of product development. The quantitative description of the qWSM is done by assigning state variables to each WS, figure 1 includes the example of the internal working space “Pipe“, being characterized by the state variable pressure drop $\Delta p$ . Furthermore, the WSPs are allocated coupling variables, based on energy conservation principles, deriving the state variable from environmental conditions and conservation quantities like thermal energy. With these variables the state equation of each WS can be formulated dependent on the coupling variables and thus on the surrounding subsystems, the neighboring working spaces. The resulting model represents the system with state equations and coupling equations for each WS and WSP respectively.

### 4.2 CFD Simulation

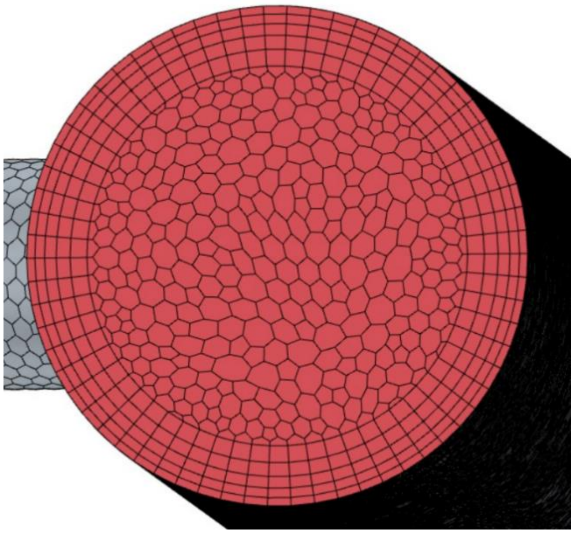

Figure 2 Two layer simulation model

Several simulations were conducted on a pipe geometry with a diameter of 5 under various conditions of surface roughness, in the qWSM referred to as “r” as can be seen in Figure 1. The conditions ranged from hydraulically smooth to a roughness height of 0.1mm, corresponding to a relative roughness of 2% of the pipe's diameter. The simulations, carried out in Simcenter-CCM+, employed the two-layer model as can be seen in Figure 2 and the function f as per Jayatilleke, C.L., with the 'Roughness Limiter' deactivated. The results indicated that the total pressure loss increased with the increase in roughness height. Specifically, for a hydraulically smooth pipe, the total pressure loss was 1029 Pa. For roughness heights of 0.025mm, 0.05mm, 0.075mm, and 0.1mm, corresponding to relative roughness of 0.5%, 1%, 1.5%, and 2% respectively, the total pressure losses were 1041 Pa, 1121 Pa, 1168 Pa, and 1202 Pa. Despite the pressure losses displaying a clear trend of increase with roughness, it is notable that the data for roughness heights of 0.075mm and 0.1mm did not significantly differ from those with smaller roughness heights. However, the total pressure losses were distinctively higher.

Further investigations were conducted on a pipe with a double diameter of 10mm. While the qualitative relations are of similar nature, the absolute values of particle velocity and pressure loss differ. These preliminary results are used as a basis for the simulation of more complex, curvature geometries, c.f. fig.3

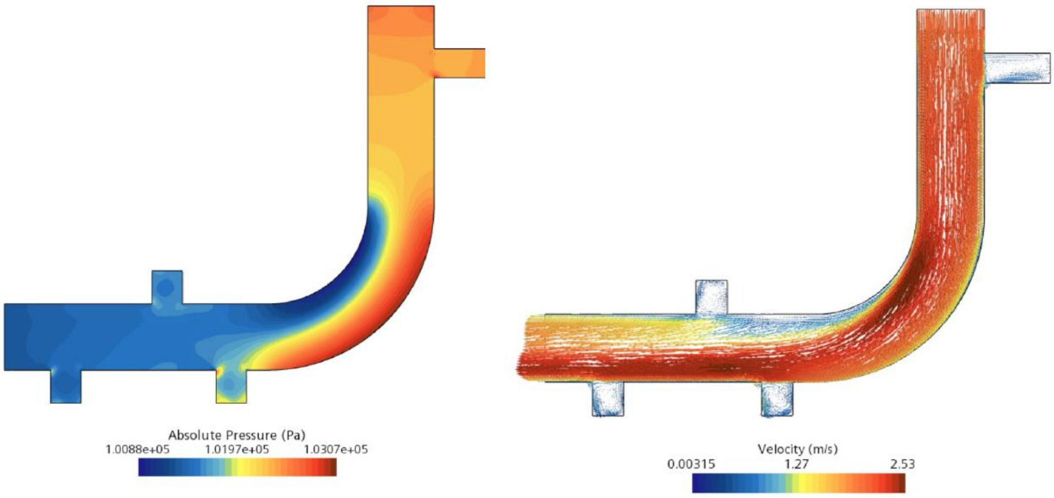


Figure 3 Fluid flow elbow pipe 5 mm

In the final phase of our research, a comprehensive examination was conducted on the dynamics of fluid flow within a cylindrical conduit, specifically an elbow pipe with a diameter of 10mm. This investigation was performed under a variety of conditions, each characterized by a distinct level of surface roughness. The range of these conditions extended from a state of hydraulic smoothness to a maximum roughness height of 0.2mm, a value equivalent to 2% of the pipe's diameter. The empirical data obtained from these experiments demonstrated a consistent and positive correlation between the height of surface roughness and the total pressure loss within the pipe. For the hydraulically smooth pipe, the total pressure loss was quantified at 1052 Pa. As the roughness height was incrementally increased to 0.05mm, 0.1mm, 0.15mm, and 0.2mm, corresponding to relative roughness values of 0.5%, 1%, 1.5%, and 2% respectively, the total pressure losses were measured at 1128 Pa, 1194 Pa, 1234 Pa, and 1260 Pa. In conclusion, the findings from this study provide compelling evidence that both the height of surface roughness and the diameter of the pipe exert a significant influence on the total pressure loss [20]. The magnitude of this impact, however, is not uniform but rather varies depending on the specific configuration of the pipe and the level of roughness. The observed trend of increasing total pressure loss with increasing roughness height was consistent across all pipe configurations and diameters tested in this study. The simulation serves as a preparation for evaluating the surface roughness of AM channels, using the state variables of a fluid under controlled ambient conditions.

### 4.4 Results and Discussion

To evaluate the accuracy of the qWSM and the simulation derived from it, two specimens of the same geometry are manufactured using an SLA printer. One was manufactured with a surface roughness of the highest surface quality as the manufacturing machine, a Formlabs 3+, is capable of while the other incorporated a statistic roughness of approximately 0.25mm. Based on the results of the simulation, three of four possible measurement locations are used to analyze the resulting pressure difference to ambient condition using water as a fluid and a fixed entry velocity of 2.12 m/s, determined by the height of a liquid column. Based on the simulation two general hypotheses are addressed:

- The pressure drop increases with a higher surface roughness.
- The pressure drop is positive at measurement location 1 and negative at position 2

The pressure drop was measured using a differential pressure sensor, at a steady state of the liquid flow, indicated by a close to constant measurement value. Every measurement location was evaluated at least three times, the distribution of the measurement data is depicted in figure 4. The measurement locations numerical designation follows figure 1 and the related WSPs. While hypotheses two is supported by the data sets, the first hypotheses can be rejected as the pressure drop of the rough specimen is significantly lower for all measurement locations. Moreover, the third measurement location shows an unexpected behavior as the pressure drop is notably higher than the simulation suggests. A root cause analysis of the observed behavior is conducted utilizing the qWSM as presented in the last section of this publication. Summarizing the results, the authors conclude that while some of the experimental results support the expectations of the simulations, there is a substantial deviation between simulated and observed behavior, which requires a more detailed investigation. However, regarding the design of channel structures including rough surfaces as it is relevant for DfAM applications, it can be observed, that the qWSM is a promising approach to analyze the effects of design solutions before implementing them. In addition to the distribution of the measurement results, an ANOVA analysis was conducted. The results are depicted in figure 5 and support the previously stated obeservations

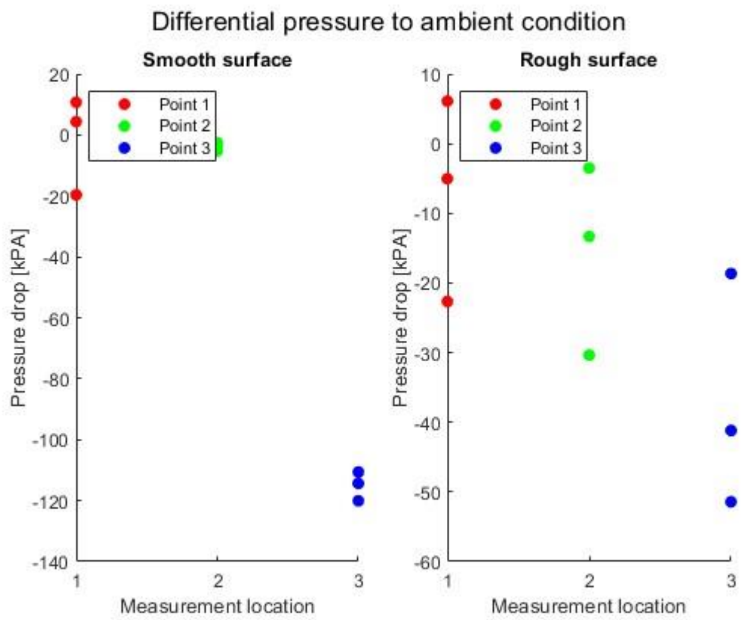


Figure 4 Experimental Data

Figure 4 presents the differential pressure results for both the smooth (left) and rough (right) surfaces. Each subplot displays three measurement points, distinguished by different colors. For each surface type, the measurement points show some variability in differential pressure.

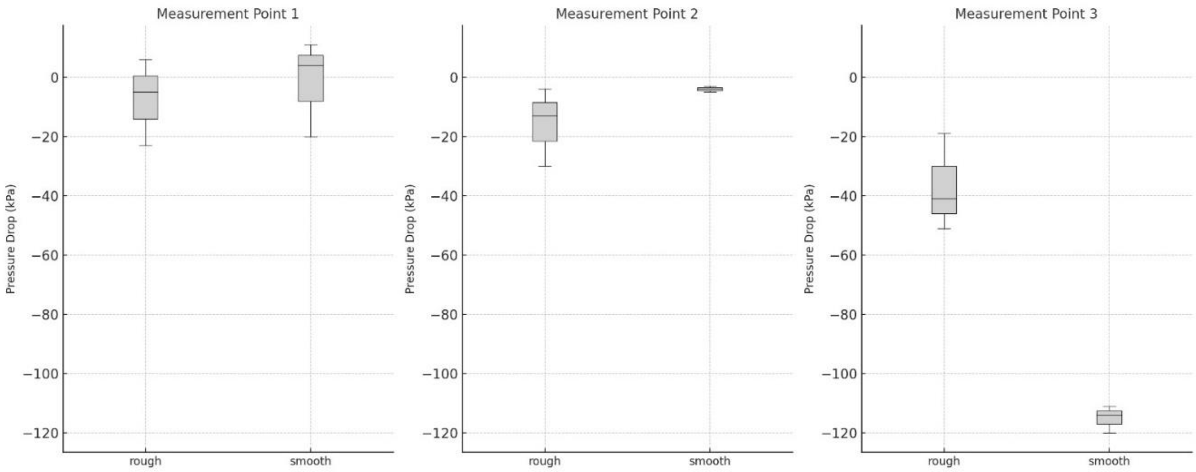


Figure 5 Anova analysis

This graph presents the distribution of measurement points for both rough and smooth surfaces. Each box plot represents a different measurement point on both surfaces. The box represents the interquartile range (IQR), the line inside the box is the median, and the whiskers represent the range of the data within 1.5 * IQR. Outliers are represented as individual points. The t-test was conducted to compare the means of the three measurement points between the rough and smooth surfaces. The p-values for all measurement points are above the commonly used significance level of 0.05, indicating that we cannot reject the null hypothesis that the means of these measurement points do not differ between the rough and smooth surfaces.

## 5. Summary and Outlook

This contribution addresses the pressing need to incorporate embedded, channel-like structures in additive manufacturing to significantly enhance its functionality. The authors have developed a robust methodology that combines DfAM principles, the qWSM and CFD simulations. This hybrid integrated design approach has advanced our understanding of the relationship between design parameters, surface quality, and functional behavior of embedded, fluid conducting channel structures [21]. While the experimental findings are promising, in the sense that the effects of varying surfaces quality can be put into a quantitative relation to the functional quantity of resulting pressure drop, major uncertainties remain in the modeling of the effects for the widespread use in product development frameworks [22]. Especially the characteristics of channel inlets into AM channels require a more profound understanding, how similar structures can be described using the qWSM to obtain a more precise prediction of the resulting behavior of a specimen. Doing so, design parameters such as diameter, curvature or manufacturing induced properties such as surface quality can be used to implement new design solutions, such as restrictors protecting sensitive sensory devices embedded in flown through AM channel structures. Using the example described above, the qWSM of the Elbow channel must be further detailed in the sense that another WS is defined for the inlet section to address the non-laminar inlet characteristic, conducting the function of a restrictors. A feasible iteration of the qWSM is shown in fig qWSM as the detail view, including additional working spaces and surface pairs to describe the turbulent interaction between the surface roughness as margin layer of the pipe in the inlet section before reaching a laminar flow characteristic. A similar function, like a geometric restriction, can be realized by a local increase of surface roughness levels before a sensitive channel section e.g., hosting sensors or where a higher-pressure drop is beneficial. A promising application in the AM sector could be micro-channels, which create exciting opportunities for miniaturized devices across various fields, such as biomedical applications. A more detailed investigation into the design of micro channels and their impact on fluid flow characteristics may unlock their full potential in AM. Additionally, to fully benefit from embedded channel-like structures, the authors intend to thoroughly analyze different AM processes. Evaluating the relationship between printing orientation, support strategies, and process parameters across a range of AM methods will help to optimize channel performance and surface quality. In conclusion, this publication marks a step forward in understanding channel-like structures in AM, but there's more to be investigated. By continuing to explore the design of micro-channels and various printing techniques, one can uncover a multitude of applications across numerous industries. Regarding the objectives of this contribution, a methodology incorporating the qWSM for the design of AM channel structures was presented and successfully tested for a prototype. However, the in-depth investigation of the correlation between ideal geometry, process parameters, printing orientation, and the resultant surface finish, remains an open subject for a variety of AM processes. The results for the SLA process of this contribution can be used to further investigate this topic. Lastly the relation of state variables and surface rough quality for a steady state fluid flow are of major importance for the characterization of surface qualities in AM channel structures and consequently for the assessment of design solutions and manufacturability. The conducted simulations and experiments are promising, nevertheless substantial future research remains, as the results of experiments and model differ, and the uncertainty of the gathered data is still on a high level.

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## References

[1] Dunagthonsuk,W.; Wongwises, S.: An experimental study on the heat transfer performance and pressure drop of TiO2-water nanofluids flowing under a turbulent flow regime. In: International Journal of Heat and Mass Transfer 53 (2010), 1-3, S. 334–344. https://doi.org/10.1016/j.ijheatmasstransfer.2009.09.024

[2] Wiberg, A. ; Persson, J. ; Ölvander, J.: Design for additive manufacturing – a review of available design methods and software. In: Rapid Prototyping Journal 25 (2019), Nr. 6, pp. 1080–1094. doi/10.1108/RPJ-10-2018-0262

[3] Pibulchinda, P.; et.al.: Influence of printing conditions on the extrudate shape and fiber orientation in extrusion deposition additive manufacturing. In: Composites Part B: Engineering 261 (2023), S. 110793. URL https://www.sciencedirect.com/science/article/pii/S1359836823002962

[4] Vaneker,T., et al. : Design for additive manufacturing: Framework and methodology. In: CIRP Annals 69 (2020), Nr. 2, pp. 578–599. https://doi.org/10.1016/j.cirp.2020.05.006

[5] Sossou,G. et al.: An additive manufacturing oriented design approach to mechanical assemblies. In: Journal of Computational Design and Engineering 5 (2018), Nr. 1, pp. 3–18. https://doi.org/10.1016/j.jcde.2017.11.

[6] Yong, H. et. al.: Additive Manufacturing: Current State, Future Potential, Gaps & Needs, and Recommendations 137 (2015). https://www.nist.gov/publications/additive-manufacturing-current-state-future-potential-gaps-needs-and-recommendations

[7] Ngo, T. et al.: Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. In: Composites Part B: Engineering 143, 2018, pp. 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012

[8] Frazier, W..: Metal Additive Manufacturing: A Review. In: Journal of Materials Engineering and Performance 23 (2014), Nr. 6, pp. 1917–1928. https://doi.org/10.1007/s11665-014-0958-z

[9] Snyder, J.; Thole, K.: Tailoring Surface Roughness Using Additive Manufacturing to Improve Internal Cooling. In: Journal of Turbomachinery 142 (2020), Nr. 7. https://doi.org/10.1115/1.4047380

[10] Schmitt, F. Kirchner, E.: The quantitative Working Space Model – Generating Knowledge in the K Space. In: Proceedings of NordDesign 2022. https://doi.org/10.35199/NORDDESIGN2022.17

[11] Debroy, T., et al..: Additive manufacturing of metallic components – Process, structure and properties. In: Progress in Materials Science 92 (2018), pp.. 112–224. https://doi.org/10.1016/j.pmatsci.2017.10.001

[12] Gibson, I. ; Rosen, D. ; Stucker, B.: Additive manufacturing technologies : 3D printing, rapid prototyping, and direct digital manufacturing. Second edition : Springer, 2015 https://doi.org/10.1007/978-1-4939-2113-3

[13] Fry, N.; et a..: Robotic additive manufacturing system for dynamic build orientations. In: Rapid Prototyping Journal 26 (2020), Nr. 4, pp.. 659–667. https://doi.org/10.1108/RPJ-09-2019-0243

[14] Sadeghi, B.; Cavalerie, P.: Progress of Flake Powder Metallurgy Research. In: Metals 11 (2021), Nr. 6, p.. 931. URL https://doi.org/10.3390/met11060931

[15] Molaei, R. et al.: Fatigue of additive manufactured Ti-6Al-4V, Part II: The relationship between microstructure, material cyclic properties, and component performance. In: International Journal of Fatigue 132 (2020), S. 105363. https://doi.org/10.1016/j.ijfatigue.2019.105363

[16] Schösser, F., Schmitt, F., Kirchner, E., and Breimann, R.: Influence of the operation strategy on the energy consumption of an autonomous sensor node, J. Sens. Sens. Syst., 11, pp.263–275, https://doi.org/10.5194/jsss-11-263-2022, 2022.

[17] Medellin-Castillo, H. ; Zaragoza-Siqueiros, J.: Design and Manufacturing Strategies for Fused Deposition Modelling in Additive Manufacturing: A Review. In: Chinese Journal of Mechanical Engineering 32 (2019), Nr. 1, pp.. 1–16. https://doi.org/10.1186/s10033-019-0368-0

[18] Chu, C.; Graf, G.; Rosen, D..: Design for Additive Manufacturing of Cellular Structures. In: Computer-Aided Design and Applications 5 (2008), Nr. 5, pp.. 686–696. DOI: 10.3722/cadaps.2008.686-696

[19] Sett, S. et al.: Lubricant-Infused Surfaces for Low-Surface-Tension Fluids: The Extent of Lubricant Miscibility. In: ACS Applied Materials & Interfaces 13 (2021), Nr. 19, S. 23121–23133 https://doi.org/10.1021/acsami.1c02716

[20] Stimpson C. K. et al.: Scaling Roughness Effects on Pressure Loss and Heat Transfer of Additively Manufactured Channels. In: Journal of Turbomachinery 139 (2017), Nr. 2. https://doi.org/10.1115/1.4034555

[21] Steffan, K.-E. W. H; et al.: Application of Manufacturing Induced Properties to Exploit the Potentials of a Hybrid Integrating Additive Manufacturing Technology. In: Procedia CIRP 119 (2023), S. 1164–1169. URL https://doi.org/10.1016/j.procir.2023.02.187

[22] Jones, B.; Garimella S. V.: Surface Roughness Effects on Flow Boiling in Microchannels. In: Journal of Thermal Science and Engineering Applications 1 (2009), Nr. 4. URL https://doi.org/10.1115/1.4001804