

Received: 14 April 2023 / Accepted: 11 May 2023 / Published online: 17 May 2023

*waterjet cutting, pre-contouring,  
near-net-shape, trimming*

Waldemar REDER<sup>1\*</sup>,  
Eckart UHLMANN<sup>1,2</sup>

## **ENABLING OF AUTOMATICALLY GENERATION OF CUTTING PATHS FOR THREE-DIMENSIONAL PRE-CONTOURING WITH WATERJET TRIMMING**

Abrasive Water Injector Jet Cutting (AWIJC) is a flexible machining process for manufacturing high-performance materials, such as titan- and nickel-base-alloys. Due to the low ductility and thermal conductivity of these materials, conventional machining is struggling with high tool costs and wear. The tool wear in AWIJC is independent of the machined material, and the process has the potential to provide a cost-efficient solution in machining high-performance materials. Trimming, a near-net-shape pre-contouring with multi-stage AWIJC, requires a detailed knowledge of cutting paths for all steps in advance. In order to enable a geometrical flexible manufacturing process, an automatically cutting path generation is necessary. This article presents an application developed with NX Open using Visual Basic. The application TrimCAD is able to provide all necessary geometries for trimming based on the geometries of initial and finished parts. Furthermore, it is possible to adjust the number of cuts and the degree of pre-contouring. All geometries are automatically exported as a standardized three-dimensional STEP-file. The STEP-geometries can be processed to the CAM-processor of the waterjet machine. TrimCAD is an innovative possibility to machine three-dimensional parts made of high-performance materials.

### **1. INTRODUCTION**

The demand for high performance materials has increased rapidly over the last years due to the increasing demand for high-tech products. The machining of high performance materials, such as composites, ceramics, and hardened metals has been a major challenge in manufacturing industries due to their toughness and resistance to traditional machining methods. Conventional machining such as grinding, milling, and drilling have limitations in machining high performance materials like titan- and nickel-based-alloys. These methods are limited by the hardness, toughness and low ductility of the materials, leading to high tool wear as well as insufficient workpiece quality. In addition, the low thermal conductivity leads to an increased heat load in the cutting area which can cause thermal damage to the tool and workpiece and compromise the material properties [1].

---

<sup>1</sup> Institute for Machine Tools and Factory Management (IWF), Technische Universität Berlin, Germany

<sup>2</sup> Institute for Production Systems and Design Technology (IPK), Fraunhofer, Germany

\* E-mail: reder@iwf.tu-berlin.de

<https://doi.org/10.36897/jme/166095>

High-performance materials are widely used in industry today, as is evident by the wide range of applications. The majority of applications is mostly used in the aerospace industry, where high material and manufacturing costs are economically acceptable through fuel savings achieved by weight reduction. One example for high performance materials in the aerospace industry is Inconel 718. The development and initial use of Inconel 718 can be dated to the early 1960s and has since become the most widely used material for passenger aircraft engines, accounting for over 30 % of the mass of a modern engine [2]. It has not been possible to develop an economical machining operation that expands the range of applications for these high-performance materials. Manufacturing technology constantly needs to adapt to the challenging material innovations in order to allow economical production. For example, ZHANG ET AL. developed a dual-phase silicon nitride ( $\text{Si}_3\text{N}_4$ ) ceramic, that leads to an improvement of the ductility of the material [3]. Therefore, plastic deformation of the material is possible that typically tends to fracture.  $\text{Si}_3\text{N}_4$  is already used in many applications but an increase in ductility offers the potential to an extension of possible use cases [4].

Abrasive waterjet cutting is a machining process whose tool wear is independent of the material being machined. Due to the decoupling of tool and workpiece, the process forces are low. Abrasive waterjet cutting can be used to machine a wide variety of materials such as metal, fiber composites, ceramics and even high-performance materials. The process is also frequently used for cutting titanium and nickel-based alloys, making it ideal for pre-contouring workpieces made of materials that are difficult to machine [5].

### 1.1. ABRASIVE WATER INJECTOR JET CUTTING (AWIJC)

Waterjet cutting is divided into pure waterjet cutting and abrasive waterjet cutting. Pure waterjet cutting is used for cutting soft materials such as polymers and food. In contrast, abrasive waterjet cutting can also be used to cut hard materials, such as steel, stone, ceramics and composites. Water abrasive jet cutting is further divided into abrasive water injector jet cutting and abrasive water suspension jet cutting. The difference between the two processes is the method of abrasive supply. Industrially, AWIJC is preferred in manufacturing and production applications due to its uninterrupted processing and the possibility of high-frequency actuation of the cutting valve. Currently, AWIJC is used in a variety of applications to process a wide range of materials. Due to the process, AWIJC is mainly limited to machining of two-dimensional geometries. The high-energy abrasive waterjet cuts through the workpiece and still contains high residual energy after exiting at the bottom of the workpiece. This remaining high energy of the abrasive waterjet is usually converted into heat in a water tank [5]. Therefore, it is essential that the abrasive waterjet is directed towards the water tank. Due to this limitation AWIJC is mainly used for two-dimensional or two-and-a-half-dimensional machining. AWIJC focuses on cutting of sheets, plates and curved panels as well as the chamfering of the aforementioned components.

There are a few three-dimensional machining operations currently being performed. Most of them are concentrated in research and aerospace applications which justifies the high manual effort required. Figure 1 shows the machining strategy for machining a three-dimensional geometry according to the current state of the art of AWIJC [6]. First, the raw

material needs to be prepared. Then the geometry to be produced is analyzed, the first manufacturing step is determined, the cutting path is defined and prepared for the CAM program.

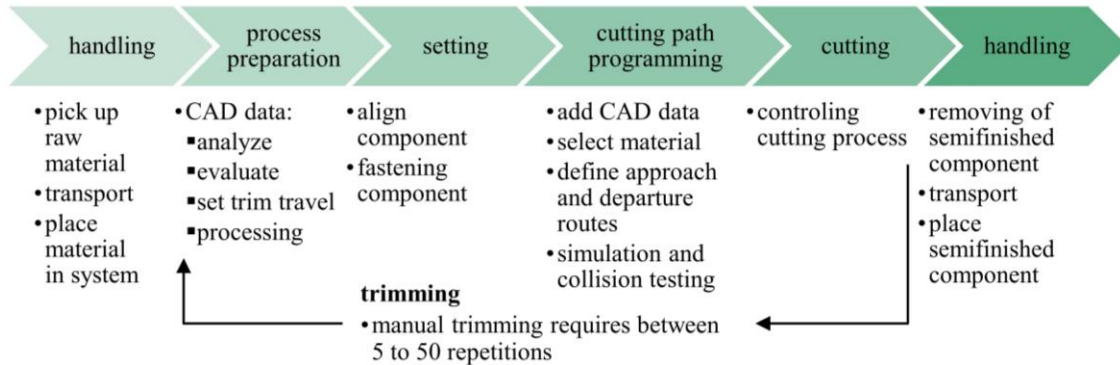


Fig. 1. Workflow in three-dimensional AWIJC by manual trimming

In the third step, the workpiece is positioned, aligned and fixed in the workspace. In the CAM software of the system, the previously prepared CAD data can be imported and further processed. The used material and tool have to be specified. Furthermore, the approach and departure paths have to be defined and a simulation and collision check needs to be performed. After successful simulation, the first cut can be performed. For the machining of a three-dimensional geometry, a single cut is not sufficient. Therefore, the CAD data must be analyzed again to define the second cut. These steps have to be repeated until the desired geometry is reached. Depending on the complexity of the component, the described loop of working steps has to be repeated between five and 50 times. Finally, the finished component can be removed from the workspace.

## 1.2. THREE-DIMENSIONAL MACHINING WITH AWIJC

There are a few examples in the literature in which three-dimensional components have been manufactured using AWIJC. However, none of the publications offered detailed descriptions of the manufacturing steps. For example, Liu and Olsen [7] fabricated surgical clamps from a round stainless-steel profile with a diameter of  $d = 9$  mm. Another example is the fabrication of chess pieces which were manufactured by Hashish [8] and Liu [9]. Furthermore, efforts to avoid a water basin and simultaneously realizing complex machining using a robot-guided cutting head were described. Hashish [10] extends the cutting head by installing a catcher arm which has a catcher cup attached to it. The remaining energy of the abrasive waterjet is converted in the catcher cup as it exits the workpiece being machined.

Another approach to three-dimensional pre-contouring using AWIJC is cutting with a controlled cutting depth [11]. The aim of the process is to remove entire volume segments by superimposing two individual cuts without cutting the entire material. Figure 2 illustrates the process. Using milling, volume segments can be removed from a workpiece by superimposing two kerfs from different sides of the workpiece. This is particularly relevant

if it is not desired to cut through the entire workpiece. Cutting with a defined kerf depth can also be applied to cylindrical geometries and is called groove turning. By superimposing two kerfs, entire ring segments can be removed [11, 12].

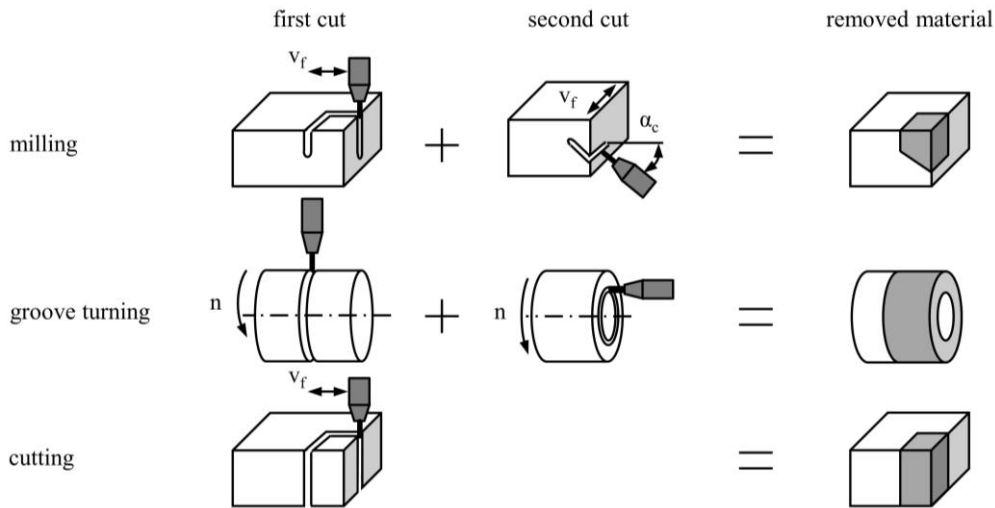


Fig. 1. Comparison of AWIJC and cutting with controlled depth

A novel approach to three-dimensional machining with AWIJC is trimming. This is a multi-stage two-dimensional cutting process that separates outer volume segments and gradually converges the workpiece to the target geometry. Existing knowledge and process parameters for cutting with AWIJC can be applied during this process [6, 13].

## 2. TRIMMING

In order to reduce the challenges of conventional machining of high-performance materials and to benefit from the advantages of AWIJC, three-dimensional components can be pre-contoured by trimming. A large amount of the material which has to be removed, can be separated with AWIJC. After pre-contouring with AWIJC conventional milling can be performed to fulfill the required component specifications. This will minimize the volume to be machined and thus the tool wear of conventional milling. For three-dimensional pre-contouring using AWIJC, manual operator effort needs to be reduced by an automated path planning. To achieve an automated path planning for trimming, the application TrimCAD was developed which will be described subsequently. The application was programmed with NX Open using Visual Basic. TrimCAD is usable within the CAD program Siemens NX, Plano, United States of America, and was successfully used within the versions from NX1899 till NX1980. The function of TrimCAD and used features are described in following sections.

Trimming is a multi-stage two-dimensional machining process with defined rotations in between which results in three-dimensional machining. Figure 3 demonstrates pre-contouring by trimming of a turbine blade. A bar stock is used as the initial material geometry. Then

the first cut is performed using AWIJC. After the first cut, a defined rotation is performed followed by a second cut. After a second rotation and the third cut, the pre-contouring by trimming is finished and the remaining material can be removed, for example, by a milling process.

By milling the turbine blade out of the bar stock, the material would have to be completely removed. In contrast, trimming allows entire volume segments to be removed by single cuts. Thus, pre-contouring by trimming reduces the volume of material to be removed by conventional machining. Uhlmann and Männel [12] compared the costs for roughing titanium-aluminide  $\gamma$ -TiAl with AWIJC, turning, milling and grinding. They displayed financial potential in pre-contouring high-performance materials with AWIJC leading to manufacturing costs of  $C_{m,t} = 33\%$  compared to turning,  $C_{m,g} = 27\%$  compared to grinding and  $C_{m,m} = 8\%$  compared to milling for machining  $V = 50 \text{ cm}^3$  of  $\gamma$ -TiAl 600 times simulating a production order. By reducing the material removal rate and the material to be removed, a big range for possible use cases for pre-contouring with AWIJC could be detected [12].

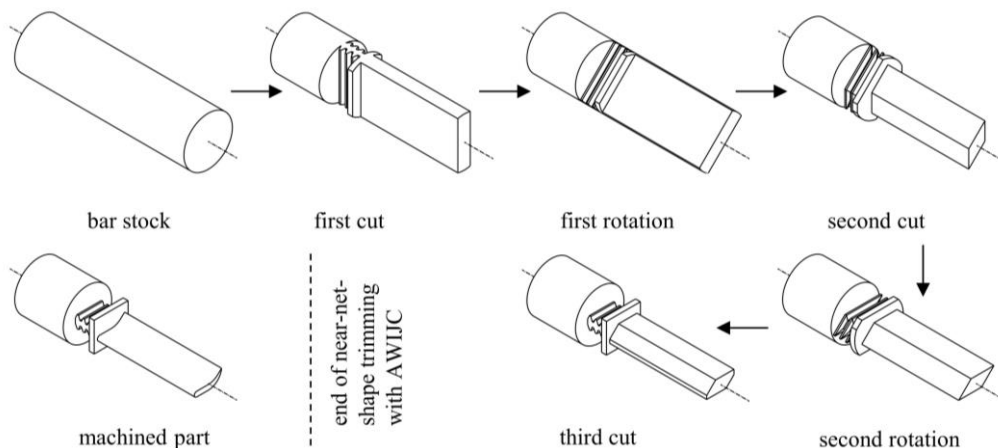


Fig. 2. Trimming as a new machining strategy for machining high-performance materials using the example of a turbine blade

The goal of TrimCAD was to develop an intuitive program that simplifies the path planning process for three-dimensional geometries using trimming. For this purpose, all necessary machining steps of the multi-stage machining process had to be generated entirely automatically based on random initial and target geometry. The fundamental functions are described in detail in the following.

### 2.1. SHADOW CURVES

In order to abstract a machining strategy for AWIJC, the principle of a shadow image of a workpiece is used while trimming. When a workpiece is illuminated by a light source and a projection surface is placed in a direct line behind the workpiece, the workpiece causes

a shadow on the projection surface. The outer contour of the shadow is called the shadow curve and represents the projection of the workpiece in two-dimensional form. Rotating the workpiece results in different shadow curves on the projection surface. The principle of the shadow curve is illustrated in Fig. 4. In the example, a turbine blade is illuminated frontally with a light source which generates a shadow curve on the reference plane for the perspective of the turbine blade being considered.

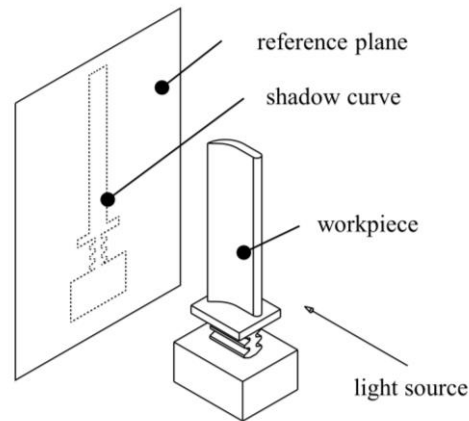


Fig. 3. Illustration of a shadow curve using the example of a turbine blade

By translating the shadow curve into a cutting curve using common CAM software for AWIJC, the principle of shadow images of a workpiece can be utilized for multi-stage trimming. For complex geometries and multi-stage machining, the actual shape of the machined part is difficult to trace. Therefore, the created shadow curve is projected on the workpiece stock to simulate a trimming process using AWIJC. This enables better tracking of geometry changes during individual cuts.

## 2.2. MULTI-STAGE MACHINING

The shadow curves on the projection surfaces can be considered as cutting paths for AWIJC. If the shadow curve is traced with a cutting head, the outer material is cut off and the projected shadow curve is extruded onto the component. If these operations are performed with various rotations of the workpiece, three-dimensional geometries can be realized. An illustrative example is shown in Fig. 5. Three rows can be seen in the figure. The top row represents the target geometry. In the middle row there is the reference plane or projection surface and in the bottom row the unmachined part, in this case a square bar. Figure 5a shows the initial state. In the figure, a red arrow has been added to each target geometry and workpiece to illustrate the orientation of the bodies. In Fig. 5b the target geometry is projected onto the reference surface. The shadow curve is then extruded onto the workpiece which is visualized in the figure by moving the cutting head along the shadow curve on the reference plane. The resulting geometry can be seen in the bottom row. Afterwards a  $\beta = 90^\circ$

counterclockwise rotation in Fig. 5c is performed. The rotations of the target geometry and the workpiece have to be identical. This can be seen in Fig. 5 by the red orientation arrows at the parts. Due to the rotation, the shadow curve on the reference plane changes. The new shadow curve is again extruded onto the workpiece in Fig. 5d. In the shown example, the target geometry would already be reached after two machining steps, with a defined  $\beta = 90^\circ$  counterclockwise rotation in between.

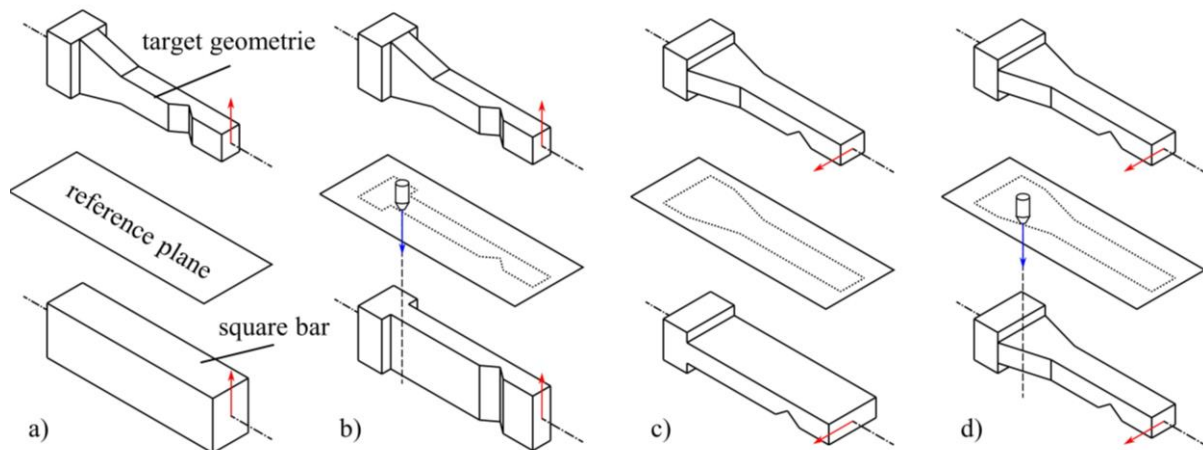


Fig. 4. Working steps while trimming; a) initial state with the target geometry in the upper row, the reference plane with the associated shadow curves in the middle and a square bar as raw material in the bottom row; b) first cut; c)  $90^\circ$  counterclockwise rotation; d) second cut

### 2.3. RESOLUTION AND ABORT CRITERION

The TrimCAD program has been provided with configuration options in order to vary the resolution of the pre-contouring detail. Also, an individual setting of the abort criterion can be determined. The resolution is the increment of the investigated rotation. With a small increment, more rotations are performed with a smaller angle. For each rotation a shadow curve is generated and a cut is simulated. Since the program is based on workpiece shadow images, only a rotation range of  $\beta = 180^\circ$  is relevant. Since each body generates the same shadow from the front and from the back and it is irrelevant whether a shadow of a workpiece is generated at  $\beta = 90^\circ$  rotation or  $\beta = 270^\circ$  rotation. Therefore, the selected resolution refers to the area of a semi-circle. The resolutions  $\alpha_{res} = 5^\circ, 10^\circ, 20^\circ, 30^\circ$  and  $45^\circ$  are available for selection. The higher the selected resolution value, the fewer cuts are simulated. This leads to a reduction of the simulation and preparation time. For a resolution of  $\alpha_{res} = 45^\circ$  four rotation angles are analyzed. However, choosing a coarse resolution may result in insufficient pre-contouring because not all relevant areas of the part are considered. The rotations of the components always refer to their initial position, i. e. the positioning in the CAD program during preparation.

The abort criterion is defined as a condition that leads to termination of the program. Generally, the program runs until the task is completed, i. e. all cuts for the selected resolution are executed. In the context of pre-contouring, the major priority is to remove as much

material as possible by performing fewer cuts. In order to design economical pre-contouring by trimming, the option of the abort criterion has been integrated. This enables control of the degree of pre-contouring. The abort criterion is a percentage value which has to be entered by the operator and defines the minimum volume of a cut to be trimmed. For example, the entry of 10% implies that at least 10% of the volume difference between target and initial geometry have to be cut off for each trimming step. Before a cut is performed, the volume which will be cut off with this trimming step, is compared with the abort criterion. To determine the abort criterion, TrimCAD automatically calculates the volume difference between the initial and the target geometry. The volume difference is then multiplied by the operator input to define the abort criterion. For each simulated cut, the separated volume is calculated. Therefore, the difference of the volume before and after the cut is measured. If the volume difference is smaller than the abort criterion, the cut is not performed and the program is terminated. If the value does not fall below the abort criterion, all cuts are performed according to the selected resolution.

#### 2.4. CUTTING SEQUENCE AND ENTIRE PROCESS FLOW

Trimming is intended to provide a cost-effective machining strategy for machining high-performance materials. Therefore, a maximum material removal by trimming while simultaneously performing a minimum of individual cuts was focused. For that reason, the selection of the cutting sequence relies on the comparison of the removed material volume. This is calculated for all investigated rotation angles. The cut with the maximum removed volume is selected and additionally compared with the abort criterion. If the separated volume is higher than the abort criterion, this cut is performed. For the next processing step, all remaining possible cuts are again simulated and the material removal volume is calculated. This repeated evaluation of the separated volume is necessary for each machining step, since the geometry and the material removal volume changes with each machining step.

Based on the selected resolution, TrimCAD calculates the rotation angles to be considered for the trimming process. The rotation angles are listed and stored internally as well as examined gradually while the program is executed. Applied rotation angles are subsequently removed in order to avoid duplication. This results in a reduction of computing time.

For documentation purposes, all relevant information of the performed cuts is saved in a list. The cuts are numbered consecutively in the list. Furthermore, the rotation angle, the remaining volume and the separated volume are stored. The list is saved as a TXT-file and can be viewed after completion of the program for further examinations.

Figure 6 shows the entire machining strategy of TrimCAD. It is divided into three main parts: preparation, execution and saving. In the first main part "preparation" the operator has to load the CAD data of the target and initial geometry in order to align them to each other. Subsequently, the folders for exporting the cutting geometries and the list with the cutting data have to be selected. Finally, the resolution of the pre-contouring needs to be selected and the abort criterion has to be defined. In the second main part "execution" the program is executed. First, the list for storing the cutting data is created and the volume of the target and



initial geometry is calculated. Furthermore, the abort criterion is calculated and the reference or projection surface is created. After these preparations, the cuts are performed by two interlocking loops. In the first loop, cuts are simulated for all rotation angles and the removed volume is calculated for each rotation angle. Afterwards, the cut with the maximum separated volume is selected. Further, this volume is compared with the abort criterion and, if it is exceeded, it is executed afterwards. For the generated geometry, cuts are simulated for all remaining rotation angles and the respective separated volume is calculated. This procedure is repeated until cuts were performed for all rotation angles or the abort criterion is enabled. Finally, the third main part “saving” is carried out. In this section the geometries are exported and saved as STP-files. Also, the list with all cutting information is stored. The main used features within NX Open were ShadowCurveBuilder to generate shadow curves, ExtrudeBuilder to extrude the shadow curve and MoveObjectBuilder to rotate geometries.

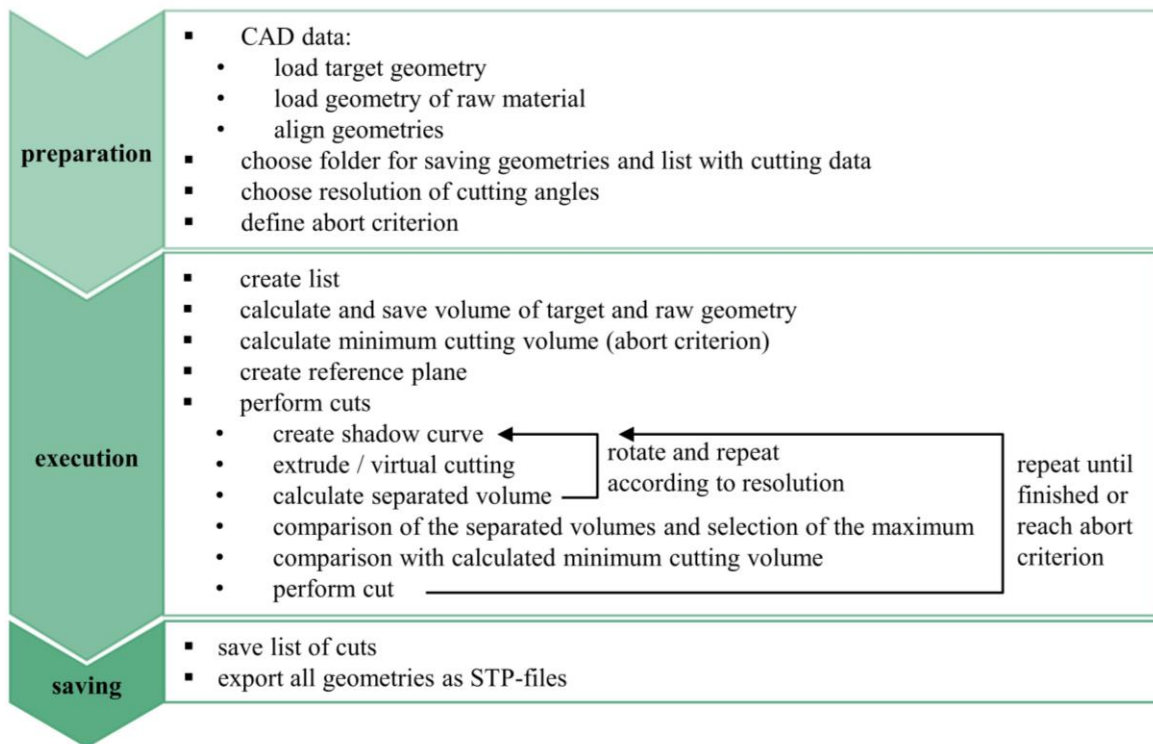


Fig. 5. Workflow within the TrimCAD software

Regardless of the complexity of the target geometry, the program takes only a few seconds to run and to export the list and geometries. Manual configuration by an operator can take up to several hours for complex geometries. The demonstrated turbine blade from Fig. 3 was simulated with TrimCAD and manufactured with trimming using AWIJC. A round stainless-steel profile with a diameter of  $d = 80$  mm was used to pre-contour a turbine blade with a total length of  $l = 155$  mm. As process parameters for trimming the turbine blade water pressure of  $p_w = 370$  MPa, an orifice diameter of  $d_o = 0.305$  mm and a focus tube diameter of  $d_f = 0.760$  mm was used. An abrasive flow rate of  $m_a = 350$  g/min was set and GMA garnet sand with 120 mesh was used. The results are presented in Fig. 7. Firstly, the geometry

produced by TrimCAD for the first cut which has the most removed material of  $V = 647 \text{ cm}^3$  is shown in Fig. 7a. The real trimming process to manufacture the given geometry is depicted in Fig. 7b and Fig. 7c. The final pre-contoured turbine blade after four cuts are illustrate in Fig. 7d and Fig. 7e. Within four trimming steps a volume of  $V = 767 \text{ cm}^3$  are removed which is equal to 97% of the difference in volume between the bar stock and the desired turbine blade. After the fourth cut the pre-contouring is finished and the remaining 3% volume can be removed by milling.

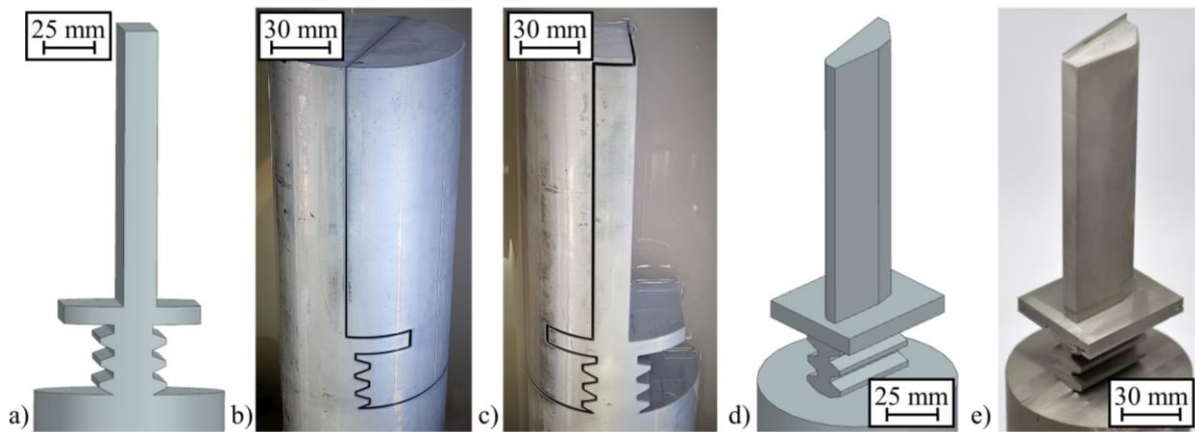


Fig. 6. Example of a pre-contoured turbine blade with trimming; a) first cutting geometry generated with TrimCAD; b) first half of first cutting path performed; c) second half of first cutting path performed; d) geometry after four cuts with TrimCAD; e) real workpiece after four cuts

### 3. SUMMARY

The development of TrimCAD has created an option for enabling AWIJC to pre-contour three-dimensional geometries. Since trimming is a multi-stage two-dimensional machining process, no additional costly parameter studies are necessary and existing parameter sets and experience can be transferred directly. TrimCAD enables an entirely automatically generation of standardized cutting geometries that can be loaded as STP-files into any CAM program for AWIJC. The program can generate all necessary cutting geometries based on the target and the initial geometry. Furthermore, the operator has the possibility to control the level of detail of pre-contouring. In addition to the automatically exported STP geometries, a list of all cutting steps is provided to evaluate the planned trimming steps. The manual effort for successful machining strategies is eliminated in order to reduce the expense of three-dimensional machining using AWIJC. By integrating a rotary axis into conventional AWIJC systems, a fully automated machining strategy can be established. In the main focus of machining high-performance materials, a cost-efficient pre-contouring can be carried out which reduces the volume to be machined to a minimum and establishes a cost-efficient machining strategy. The geometrical flexibility of trimming is limited for undercuts due to the principal of shadow images of workpieces. Furthermore, trimming is able to manufacture rounded geometries, but they require many manufacturing sequences which would lead to

rising machining time. As shown in Fig. 7 it is recommended to limit the pre-contouring. With the presented program and the designed machining strategy, the state of the art in machining of three-dimensional geometries of high-performance materials is extended. Thus, in the future, machining costs of difficult-to-machine materials can be significantly reduced by a cost-effective pre-contouring which needs to be quantified in further investigations.

#### ACKNOWLEDGEMENTS

*This paper is based on results acquired in the project JetTrim (ZF4067143LL9), which is kindly supported by the Zentrales Innovationsprogramm Mittelstand (ZIM). The project was carried out in cooperation with Maximator Jet GmbH, Schweinfurt, Germany.*

#### REFERENCES

- [1] KLOCKE F., KÖNIG W., 2007, *Fertigungsverfahren 1: Drehen, Fräsen, Bohren*, Springer, Berlin, Heidelberg, 2007.
- [2] QI H., 2012, *Review of INCONEL 718 Alloy*, Journal of Materials Engineering, 2, 92–100.
- [3] FRANKBERG E.J., 2022, *A Ceramic that Bends Instead of Shattering*, Science (New York, N.Y.), 378, 359–360.
- [4] ZHANG J., LIU G., CUI W., GE Y., DU S., GAO Y., ZHANG Y., LI F., CHEN Z., DU S., CHEN K., 2022, *Plastic Deformation in Silicon Nitride Ceramics Via Bond Switching at Coherent Interfaces*, Science (New York, N.Y.), 378, 371–376.
- [5] KOLB M., 2006, *Wasserstrahlschneiden, Materialbearbeitung mit einem Hochdruckwasserstrahl*, Die Bibliothek der Technik, Band 295.
- [6] UHLMANN E., ANDERS S., JACZKOWSKI R., REDER W., 2020, *Near-Net-Shape Trimming Process by Abrasive Water Jet Cutting of High-Performance Workpieces for the Aerospace Industry*, SSRN Journal, 35, 93–98.
- [7] LIU H.-T., Olsen. J.H., 2013, *Application of Abrasive-Waterjet for 3D Machining*, WJTA-IMCA Conference and Expo.
- [8] HASHISH M., 2018, *Intelligent Energy Field Manufacturing: Interdisciplinary Process Innovations*, (Ed.: W. Zhang), CRC Press, 141–171.
- [9] LIU H.-T., 2017, *“7M” Advantage of Abrasive Waterjet for Machining Advanced Materials*, Journal of Manufacturing and Materials Processing, 1, 1–19.
- [10] HASHISH M., 2013, *Current and Potential Robotic Abrasive Waterjet Systems*, WJTA-IMCA Conference and Expo.
- [11] FALTIN F., 2018, *Endkonturnahe Schruppbearbeitung von Titanaluminid mittels Wasserabrasivstrahlen mit kontrollierter Schnitttiefe*, Hrsg., Uhlmann E., Dissertation, Technische Universität Berlin.
- [12] UHLMANN E., MÄNNEL C., 2018, *3D-Vorkonturierung mittels Wasserabrasivstrahl*, Zeitschrift für wirtschaftlichen Fabrikbetrieb, 113, 479–483.
- [13] REDER W., UHLMANN E., ANDERS S., 2021, *Mit dem Wasserabrasivstrahl in eine neue Dimension*, VDI-Z, 163, 48–50.