FlexiSTAT

Project funded by the European Commission within
the Seventh Framework Programme (2007-2013)

Grant agreement no.:
605717

Instrument:
Research for the benefit of SMEs

Project acronym:
FlexiSTAT

Project title:
Production Flexibility and Efficiency through Simultaneous Three Axis Turning

Start date of project: **1st November 2013** Duration: **24 Months**

Final Report

Date: **23rd of December 2015**

Please provide an executive summary. The length of this part cannot exceed 1 page.

In the manufacturing of industrial parts, turning is one of the most important processes, besides milling and drilling. More than 35 % of all cutting machines in SME industry are turning machines because turning is simple and flexible. Due to this, SMEs are able to produce a huge range of flexible products with only one turning machine. However, the major problem in turning is that the high flexibility can only be reached by frequent tool holder changes. Due to the geometrical limitations in turning for every variation of the work piece shape a tool holder change is necessary - an important weakness that needs to be abolished.

In the project »FlexiSTAT« the technology of simultaneous three axis turning was developed. Simultaneous three axis turning is a modification of conventional turning where the tool is moved in a third rotational (B) axis besides the already existing translational (X, Z) axes. This additional movement is realized by the integration of the already existing but yet unused B-axis of turn-/mill or mill-/turn centers into the turning process. This has following advantages:

- The technology is applicable in almost all SME shop-floors on already available machines
- Low investment costs are necessary due to the use of already available machines.

To make the technology of simultaneous three axis turning applicable at the SME shop-floor, R&D activities in three different fields were performed:

<u>1. Process Planning</u>
Development of a CAM-System (Computer Aided Manufacturing), which allows to activate and to control the additional axis efficiently and without collision.

<u>2. Machining</u>
Development of models, rules and methods to design the three axis turning process for arbitrary workpieces in an efficient and optimal way

<u>3. Tooling</u>
Development of tool inserts, tool holders and tool measurement systems which improve the efficiency of simultaneous three axis turning

During the project all developments were integrated in one machine tool to realize simultaneous three axis turning. Besides that the technology was benchmark regarding the economic benefits. It was shown that by simultaneous three axis turning the following can be achieved:

- Significant increased flexibility, due to an additional fully controlled tool movement axis
- Reduced tool consumption (-50%) because the applied tools can be used more efficiently
- Reduced amount of tool holders in stock
- Less cost due to reduced tool consumption (-50%)
- Reduced waste and reduced consumption of rare resources
- Shorter production time, unproductive tool and tool holder changes are reduced (-20%)

Please provide a summary description of the project context and the main objectives. The length of this part cannot exceed 4 pages.

Initial Situation

In manufacturing of industrial parts, turning is one of the most important manufacturing processes, besides milling and drilling. Turned parts, like mandrels, rings, disks etc. can be found in all areas of our daily life: in cars, planes, ships, trains, bicycles etc. (figure 1.1). More than 35 % of all cutting machines in SME industry are turning machines. The reason for this is, that turning is simple and flexible usable. Due to this, SMEs are able to produce a huge range of products flexible with only one turning machine. However, the major problem in turning is, that the high flexibility can be reached only by frequent tool holder changes. Due to the geometrical limitations in turning, for every variation of the workpiece shape, a tool holder change is necessary (see figure 1.2), an important weakness to be abolished.

Figure 1.1: Examples for turned parts

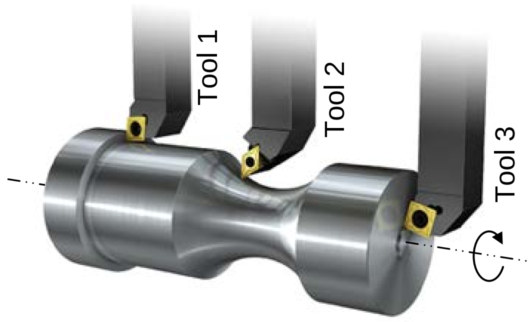

Figure 1.2: In turning, for every shape variation, a tool holder change is necessary

Due to this, nowadays tool manufacturers have a product portfolio of more than 4000 different tools and more than 2000 different tool holders for turning. To be able as SME to react flexible on changing customer demands, it is necessary to have always a certain amount of these standardised tools and tool holders in stock. Otherwise it might happen, that required tools or tool holders are not available and need to be ordered first. This can take a couple of days, in which the machines cannot be used for the envisaged task and the time of delivery is delayed due to this.

SME manufacturers have therefore an average stock of about 100 different tools and 50 different tool holders per turning machine. This ties up capital and space on the one hand. On the other hand, the frequent tool and tool holder changes are time intensive and cost intensive. Summarized: the extreme high amount of needed tool holder is a serious problem.

Another serious problem in turning operations is the high tool wear especially when high-tech materials need to be machined, like high alloyed steels, super alloys or fibre reinforced composites. These materials have great mechanical properties on the one hand, but are extremely difficult to machine on the other hand. This leads to immense tool wear and to tool lives with less than 3 minutes (e.g. IN718DA). But even in turning of common steels tool life is seldom above 20 minutes. The tools, which are usually used, are made of rare, expensive high end materials (10–40 € per tool). In combination with the low tool life (3 - 20 minutes), the cost for tools are immense. Furthermore: frequent tool changes leads to a high unproductive times.

Against the background, that a steady increase of complexity in SME customer products takes place, and the materials become steady more difficult to machine, turning is losing more and more at its competitiveness, as well as the applying SMEs. To catch up this gap, SMEs need solutions to use their turning machines / processes more effective, with less tool / tool-holder deployment, less production time and less cost.

Project Approach

With trend upwards, on SME shop floors about 30-35% of the turning machines are so called turn-/mill-centres. These are "hybrid" machines, which are able to perform turning and milling on one machine. The benefit of these machines is, that only one machine is needed instead of two complementary machines. This gives the SMEs a higher flexibility at less cost, with less tied up space and less energy consumption. The approach of this project is, to use the kinematic properties of this machine type, to meet the above mentioned problems. Turn-/mill-centres have 5 movement axis (for the milling operations) but are using in turning only 2 axis. The remaining 3 axis are switched off during the turning process, because no technology was available yet to control these sufficiently. This project aimed therefore to develop a technology, which allows to "switch on" and control the swivel axis (b-axis) in turning operations (see fig. 1.3).

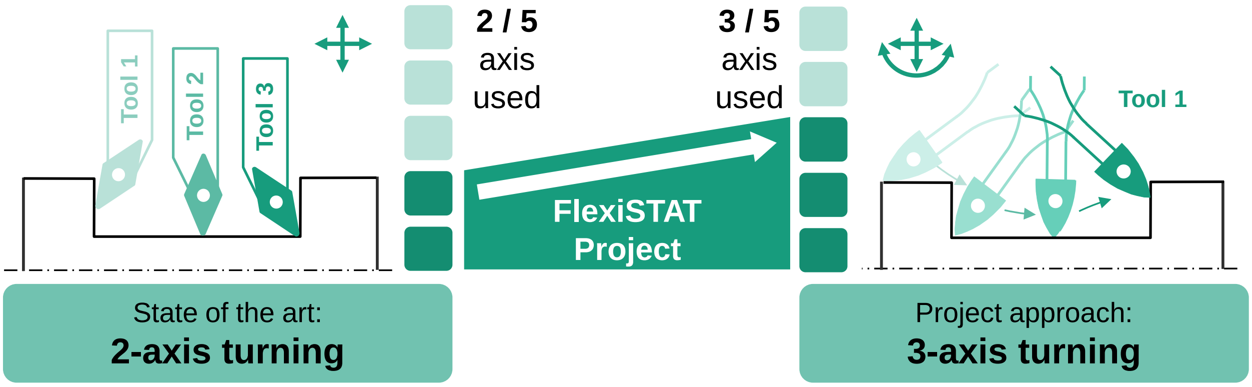

Figure 1.3: Project approach is the activation of the swivel axis in turn-/mill-centres in turning operations

This approach respons to the above mentioned needs twofold:

1) The geometrical limitations in turning are reduced (figure 1.4, left). This leads to a significant increase in flexibility & effectiveness in turning operations. Most workpiece geometries can be machined with only one single tool holder instead of a collection of different tool holders. This leads to a reduction of tool holder purchases and to a reduction of tool holders in stock. Purchase costs and space for storing can be saved. Furthermore, the amount of manual tool holder changes is decreased. This leads to a decrease of cost intensive man power and a decrease of non-productive time.

2) The tool wear is distributed over a larger area of the tool edge (figure 1.4, right). Due to this the expensive tools can be used more efficiently and the tool life can be increased significantly. By this, the amount of necessary tools is reduced and therefore the tool purchase costs are reduced as well. Furthermore, less tool changes are required. This leads to a decrease of cost intensive man power and a decrease of non-productive time.

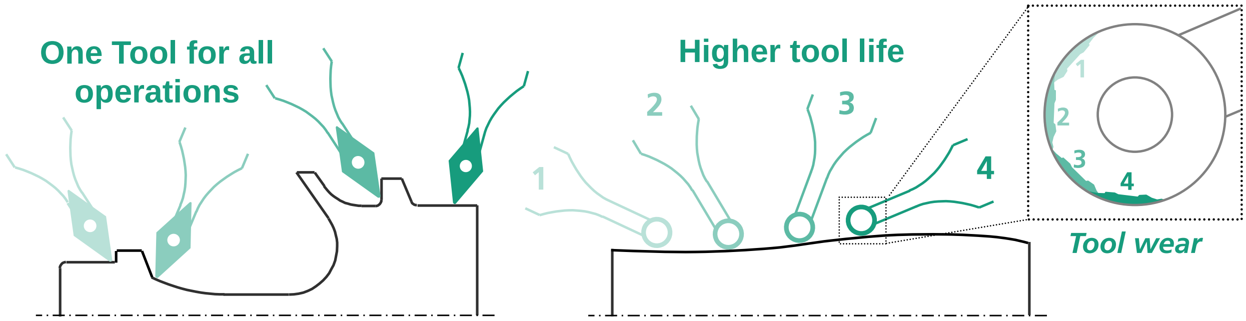

Figure 1.4: Benefits of Flexible Simultaneous Three Axis Turning (FlexiSTAT)

Scientifical and technological objectives

The overall objective of the project "FlexiSTAT" was to provide an efficient "turnkey ready" Technology Package to the SMEs, for an increased flexibility & effectiveness of turn-/mill-centres. In order to reach this overall objective, it was necessary to close several technology gaps, which prevented the reliable application of the technology yet. These gaps were addressed in three different Modules: Process Planning, Machining and Tooling, see figure 1.5.

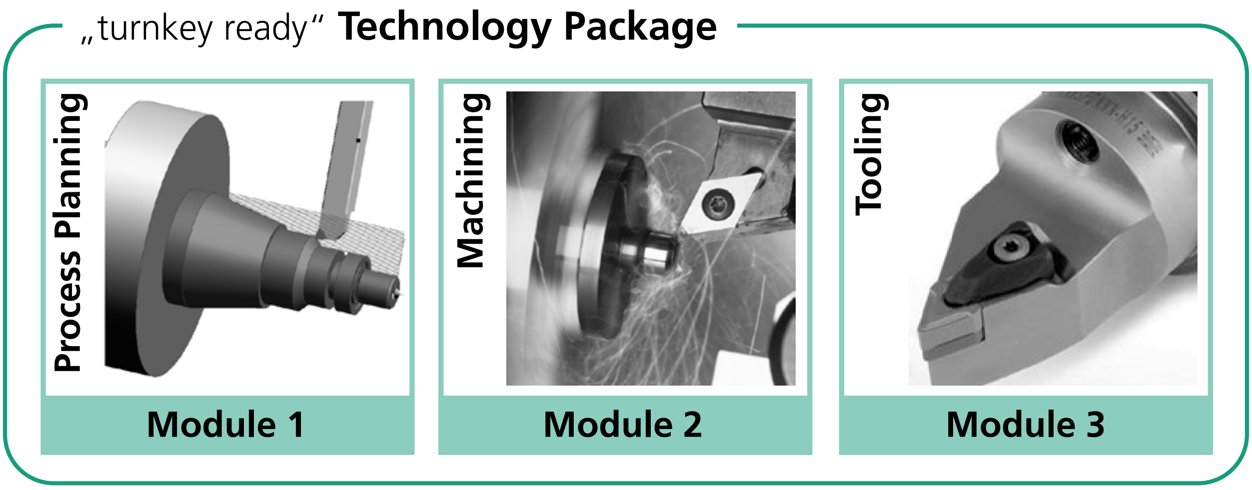

Figure 1.5: Objective was to close existing technology gaps and to develop a "turnkey ready" technology package

The developed "Technology Package" compromises innovative hardware, software and knowledge. It is built upon multiple advanced solutions to be integrated to existing technologies in order to perform simultaneous three axis turning. Therefore, the specific scientific and technological objectives in the project were:

- The development of a process planning system (Module 1), which is able to guide & control the third axis reliable and fully automatically,
- The development of machining strategies (Module 2), which define how the third axis has to be guided to meet the needs of SMEs in an optimal way,
- The development of innovative tool systems (Module 3), which are optimized for three axis turning and give a further increase of efficiency and flexibility to the SME-users,
- The combination of this solutions with each other, and with existing technology to a reliable working technology package.

The single elements of the technology package are as follows:

Module 1 – Process Planning:

In the first module, the goal was to develop a CAM (Computer Aided Manufacturing) module for process planning activities. This CAM-module, which can be used at the end-users on every state-of-the-art computer, is capable to control the third axis and to generate the three axis tool path fully automatic. This happens in a first step by loading a computer model of the workpiece into the CAM-system. In a second step, tools and process parameters are chosen by the user. Afterwards the CAM-module is planning the optimal and collision free tool path for the machining, with a three axis movement. These movements are saved and transferred in standardized machine code to the turning machines, which will do the simultaneous three axis turning machining then.

Module 2 – Machining:

To understand how the tools have to be moved and how the process parameters have to be set, and to achieve an optimal simultaneous three axis turning machining, new knowledge had to be obtained. In the second module, models were developed, which allow the prediction of all necessary output variables in advance. Such output variables are for example: the generated surface quality, the tool wear, the machining accuracy, the force development etc. These models were used to investigate the optimal machining strategy regarding the mentioned variables, for every customized machining case. The models can be used on the one hand by the machine controller to plan the optimal process manually, but were also implemented in the CAM-system in Module 1. By this, the CAM-system can do an optimal tool way planning for every individual machining case.

Module 3 – Tooling:

Basically, the results from Module 1 and 2 are sufficient enough to perform simultaneous three axis turning, but due to the enhanced geometrical freedom, new approaches in tool and tool holder design are possible, which promise a further increase of effectiveness and flexibility of simultaneous three axis turning. Therefore novel tool inserts and tool holders were developed to support the advantages of three axis turning. In addition an optical tool measurement system was developed, to enable a fast, accurate and repeatable measurement of the tool inserts.

Please provide a description of the main S & T results/foregrounds. The length of this part cannot exceed 25 pages.

Table 2.1 gives an overview the results which were obtained in the FlexiSTAT project. In addition it is shown who is responsible for the development. Afterwards the results are presented briefly.

Table 2.1: Overview of results which were developed in the FlexiSTAT project

Mod	No.	Result	Main Developer
1	1.1.	Basic geometry algorithm module to calculate if the tool position is collision free ("3-axis library")	ModuleWorks
	1.2	CAM-module to generate a collision free tool path	Fraunhofer IPT
	1.3	CAM-module to generate a technological reasonable and optimized tool path	Fraunhofer IPT
	1.4	CAM-System for end user to use and apply three axis turning	Exapt
2	2.1	Models for the investigation of the process output parameters	Fraunhofer IPT
	2.2	Process design rules for three axis turning	Fraunhofer IPT
	2.3.	Method to investigate the optimal machining strategy	Fraunhofer IPT
3	3.1	Novel tool holders with a smart cooling control, optimized for 3-axis turning	Tekniker Fraunhofer IPT Metaldur
	3.2	Novel tool inserts optimized for 3-axis turning	Tekniker Metaldur
	3.3	Novel tool measurement system (hardware, software and algorithms)	IMIX
	4.1	Directly driven B-axis head for heavy turning machine tools	Monforts
	4.2	B-axis heads for high precision turning machine tools	Hembrug

Results of Module 1 (Process Planning)

In Module 3 a CAM (Computer Aided Manufacturing) module was developed for process planning activities. The CAM-module can be used at the end-users on every state-of-the-art computer to control the third axis and to generate a fully automatic three axis turning tool path. To achieve this, in a first step an algorithm was developed to analyse if the tool and the workpiece are collision free for arbitrary tool path points, see figure 2.1.1.

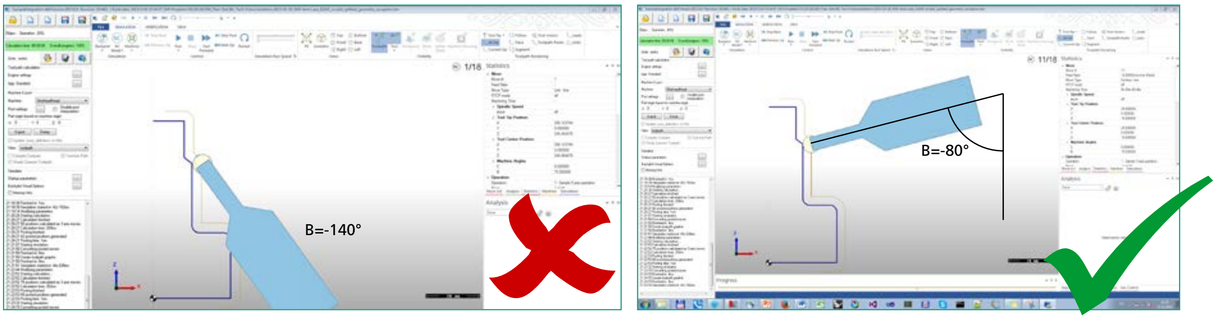

Figure 2.1.1: Algorithm to check if the tool/workpiece engagement is collision free

In the algorithm arbitrary workpiece and tool (insert & holder) geometries can be used, as the geometries are described mathematically by splines. The tool and workpiece geometries can be placed in arbitrary positions in the machine room to check if these collide with each other. By this it is possible to investigate if a first tool path is collision free. However for an optimized tool path planning a CAM-module was developed first which determines the possible, collision free tool inclination angle for each discreet tool path point (see figure 2.1.2).

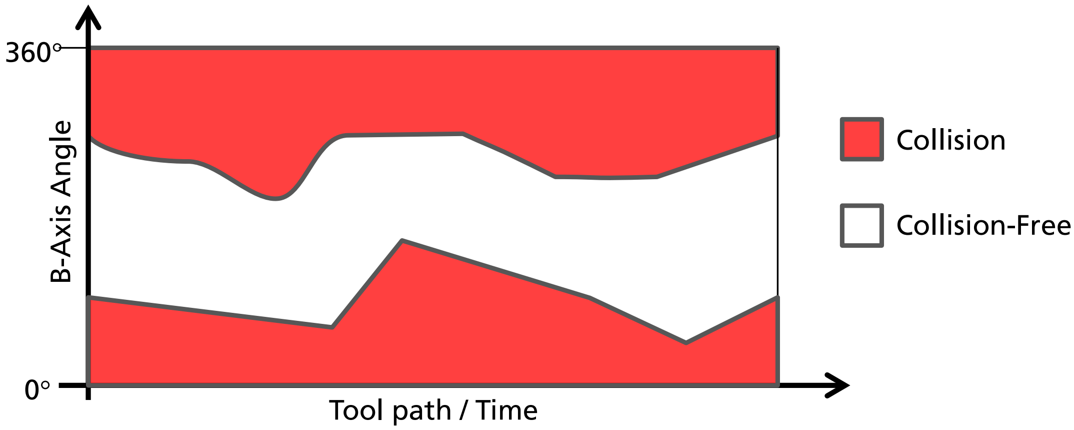

Figure 2.1.2: CAM-Module to investigate the collision-free areas along the tool path

By the module it is possible to determine the collision free areas / B-axis angles along the entire tool path. By planning a NC-tool path in this area the entire tool path is collision free. However, this is just a geometrical engagement. In practical turning the inclination angle of the tool has also an effect on the machining result. Therefore a second “map” is generated (based on the results in Module 2 – machining) to determine the areas where a machining is reasonable, see figure 2.1.3.

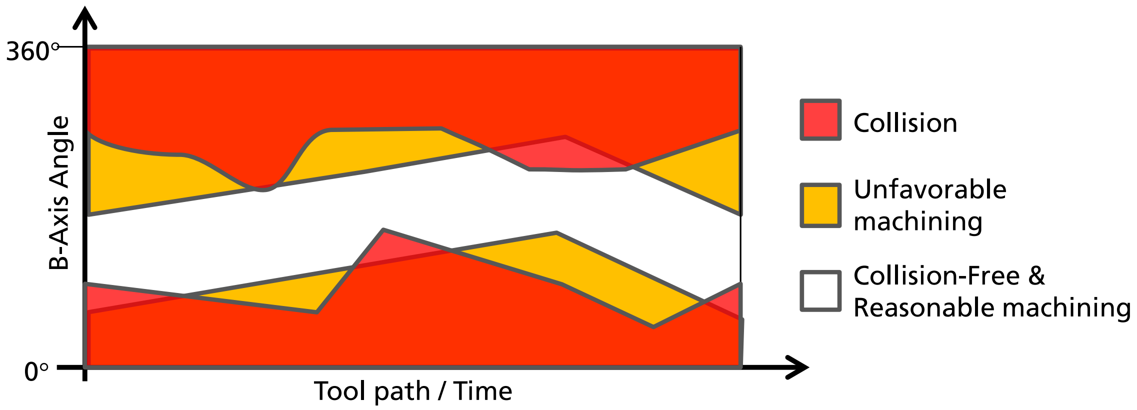

Figure 2.1.3: CAM-Module to investigate the reasonable machining areas along the tool path

Based on this information a CAM-module was developed which puts the tool path in the collision free & reasonable machining area. Hereby the results from Module 2 (Machining) are used, see figure 2.1.4.

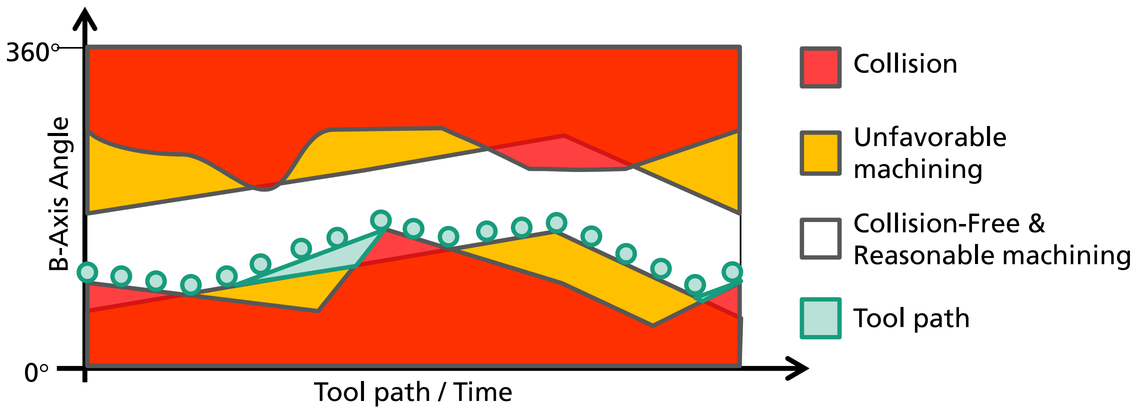

Figure 2.1.4: CAM-Module to investigate the optimal tool path

By the developed algorithms and CAM-modules it is now possible to create fully automatically a tool path which is collision free and optimized in terms of the machining process. These results were embedded in a CAM-system to make the results available for industrial users. For a better demonstration this is shown in a following use case:

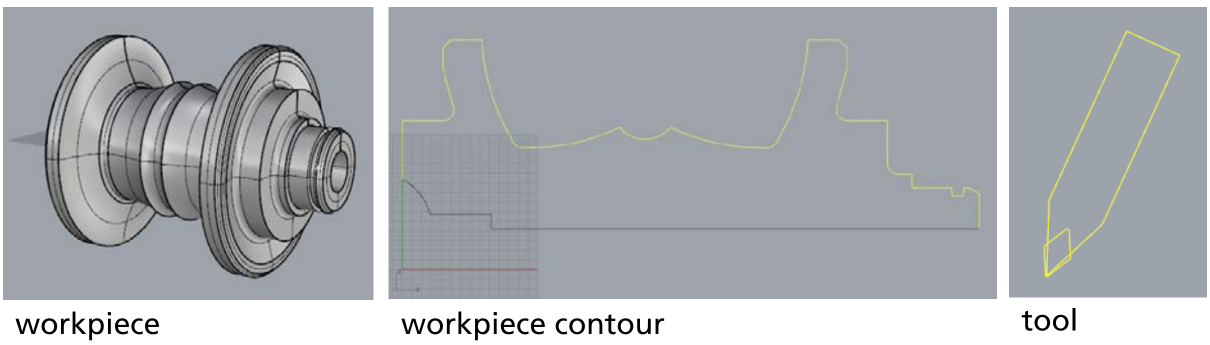

Figure 2.1.5: Use-case (workpiece and tool) to demonstrate the automatic tool path generation

By the developed CAM-system a tool path was generated for the mentioned use case. Figure 2.1.6 shows the generated tool path as well as the tool inclination angle at each discreet point of the path. This data can be transferred then by a post processor to a NC-code to realize collision free, reasonable tool path for simultaneous three axis turning.

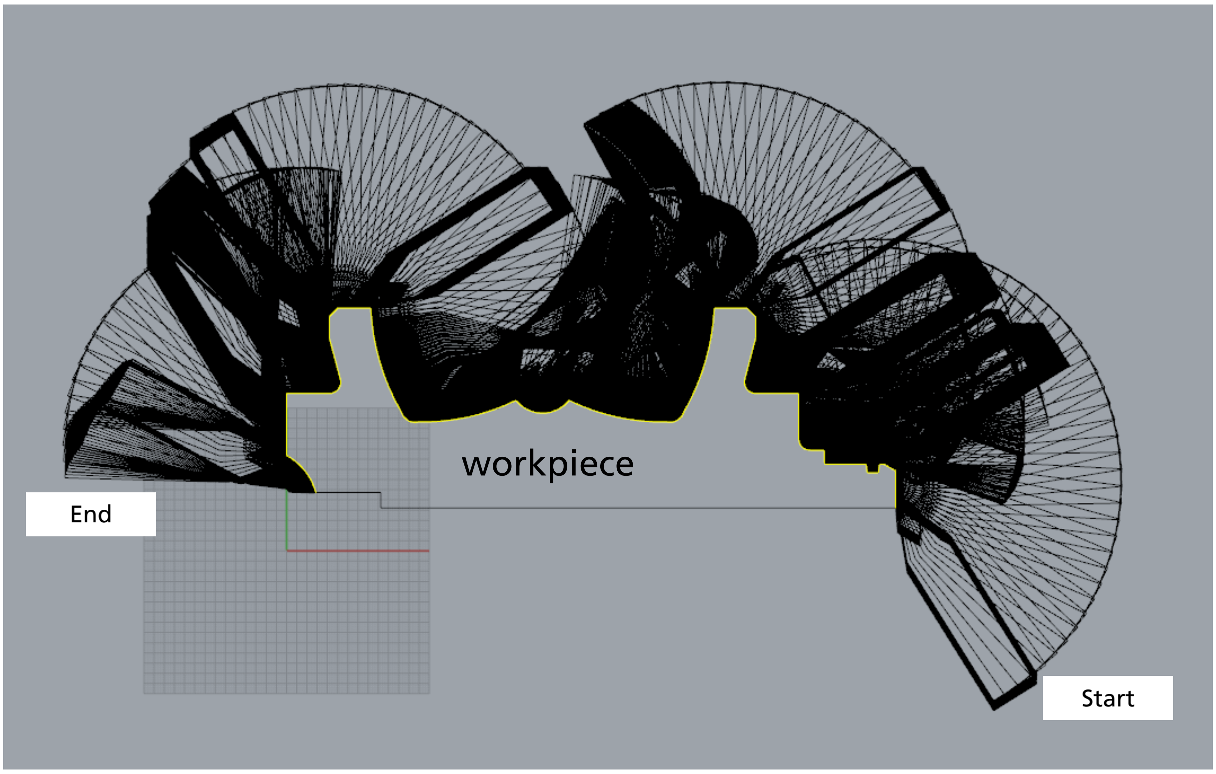

Figure 2.1.6: Tool inclination at discreet points along the tool path

Results of Module 2 (Machining)

In Module 2 knowledge was developed to understand how the tools have to be moved and how the process parameters have to be set to achieve an optimal simultaneous three axis turning machining. For this several models were developed, see figure 2.2.1

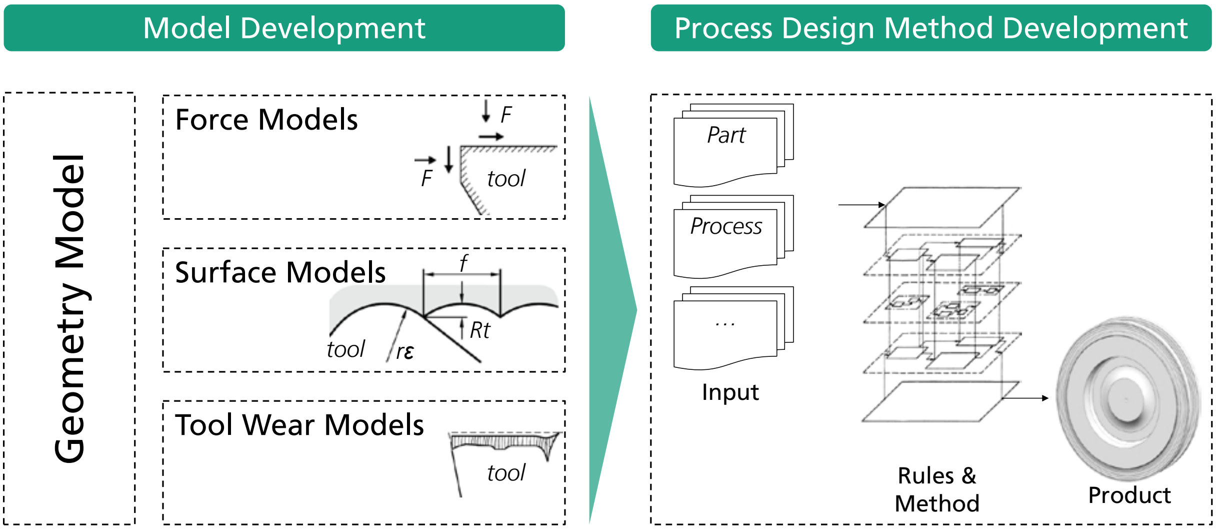

Figure 2.2.1: Models to understand (and optimize) simultaneous three axis turning

In a first step a geometry model was developed to be able to calculate the geometrical engagement between the tool and the workpiece in simultaneous three axis turning. The mathematic model is based on analytical functions and can used for arbitrary ISO-tool geometries. By the model it is possible to calculate all important uncut chip parameters like cross-sectional area, uncut chip width, uncut chip thickness etc. Besides that it is possible to visualize the uncut chip, see figure 2.2.2.

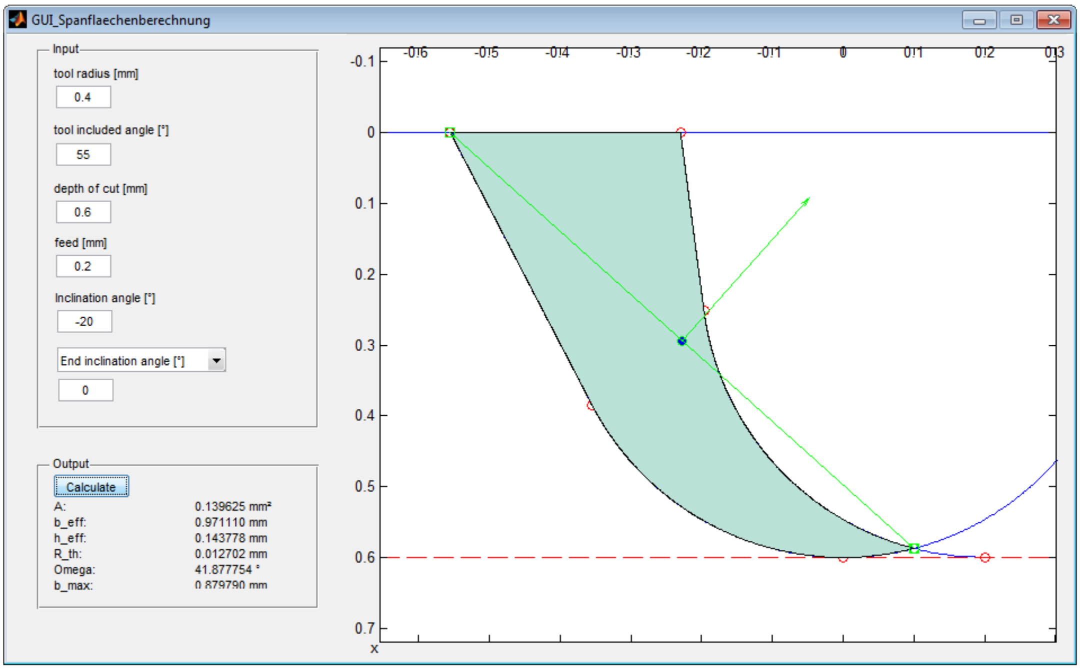

Figure 2.2.2: GUI (graphic user interface) of the developed geometry model

For a better use the model was embedded in a MatLab program with graphical user interface (GUI). In the program it is possible to enter all important input parameters (e.g. tool radius, feed, cutting depth, tool inclination angle, tool rotation etc.) and get all information about the geometrical engagement back. Also a visualization of the uncut chip is possible.

Based on the geometrical model a force model, a surface generation model and a tool wear model were developed. Figure 2.2.3 shows the basic structure of the developed force model

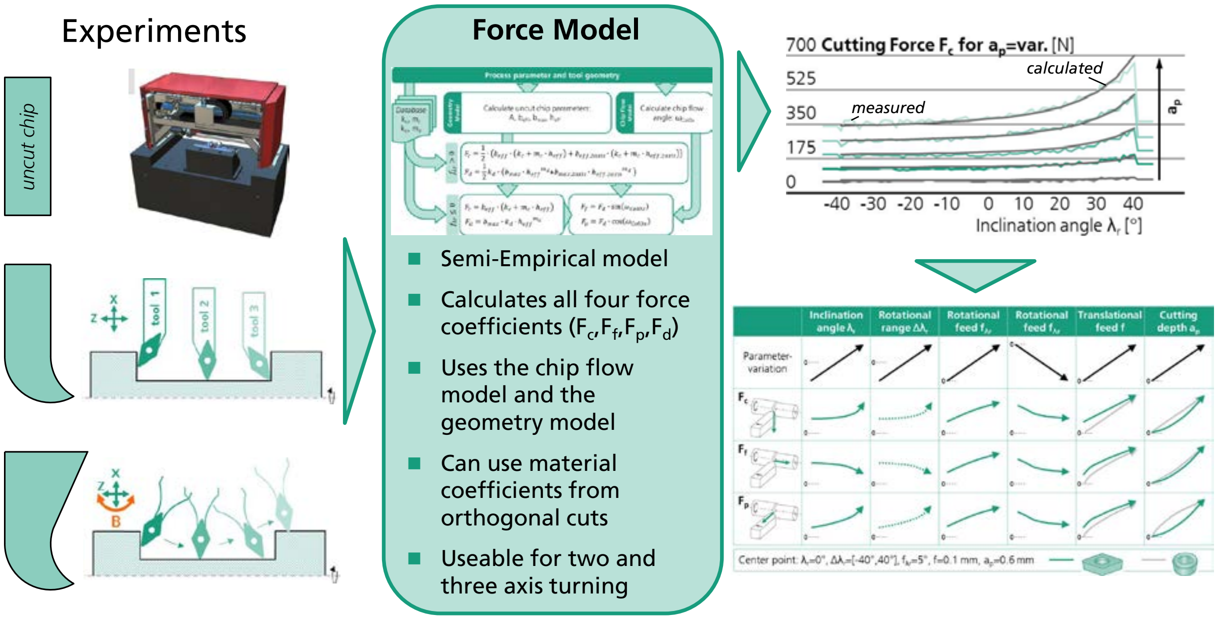

Figure 2.2.3: Structure of the developed force model

For the development of the force model extensive machining experiments were conducted. In a first step orthogonal cut experiments were conducted with simple uncut chip shapes. Afterwards the complexity of the shapes was increased slightly to see which impact this has on the force development. Based on the made observations a semi-empirical model was developed to calculate all four force coefficients (F_c, F_f, F_p, F_d). The model can be used for two and for three axis turning processes. However, subsequently the model was validated and used to investigate which effect the additional tool rotation in simultaneous three axis turning has on the force development.

Also a surface generation model was developed, see figure 2.2.4. The model is based also on cutting experiments in simultaneous three axis turning. It was found that a tool displacement has a negative effect on the surface quality. Therefore an analytical macro-geometrical model was developed to be able to calculate the tool displacement. By this the surface quality, in particular the waviness can be improved significantly. To calculate the resulting roughness afterwards, the previous geometrical model can be used. However, both models were used afterwards to investigate which effect the additional tool rotation in simultaneous three axis turning has on the surface quality (waviness and roughness).

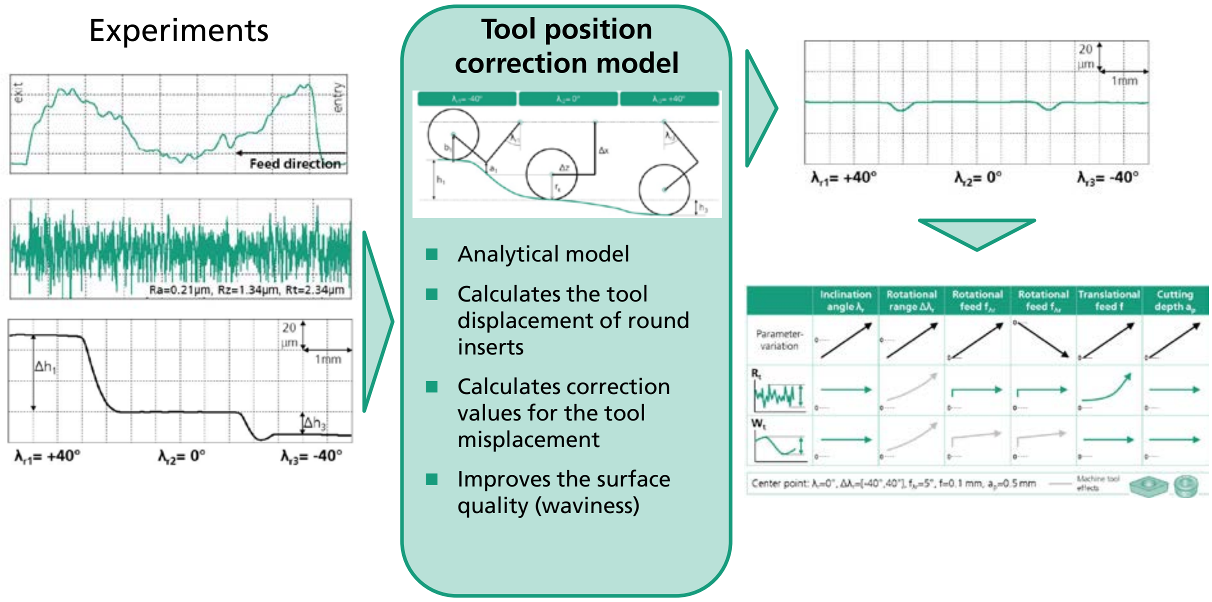

Figure 2.2.4: Structure of the developed surface model

As a third model a tool wear model was developed, see figure 2.2.5. For this it was investigated in first steps in experiments which effect the addition tool rotation has on the tool wear rate. This observation was described in a mathematical way. The developed semi-empirical model is capable to calculate the location of the tool wear on the edge, the wear over time, the location of the maximal tool wear, the shape of the wear and finally the effect of a process parameter variation on the tool wear.

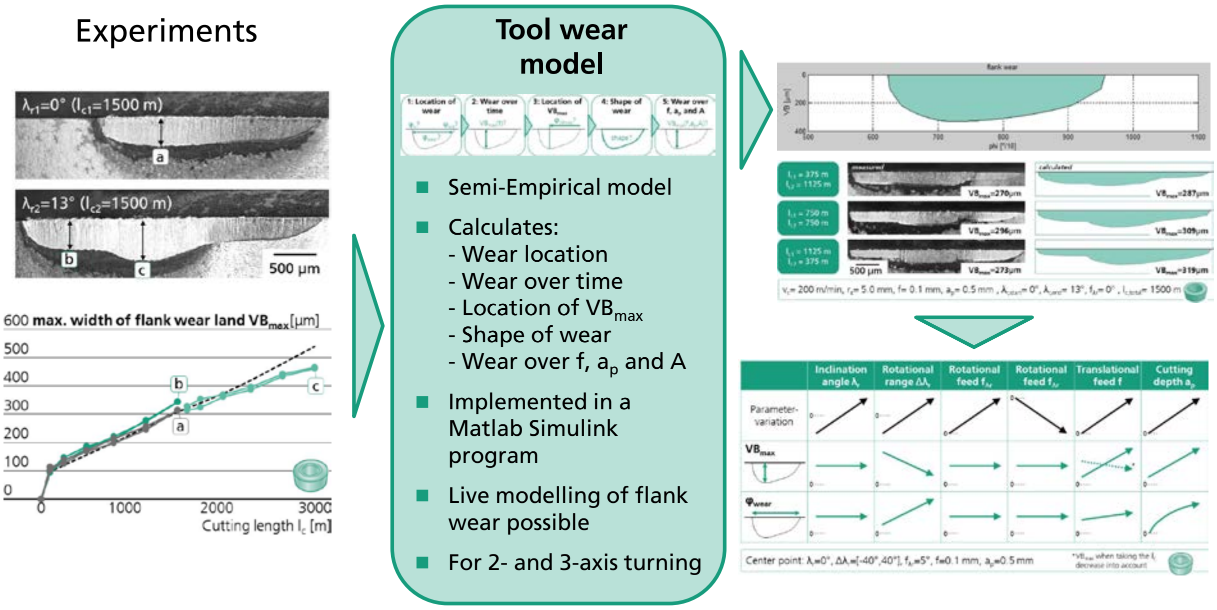

Figure 2.2.5: Structure of the developed tool wear model

The developed algorithms were implemented afterwards in a Matlab program for a better application. By the Matlab program it is possible to simulate the tool wear development for a wide range of process parameters. Besides that it is possible to use the model for two axis and for three axis turning. However, the model was used afterwards to investigate which effect the additional tool rotation in simultaneous three axis turning has on the tool wear / tool life.

Based on the develop models a list of several process design rules were ablated. The rules summarize the major findings of the previous investigations in an easy and applicable way. Due to confidential reasons these rules are listed in a separate, confidential deliverable. However, to be able to design simultaneous three axis turning processes for arbitrate workpieces in an optimal way a process design method was developed. Figure 2.2.6 shows an extract of this method for roughing processes.

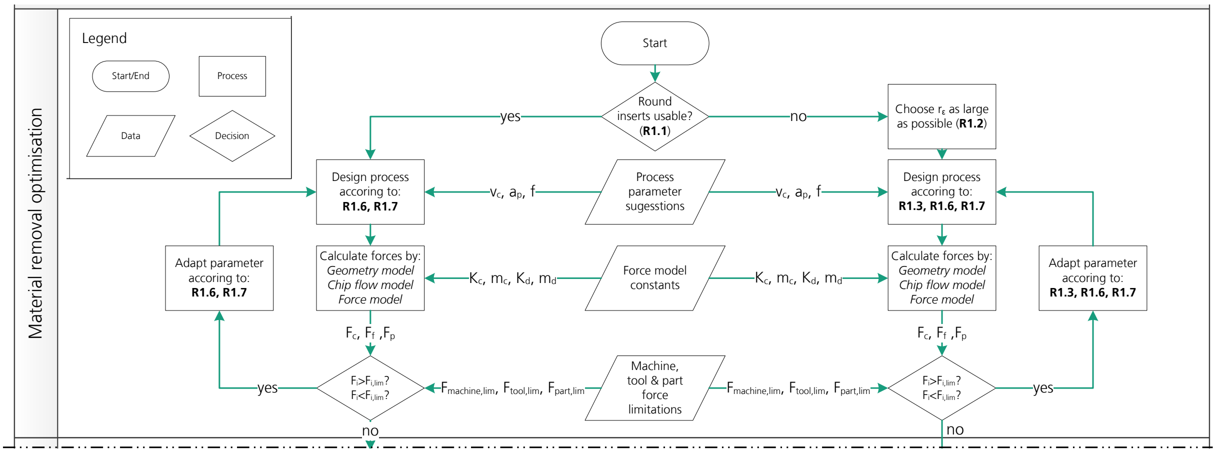

Figure 2.2.6: Extract of the method to design roughing processes in three axis turning.

By going step-wise through the model it is possible to design simultaneous three axis turning processes for arbitrary workpieces and for each individual machining case. The method can be used manually to design simultaneous three axis turning processes but is also implemented in the CAM-system (module 1 – process planning). By this all rules are considered already during the automatic, computer aided process design and NC-code generation.

Results of Module 3 (Tooling)

In module 3, tooling related solutions were developed to increase the benefit of simultaneous three axis turning. This encompasses the development of new tool inserts, tool holders and in particular a suitable tool measurement system.

An additional rotation in turning makes it possible to change the inclination of the insert during the cutting process. In two axis turning, for example, the contact point between tool and workpiece is rigid and dependent from the workpiece geometry. In three axis turning, it is possible to define the exact contact point between tool and workpiece and change this by rotating the third axis (b-axis). This allows the combination of different geometry shapes in one "hybrid" tool and uses these dependent of the particular machining situation. The idea of this is shown in figure 2.3.1.

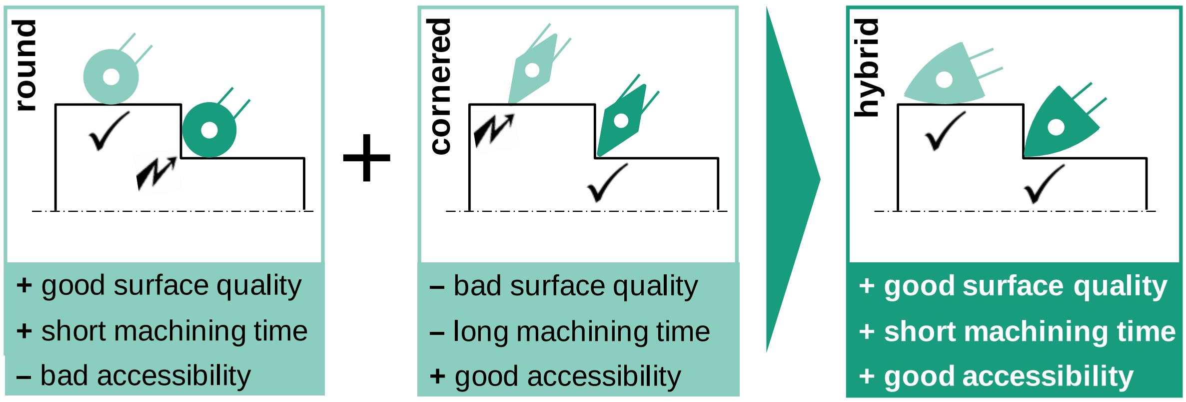

Figure 2.3.1: Hybrid tool inserts to increase the benefit of simultaneous three axis turning

In the project different shapes of such hybrid tool were developed and benchmarked regarding stability, accessibility, surface quality, machinability etc. Afterwards two particular shapes were selected with the highest potential regarding simultaneous three axis turning. For these two shapes specific geometries were ablated then, by using FEM-investigations and geometrical engagement investigations. Afterwards prototypes were developed, see figure 2.3.2.

Figure 2.3.2: Novel hybrid tool insert prototypes

The developed tools were tested afterwards in machining testes. It was shown that the tools show the same process behavior and tool wear development like standard Iso-inserts. But in terms of accessibility the developed inserts have a much higher potential than yet available standard inserts. In the machining test all geometrical features of the demonstrator part could be machined by one single tool insert.

During the machining tests with simultaneous three axis turning it was found that a rotation of the B-axis has negative effects on the machining results when using high-pressure cooling. Nowadays high-pressure cooling is state of the art when machining difficult to machine materials. Hereby the chipping zone is not flooded by the coolant (p=4-5 bar) but shot with high pressure right into the chipping zone. Figure 2.3.3 illustrates this.

Figure 2.3.3: Different types of coolant supply. A: flood cooling (4bar), B: HP-cooling (70 bar), C: HP-cooling with injection nozzle (70 bar)

Using high-pressure cooling brings two major benefits. First the chip is broken due to coolant beam. Instead of long chips, which are difficult to remove, small separated chips can be generated. The second major benefit is the significant reduced tool wear. Due to the improved cooling, the tool wears less. Thus, the cutting speed (=productivity) can be increased and the tool cost decreased significantly. However, when using simultaneous three axis turning and/or the newly developed hybrid tools the benefits of high-pressure cooling cannot be fully used. Figure 2.3.4 illustrates why.

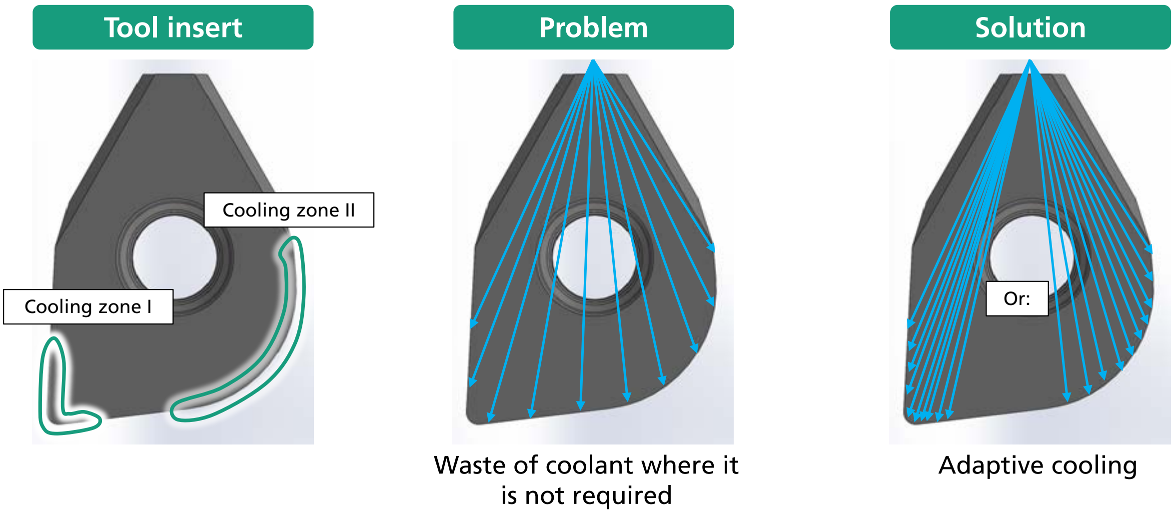

Figure 2.3.4: Problem in simul. three axis turning when using high pressure cooling

When using hybrid tools and/or round cutting inserts in combination with simultaneous three axis turning, the coolant beam must cover a wide range of the tool edge. In most cases the cutting zone is limited to a small range of the tool edge tough (here: cooling zone 1 & 2).

Consequently, coolant is applied where no cooling is required. Due to this, the pressure/velocity and the amount of coolant are decreased in the actual cutting zone. By this the positive effect of high-pressure cooling is decreased significantly. A solution is, to adapt the coolant beam to the individual cutting situation. But, no technical solution is available for this right now. Therefore, during the project a special tool holder was developed, which is capable to direct the coolant beam right to the cutting area where it is needed. Figure 2.3.5. shows a first prototype.

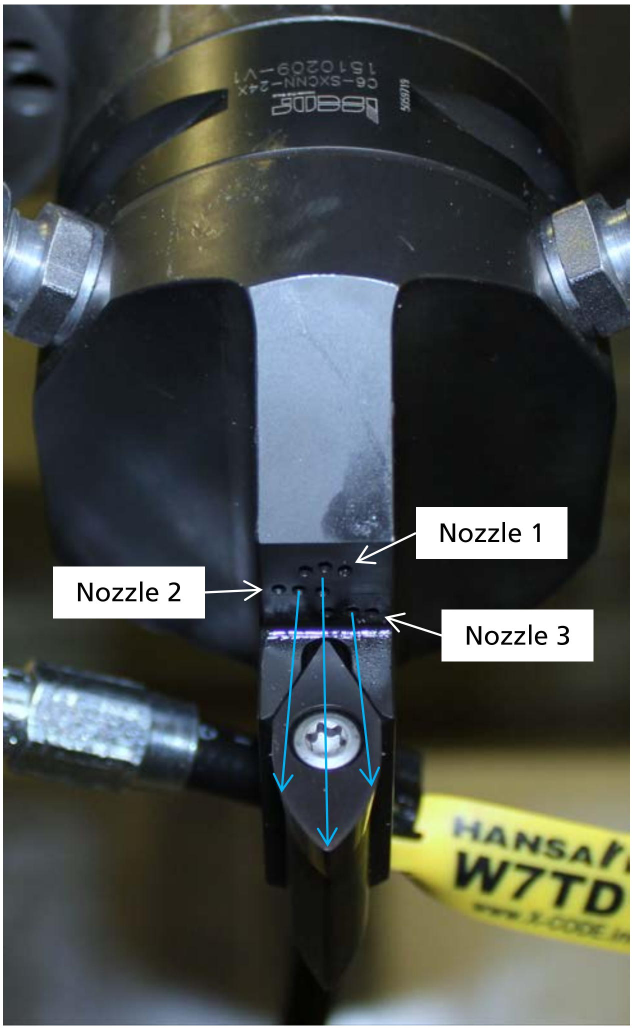

Figure 2.3.5: Prototype of tool holder which is capable to control the direction of coolant beam

The developed tool holder has 3 nozzles where the coolant is coming out. The coolant is not coming out through all nozzles at the same time, but only through one single nozzle. By this all coolant beam goes straight to the cutting zone. It has to be mentioned here that the tool holder has only one single coolant inlet but three different outlets. The separation and control of the coolant is done by a special developed mechanism in the tool holder body. By this mechanism it is possible to control the direction of coolant beam by a certain NC-code command. Nonetheless it is a standard, iso-conform tool holder with a Capto C6 interface. No additional hardware modifications on the machine tool are necessary to use the developed holder. Due to confidential reasons, and as the system shall be patented, here it is not explained how the system works. For more information please see the confidential deliverables.

The third part within Module 3 is the development of a suitable tool measurement system. State of the art systems are just able to measure the classic, standardized two-axis turning tools. Novel tool geometries, which are developed in the first part of this module, cannot be measured sufficient by existing systems. Besides that state of the art systems are not accurate enough for simultaneous three axis turning (as more tool information are required due to additional axis). Therefore an optical tool measurement system was developed to measure tool for simultaneous three axis turning in an accurate and fast way. Figure 2.3.6 shows the principle of the developed system.

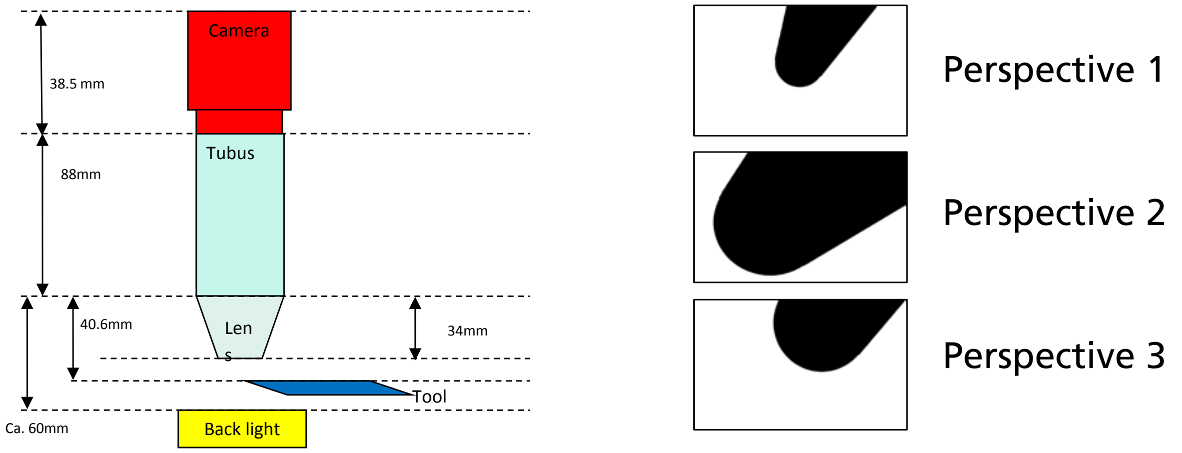

Figure 2.3.6: Principle of the developed tool measurement system

The system works in a way as a high precision camera takes a picture of the tool. Afterwards an algorithm is analyzing the picture of the tool and calculating all important tool parameter. Figure 2.3.7 shows the setup of the developed measurement system in the machine tool.

Figure 2.3.7: Developed optical measurement system in the machine tool

The measurement system is mounted in the machine tool. A robotic arm brings the measurement system into the measuring position. Afterwards a referencing of the system takes place in the machine tool. For this a special referencing tool is engaged and measured. Afterwards the tool is measured. The entire process is also shown in a YouTube Video (https://youtu.be/ArBsuVN0vLA). However, besides the position of the tool insert (in X, Y, Z direction) also the shape of the tool is measure (R_{min}, R_{max}, R_{mid}, etc.). Machining tests show that the measurement accuracy is with +-0.1 µm very accurate. The entire referencing & measuring process takes less than a minute. As reference: the manual measuring process took 10 minutes and was less accurate.

Further results

Besides the developments in the three modules further developments were made in the project. The company Monforts for example developed a new B-axis head for its machine tool which is more accurate and stiff, see figure 2.4.1.

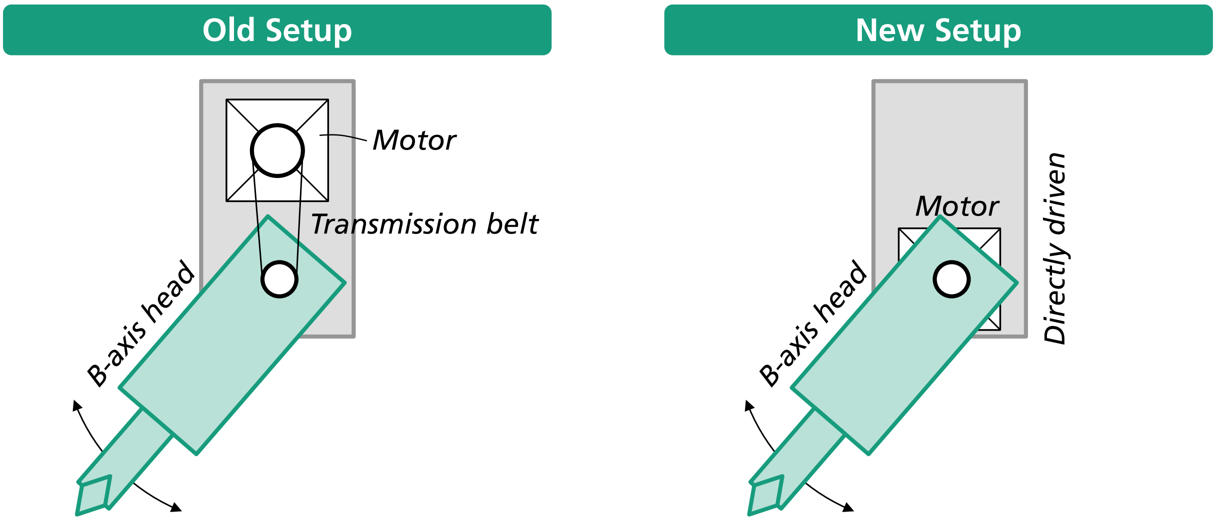

Figure 2.4.1: Original (old) setup and new setup of the B-axis head (Monforts machine tool)

The old B-axis head was driven by a belt drive. The belt has no high stiffness and is therefore not accurate enough for simultaneous three axis turning. Therefore inaccuracies on the workpiece surface occur. As a consequence a new B-axis developed and build which can take much higher loads (torque) than the previous B-axis. By the direct drive it is possible to keep the B-axis in control (=no clamping) and move it simultaneously even at roughing operations. However, at heavy duty roughing operations the B-axis has to be clamped (camping force > 30 kN). Nevertheless here a 2+1 turning is possible (turning in 2 axes and moving the B-axis when no cutting takes place +1). Figure 2.4.2 shows the newly mounted b-axis head on the machine tool without casings,

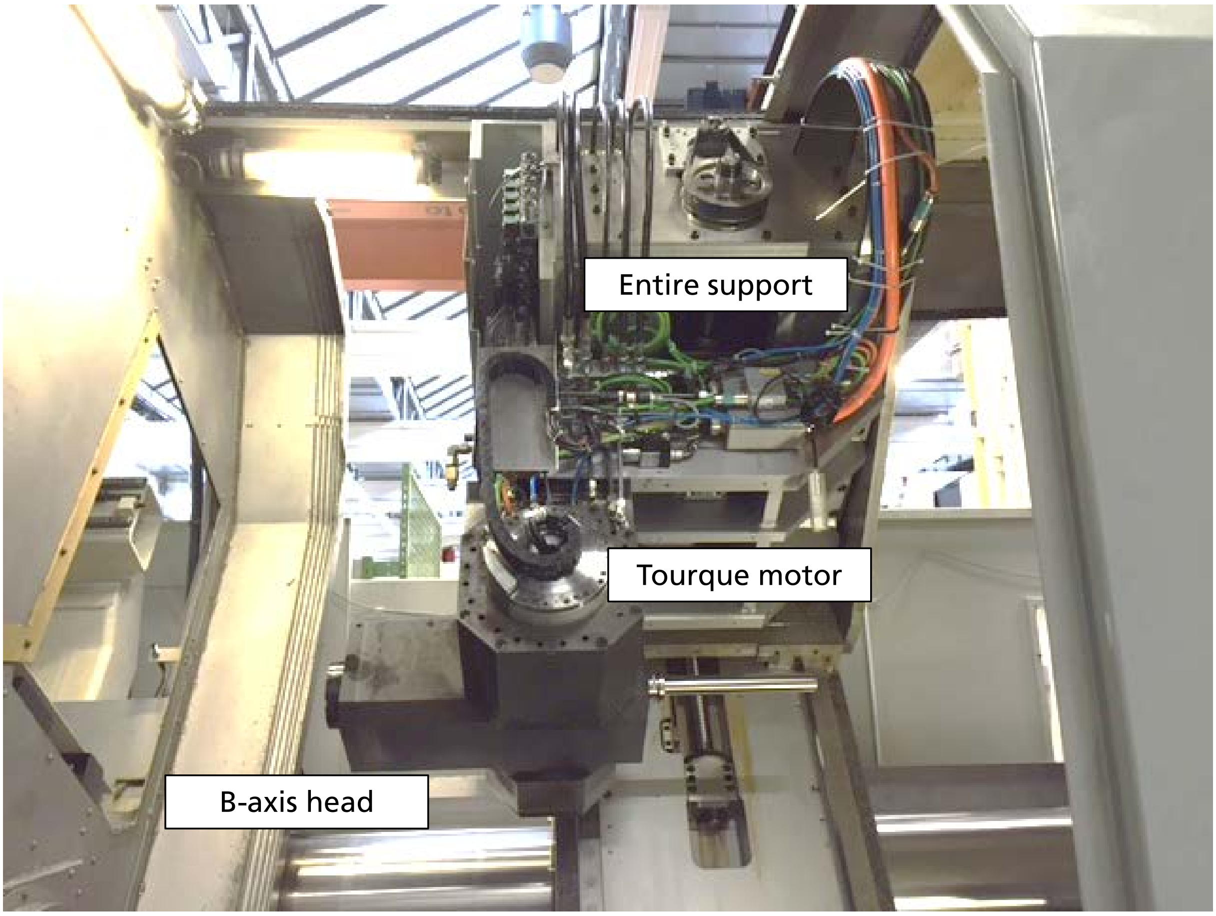

Figure 2.4.2: Newly built B-axis head, specially made for simultaneous three axis turning

Also the high precision turning machine (Hembrug 100CNC) was upgraded. The participant Hembrug developed a new B-axis head for its turning machines, see figure 2.4.3 and 2.4.4

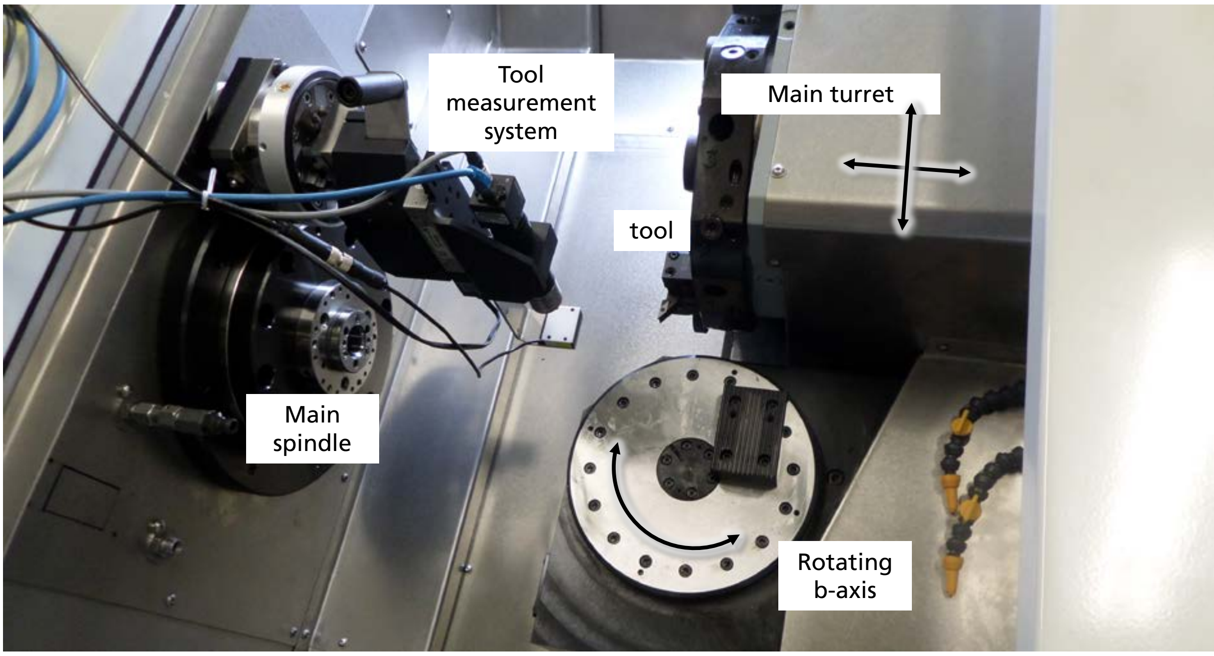

Figure 2.4.3: Pictures of the machine and the machine room (view 1): It shows the integrated b-axis and the integrated tool measurement system

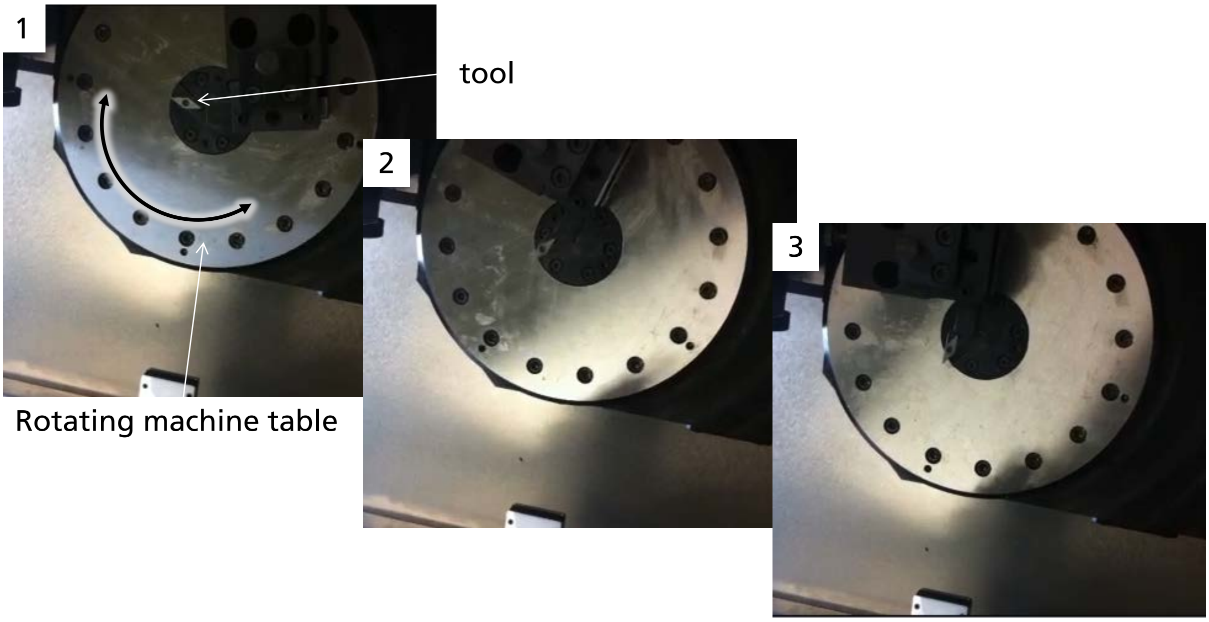

Figure 2.4.4: Picture of the b-axis table with a mounted tool, which rotates around its own axis

The additional B-axis head is directly driven and completely NC-controlled. A prototype was built and integrated into a Hembrug turning machine. Cutting experiments show, that the B-axis can be controlled in the same way as on the larger Monforts machine tool. By this the developed CAM-system and also the developed tools can be used on both machines the same way.

Please provide a description of the potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and the exploitation of results. The length of this part cannot exceed 10 pages.

Technological and economic impact

To evaluate the technical and economic impact of the results of flexiSTAT a demonstrator part was manufactured and a corresponding case study was conducted. The defined demonstrator is a part from an SME end user to accelerate fluids, see figure 3.1.

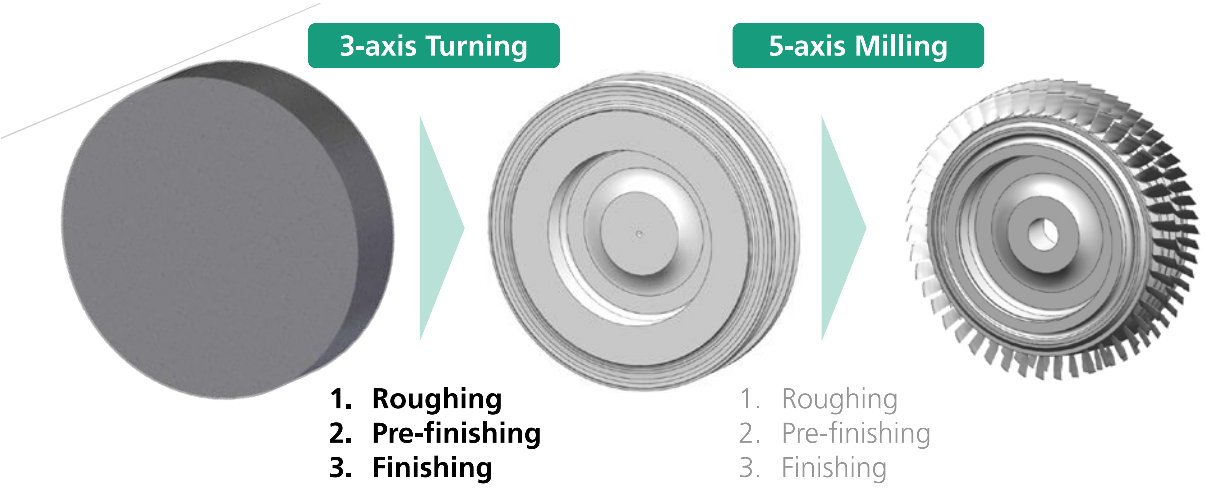

Figure 3.1: Demonstrator part and corresponding process chain of manufacturing

The initial material is a round, saw cut part. In a first step a turning of the material is required. The turning process can be separated into three machining processes: 1. the roughing, 2. the pre-finishing, 3. After turning the part is machined by 5-axis milling. This process was not focused here. It has to be mentioned though, that the milling process can also be performed on the same machine tool and in the same clamping as the turning process. The reason is that for simultaneous three axis turning a turn-/mill- or mill-/turn-center are used. However, figure 3.2 shows the final, turned part.

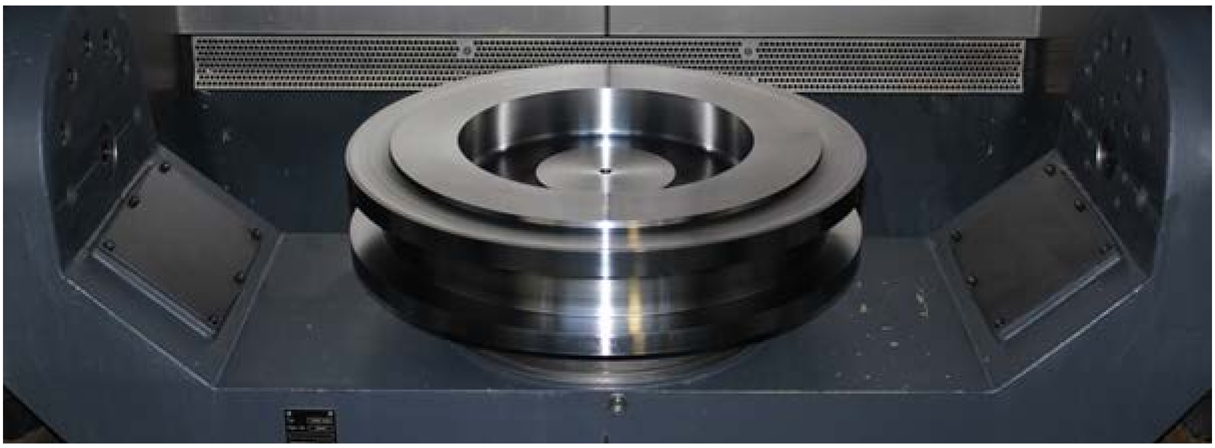

Figure 3.1: Demonstrator which was manufactured by simultaneous three axis turning / flexiSTAT technology.

A first technical evaluation shows, that by simultaneous three axis turning all requirements (form tolerance, surface quality etc.) can be met, see figure 3.2. It is shown that all required form tolerances can be achieved. Also the required surface qualities can be achieved by simultaneous three axis turning. As the demonstrator usually manufactured by conventional two axis turning, and a manufacturing by simultaneous three axis turning is also possible, it can be concluded that simultaneous three axis turning is from a technical point a serious alternative to conventional two axis turning.

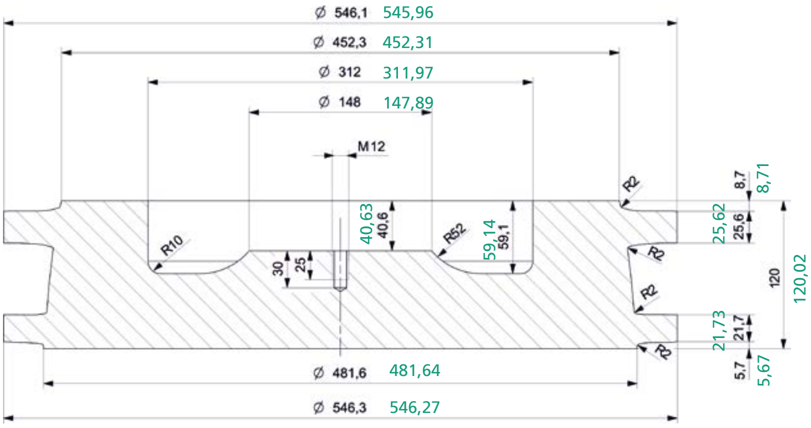

Figure 3.2: Achieved tolerances when machining the demonstrator by simultaneous three axis turning.

To evaluate also the economic impact of simultaneous three axis turning, the working times and tool consumption was recorded during the machining of the demonstrator. Figure 3.3 lists the time and cost when roughing, pre-finishing and finishing the demonstrator part. Time and cost are separated in "machining related" (= pure cutting time/cost) and "tool related" (=tool insert cost, tool insert change, tool holder change, tool measurement time/cost).

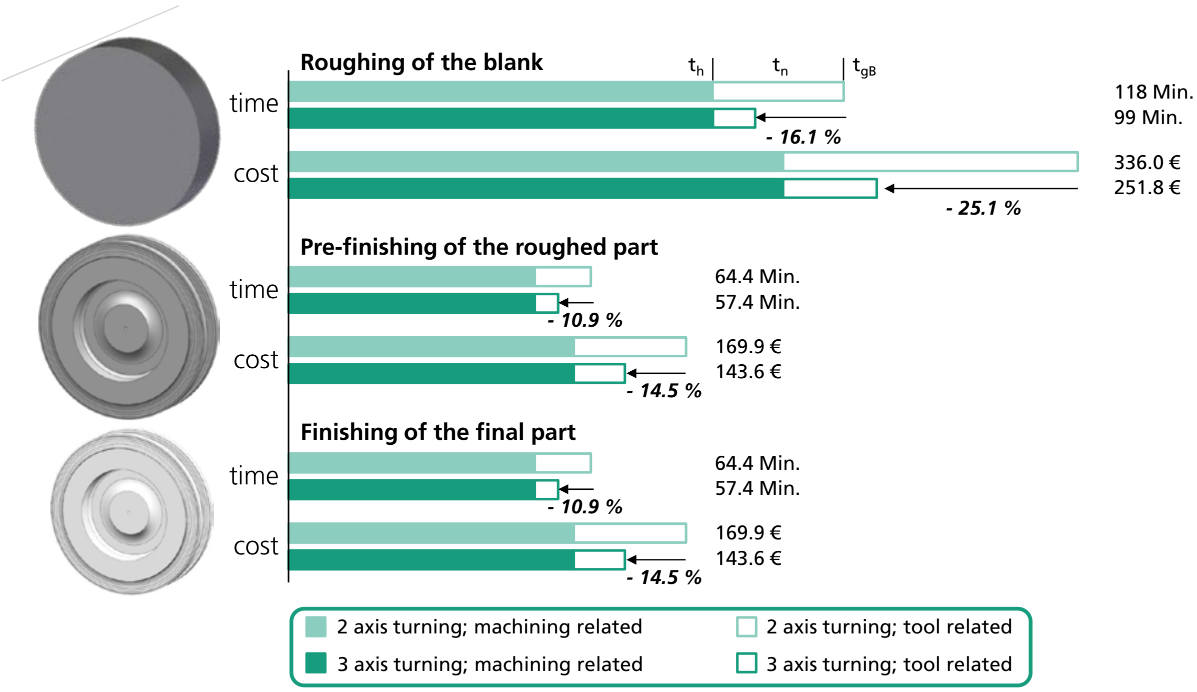

Figure 3.3: Machining times and cost in two and three axis turning for each machining step

It is shown that for all three machining steps the machining related times and cost are the same in two axis turning and in three axis turning. The reason is that the cutting parameters (v_c, a_p, f) in both are the same. Thus, also the cutting time is the same and therefore the related cost. However, when focusing on the tool related times it is shown that these can be decreased significant. In all cases the tool related times can be decreased by more than 50%. Due to this also the tool related costs can be decreased by more than 50%. Therefore, in roughing the total manufacturing time can be decreased by 16.1% and the cost by 25.1% by using simultaneous three axis turning. In pre-finishing and in finishing the manufacturing time is decreased by 10.9% and the cost by 14.5%. The total times and cost which can be saved due to simultaneous three axis turning are shown in figure 3.4.

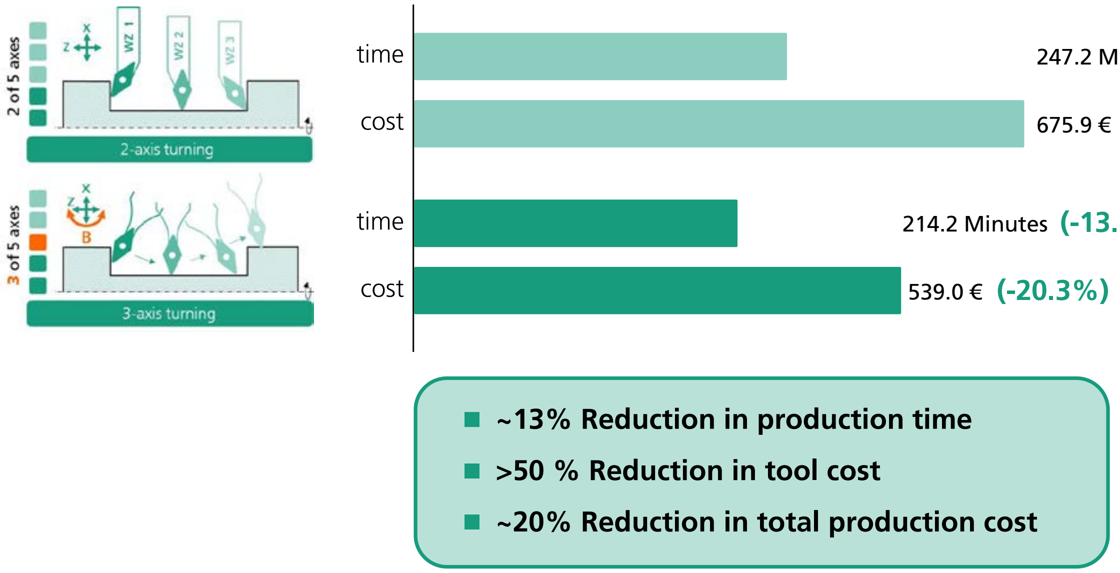

Figure 3.4: Machining times and cost benefits of simultaneous three axis turning in comparison to conventional two axis turning.

Dissemination and exploitation activities

To access the market with the obtained results (see previous table 2.1) and to exploit these, a two level approach is foreseen:

- Level 1: Exploitation of the CAM-system with integrated knowledge (Results, 1.1; 1.2; 1.3; 1.4; 2.1; 2.2; 2.3)
- Level 2: Exploitation of tool systems and machine tool components for further impact (Results, 3.1; 3.2; 3.3; 4.1; 4.2)

Level 1 content:

The CAM-system (R1.4) is a software module which can be used at SME manufactures to realize three axis turning and performing the tool path planning. To realize this, several sub developments are required (R1.1; R1.2; R1.3; R2.1; R2.2). The basic geometry algorithm module (R1.1) as well as the CAM-module to generate a technological reasonable, optimized and collision free tool path (R1.2; R1.3) will be integrated in the CAM-system (R1.4). Besides that the results R2.1, R2.2 and R2.3 are also used in the CAM module and system to optimize the tool path planning. By purchasing the CAM-system, the end user is able to perform three axis turning on his already existing machine tools.

Level 2 content:

To gain a higher benefit & impact of simultaneous three axis turning, the developed tooling system (R3.1; R3.2; R3.3) can be implemented at the end-users in addition. The tool and tool holder are using international standardized mechanical interfaces (like VDI, HSK, Capto etc.) so that a tool and tool-holder change is easy possible by "plug and play". No electrical or control-integration is required. The optical tool measurement system uses standardized interfaces as well, so that an easy replacing of already existing systems is possible. To obtain an even higher benefit from simultaneous three axis turning it is also possible to upgrade (or retrofit) the machine tool by newly designed B-axis machine tool heads. This is possible only on the machine tools of the both machine tool participants (Monforts and Hembrug) tough.

Market access of Level 1 & 2:

Both levels or rather modules can be used and exploited as stand-alone versions, independent of each other. But to get the highest benefit of the technology and to use synergy effects it is recommended, that both modules are implemented at SME-end users at once. Figure 3.5 shows the expected time-to-market of both levels.

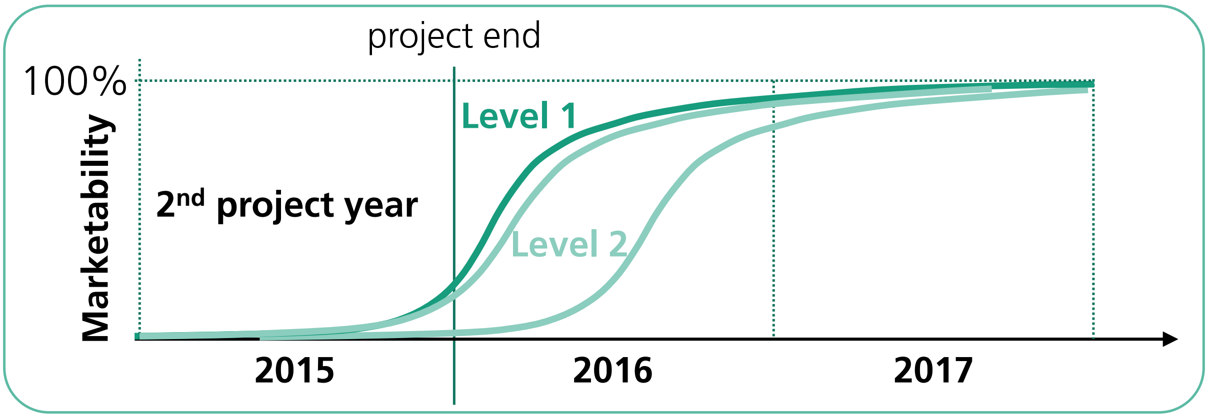

Figure 3.5: Expected time-to-market of the developed FlexiSTAT technology package

Against the background, that the CAM-system and the tooling solutions are using standardized interfaces, these can be disseminated very fast in industry. It is foreseen to bring the Level 1 results (CAM-Module & System) on the market in the middle of 2016, latest by end of 2016.

The results Level 2 are a bit slower in market reach, as a production is necessary. Besides that the marketability of the individual developments varies strongly. The B-axis heads (R4.1; R4.2) reached marketability already and are sold presently. Also the optical tool measurement system (R3.3) is sold already. The developed tool inserts and tool holders are market ready by middle of 2016. The new invented tool holder with coolant control (need to be patented first) will not reach marketability in 2016. For this product further development is required. A realistic product is available by middle/end of 2017.

5. Dissemination and exploitation activities

To ensure a fast and efficient dissemination and exploitation of project results and the advantages of simultaneous three axis turning, the in table 3.6 named actions were/are conducted. These address the industrial community in first place, but also the scientific community.

Table 3.6: Activities to disseminate and exploit the results of FlexiSTAT.

Type	Content	Responsible	Audience	Status
Confidential internet presence	A secured internet page was set up, where only FlexiSTAT participants have access to. On this page all important information and results are uploaded.	IPT	FlexiSTAT participants	**done**
Public internet presence	A public webpage aws set up with information about FlexiSTAT and consortium.	IPT	Industrial applicants, TP component supplier scientific staff, interested public	**done**
Flyer & poster	Handflyers are lay out at the research facilities, as well as posters to present FlexiSTAT.	IPT, Tekniker		**Partly done & in**

				progress
Meetings	Every 6 month, meetings were conducted for exchange of knowledge and management issues. Gained knowledge can be disseminated as fast as possible by this to the participants and applied.	All	FlexiSTAT participants	**done**
Publication (industrial)	Publications about FlexiSTAT technology, potential of technology, results etc. were published in national and international industry magazines.	IPT, Tekniker	Industrial applicants, TP component supplier	**Partly done & in progress**
Show-cases	The technical capabilities of the FlexiSTAT technology was demonstrated in a case study	IPT, Tekniker	Industrial applicants, TP component supplier, interested public	**done**
Publication (scientific)	Papers were published regarding scientific models and results	IPT, Tekniker	Scientific staff, R&D departments in industry	**Partly done & in progress**
Photos of development	The developments were photographed by a professional photographer and reworked afterwards. The pictures were provided to all participants to disseminate & exploit the results	IPT	Industrial applicants, scientific staff, interested public	**Partly done & in progress**
Videos of development	Videos of the made developments on YouTube and on other video platforms: - Optical tool measurement system - CAM-Module/System - Sim. three axis turning	IPT	Industrial applicants, scientific staff, interested public	**Partly done & in progress**
Fair participation	All participants attended fairs to disseminate the results, which were obtained in the project.	All	Industrial applicants, TP component supplier, scientific staff, interested public	**Partly done & in progress**
Conference participation	RTD performers participated in conferences to disseminate scientific results.	IPT, Tekniker	Scientific staff, R&D departments in industry	**Partly done & in progress**

Patents	A patent is envisaged to protect the new invented tool holder with coolant control function	IPT, Tekniker	n/a	**In progress**
Workshops	A workshop took place at the facilities of Fraunhofer IPT where staff was introduced and trained in the correct use of FlexiSTAT technology (CAM-systems, NC-coding, tool measurement system, turning machines)	IPT	Applicants	**Partly done & in progress**
Education integration	The results will be integrated into the course "Manufacturing Technology" by Prof. Klocke at RWTH University.	IPT	Students & scientific staff	**in progress**