2019 WJTA Conference and Expo
November 11-13, 2019 ● New Orleans, Louisiana

Paper

TECHNOLOGICAL ANALYSIS OF DIFFERENT ABRASIVE WATER JET MACHINING STRATEGIES FOR BLISK ROUGHING

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ABSTRACT

In recent years the production of BLISK (blade-integrated disks), to achieve an efficiency increase in civil aero engines, is highly demanded. To increase combustion efficiency, higher burning temperatures in combination with a higher over-all pressure ratio are necessary; the limiting factor is on the material side. From a production point of view, BLISK made of high-temperature resistant materials are hard to machine and therefore they are very cost and resource intensive parts. In order to remain competitive in the future and to combine higher productivity with better process reliability, promising manufacturing technologies like abrasive water jet (AWJ) machining need to be examined with regard to their technological and economic performance.

This paper reveals promising AWJ machining strategies for turbomachine production. Two machining methodologies have been introduced and discussed: cutting through the work piece and controlled-depth machining, often referred to as AWJ Milling. Technological analysis of experimental results is conducted in terms of necessary surface quality and simultaneously minimizing the machining time. Potential AWJ technology for BLISK roughing will be assessed and validated by machining a BLISK demonstrator made of Inconel 718 alloy. Finally, the experimental results will be evaluated and the feasibility of BLISK roughing by AWJ machining is discussed.

1 INTRODUCTION

The future demand for high-performance parts will increase significantly throughout all knowledge-based European industrial sectors like aerospace, automotive, energy, construction, consumer, and medicine. Integrated Turbomachine components like BLISK (= blade-integrated disk) are technologically characterized by a high material volume processed and invariable restrictions in quality requirements. An effective cost reduction of those parts concentrates on the machining process itself. The production time and machining costs must be reduced to remain competitive in high-wage countries. Consequently, the growing BLISK market calls for competitive production solutions, continuously improving existing processes and process chains.
Higher overall pressure ratio in combination with higher combustion temperatures are central strategies to increase engine efficiency. Modern airfoil blades are characterized not only by a complex geometry for the efficient aerodynamic implementation, but also by means of special high-performance materials to withstand operation loads. The next key improvement in engine technology is in particular the application of enhanced materials capable of amplified temperatures. Nevertheless, advances in material technology also require a further development in production technology to get the technological achievements of products economically and ecologically acceptable.

To dominate operational loads and increase thermal efficiency of turbomachines, high strength nickel-based alloys are in common use. Developments in metallurgy and manufacturing methods have led to one-piece integrated parts that improve mechanical properties and to reduce weight [1]. The BLISK design – successfully used firstly in military engines – is a promising alternative to fir-tree design. It found its way to latest civil aero engine concepts, where operational improvements must surpass costs in the end. These parts are typically milled from the solid; accordingly, a huge material volume must be removed in the primary roughing process step. The increasing demand of aero engines calls for higher batch sizes of these high-tech parts. Hence, the roughing process of BLISK made of nickel-based alloy Inconel 718 by conventional milling reaches its technological and economical limit. Turbomachinery components made of today's high-tech materials like the nickel-based alloy 718 are conventionally hard to machine and therefore require individual machining solutions. The machining approach is dependent of the available machining technology and the geometrical features of the work piece. Conventional machining methods such as milling uses several machining steps to obtain the final geometry and surface quality. For the rough machining process, a high material volume needs to be removed effectively from the solid before further finishing steps can be applied. The tool wear and therefore the machining costs are extensive for those rough machining approaches [2].

In contrast, abrasive water jet (AWJ) machining is already an alternative in the industry for cutting applications in a wide range of materials or compositions thereof. AWJ cutting is characterized by a high cutting performance. Especially when cutting high tech alloys or composite materials, process variants like AWJ milling promises to have huge overall advantages over other conventional and non-conventional processes [3]. However, the application of AWJ milling is not common in industry yet. During the last decades, water jet technology emerged applications, but it still lacks necessary developments supporting a wide industrial acceptance: Precise machining of complex geometries in thick work pieces like BLISK, needs commonly a huge expertise to handle the water jet characteristics [4]. This is mainly because insufficient software tools are used for complex tool path programming. Conversely, commercially available computer-aided manufacturing (CAM) software was originally developed for geometrically defined processes like milling and cannot be directly applied [5]. In general, the adaption of the machining strategy to the post process needs will further improve the precision and cutting performance of the involved processes and therefore judge between cost effectiveness and product quality. AWJ has shown to be a potential candidate to substitute conventional rough machining processes of BLISK [6]. Hence, the technological potential of different AWJ rough machining strategies urgently needs to be assessed.

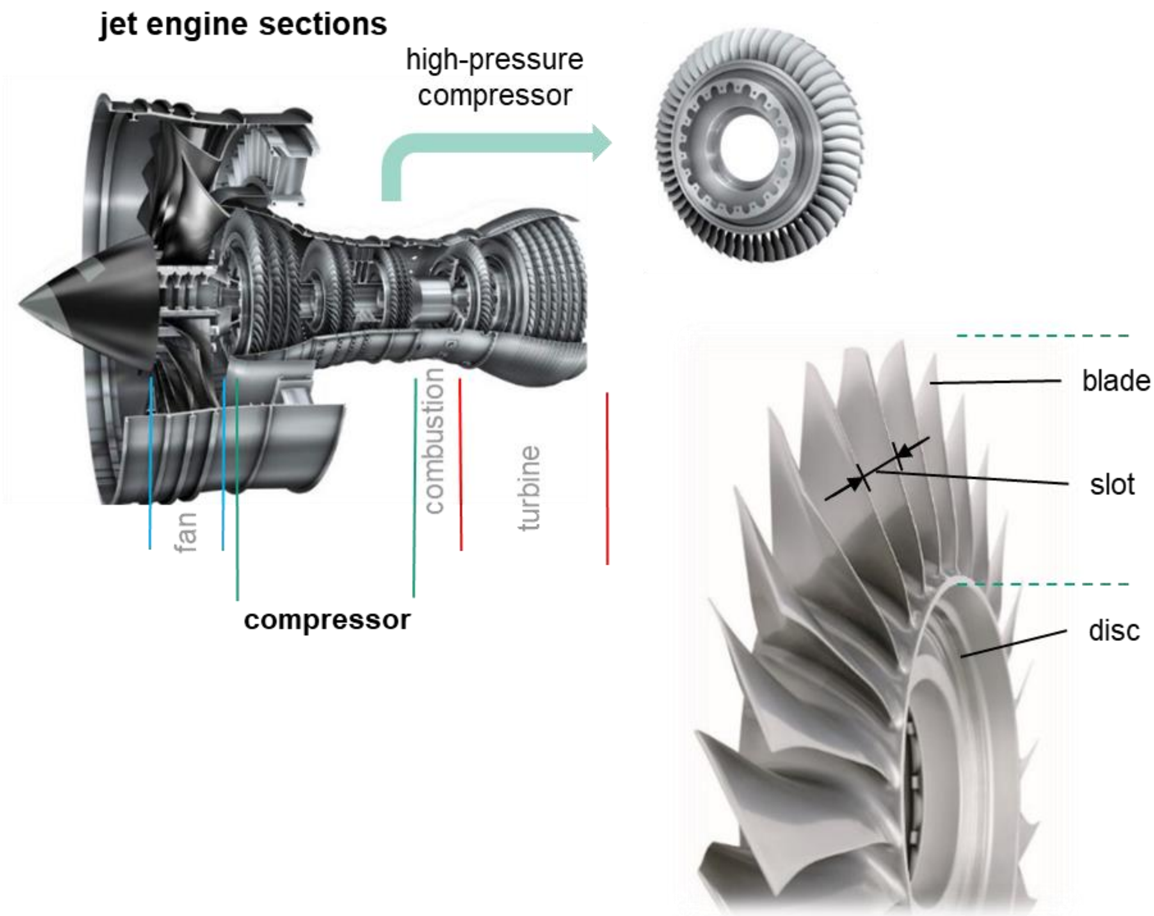

Figure 1: BLISK part within a modern jet engine compressor section [Image sources: MTU Aero Engines AG, Sandvik AB]

2 MACHINING STRATEGIES FOR BLISK ROUGHING

The goal of rough machining is to approximately size and shape the work piece before it is refined in later processing steps. To economically optimize this process, a high material volume shall be removed quickly. In the case of BLISK manufacturing, it is of high importance to avoid contour damage since there are high-value integrated parts. Hence, precaution efforts, e.g. a defined safety offset to the final geometry, are needed for the intermediate machining steps. AWJ machining inhibits a large number of process parameters that encounters time-dependent non-geometrical uncertainties of the jet tool. Additional constraints must be considered to outbalance the process both technologically and economically. To achieve this goal, jet characteristics like the jet trail back has to be accounted for selecting the machining strategy. Industrially used AWJ cutting through (CT) is the simplest way of roughing a contour (**Figure 2**). The removed material is limited by the match of the straight-line cutout approximating the target geometry. However, as cutting depth increases or shape becomes more complex, additional constraints are given. Controlled depth machining (CDM), commonly referred to as AWJ milling, is theoretically the more flexible procedure to match a freeform contour but it lacks experience and its application is significantly more challenging [7].

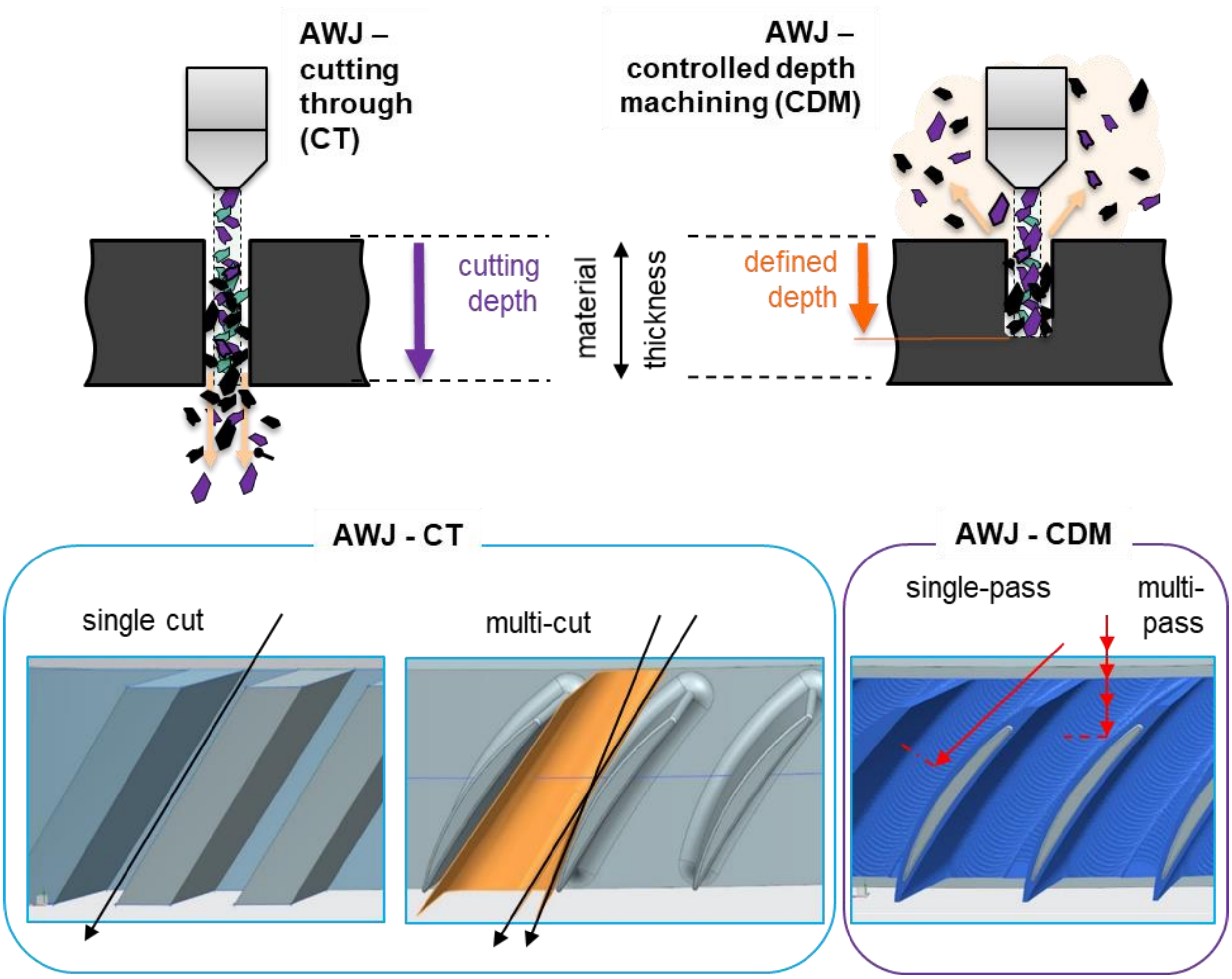

Figure 2: Potential of AWJ rough machining strategies

2.1 Cutting Through (CT)

Two cutting strategies can be distinguished: first, performing a single cut or second, performing several cuts to approximate the final shape. In both cases, the individual cuts go completely through the work piece. Cutting through (CT) is the most convenient AWJ machining application, often used for 2D orthogonal cuts in industry. In contrast, the blade airfoil geometry demands a 3-dimensional approach by the application of a five-axis tool path. Generally, machining is limited to convex shapes since concave undercuts are not applicable for cutting completely through the work piece. Notice that the effective cutting depth is at least equal to the material thickness. The required cutting performance is extended further by tool paths angled to the work piece surface. The machining time will be affected negatively as it increases with increasing cutting depth. It can be expected that the jet trail back will increase, too. Especially at non-linear movements or going through edges of the tool path, the latter must be considered: Cutting a complex shape takes more time than performing a straight cut. Contour damage can be a result, especially on cumulative cutting depths; it goes along with the non-linear reduction of the cutting rate when cutting depth increases.

On the other hand, multi CT strategies make use of more than one single CT to approximate the final contour. As a positive result, the effective cutting depth will be a reduced amount of the previous single cut CT strategy. A decreased cutting depth offers several advantages such as less jet trail back and better surface quality. In other words, and for related instances, this enhancement to classic CT promises to be more effective in terms of material removal due to the applicability of higher feed rates in regions of effectively reduced cutting depth. Since the tool path becomes more complex, further constraints exist: The accessibility of the AWJ head must be checked as well as the clearance of the jet process itself not to affect neighborhood contours.

2.2 Controlled Depth Machining (CDM)

Controlled depth machining (CDM) shapes the work piece by superposition of numerous kerf profiles of defined depth. It is also referred to as AWJ milling due to its similarity to conventional milling processes. Here, two basic CDM techniques can be categorized: First, the machining of one single kerf, or second, the repeated application of several toolpaths of minor depth to achieve the aimed depth. For the first, almost the same constraints hold as for classic cutting, except that a well-defined depth must be machined. At given process parameters, the applied feed rate shall be constant. Due to reflections similar to jet trail back, the jet exits along the kerf leading to increased material removal [6]. Especially when machining complex contours, the AWJ must avoid contour damage by secondary material removal of the remaining AWJ. Applying an impingement angle in the feed direction could theoretically compensate the AWJ vector. However, the machine plant must be capable of control relevant process parameters. When using a 5-axis tool movement, even small impingement angles however lead to a decrease of the feed rate due to extended spatial travel of the machine axis system. CDM technique promises to make the AWJ machining process more efficient for 3D applications. Shape complexity can be extended over straight line cut outs, even convex shapes can be machined by lateral increment of the kerf profiles, e.g. when machining the airfoil upper part. If concave shape machining becomes necessary, access to the counterpart work piece side has to be granted, e.g. by turning the work piece. The transition to 3D CDM corresponding to conventional milling is implemented if several kerfs are concatenated to machine a certain contour. Instead of single kerf profiles to cut out a piece, the covered material volume is removed completely here line by line. Further, lateral and vertical tool paths are composed to machine a 3D shape. The time-dependent interaction of the AWJ tool with the work piece surface is similar to single-pass CDM cutting strategies. General for CDM techniques, both the contour complexity and the dynamics of the machine plant play an important role.

3 EXPERIMENTAL APPROACH

Several technological aspects limit the economic use of the AWJ manufacturing process within a process chain. Assuming presupposed standards for the interfaces, this technological analysis will focus on the technological aspects of AWJ rough machining. In particular of interest are the characteristics of the process parameters and their relationship to possible machining strategies. Different experimental plans for both machining strategies, i.e. cutting through (CT) and controlled depth machining (CDM), were carried out. Here, the objective concentrates on an economic roughing process to machine a contour close to the final geometry. Machining quality was analyzed by surface quality of the cutting edge lower area where the AWJ exits the work piece. In contrast to CT experiments, the CDM was analyzed by the geometrical characteristics of the kerf ground. ***Figure 3*** gives an overview of the individual measurement areas. In general, tow criteria are considered to evaluate the quality of the experimental results: first the achieved material removal rate (MRR) and second the cutting quality of the machined parts by means of surface roughness analysis. A statistic description of 2D surface measurements S uses quite more data even although conventional line measures such as roughness values R that were quite common for the analysis of periodic surfaces generated by milling. Contrary, the AWJ machined surface is more of a stochastic nature. Areal surface measures are definitely desirable to achieve robust results. Hence, the areal surface parameters S according to ISO 25178 were used for analysis of the surface quality [8].

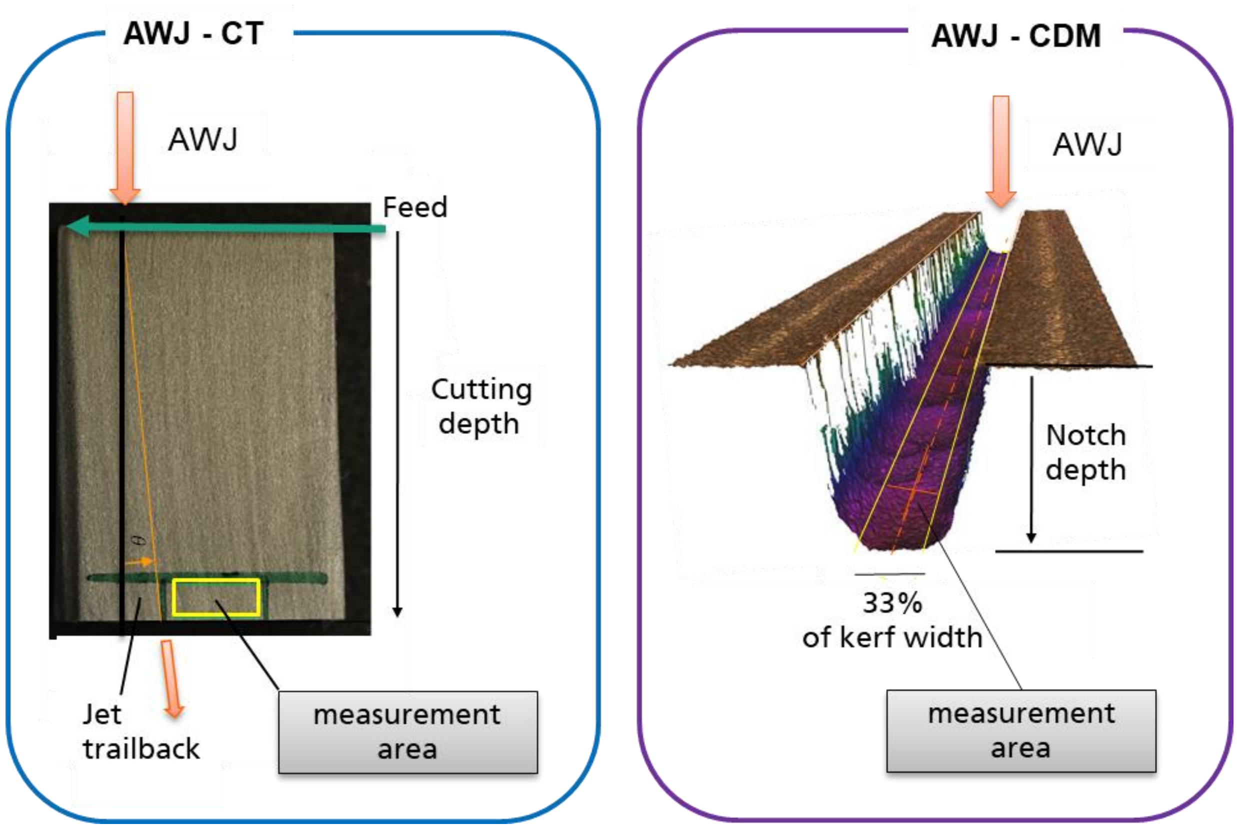

Figure 3: Analysis scheme of the test pieces

4 PROCESS DEVELOPMENT

An H.G.Ridder Type Waricut HWE P2030 5-axis AWJ machine tool was used for experiments, supplied with a UHDE Type 6045 intensifier pump. Parameter studies were conducted based on design of experiments methods and a cause-effect analysis of the machining strategies. As first experiment for cutting through (CT), a screening by comparative design was conducted to choose between two suitable AWJ configurations and to assess the machine tool for parameterization. Two standard AWJ set-ups of orifice diameter $\emptyset D_O$ and focus tube inner diameter $\emptyset D_F$ were used for the experiments for cutting different material thickness of nickel-based alloy 718:

- Configuration I: $\emptyset D_O = 0.25\ mm$ / $\emptyset D_F = 0.78\ mm$
- Configuration II: $\emptyset D_O = 0.30\ mm$ / $\emptyset D_F = 1.02\ mm$

The screening experiment revealed that AWJ configuration I of $\emptyset D_O = 0.25\ mm$ / $\emptyset D_F = 0.78\ mm$ has showed the best overall results in both cutting performance and surface quality. Following, this configuration was used for optimizing the process parameters using a central composite design for CT. Furthermore, a study to assess controlled-depth machining (CDM) was conducted in analogy based on a full factorial design due to the significantly higher process complexity. The most important AWJ process parameters have been identified, namely the feed rate v_F, the pressure p and the abrasive mass flow $\dot{m}_A$. **Table 1** gives an overview of the AWJ parametrization range.

Table 1: *Optimization scope of AWJ parametrization*

AWJ machining	Pressure p in [MPa]	Abrasive mass flow $\dot{m}_A$ in [g/min]	Feed rate v_F in [mm/min]
CT: 20 mm	200 … 500	200 … 600	18.6 … 40.0
CT: 30 mm			11.7 … 24.6
CT: 40 mm			10.2 … 15.8
CDM	100 … 500	60 … 480	250 … 3000

The evaluation revealed that similar surface quality levels could be achieved by different AWJ process parameters. Consequently, the process parametrization was optimized for a defined cutting quality. This allows a better comparison of the results. The results revealed that the machined quality was in general contrary to the material removal rate (MRR). The only exception to this finding could be found for CDM with a feed rate beyond a critical threshold which yields a high surface quality even though increased AWJ cutting performance. This means in practice that if the feed rate is maintained beyond a critical threshold level, the MRR can be increased by an increase of the pressure and of the abrasive mass flow without drawbacks in the achieved surface quality.

Eventually, the findings were used to find a combination of AWJ process parameters that maximizes the MRR while optimizing the surface quality. The maximum surface height S_z and the root square height S_q were set to a defined target level. A quadratic model has been fitted for each response, which were combined to determine the composite desirability of the multi-response system. **Table 2** provides an overview how the proposed process parameters might be optimized for this purpose. Please note that the surface quality between CT and CDM differs due to the different machining principles. For CT, it can be seen that with increasing material thickness, a similar cutting performance can be achieved by increasing the abrasive mass flow within a constant pressure level while adapting the feed rate according to the material thickness. In contrast, CDM proposes both lower pressure and reduced abrasive mass flow values in combination with a significantly higher feed rate.

Table 2: *Experimental optimization of AWJ parametrization*

AWJ machining	Pressure p in [MPa]	Abrasive mass flow $\dot{m}_A$ in [g/min]	Feed rate v_F in [mm/min]	Feed rate v_F in [mm/min]	Surface Height S_q in [µm]	Surface Height S_z in [µm]
CT: 20 mm	387	397	26.65	MAX.	10	100
CT: 30 mm	390	435	17.46	MAX.	10	100
CT: 40 mm	397	600	10.44	MAX.	10	100
CDM	400	180	3000	MAX*.	15	150

5 CASE STUDY

A BLISK demonstrator geometry with typical geometrical features is used to debate the relevant rough machining specifications or roughing such a target geometry, a machining offset is needed to ensure that the target geometry is not damaged in any case. The computer aided design (CAD) data model of the BLISK was modified to generate the offset surfaces. The offset is approximates the original BLISK contour by an additional material volume added. For this investigation, the convex shape of the air foil blade is aligned by three main surfaces. In contrast, the backside of the blade is designed by a single surface. This modification is necessary to tolerate machining steps close to the final contour. All CAD modifications were done in Siemens NX software. An overall offset value of 0.6 mm was chosen, which is typical for conventional rough milling.

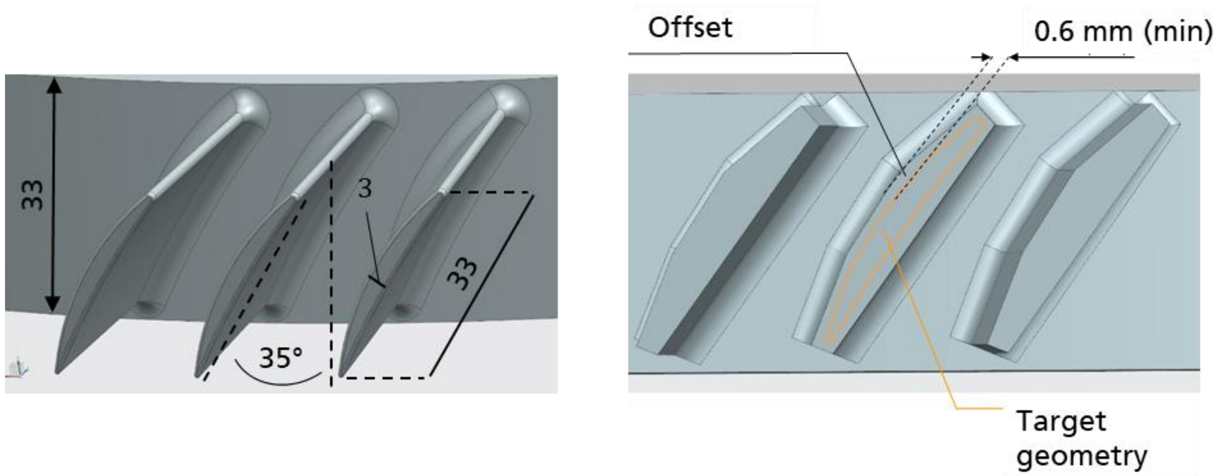

Figure 4: Geometry offset added to the contour of the BLISK CAD model

5.1 Proposed machining approach

In order to develop a proposal for optimized AWJ BLISK machining of given geometry, the developed tool path was applied to CT and to CDM so that in summary four different strategies were compared in terms of the removed material volume and the machining time. For CT, it is well known from the results of the parameter study which feed rate can be realized for a certain material thickness at a given quality. The time needed for single CT was measured as well as the total material volume to be removed by the corresponding cutout volume. It is highly important to sort the cut out pieces since the cutting quality decreases with increasing cutting depth. Therefore the remaining work piece exhibits the higher quality surface while the cut out material exhibits the inferior quality surface. Here, the 3rd cut represents the foremost cutout part. It is evident that for the second strategy, the multi-cut strategy, two cuts of defined depth have to be performed in the beginning (1st cut and 2nd cut). Because of the limited distance between the two airfoil blades, it was necessary to adapt the AWJ parameters so that the neighboring airfoil contour not to be damaged. In addition, the real machine system is limited in dynamics so that the high feed rate values could not be reached along the 5-axis tool path. The most promising way to machine a limited cutting depth is by increasing the applied feed rate. Note that the cutting contour of the voluminous single cut (3rd cut) was used in order to make the part fall out. Accessibility of the fourth cut was then possible so that the small portion in the lower part of the airfoil was removed as well. For the CDM strategies, the same procedure was followed but instead of cutting through, multiple kerfs of defined depth were machined until the comparable cutting depth was achieved. ***Figure 5*** gives an overview of the tool path design and the corresponding cut out pieces. The geometrical constraints of minimum cutting depth and allowed depth tolerance until neighborhood contour were estimated and rated according to the CAD geometry (**Table 3**). This helps to optimize the toolpath design and parametrization prior application. The CAM simulation is restricted to straight lined tool path and does not show varying cutting depth or interference.

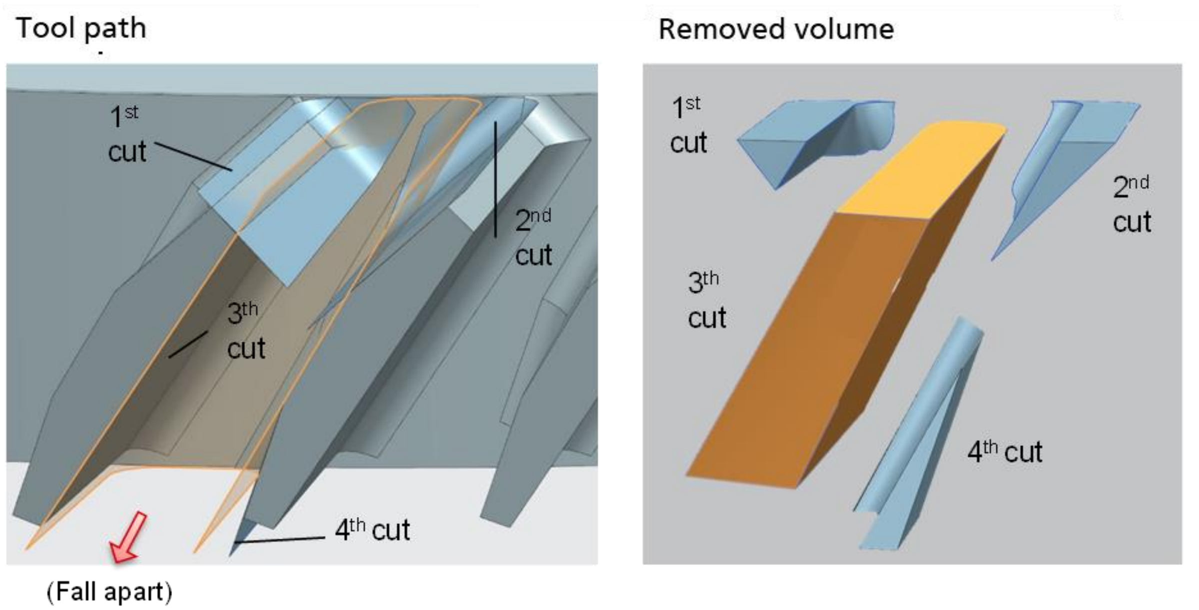

Figure 5: Tool path design and cut out pieces

Table 3: Geometrical features of the cut out pieces

Cut No.	**Material volume V** in [mm3]	**Tool path length l_T** in [mm]	**Minimum cutting depth t_{min}** in [mm]	**Allowed depth tolerance** in [mm]; **Relative to minimum cutting depth t_{min} in [%]**
1	458.53	44.09	5.45	9.77 (179%)
	855.79	40.94	15.14	19.26 (127%)
3	14 930.8	75.58	41.58	-
4	837.17	33.34	16.08	-

The categorization of discussed strategies was done by the stand-alone machining times that were calculated by means of the geometrical features and the proposed process parametrization. In **Table 4**, a comparison of the technological specifications is presented. Notice that the CT equivalent cutting times on the left side of were calculated by the experimental results based on the geometrical constraints of **Table 3**, e.g. the required CT time of cutting an equivalent material thickness. Even though the values in brackets are basically not applicable for CDM approaches, it helps to benchmark the different strategies. The equivalent MRR' of the CT cutouts was compared to the fixed MRR of the CDM kerfs assuming that the MRR of the individual notches remains constant even tough superposition. Here, 3D CDM means that the complete volume of the cut out pieces was machined completely whereas for 2D CDM a single cut comparable to CT was obtained by overlaying several notches up to a desired depth. Hence, a basic comparison of 2D CDM and CT was calculated by the kerf volume needed to be removed by obtained MRR. Accordingly, the result was then compared to the equivalent cutting times of CT. As the estimated kerf volume significantly influences the calculated 2D CDM machining times, a mean kerf width of 0.70 mm was used here that matches a typical CT kerf width. It was found for this comparison of stand-alone machining times, that choosing the machining strategy is strictly depending on the geometry to be removed. Hence, the lowest individual machining times marked in bold letters for each cut out geometry was selected. Because it is important that the 3rd cut will fall out of the work piece, CT was chosen instead by practical manner for this operation despite the slightly higher machining time. In contrast, 3D CDM takes much longer because of the huge material volume of the 3rd cut; CT is the proposed approach here. As a first comparison of machining this geometry, the additional machining time of the close-to-contour improvements (cut No. 1, 2 and 4) were approximately 25% higher than of the basic 3rd cut.

Table 4: Overview of the stand-alone machining times for the proposed strategies

	CT Equivalent		CDM			Strategy combination
Cut No.	**MRR'** in [mm^3/min]	**Cutting Time** in [mm:ss]	**MRR** in [mm^3/min]	**3D CDM Time** [mm:ss]	**2D CDM Time** [mm:ss]	**CT/CDM Time** [mm:ss]
1	(956.7)	(00:29)	1288	00:21	**00:16**	**00:16**
2	(1421.4)	(00:36)		**00:11**	00:41	**00:11**
3	3160.8	**04:43**		11:36	**03:29**	**04:43**
4	1129.9	00:44		00:39	**00:36**	**00:36**
Total time		06:33		13:16	05:02	06:15
Machining time of cut No. 1,2,4		01:49		01:40	02:52	01:32
Add. time in [%]		+ 27.8 %		+ 12.6 %	+ 30.8 %	+ 24.4 %

5.2 Machining of Demonstrator

Finally, a demonstrator geometry has been machined to validate the intermediate results of the findings under real circumstances.

Table *5* shows the machine parameters used according to the previous approach of using both CDM and CT strategies. The machining times for the individual cuts were recorded directly while machining. As practical result to the geometrical constraints, to the positioning movements of the AWJ head and to the NC-code optimization, the real machining times of the case study may differ from the previous findings of the theoretical approach (**Table 4**). Further, the parametrization of the AWJ process was optimized according to the AWJ machine constraints. In particular for CDM, the NC code was compressed to avoid unnecessary 5-axis movements of the machine in the region of turning points that helps to maintain the necessary constant feed rate. Prior machining, the federate along the NC tool path was simulated. This helps to precast the machining result leading to smaller the rejection rates of real manufacturing. Accordingly, the process parameters were tuned to maintain the necessary depth.

The machining process was optimized to avoid any damage of the target geometry. Notice that the minor differences in machining times was in both directions due to NC tool path optimization, e.g. by locate quality drawbacks of machining into the fall apart cut out pieces. For CT, there are two tactics to compensate the jet trail back. First, the AWJ impingement angle can be calculated to compensate jet trail back. This strategy maintains the same position level for both the entry and the exit side of the cutting line leading the AWJ curvature ahead of the feed direction. In contrast, a more easy way to program is to locally control the jet trail back by reducing the feed rate at the turning region. At a certain distance around the turning point, which should be at least the distance of the je trail back length, the feed rate is reduced. This allows the trail back to catch up before the AWJ changes its direction at the turning point. In analogy, the feed rate is increased when moving out the crucial region. Most machine controllers offer such a feature because the turning points of the tool path can be detected automatically and the feed rate is one of the easiest parameters to be controlled for cutting. Here, the feed rate at a certain distance of the turning point is reduced to 30% of the straight line feed rate value. In contrast, changing jet shape compensation by a tilted AWJ head is mostly not considered. For CDM, AWJ shape compensation may be indispensable due to the diverse material interaction and dynamic constraints. More important, the AWJ movements must maintain a constant feed rate to machine an equal depth. It must be ensured that the demanding high feed rates can be realized along the tool path; sharp turning points may be rounded to avoid feed rate drops along the tool path. The combination of the technological analysis with the individual machining times revealed that the combination of CDM and of CT strategies are a promising AWJ roughing approach. ***Figure 6*** shows the machined demonstrator geometry made of Inconel 718 alloy at real conditions. Here, the individual cut outs for the complete work piece were machined in a serial manner. In addition, by an extended machining time of cut No. 2, the unavoidable process irregularities of the bottom-end were relocated to the cutout piece. This helps to reduce individual machining times further. After the first two CDM operations were done, the 3rd cut out pieces were cut and falls apart allowing machine head clearance for the following 4th cuts.

Table ***5: Parametrization used for machining of demonstrator***

Cut No.	AWJ Strategy	Volume V in [mm^3]	Machining time T_m (m:ss)	Eff. MRR (mm^3/min)
1	CDM	458.5	0:31	≈ 886
2	CDM	856.8	1:05	≈ 790
3	CT	14930.8	4:25	≈ 3380
4	CT	837.2	0:32	≈ 1569
$\sum cut$		17083.3	6:33	≈ 2608

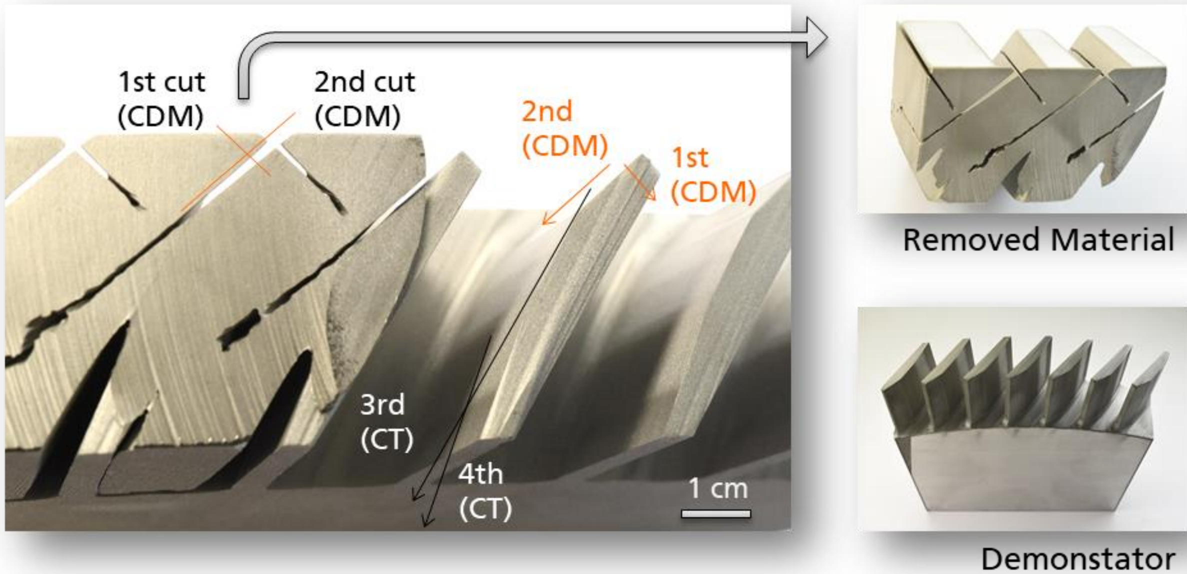

Figure 6: Machined demonstrator of applied strategies

6 SUMMARY AND OUTLOOK

In this paper, a proposal for optimized BLISK roughing by means of abrasive water jet (AWJ) machining was developed. The proposal is optimized in two ways: first, it is ensured that a satisfying surface quality is obtained and second, a strategy is identified which minimizes at the same time the production costs. In the following, two methodologies for AWJ BLISK roughing have been introduced and discussed: cutting through (CT) and controlled-depth machining (CDM). Parametrization studies have been set up for both CT and CDM by using design of experiment (DoE) methods. The use of areal surface analysis techniques have proven to be a good approach in terms of robustness of surface analysis, replacing conventional line measurements. In total, a huge optimization potential of AWJ process parameters for different demands has been identified in this work.

The comparison of different machining strategies confirms both the technological and economic advantages of AWJ machining for complex applications. It has been illustrated by experimental investigation that not only the right parametrization of the AWJ process influence the machining result. Performance, machining quality and costs must match both the AWJ machining strategy and the geometrical features of the work piece. The validation of this technological analysis of BLISK rough machining strategies has proven that CDM strategies facilitates close-to contour AWJ roughing. The practical machining of a demonstrator geometry confirms the validation of the parametrical findings.

In future work, optimization of the machining process should be considered. The technological findings should be extended by a cost analysis. There is probably a significant potential for improvement of the AWJ process by optimization of the abrasive-material interaction. Optimizing the impingement angle in an intelligent way could possibly minimize the amount of reflections yielding a more material removal efficient process. Future developments should target the development of appropriate CAM tools for AWJ machining in order to ease tool path planning and make AWJ an easy-to-use technology. In addition, a further optimization of the machine plants in terms of higher feed rates would be highly desirable. To summarize, the AWJ technology is a comparatively young technique that already produces high quality machining results as shown in this work but that still exhibits a huge potential for further optimization.

7 ACKNOWLEDGEMENTS

This paper is based on results acquired in collaborative R&D work, kindly supported by the ICTM International Center for Turbomachinery Manufacturing in Aachen.

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9 NOMENCLATURE

AWJ	Abrasive Water Jet
BLISK	Blade Integrated Disc
CT	Cutting Through
CDM	Controlled Depth Machining
MRR	Material Removal Rate
S_q	Surface Root Mean Square Height
S_z	Surface Maximum Height
$\dot{m}_A$	Abrasive Mass Flow
p	Water Pressure
v_p	Feed rate
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
V	Material Volume
l_T	Length of Tool path
t_{min}	Minimum cutting depth