3D&FPP

Interreg 2 Seas Mers Zeeën

EUROPEAN UNION

European Regional Development Fund

O 1.1 – Feasibility study/preparatory research report

Partners	TNO, HR, Hittech,3T, Exeter and Argon
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Applicable & Reference Documents

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RD01	Application Form	Interreg	3D&FPP_ApplicationForm_final.pdf	Submitted	20170720
RD02	D3.1.1 System Design Document	Hittech	2818_DR_System-Design-Document_V01_20170403.pdf	Submitted	20170403
RD03	D 1.1.1 Clamping requirements	TNO	2818_DR_Interreg_3D&FPP_Requirement-Document_V01-A-TNO_20170324.xlsx	Submitted	20170324
RD04	D 1.2.1 Industrial clamping requirements	TNO	D1.2.1 Industrial requirements report for flexible clamping systems 3DFPP_V2.0_20170927.docx	Submitted	20170927
RD05	Influences of the geometrical engagement properties towards the cutting force signal of RCD in milling	Krasimir Asenov – Industrial Technologies	Machining-forces-testreport-Kistler-ZHAW-Englisch_20170131.pptx	Obtained info	20170131
RD06	D 1.4.1 3D Scanning requirements and technology selection report	Argon	Annex D 1.4.1 3D Scanning requirements and technology selection report.pdf	submitted	20170428
RD07	D 1.7.1 State of the art of post processing by polishing	Hittech	2818_DR_State-of-the-art-in-polishing_3D&FPP_V01_20170331.pdf	submitted	20170331
RD08	D 3.2.1 Requirement Definition	Hittech	2818_DR_Interreg_3D&FPP_Requirement-Document_V02-A-HM_20170406.pdf		20170406

Activity/ deliverable	Title	description	Delivery month
O 1.1	Feasibility study/preparatory research report	After the design phase is finished the partners will present the design of the integrated post processing solution in the first progress event. The design will be presented to the observer partners and to their respective networks and members to ensure market uptake.	20171231

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1 EXECUTIVE SUMMARY

3D metal printing opens up new design solutions leading to higher performance products or complex geometries at lower costs. Examples are lighter products or products with increased cooling performance. However, post-processing steps are often required after 3D printing. For example, these steps are needed to realize the required accuracy or the required surface roughness of the part. For this purpose, milling, drilling and polishing steps are often used. These steps significantly contribute to the total cost of the 3D metal printed product.

The Interreg 2 Seas project 3D&FPP aims at a reduction of production time of 50% and production cost of 30% of post processing process. This must be realized by optimizing the combination of 3D metal printing with flexible post processing. The main process steps are printing, (re-)clamping, scanning/measuring, CNC milling and/or polishing, unclamping and quality check. In order to determine the requirements for the flexible post processing process, use cases were defined from different industries. Based on these requirements, system level requirements are determined. Also requirements are determined for each process step, being: clamping, scanning, polishing and CAD/CAM integration. A state-of-the-art study was also conducted for these four steps to find out more about the available solutions in the closely related areas or domains.

Various possible concept solutions were determined for the four process steps. These concepts were compared via trade-off tables and ranked according to the most important criteria. This is partly realized on the basis of literature and described in this output document.

This already gives a good indication of the most promising concepts. The concepts selected based on the requirements for the four process steps are:

<u>Clamping</u>

Three options for clamping were selected as suitable, scored on several aspects like tool accessibility and clamping force.

Firstly, a special interface function, which can be printed additional to the product for clamping, can remain on the product or can be removed later. This method is typically used when post processing large numbers of casted parts.

A more innovative approach would be use of a hot let: a liquid that can be solidified around a part of the product and/ or in a certain product orientation. The product can be removed again by changing the material from solid to liquid.

Finally, a promising concept is the use of a bed of pens. The product is held in a certain orientation by means of a large number of pins that can be locked in a certain position.

These clamping technologies will be further investigated in the next phase of the project.

<u>Scanning</u>

At the moment, scanning is often used for quality inspection of a printed part. The following technologies were considered: structured light 3D scanning, laser triangulation 3D scanning and Computed Tomography (CT) 3D scanning. Structured light 3D scanning and laser triangulation 3D scanning can be used to measure outside dimensions. CT 3D scanning can be used to measure also the internal dimensions of the product. None of the three methods, however, provide the accuracy needed for inspection after milling and polishing. The first two technologies can be used to inspect the product after printing and before post processing. Therefore, the focus will been on using scanning technology to define the orientation of the product with respect to the clamp, such that this info can be used in a later stage of the process to for instance re-orientate the CNC machine bed.

Polishing

Three promising concepts for polishing 3D printed metal parts were selected, to achieve low surface roughness and to maintain sufficient accuracy.

The current state of the art is domeless rotary vibrators, in which the product is tumbled in an environment of, for example, small stones.

A more innovative method is using polishing techniques, combined with robotic supported polishing, instead of doing it manually.

For the future, laser polishing is seen as a promising method for polishing while maintaining sufficient accuracy.

CAD-CAM integration

For CAD CAM integration, two main routes are identified: integration with CAM and integration with CNC.

In order to mill the part to the required dimensions, a surplus of material must be present. This is called stock. The available stock can be determined based on scanning the object. This route is called "integration with CAM system" in this document.

With conventional milling, the stock model for the product is often a block of material in which the product fits. Although the actual stock for an AM product is different than a block, it is believed that this approach could still be used. This method is called "integration with CNC system".

The main innovation of this project is seen in making an optimal combination of available processes for clamping, scanning and polishing. All concepts have been scored with regard to the aim of a 50% reduction in production time and 30% reduction in production costs. In addition, attention is also paid to the maturity of the concepts and the feasibility of bringing the TRL level from 3 to 7. A final concept choice will be made after the feasibility tests as described in O2.1.

The required integration work and testing of the integrated approach will be realized in the next phase of the project, development of integrated post processing method (WP2).

2 INTRODUCTION

2.1 3D&FPP PROJECT

Metal 3D printing technology has the potential to revolutionize design, production and supply of parts in aerospace, automotive, shipping, smart things, etc., once viable solutions are developed to integrate it with traditional technologies for post processing. So far, exploitation has been limited, because the post processing of AM (Additive Manufacturing) manufactured parts is still too costly in terms of time and energy. Awareness in industry is lacking, hindering the widespread adoption of AM as a tool for developing innovative products and processes.

Interreg 2 Seas project 3D&FPP aims to integrate metal 3D printing with flexible post processing. The project's objective is to design, develop and implement one efficient, fast and affordable post processing solution based on existing technology that can be part of an integrated system for post processing AM parts. This will help to significantly increase the possibilities for 3D metal printing in industries that need high precision manufactured metal parts, e.g. medical industry, semiconductor industry, maritime industry, aviation, and new emergent clean tech industries.

3D&FPP aims to result in a reduction of production time of 50% and a reduction of production cost of 30% of post processing by developing new applications for its integration into a 3D production chain – like integration of CAM (Computer Aided Manufacturing), the mapping of printed parts, a solution for flexible clamping and a solution to integrate the surface polishing step in the 3D printing process.

3D&FPP project partners are Rotterdam University of Applied Sciences (lead partner, in the form of RDM Centre of Expertise, NL), RDM Makerspace (NL), TNO (NL), Hittech Multin (NL), 3T RPD (UK), University of Exeter (UK), and ARGON (BE). A further 24 observer partner organizations from (mainly) the Interreg 2 Seas regions are also involved.

This project has received funding from the Interreg 2 Seas programme 2014-2020 co-funded by the European Regional Development Fund under subsidy contract No 2S01-097_3D&FPP.

2.2 POST-PROCESSING PROCESS FLOW

Additive manufacturing by 3D metal printing involves various production steps. To have a good understanding of the process of 3D printing and post-processing and how all process steps are linked, a flowchart is generated. The flowchart consists of production steps (blue), professions involved (combined areas in various colours) and communications (dotted lines).

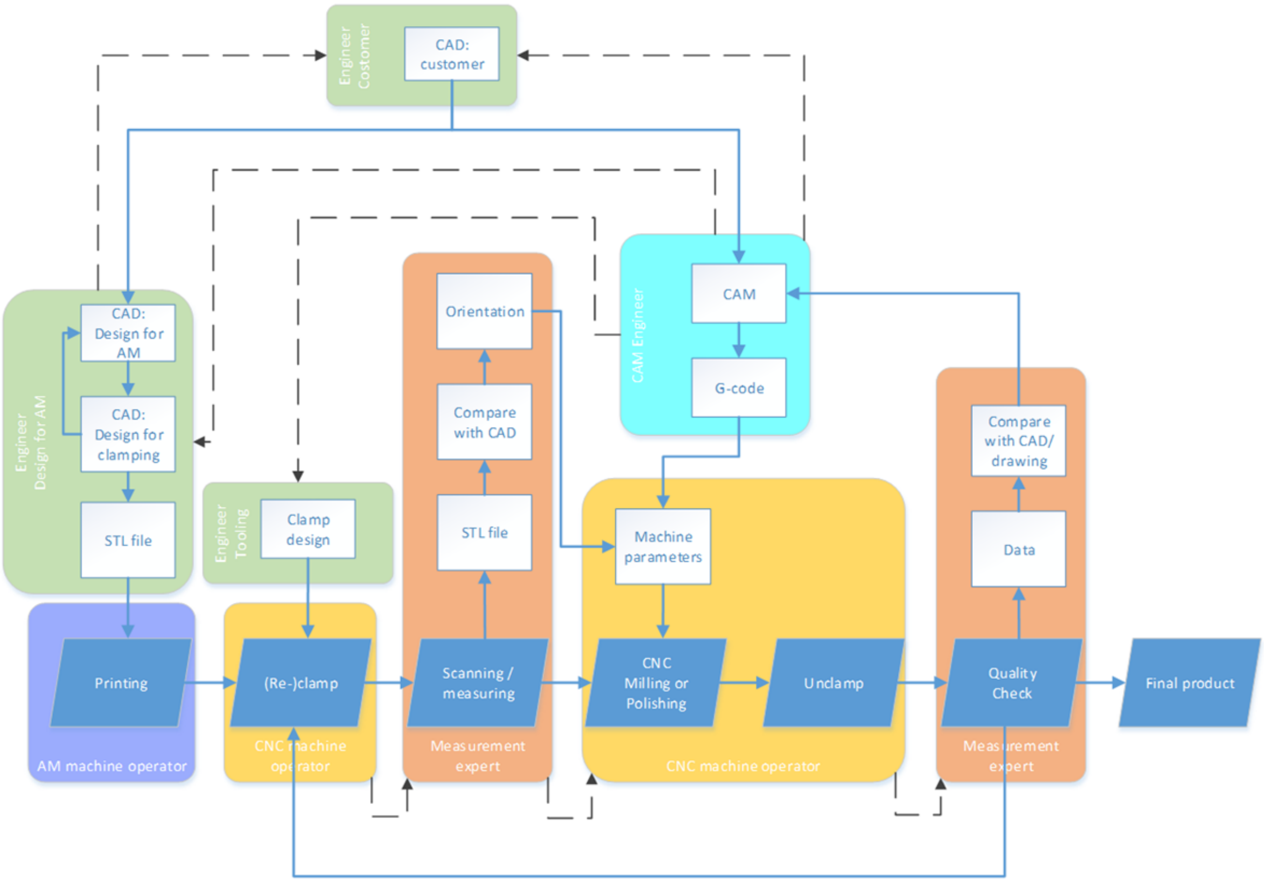


Figure 1: Process flow production and post-processing 3D printed parts

Several iterative loops are present before the final product is finished. For instance, after the quality check a product might need to be re-clamped for additional post-processing. The same process steps apply for products that need post-processing on all sides. Another return loop is present between the “Design for AM” and “Design for clamping”. Later, in this report more details are given regarding the clamping and design rules.

The added value of this project is its holistic or integral approach. The separate post-processing steps are considered as a whole, leading to time and cost reductions. Integration in this sense means the exchange of information between various systems rather than creating one big ‘post-processing machine’.

2.3 User cases:

The customers in the 3D&FPP project are defined as the industries presented in the overall objective above/introduction (such as semiconductor industry, aviation, etc.). As a link between the customers and the project objective several user cases have been gathered from the various industries. At a later stage the user cases will be expanded, but at the time of writing the defined user cases are:

1. Mirror object (representing the semiconductor industry)
2. Gearbox (automotive industry)
3. Cooling core (injection moulding industry)
4. Airplane hinge (aviation industry)

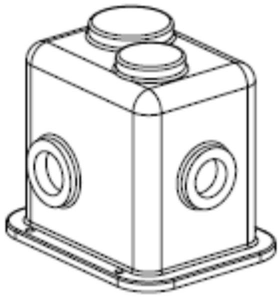
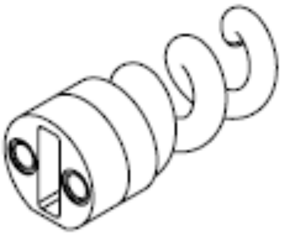
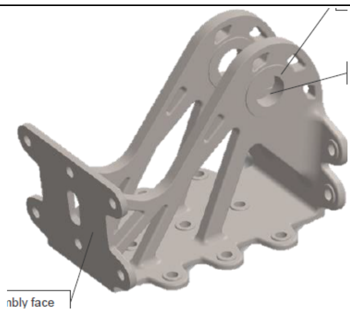
 Mirror object	 Gearbox
 Cooling core	 Airplane hinge

Figure 2: Images of the user cases

2.4 POST PROCESSING FABRICATION SEQUENCE

Probably the most important activity in this 3D&FPP project is to define how which specific tasks will be incorporated in the post processing algorithms. To understand what this, own developed, piece of software must capable of, a production and optimization sequence of printed part production is established (see list below). In general, if a specific step can be performed by a commercial product/ software this will be the first choice, if not, it will be developed and/or listed in a design guide within this 3D&FPP project.

If we look in more detail to the optimizing strategy for post-processing 3D printed parts, which are defined as Near Net Shape parts [NNS], the following optimizing strategy is drafted:

1. Print the product within general tolerances.
2. Only print additional material where post-processing is required based on the technical requirements as shown in the Technical Product Documentation (TPD).
3. Make a scan of the printed product and use this data together with the CAD data for comparison of the two data sets.
4. During comparison, exclude stock and/or support structures.
5. During comparison, make a “best fit in tolerance zone” with the NNS model. And check if its geometry is within spec.
6. (Re-)orientate model only by using near net shape [NNS] geometry.
7. Check if stock-allowance is sufficient to post-process.
8. Create rotation matrix.
9. Re-clamp the product as required.
10. Use rotation matrix information to update the CNC/polishing machine and finish post-processing.

In the upcoming months this theoretical strategy will extensively be tested and refined if necessary.

2.5 System Description

Based on the post processing fabrication sequence the 3D&FPP project must fill the gap between the current available technologies (detailed in paragraph 2.7) and the process flow of figure 1 which describes the integrated system in logic steps.

During the 5 technical meetings and the 2-weekly technical-teleconferences the system base design was discussed intensively. This was an iterative process and the design has been updated by every new insight (state of art report, visit of exhibition, expert input) has led to the following design parameters.

From a high abstraction level, the following key elements are formulated. In other words, the 3D&FPP system must consist of:

1. A carrier structure with a fixed machine interface, which consists of a marked/known orientation reference, which can travel through different machine stages.
2. A flexible clamping system, which is integrated at the carrier structure.
3. A scanning system (hardware and software), which can compare volumes/tolerances and defines the orientation of a product with respect to the carrier structure.
4. CNC milling step that will remove the support structures and brings the part to its final geometrical shape.
5. Polishing step that will brings the selected surfaces to the required roughness. Impact on the geometrical shape to be minimized as possible.
6. An algorithm (software), including a human interface (HUI) which can integrate the comparing and orientation data with the milling /polishing step.

The coherence of these key elements is of course described in the next paragraphs.

2.5.1 Carrier structure and flexible clamping

Because of the capability of 3D printing - designing almost the unimaginable - a great variability of (odd) shapes can be made. Because of this, in combination with the lack of perfectly flat surfaces (due to the limited accuracy of printing), it is not possible to have a known fixed position of the 3D printed product in a regular machine-clamp system. Therefore, a smart and flexible clamping system is required (see chapter 3.1). If this clamping system is integrated into a carrier structure, which has a fixed reference to the machining equipment, it is possible to exchange this carrier platform though the several post-processing machines. Since the exact position of the printed part is still unknown, a scanning system is required to measure the 3D printed object with respect to the carrier structure to determine its orientation.

2.5.2 Scanning system

The scanning system shall be able to scan the 3D printed object with respect to a known fixed interface. An algorithm shall convert the scanned data into a rotation & translation matrix that will feed into the machining step.

A schematic approach is presented below. A detailed description of the process is given in chapter 3.2.

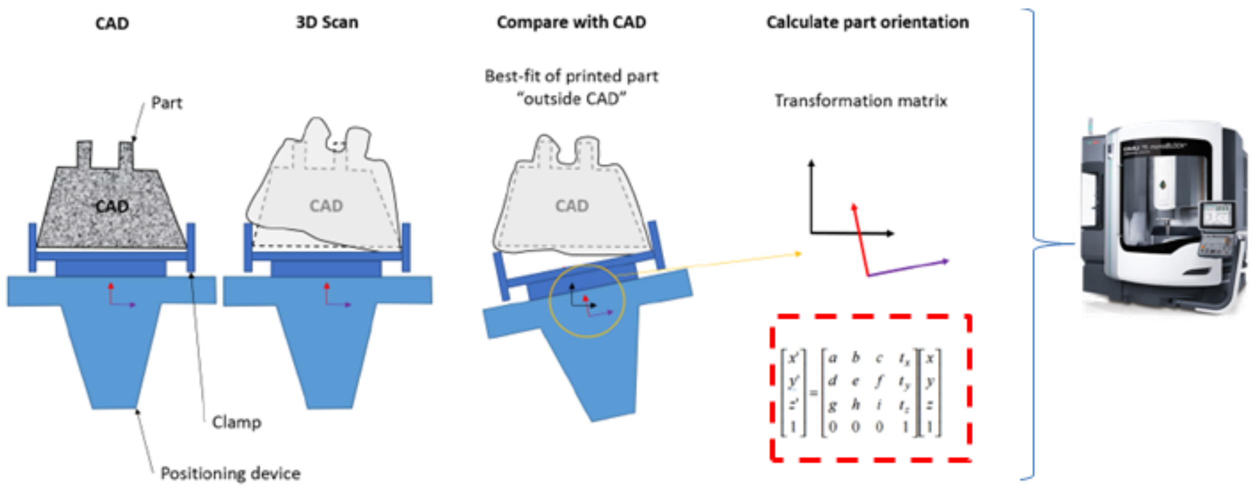


Figure 3: scanner system

The scanner should have a good repeatability, which is the deviation in output of the scanner data between several consecutive measurements should be low. Also, it should be able to cope with glossy metal surfaces.

2.5.3 Machining: milling and polishing

The 3D&FPP project goal is to reduce costs mainly by reducing time (labour). This refers to a high level of automation. All 5-axis milling machines, and in some cases polishing machines have dedicated control parameters (G-code) in which they can be programmed. The main objective is to use the commercial available hard- and/or software and interchange its control parameters with new ones, dedicated to 3D&FPP post-processing.

For a milling machine there are different possibilities to change its control parameters:

- Change in the CAM software the orientation of part coordinate system with respect to the machine coordinate system, and run the post again.
- Change, after having a compiled G-code file, the G-code parameters directly with the newfound offsets.
- Change the index table of the CNC milling machine how will orientate the machine bed to a new absolute position.

Depending on the chosen solutions (program based) the same approach is applicable for polishing machines. These options and effects on the system are described in more detail in chapter 3.5. The solutions of polishing are described in chapter 3.3

2.6 SYSTEM REQUIREMENTS

The main design driver of the 3D&FPP project is saving time and directly related, costs. All requirements and (sub-system) specifications are aimed to meet this goal. To understand how much costs can be saved, first there must be an understanding of what the costs are of post-processing a 3D printed part. Chapter 3.1 clamping summarizes the strategies in which this is investigated and what the main design drivers are.

After the feasibility tests the conclusions can be drawn on which of the concepts is preferred.

Furthermore, requirements are necessary to define the 3D&FPP system and its performance. To work together, all requirements must be clear (defined) and transparent to all partners. Therefore, one single “Master” document is created.

Here, all (sub-) system level requirements, which all partners have to define themselves (WP1) are combined/ merged into a “General requirement document”. This document is the leading document during the whole duration of the project. Hittech Multin is the owner of the “Master” document and will revise the status and contents when necessary.

hitech group

2818 Interreg 3D&FPP - Requirement Document
Sheet: General requirements

Interreg 2 Seas Mers Zeeën 3D&FPP

ID	Module	Raised by:	Tiltle	Description	Value	Unit	Justification / rationale	Verification method / plan	lead / responsible partner	Interfaces with:
Flexible Post Processing Machine [FPP]										
Req.FPP.001	FPP	Interreg	Time reduction	reduction of production time with respect to the current part processing method shall be:	50	%	RD01-A2.1 project summary	1. plan ---> current status (use 3D model [RD05] as input what have to change to meet requirement. 2. measure time before / after	3T-RPD	all
Req.FPP.002	FPP	Interreg	Cost reduction	reduction of production costs with respect to the current part processing method shall be:	30	%	RD01-A2.1 project summary	1. plan ---> current status (use 3D model [RD05] as input what have to change to meet requirement. 2. calculate based on time reducitan and eq. Material cost the overal saving		
Req.FPP.003	FPP	Interreg	Part dimension	The maximum part volume is set to:	400x400x400	mm	Project is based at powderbed printing [RD01]; Largest commercial available EOS machine is used as benchmark: EOS 400	method: suitable measuring device		
Req.FPP.004	FPP	JVAL	Part dimension	The minimal part volume is set to:	20x20x20	mm	approx half of the use case length^3.	method: suitable measuring device		
Req.FPP.005	FPP	Interreg	availability of hardware	builiding	1	-	3D Printing: EOS M 400. Not available at RDM makerspace	-		
Req.FPP.006	FPP	JVAL	availability of hardware	milling	1	-	5 axis milling machine: DMU 75 monoblock: Not available at RDM makerspace	-		
Req.FPP.007	FPP	JVAL	availability of hardware	[illegible]	1	-	TBD--> depending on future research to meet	-		

Figure 4: Example of one tab of the requirement document.

The sub system requirements will be described in more detail in the following chapters. And as can be expected, the upcoming period will be crucial to validate the requirements as set at the beginning of the project.

2.7 Current key production components

The following paragraphs summarize the various production and post –production components of which the 3D production system consists of.

2.7.1 3D Printing

The production process starts with a printed product. At partner 3T RPD various (EOS) printing machines are available, and all of them are of the powder bed printing type. Therefore, in this project we will focus our efforts on 3D printed products using that technology. This narrows down the possible range of printed products, product accuracies and characteristics. It is currently not foreseen to make the project result generic in the sense that it is easily implemented for other printing technologies as well.

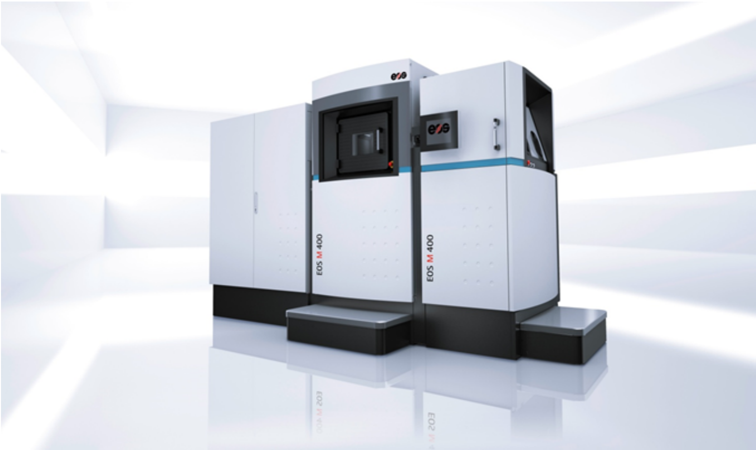


Figure 5: Picture of the EOS 400 printing machine

2.7.2 Clamping

The printers build the products on a metal plate, called a build plate. Subsequently, the products are removed by rough working or threading (EDM) and the printing powder is removed. Next the products must be clamped, both for transport and during post-processing purposes. The clamp must fulfil seemingly contradictory requirements. During post-processing g the clamp must have a high stiffness and clamping force to avoid machining to be out of tolerance. On the other hand, the clamp must deal with often hollow or lattice structured printed products which limits the allowable clamping force.

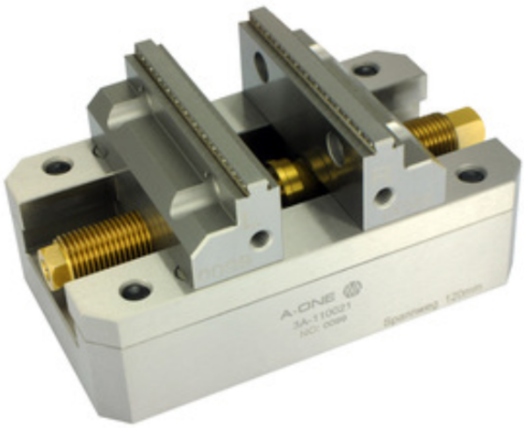


Figure 6: Example of a conventional machine clamp (Erowa)

2.7.3 Scanning

Measuring of the products is necessary for several reasons:

1. During measuring procedures, the 3D printed product needs to be handled and re-clamped. Each time the spatial reference between the product and the clamp or machine

gets lost. Currently this is solved by manual gauging, which is time consuming and thus costly.

2. The printed product almost never directly complies with the required tolerances. Measuring the deviations between the printed product and the required product geometry is required to drive the subsequent post-processing machines.
3. The geometry of the final product is typically validated with accurate measurements taken by a coordinate measuring machine (CMM). It is interesting to investigate in the 3D&FPP project if the final quality check can be done with the same equipment as the intermediate measuring systems.

Alternative solutions to the measuring systems mentioned above will be explored in the 3D&FPP project, for instance the use of optical scanning systems. Since optical scanning systems cannot easily measure internal features (such as cooling channels), it should be investigated if a combination of different measuring techniques is beneficial.

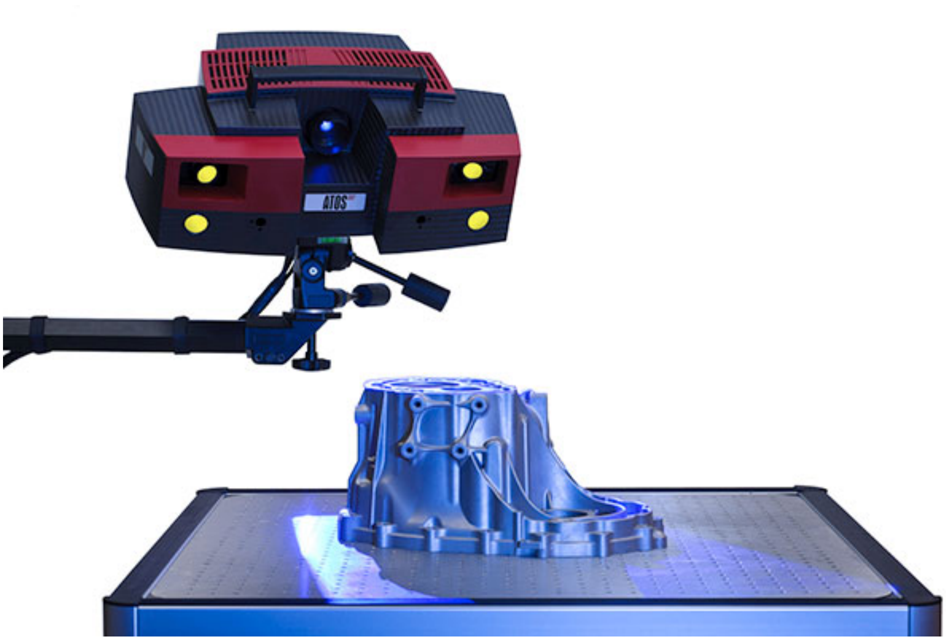


Figure 7:Example optical scanning system: GOM optical measuring system

2.7.4 Post-production Components

Milling

After identification of the deviations of the printed product from the allowed tolerances, the product must be post-processed. This is often done by means of milling. In the 3D&FPP project the focus is on milling with DMG MORI machines such as the DMU 75 monoBLOCK as shown in Figure 8 left.

Polishing

Often the required product contains polished surfaces. Therefore, a polishing step is required on the printed product. Traditionally this is done by hand, for instance by blasting. In the 3D&FPP project various polishing methods will be identified and investigated if it is possible to automate the polishing process, with for instance laser polishing (see Figure 8 right).

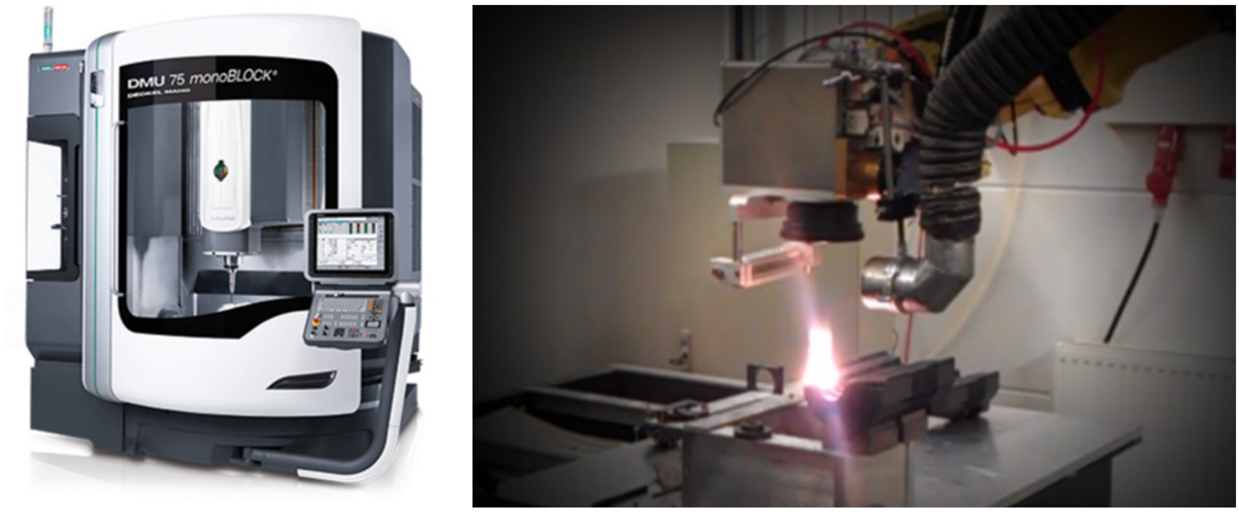


Figure 8: left: Milling machine; right laser polishing

The next part of this report is assigned to the module concepts description. The high level system design and interconnections as within the different modules as described previously, is written in more detail below.

3 Module concept description

3.1 Clamping

3.1.1 Introduction/Scope

The potential efficiency gain and cost reduction by employing an integrated systems approach is a major driver of this project. Many of the separate techniques such as CAD/CAM software, clamping systems, 3D scanning/measurement probes and surface polishing are well understood, however are not integrated into one system.

- For instance parts have to be clamped multiple times to be transported between various machines, and subsequently a lot of time is wasted
- CAD/CAM, the mapping of parts for all processing steps
- Consuming measurements (for instance in order to determine how the part is positioned in a machine).

By having an integral view (Figure 9) on the complete production chain and making the right decisions for both printing and post-processing in the design phase a more balanced hybrid solution between additive and subtractive manufacturing can be made.

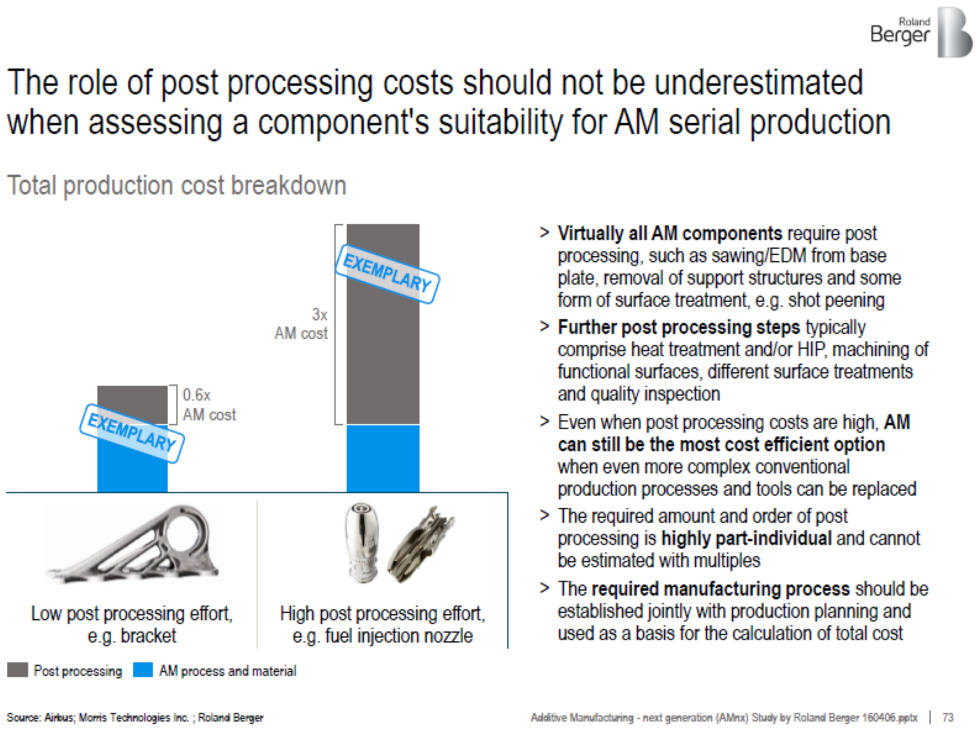


Figure 9: role of post-processing

3.1.1.1 Systems Engineering Approach clamping

In the first phase of this project a systems engineering approach has been followed to get a good view on the commercial and technological challenges for an integral print- and post-processing solution for metal parts.

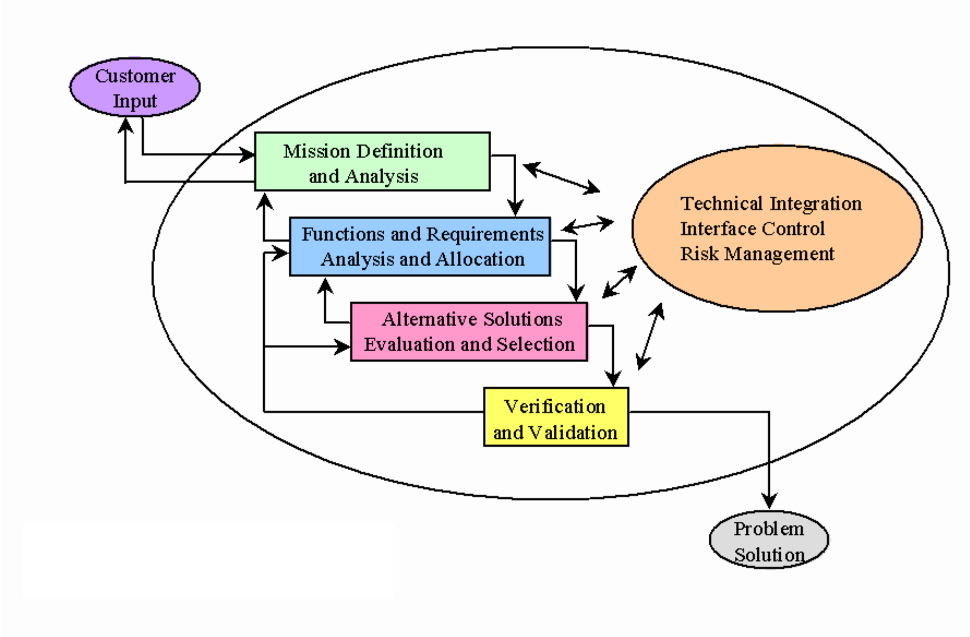


Figure 10: system engineering approach

Via an iterative approach an analysis of requirements, interfaces, concept/solution directions has been made. As reference a state-of-art investigation has been done to explore available solutions in the market, hereby also looking to other domains (like subtractive manufacturing solutions). Finally a trade-off is made of available solution directions against selection criteria (mainly based on system/function requirements). The most promising concept directions will be validated by a proof of principle test to verify its capability and come to a final conclusion/choice for the system/function concepts.

Hittech has described the system aspects in the system design document [RD02].

From this system view, a decomposition is made into the main system components (printing, clamping, scanning, post-processing/finishing and CAD/CAM integration) and each component got its own (error) budget. In the whole production chain, where a printed, near net shape, product needs to be handled between several process steps, there are several contributors that add up to an ‘uncertainty window’ in which the to-be-manufactured final product is positioned/located with respect to the machine. Therefore, a stock model is required that takes into account all related contributors to be sure that the final product can be manufactured. State-of-art is a requirement of 1 mm material surplus: the less material / material surplus, the cheaper the product (by saving time and costs for printing and post-processing).

Because each system component has its own interface and requirements for the system and certain design rules have to be taken into account, it is a challenge to find solution scenarios for the entire value chain, which can save 30% production costs and reduce the post-processing time to 50%. For a realistic process and to prove we can realize these targets, user cases have been defined, covering several critical aspects of post-processing (by their unique product geometry and features). By comparing the cost and lead-time aspects of current state-of-art methodology with projected concept solutions a view can be given on the expected outcome of proposed system design and main contributors will become clear. A critical remark here is that one of the scenarios could also be that by adding/modifying steps during printing a substantial reducing of cost and lead-time could be realized. It is often possible to **reduce the post processing effort** by keeping the entire process in mind during the design stage.

Therefore, system border will be the whole value chain from CAD design till post-processed part. Another critical remark is that series size can have a large impact. In today's situation 3D printing is still often used for fast prototyping, therefore series size is 1, however we are in the transition to make 3D printing attractive for industrial manufacturing and series sizes go up. Therefore, we will show the impact for several series sizes to put this in perspective and show where break even points are with respect to conventional manufacturing solutions (best compromise as hybrid solution additive/subtractive).

A typical post processing chain comprises the following elements – different combinations and orders may be required:

- Powder removal
- Heat treatment: stress relieve
- Sawing/EDM: Separation of part from metal base plate, removal of support structures
- Hot isostatic pressing: Reduction of remaining porosity to improve fatigue resistance and/or
- Heat treatment: control of material properties
- Machining: Preparation of functional surfaces, compliance with geometrical tolerances
- Surface treatment: Fabrication of required surface quality and/or surface hardness
- Quality inspection: Control of dimensional accuracy, surface and material properties

The clamping function provides an interface during all these critical process steps and mainly needs to secure position/reference and stability during these steps. Next to this the clamping tool could provide an interface for automated robot handling and reduce labour impact.

The clamp must fulfil seemingly contradictory requirements: during machining the clamp must have a very high stiffness and clamping force to avoid machining out of tolerance, but on the other hand the clamp must deal with often hollow or lattice structured printed products limiting the allowable clamp and machining force.

TNO will be dealing with designing a suitable clamp and clamping strategy.

- Industrial Requirements are described in deliverables D1.1.1 [RD03] and D1.2.1 [RD04]
- State-of art investigation is described in deliverable D1.3.1 (A1.2) [RD02]

The output document summarizes on:

- Cost and lead-time overview for each processing step in workflow based on user cases as reference for project objectives
- Trade-off of concepts (via the selection matrix table we discussed) both on separate work packages of partners as well as for the whole integral system → what is the suggested integral solution by which we can meet our project objectives. Note TRL level is 3-5 in this phase (M1), so solutions directions are mainly derived from available solutions in the market and not based on low TRL (research) solutions (Figure 11). By proper systems engineering the right fit can be explored. (example Additive Industries, where labour is replaced by automation)

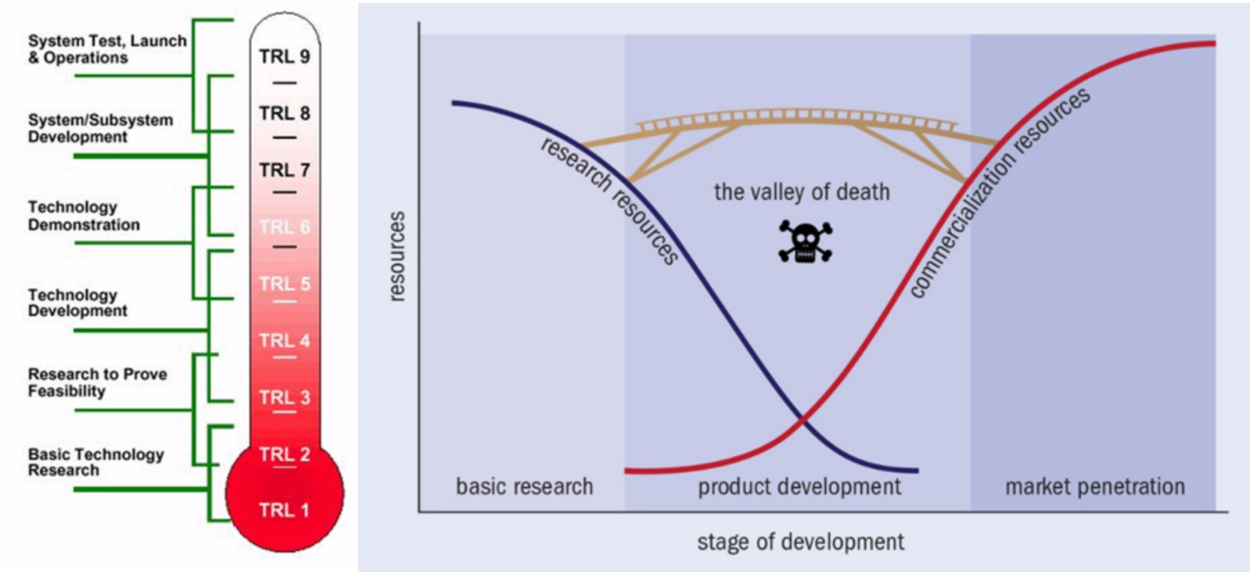


Figure 11:left: description of TRL levels; Right: Valley of Death in product development

3.1.1.2 A1.3 IDEA GENERATION AND CONCEPT DEVELOPMENT

Ideas for innovative clamping concepts relevant for the use cases were generated. In two sessions with the technical specialists at least five innovative clamping concepts were considered and ranked with regard to the requirements. The most promising clamping principle will be selected for further development.

Several workshops and brainstorms have been held to generate ideas.

- 8 June 2017: TNO brainstorm (minutes Notulen_brainstorm_TNO_8-6-2017.docx)
- 22 June 2017: brainstorm TNO met Hittech (TNO2017_06_22__3DFPP_brainstorm_TNO_notulen.pptx)

Picture of brainstorm session between TNO and Hittech is illustrated in figure 12.

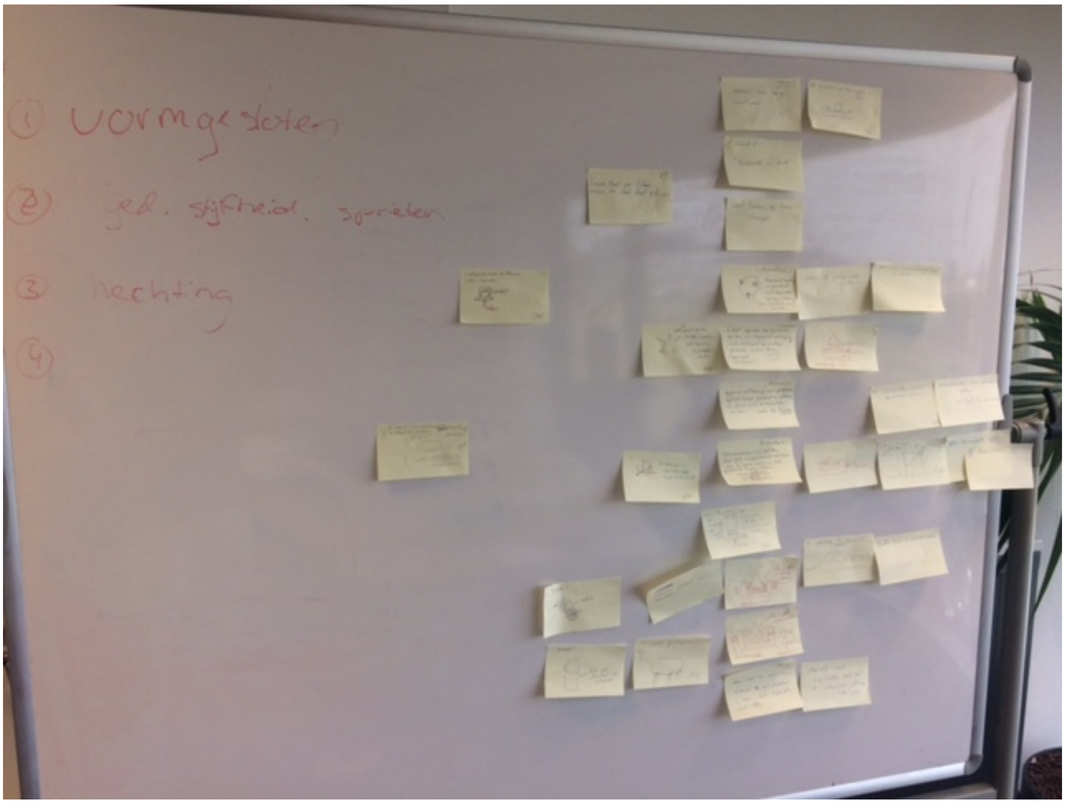


Figure 12: brainstorm session TNO/Hittech

A lot of clamping concepts have been generated. These will be discussed in this chapter. To come to the most promising concept directions a concept trade-off is done via a trade-off table.

Via the system engineering approach was learned how to put the clamping challenge into perspective and what the relevant success factors are. These resulted in below criteria.

Main selection criteria for concepts are:

- Work preparation time, diversified in
    - set-up time on machine (recurring clamping cost in production) - time needed to clamp/unclamp
    - dedicated work preparation for product (non-recurring-engineering cost)
- Production cost (TCOO-Total Cost Of Ownership)
- Number of (re)clamping
- Ease of use and required expertise level of operator
- Clamping stability
    - Stiffness given post-processing forces / sensitivity for chatter (resonances)
    - Temperature behaviour (CTE-effect/shrink/tempering). CTE (Coefficient of Thermal Expansion)
    - Intrinsic stiffness of the product itself (as global structure, but also on local areas where thin walls are present)
- Positioning accuracy and reproducibility of workpiece
- Zeroing
    - Reproducible Interface available
    - Time required to measure/allocate product with respect to 0-reference of machine (via CMM-sensor or via 3D scanner (Argon)
- Accessibility of machining (milling tools) and measurement tools (probe touching for measurement)
- Level of automation
    - (robot) Handling interface available?
    - Implementable in CAD/CAM flow (for example new design for post-processing rules adding clamping functionality to product – like Magics does for print supports)
- Modifications to product required? Do they remain after PP and are these allowed?
- Does solution fit to an existing standard interface?
- How flexible and universal is the solution

With respect to stability it is important to have the right bandwidth of required clamp stiffness. Looking to the required machining/finishing requirements of the user cases, we see tolerances of up to 5µm on the product drawings. Together with Kistler an investigation has been done to determine typical post-processing forces [RD05]. These are in the range of 50-150N for a finishing cut of 1mm (as stock). This results in stiffness requirements of at least 10^6N/m. When assuming:

- 100 N post-processing force, end accuracy 1 µm → 10^8N/m stiffness is required (extreme high)
- 10 N post-processing force, end accuracy 10 µm → 10^6N/m stiffness is required

Heat generation in the product due to post processing is considered limited since, heat dissipation is done via the chips that come of the product. Next to this cooling water is applied during processing.

3.1.2 Clamping concepts.

Main Categories:

- Baseplate modifications
- Printing additional interface (handle, frame, struts)
- Liquid to solid (phase change fluidic-solid, glue, ice, …)
- Soft clamp
- Conventional/others = state-of-art

3.1.2.1 Base plate modifications

Since an AM product is printed on a metal build plate, already an interface structure is provided to the product via this base. For the first clamping step (typically applied for 5-axis milling) the product could stay on the baseplate, and the baseplate could be used as clamping interface (Figure 13). Via wire EDM the baseplate can be cut in parts and divided in multiple bases for products with accurate clamping interface (wire EDM is accurate up to micron level).

- wireEDM is already used to cut printed products from the base/build-plate, so infrastructure is already there (no additional investments needed)
- wireEDM will now be done perpendicular to this cut direction
- Most metal build plates are scrapped after production (no big value in these plates, only for special materials)
- According 3T no remaining stresses in product after heat treatment

The product can be clamped onto an existing clamping system (as used for conventional machining) and handled by a robot to the next processing station. So-called quick-exchange pallet system (and provided by suppliers like Erowa and Schunk).

Alternative is to print directly on a Erowa-like interface plate (figure 14, 15).

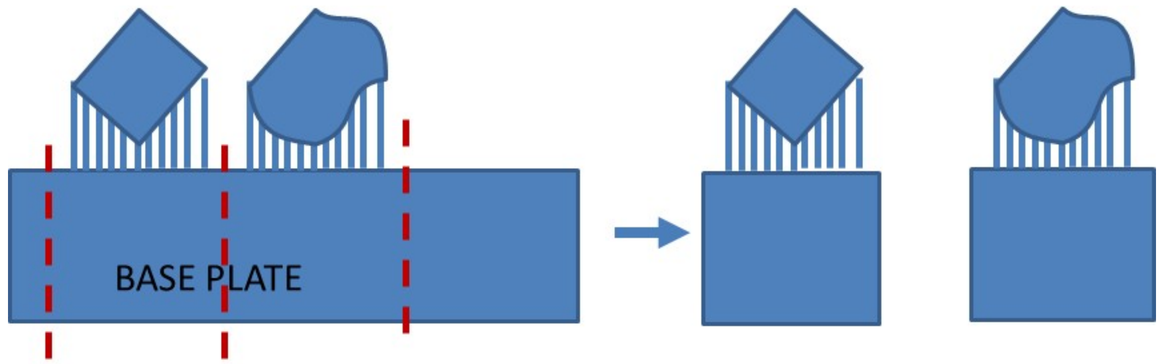


Figure 13: wire EDM of baseplates

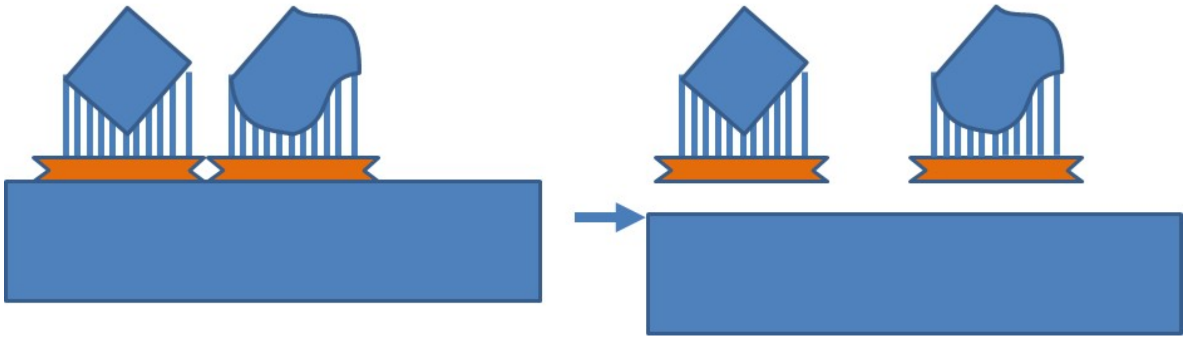


Figure 14: variation on baseplate concept / printing on standard (Erowa/Schunk/xx) clamp plate

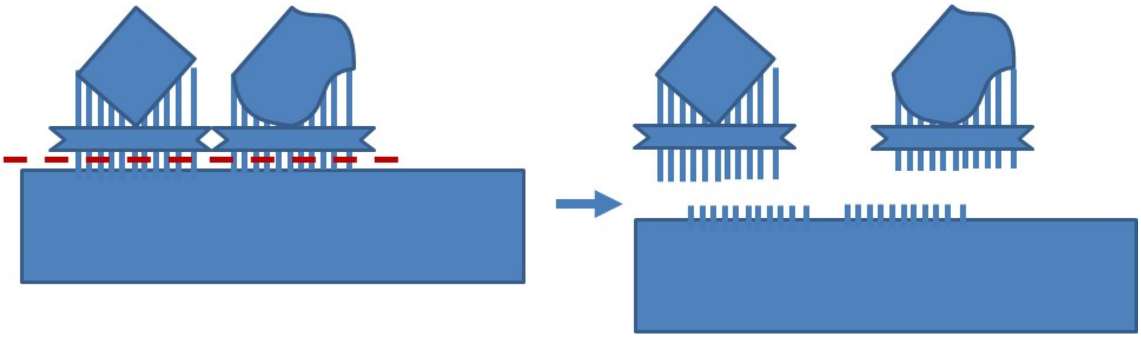


Figure 15: print a regular clamping interface

Challenge here is to combine design for printing and design for post-processing design rules, given the required support structures. Furthermore the support structure should be designed such that it can deal with the post-processing forces. For example in the Hittech user case the product is built under 45 degree angle for manufacturability aspects of 3DP (Figure 16), limiting the accessibility for machining the accurate holes on both sides of the product. Here it is difficult to find a compromise for both clamp positioning and build supports, which makes this solution less interesting. Maybe a certain part of the product portfolio has benefit of this method.

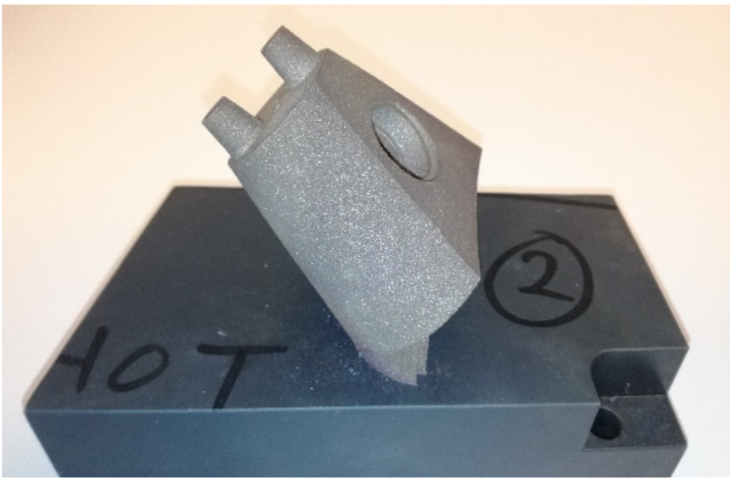


Figure 16: Hittech user case

3.1.2.2 PRINTING ADDITIONAL INTERFACES

This methodology is often used in automotive parts production, where casting products are post-processed (Figure 17). For example, see http://www.mgg.nl. Since SLM products have comparable characteristics as casting products (both are near-net-shape products/half-fabricates) these parts must go through comparable post-processing steps to get the product to required tolerance/finishing. However, these automotive parts are manufactured in mass production, which makes it affordable to spend NRE (Non Recurring Engineering cost) on these parts and design an optimized (and automated) clamping solution. Here design for post-processing is applied by adding interface points at non-critical locations (holes or 'ears' e.g. support lips) to a product that can be used as support points for (hydraulic) clamping and for automated handling (Figure 18). Those interfaces remain part of the product. Drilling a hole in a product is often not allowed, so a support is preferred.

Figure 17: example of automated automotive part processing (MGG)

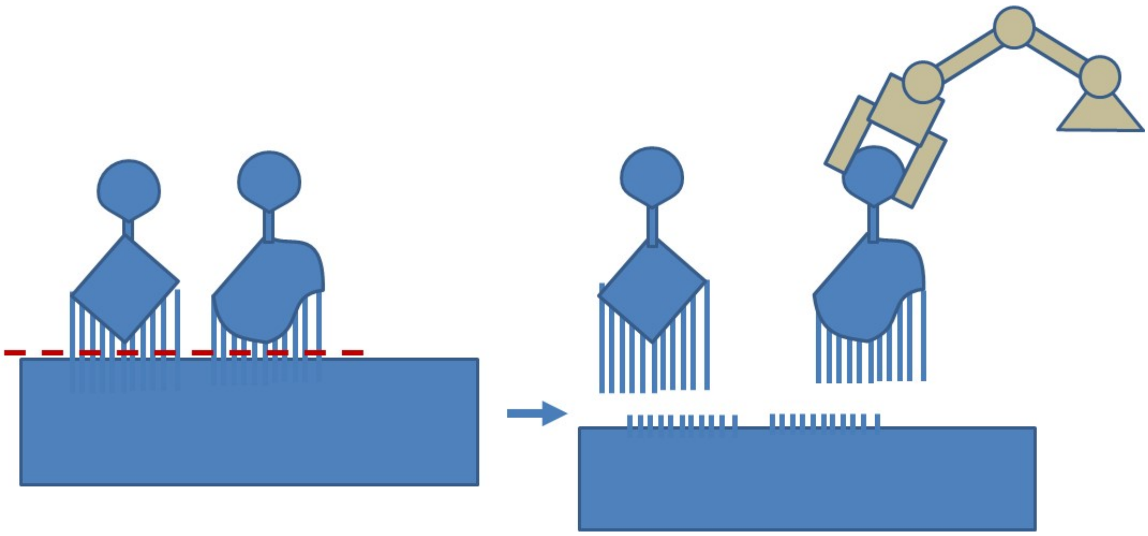


Figure 18: printing additional clamping and handling interface(s) to product

Also, modular clamping solutions are available at suppliers like Schunk (Figure 19) that have comparable characteristics as described here. Additionally, this set-up can be easily modified for other products and is not product specific.

The idea of adding universal interface point(s) to a to-be-printed structure is that via design rules for post-processing the CAD-file will be modified automatically, like is done for adding support structures for printing via magics, and a modular clamping interface can be used to support the product during post-processing.

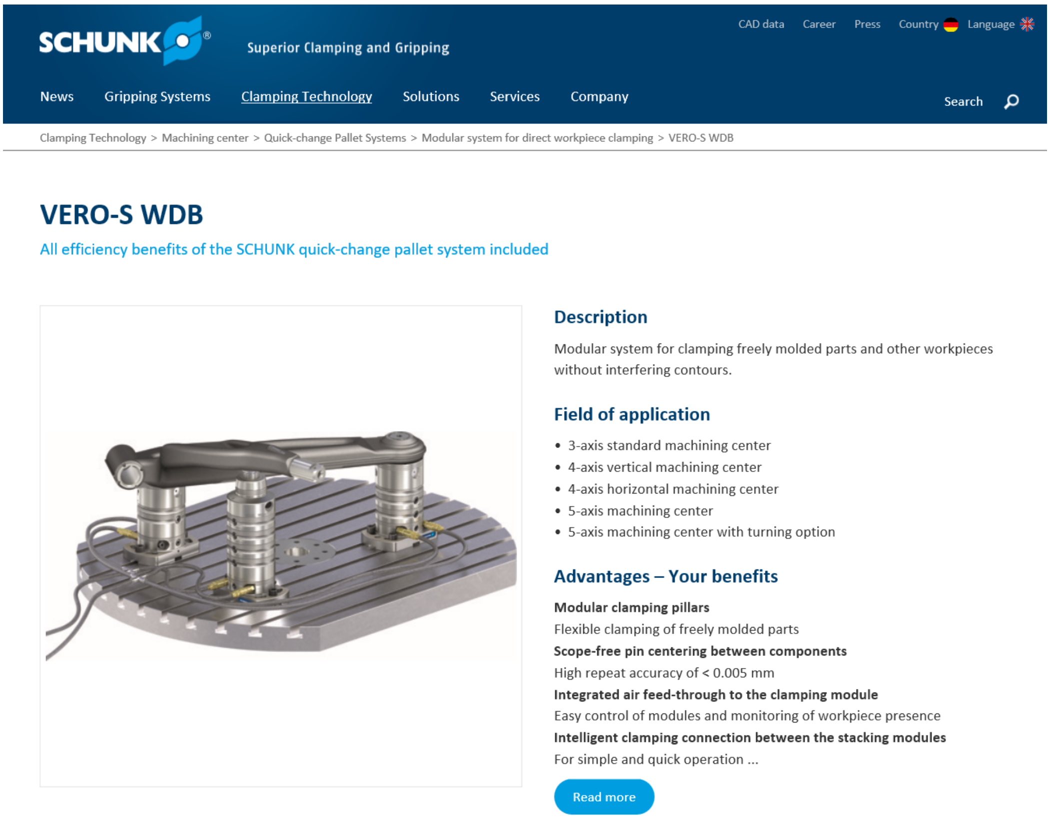


Figure 19: Schunk modular clamping system

3.1.2.3 Flexible fixation via adhesion/phase transition (liquid to solid and vice versa)

When a substance can be activated/cured by temperature, UV, etc to change its state from liquid to solid a product can be clamped in a fixture.

To remove a product from its fixture, the substance should become liquid again or alternatively be easily removable (mechanically, chemically, ultrasonic, …)

Several materials have been researched to look for the right properties and implementation aspects. Materials considered are:

- glue
- metal (with low melting point, phase transition)
- polymers (with phase transition)

Heating or cooling are often required to change the state of the substance. This temperature impact could affect the geometry of the to-be-clamped product due to thermal expansion/shrink, change of microstructure in product, stress release, etc. When this temperature impact could only be local this effect could be minimal/neglectable. In case of a clamping interface on multiple points (at least 3) this might be a good compromise. However, in this case it requires a product that has sufficient intrinsic stiffness to resist the post-processing forces and have almost no deflection. When supporting a product on 3 points (as expressed in Figure 19– Schunk flexible clamp) there is a lot of product overhang, without clamping support. Here also chatter is a risk (product resonance due to machining forces) causing machining tracks/roughness on the product making final surface finishing more difficult. Benefit however is the easy access to the product.

Several solution directions have been generated:

- Weiguss – liquid metal
- Hotmelt
- Ice
- Silly putty
- Gypsum
- Magneto rheologic fluid

By 'freezing' the product to a clamp/base plate a flexible clamp solution is obtained. However often a flat interface plane is required, where the gap between and adhesive/liquid should be kept to a minimum (Figure 20), since stiffness of adhesives are often significantly lower.

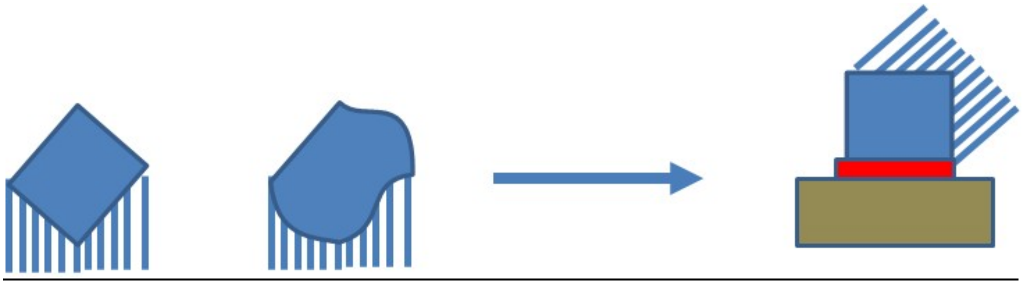


Figure 20: flexible fixation via adhesive

<u>Liquid metal</u>

Alternative for polymer-like adhesives is liquid metal (Figure 21). Weiguss has a liquid clamping alloy that melts at 70 °C (becomes liquid in hot water). This strategy can be seen in this movie: https://www.youtube.com/watch?v=G1st-VELn4E.

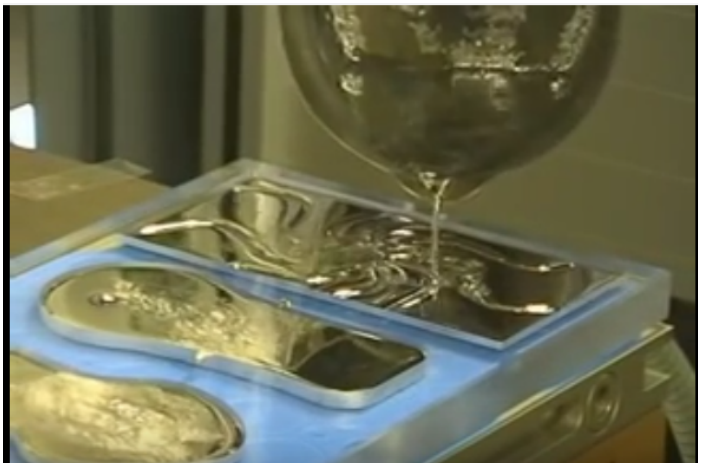


Figure 21: Weiguss liquid metal as clamping alloy

However, these materials are very expensive (few hundred euro per kg) and contain hazardous substances for health and environment. The advantage is that the materials can be used multiple times.

In liquid metals different alloys are available, with different melting points and additives. Base material is bismuth, with additives like Cadmium or Lead.

Hot melt (pool)

Alternative is to apply fillers (glass, carbon fibre, etc) in the adhesive to increase stiffness. In that way the soft clamp structure might be replaced completely by adhesive and only a 'bucket' as baseplate is necessary to clamp a product structure. This bucket can be filled around the (bottom part) of the product. The adhesive substance should then at least have comparable properties as Aluminium, which is currently applied as soft clamp material. It is called soft clamp since the stiffness of Aluminium is typically lower than the to-be-clamped product. When the clamp is closed mainly (small) deformations will occur in the soft clamp and the product itself is not damaged/deformed.

Possibly can be anticipated on these challenges with a hotmelt system, with or without fillers. Several hotmelts have been explored:

- Hotmelt 1
- Hotmelt 2
- etc

These will be tested for their mechanical properties and behaviour under load conditions in an experimental set-up – see output document O1.1. Hotmelt could be an interesting solution direction when the hotmelt is also easily removable after post processing.

Ice/freezing

(also described in state-of-art document)

This unusual method of work holding is suitable for irregular, fragile parts that are very difficult to grasp. Achieves clamping without part distortion by freezing the workpiece to the machine table in a few seconds, while a heating pump thaws the workpiece for quick removal. Ice requires a temperature below zero, freezing the product results in a delta T with respect to the machine environment and is expected to introduce an error due to expansion after post-processing. According to supplier (Spreitzer, AME) no product deformations are introduced and 150 N/cm2 hold force is feasible for parts up to 250x150mm.

Since only flat product interfaces can be clamped this technology has its limitations towards 3d printed products.

Silly Putty

Silly Putty is a toy based on silicone polymers that have unusual physical properties. It bounces, but it breaks when given a sharp blow, and it can also flow like a liquid. It contains a viscoelastic liquid silicone, a type of non-Newtonian fluid, which makes it act as a viscous liquid over a long time period but as an elastic solid over a short time period. Because of its adhesive characteristics, it is used in optical manufacturing to lap/grind – for example astronomical telescope mirrors. See https://www.photonics.com/Article.aspx?AID=52253 and https://wp.optics.arizona.edu/.../wp.../Anderson-and-Burge.doc https://www.tno.nl/en/focus-areas/industry/semiconductor-equipment/industrial-instrumentation/optics-manufacturing/

Gypsum

Is very flexible, but not seen as end solution given material properties.

Magneto rheologic fluid is a magnetically-sensitive fluid that temporarily stiffens when exposed to a magnetic field http://www.quilcedacarvers.com/0w769e3n/is It is a futuristic material and can obtain viscosities of a weak plastic.

3.1.2.4 Soft clamp

In case of a complex interface geometry a course soft clamp-like structure could be used in which a liquid/adhesive is applied as interface layer. This soft clamp structure is a negative of the to-be-clamped product geometry, however never exactly fits to the product, certainly at the first clamping step while the 3D-printed outer geometry is not very accurate. By this hybrid concept the tight properties (accuracy, roughness) required of the interface-layer can be overcome. See Figure 22. The applied adhesive material in the interface layer doesn't need a high E-modulus since the gap size is limited and will have a neglectable influence on total clamp stiffness.

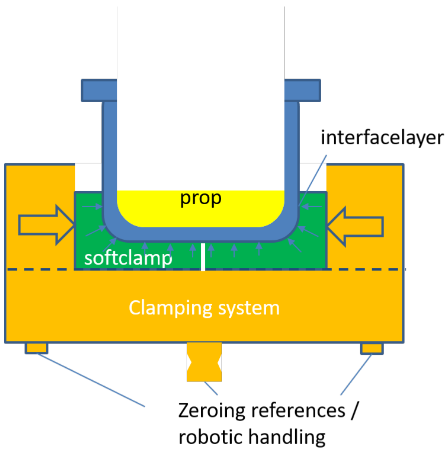


Figure 22: soft clamp geometry

Overlooking this strategy, several steps are required to come to a clamped product that require lead-time and (NRE)cost and therefore might be a solution for high-value products with very critical accuracy demands. On the other hand, this method doesn't require a very accurate clamp geometry and could be realized time&cost efficiently – here it might be interesting to print the negative clamp structure.

FDM clamp printing

Markforged is presenting their FDM-printer as a solution for printing soft clamps (as negative for freeform products), see Figure 23. This 3D-printer for tools can be put in production environment next to milling machine.

Claim Markforged:

- Cheaper than milled Aluminium soft clamps → 10x faster and cheaper
- Comparable stiffness as aluminium (carbon fiber added to nylon 12 increases stiffness 20x)

For more information about the Markforged proposition, see: https://markforged.com/case-study/the-mark-two-secures-a-firm-grip-in-robotic-automation/

Figure 23: nylon printed soft clamps (Markforged)

However, printing the required geometric accuracy of the soft clamp directly is considered as not feasible. Next to this the FDM printer prints a layer wise structure of nylon (PA12) in which carbonfiber is applied to increase the stiffness/strength. In-plane these properties will be OK, however in Z-direction there is no carbonfiber connection between layers, resulting in anisotropy. This makes the clamp weak when out-of-plane machining forces are applied to the to-be-post-processed product.

3-point fixation with UV resin/glue dots/laser welding

Here a 3-point clamping method could be an outcome, where the product is attached/glued to the 3 support points and hardened by UV-curing. Releasing the product can then be done by acetone (without leaving any marks on the product). The product is then supported on 3 studs/pillars (for example like shown in the Schunk figure). One could also think of laser welding a product to these 3 supports temporarily (only local heat is applied not deforming the product structure). However, the question remains whether a 3-point support is providing sufficient support stiffness given a (hollow lightweight) 3D printed structure with overhanging structures that need to be milled.

Defined stiffness/determined fixation

Idea is to have a smart support structure in product design enabling 6DOF determined fixation with known 'zero' in product. Based on the 'design construction principles' theory of M.P. Koster one could think of a product with additional printed wires to it that fix the product to a base (Figure 24).

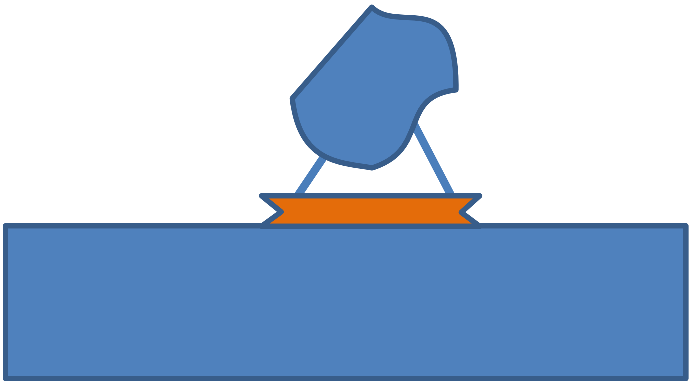


Figure 24: 6DOF determined fixation via 'wires'

Difficulty of this strategy is to design a structure that is printable (based on the design rules for printing), doesn't limit access of milling tools to the product and provides sufficient stiffness to the product (mainly at product locations far away from the wire positions where torque forces are highest). Therefore, this concept is not seen as most feasible.

In line with this one could also think of a 'wireframe' keeping all products together like used in manufacturing of toys (Figure 25). By injection moulding a frame with parts is manufactured that holds all products together. However here only in-plane stiffness is achieved, and products are very sensitive to out-of-plane forces.

Figure 25: toy frame concept

Electromagnetic clamping

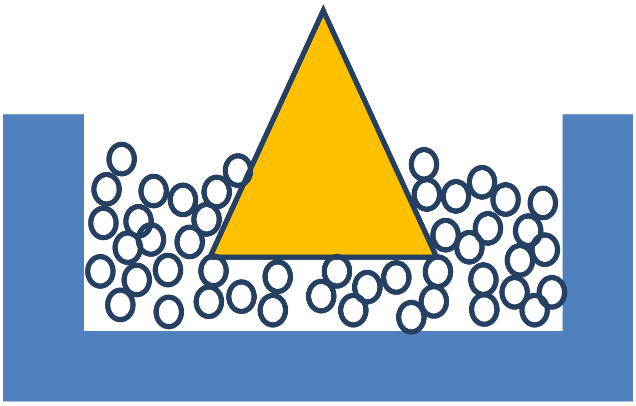


Figure 26: electromagnetic clamping

When applying balls instead of wires one could also clamp a structure (Figure 26). By applying an electromagnetic force (via coils) the balls could be attracted to the (blue) frame and enclose the (orange) product structure. This looks like a method sometimes used for positioning a product, where a vacuum bag is applied filled with beads (Figure 27). Downside of this method is the achievable stiffness.

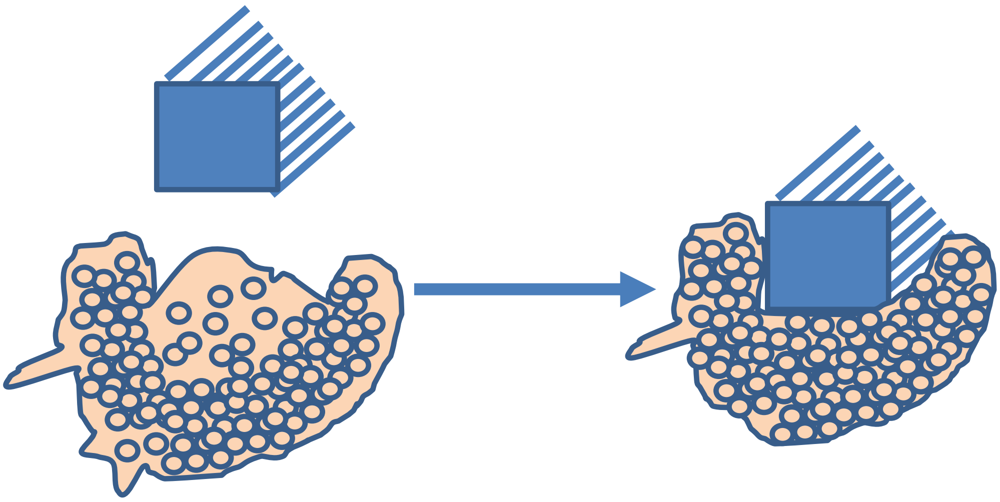


Figure 27: vacuum bag with beads

Spring nest

Another way of defined clamping of a structure is the so-called 'spring-nest' also from the design principles of M.P. Koster. This is illustrated in Figure 28.

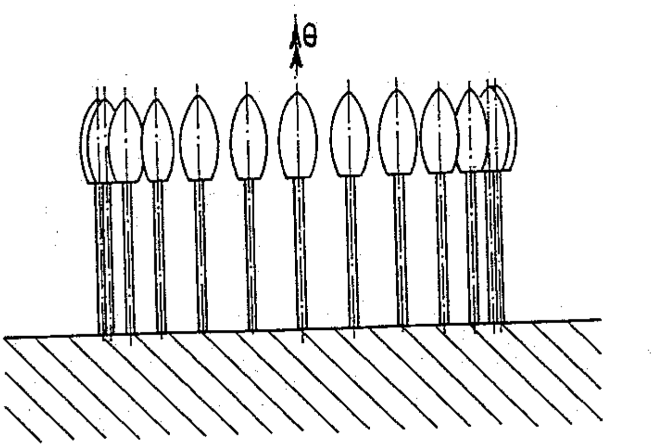


Figure 28: spring nest

This method is for example used in accurately clamping and positioning of lenses. This inspired us to think about a design solution where pins could be positioned in a flexible way to a product, like shown in Figure 29.

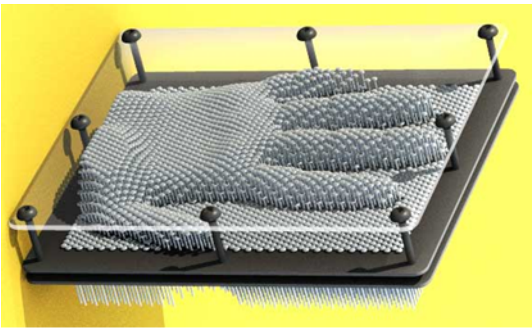


Figure 29: spring nest

Further research brought us to the company matrix innovations, who have a commercial product available delivering this functionality. The clamp principle is shown in Figure 30:

Figure 30: www.matrix-innovations.com

In this set-up each pin is spring loaded. When all these pins are released, via one central clamp, a product can be positioned between 2 clamping blocks (preferably on a bottom-plane/reference such that the product is supported in Z-direction) and the 2 clamping blocks can be shifted towards each other. When the product is touched each pin will shift in the clamp with a given pretension. Once the product is enclosed by sufficient pins, all pins can be blocked with the central clamp and the product is fully locked in position. In Figure 31 you can see a test result with an available demonstrator (with 6mm pins).

Figure 31: matrix clamp with (polymer) user case Hittech

On the website one can see several videos of their applications. It is also possible to configure a robot gripper with this clamp to transport products between processing stations.

3.1.3 CLAMPING CONCEPT TRADE-OFF

To select the most promising concept a concepts trade-off is done via a scoring table (Table 1: trade off table with clamping concepts., where concepts are scored against the main selection criteria.

Table 1: trade off table with clamping concepts.

	clamping stability	Clamp force	clamp time	declamp time	1st clamping	2nd clamping	clamping interface	tool accessebility	Environment	cost 30%	time 50%	remarks	total
baseplate modifications	5	5	5	1	5	1	3	3	5	3	3	1st clamping only	3.5
Printing extra interface													
Handle	3	3	5	4	5	4	3	4	5	3	3		3.8
Frame	3	3	5	4	5	3	3	3	5	3	3		3.6
struts	3	3	5	4	5	4	3	3	5	3	3		3.7
Liquid-solid													
liquid metal	4	4	4	4	5	5	4	4	2	4	4	commerial available	4.0
hot melt	?	?	5	4	5	5	3	4	2	5	5	fiber reinforced?	4.2
ice	3	3	5	5	5	5	2	3	2	3	3		3.5
cast	3	2	4	2	5	5	4	4	3	5	5		3.8
UV resin	4	4	5	1	4	4	4	4	5	3	4		3.8
softclamp													
clay afdruk	3	2	4	1	4	4	3	4	4	5	5		3.5
fill a thin gap	5	4	3	3	4	4	4	4	4	2	2		3.5
Bed of pins	4	4	5	5	4	4	5	3	5	4	4	commerial available/matrix	4.3
FDM print	4	4	2	3	5	5	3	4	3	2	2	fiber reinforced?	3.4
Press in a thermoplast	3	3	4	4	5	5	3	3	4	4	4		3.8
Other													
welding dots	4	4	4	3	5	3	4	3	4	4	4		3.8
UV curable glue dots	4	4	4	3	5	4	4	3	5	4	4		4.0

Based on this trade-off 3 main concepts follow from the evaluation.

1. Print additional clamping interface to product (Figure 32)
2. Liquid-solid (2-phase) interface (hotmelt, thermoplastic). (Figure 33)
3. Bed of pins (Figure 34)

The first concept is printing an additional interface(s) to the product to clamp/handle the product and is derived from automotive industry (post processing casting products). Big advantage here is that no additional tooling is required. The main question here is whether sufficient stiffness is available to support the product – possibly multiple interfaces are required to support the product properly. Also, the pins on the interface-block need to be dimensioned such that they are easily removable.

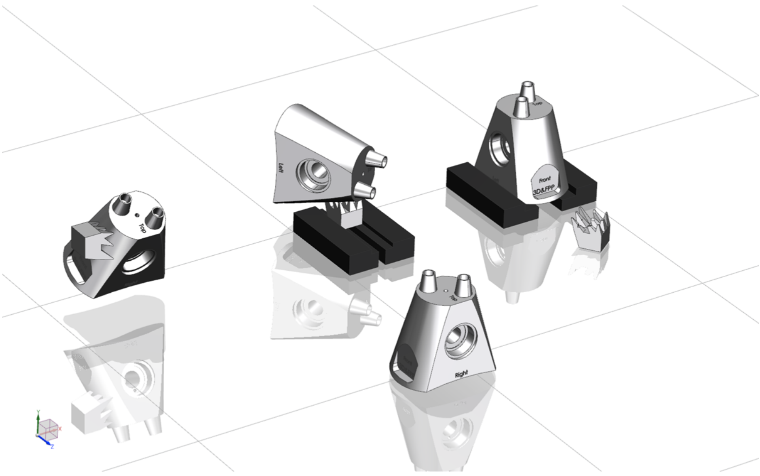


Figure 32: concept sketch of additional clamping interface.

The second concept is not really applied in industry and still has some question marks to be researched for feasibility, like stiffness, adhesion and removal after post-processing.

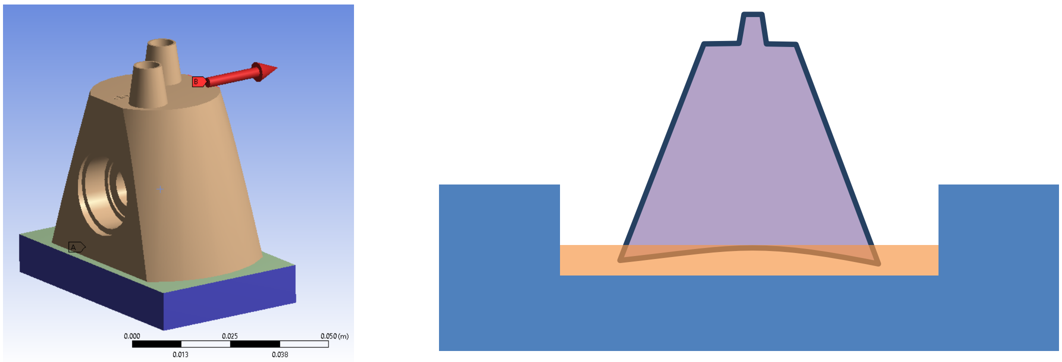


Figure 33: concept of object in a "bath" with Hotmelt

The 3rd concept has quite recently been introduced, but still not widely used in industry. According the supplier several (automotive) companies are performing trials to prove feasibility. To perform feasibility tests the right clamp configuration has be ordered (with pins of 3mm diameter).

Figure 34:object clamped in bed of pins. Clamp is from Matrix-innovations

The feasibility tests of these 3 concepts will be further described in output document O2.1.

3.1.4 Series size effect

Another dominant parameter that has not been part of the trade-off is the series size. The series size effect can be very substantial, since the relation between fixed and variable cost shifts. Depending on the series size of parts the break-even point can vary. To further explore this a sensitivity analysis has been done (Figure 35).

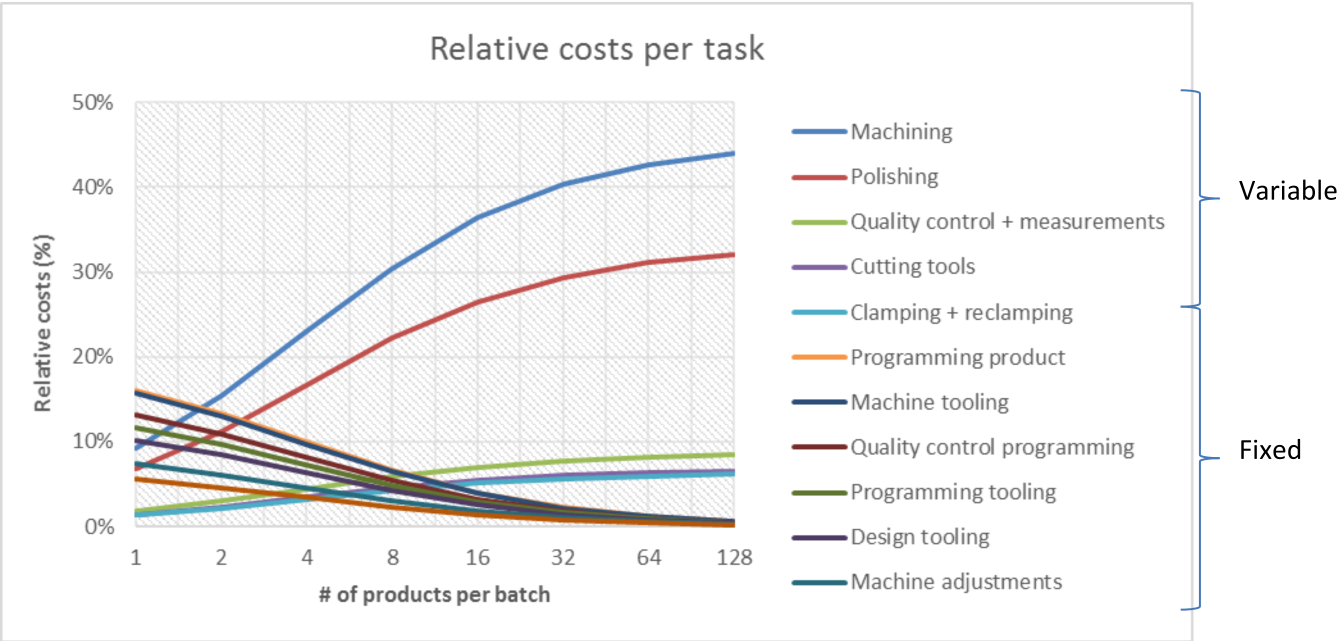


Figure 35: cost analysis as function of series size

Based on this analysis one can see the impact of series size.

- Batch size 1 : 20.4% variable cost; 79.6% fixed
- Batch size 16 : 80.4% variable cost; 19.6% fixed

This analysis is done based on the commercial information as described for the 4 user cases in document D1.2.1. Figure 36 gives an overview of the analysis result in numbers:

Specific relative cost per task per # of units per batch	Fixed/Variable	Task	1	2	4	8	16	32	64	128
	Variable costs	**Machining**	9%	15%	23%	30%	36%	40%	43%	44%
	Variable costs	**Polishing**	7%	11%	17%	22%	27%	29%	31%	32%
	Variable costs	**Quality control + measurements**	2%	3%	4%	6%	7%	8%	8%	8%
	Variable costs	**Cutting tools**	1%	2%	3%	5%	5%	6%	6%	7%
	Variable costs	**Clamping + reclamping**	1%	2%	3%	4%	5%	6%	6%	6%
	Fixed costs	**Programming product**	16%	13%	10%	7%	4%	2%	1%	1%
	Fixed costs	**Machine tooling**	16%	13%	10%	6%	4%	2%	1%	1%
	Fixed costs	**Quality control programming**	13%	11%	8%	5%	3%	2%	1%	0%
	Fixed costs	**Programming tooling**	12%	10%	7%	5%	3%	2%	1%	0%
	Fixed costs	**Design tooling**	10%	8%	6%	4%	2%	1%	1%	0%
	Fixed costs	**Machine adjustments**	7%	6%	5%	3%	2%	1%	1%	0%
	Fixed costs	**Material cost tooling**	6%	5%	3%	2%	1%	1%	0%	0%
		Fixed costs	*79.6%*	*66.1%*	*49.4%*	*32.8%*	*19.6%*	*10.9%*	*5.7%*	*3.0%*
		Variable costs	*20.4%*	*33.9%*	*50.6%*	*67.2%*	*80.4%*	*89.1%*	*94.3%*	*97.0%*
		Total costs	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Figure 36: cost breakdown

The smaller the series size, the more the need for a flexible clamping solution (low NRE). The higher the series size, the more room for design of product specific clamping solutions. In automotive casting products this is extremely the case where special automated clamp fixtures are designed for mass manufacturing/post-processing of products.

3.2 Scanning

3.2.1 Introduction

In the current post-process workflow 3D measurements are often used for the quality inspection of printed parts in between the process steps (e.g. before heat treatment or polishing) to evaluate the part deformations due to these post-processing activities and for the final dimensional quality inspection. However, the results of these measurements are always used in a reactive way, after the part has been produced and post-processed the final quality is checked. By integrating the 3D inspection in the process chain, one can use the feedback to actively finetune the post-processing activities to directly improve the quality of the end product. See also Figure 1: Process flow production and post-processing 3D printed parts.

After the 3D printing but before the post-processing the printed part can be digitized with a 3D measurement system to compare the geometry of the actual printed part with the CAD file to identify incorrect parts (final part can’t be made from actual printed geometry) and give feedback and input for the post-processing steps (e.g. the CNC milling process) how to mill the final form out of the printed form in the most economical way.

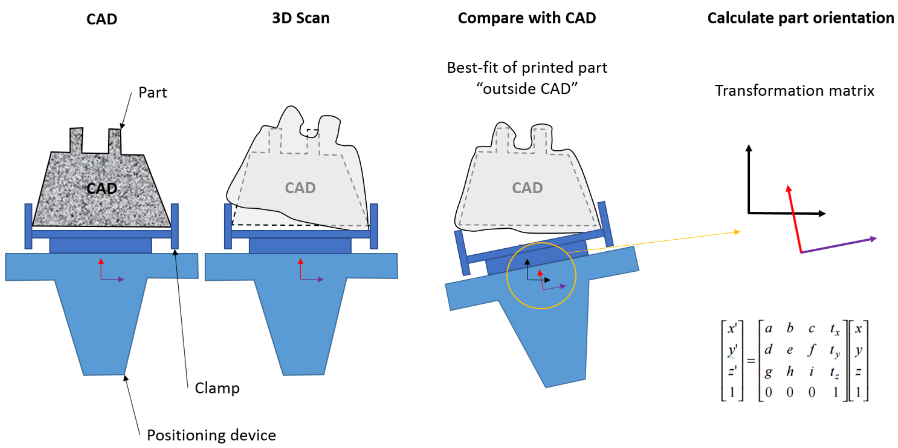


Figure 37: Schematic representation of feedback to CNC milling program

Different types of technologies are available to perform these 3D measurements and are described in detail in the D1.4.1 report [RD06]. After the preselection the following concepts were identified as the most promising and test measurements were performed.

- Structured light 3D scanning
- Laser triangulation 3D scanning
- Computed tomography 3D scanning

3.2.2 STRUCTURED LIGHT 3D SCANNING

The pattern is projected onto the part by a projector and a camera, offset slightly from the pattern projector, looks at the shape of the pattern and calculates the distance of every point in the field of view. By using the trigonometric triangulation method, the distance from the sensors to the light source is known and the complete 3D shape of the surface can be calculated.

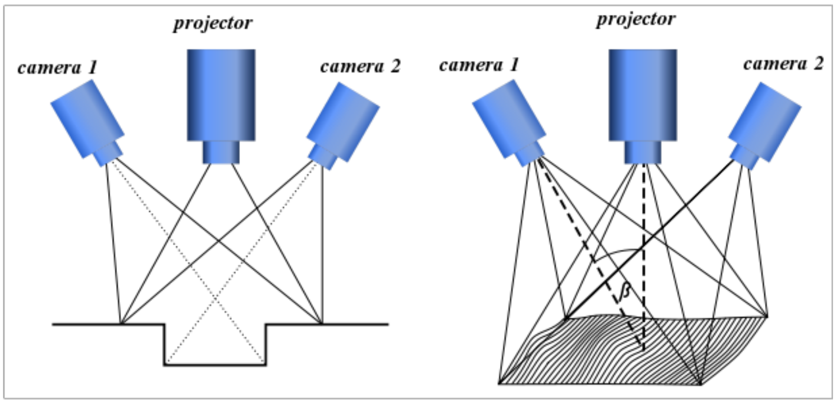


Figure 38: Field of view of structured light 3D scanner with pattern projection

Due to the large field of view (ranging from 60 mm to 2 m) of the cameras, entire faces of the printed parts can be scanned from 1 position resulting in fast measurement cycles.

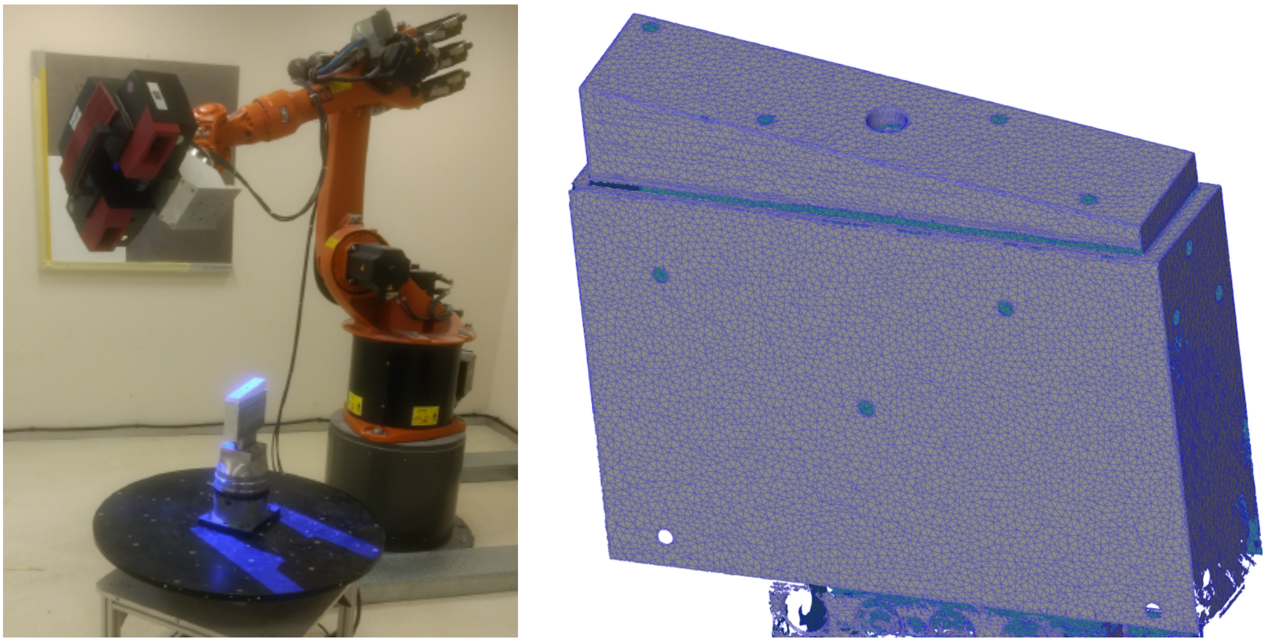


Figure 39: Example of a structured light scanner in an automated robot cell and the resulting 3D mesh of the part

3.2.3 Laser triangulation 3D scanning

This technology uses the same setup as the structured light scanning with a light source, a camera and the triangulation methods to calculate the 3D surface of a part but it uses a laser source instead of a light projector. To speed up the measurement process often a laser line is used instead of a single point.

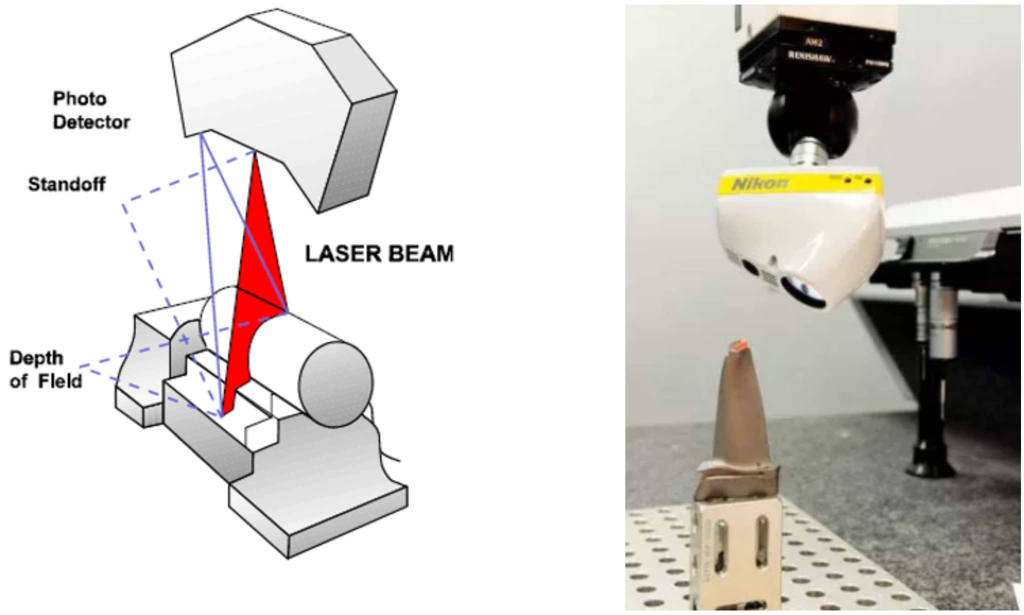


Figure 40: Example of a laser line scanner

The laser line is better suited for the digitizing of highly reflective surfaces but due to the specific standoff and depth of field some part areas (pockets, sharp corners, …) will be difficult to capture and part specific measurement programs will be required to achieve the required measurement results.

3.2.4 Computed tomography 3D scanning

3D printed parts often have complex 3D shapes with internal structures that are nearly impossible to measure with the conventional 3D scanning techniques. The industrial CT scanning systems use irradiation (usually with x-rays) to produce three-dimensional representations of the scanned object both externally and internally. However, to achieve the best scanning results a large set of scanning parameters must be defined specifically for each part (material, geometry and orientation) making it a very difficult process for automation.

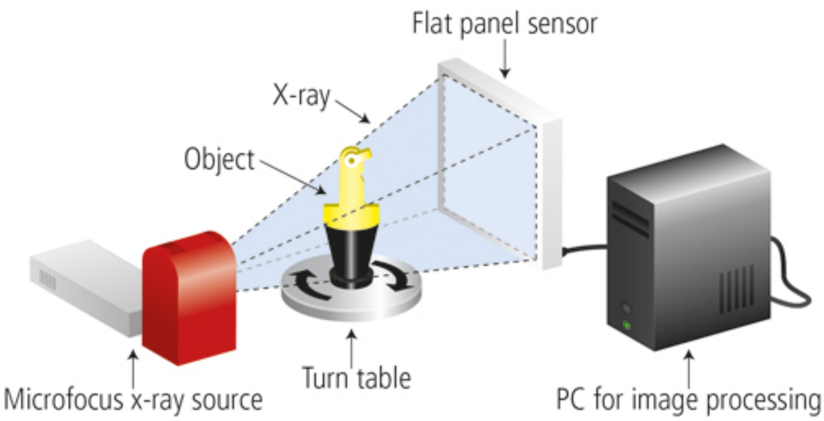


Figure 41: Concept of CT scanner

3.2.5 Technology trade-off

The application for 3D printing has a big influence on the scoring charts of the technologies. For one off production the aspect of flexibility (setup time with human interaction) is more important than for series production where aspects of cycle time become more important. Therefore, the trade-off table has been split for these 2 applications. For the scoring a range 1-5 will be used, 5 being the best and 1 the worst scoring per criteria.

Table 2: technology trade-off for batch printing

Batch printing	3D Structured light	Laser line 3D scanning	CT scanning
Accuracy	4	4	3
Cycle time	4	4	3
Automation	5	5	4
Cost of technology	3	4	1
Internal measurements	1	1	5
Total	17	18	16

Table 3: technology trade-off for one off printing

One off printing	3D Structured light	Laser line 3D scanning	CT scanning
Accuracy	4	4	3
Cycle time	4	2	1
Automation	5	2	1
Cost of technology	3	4	1
Internal measurements	1	1	5
Total	17	13	11

3.3 Polishing

3.3.1 Introduction to Surface Quality and Polishing

Surface quality is described in many forms by different fields. In industrial design terms it is referred to as *Gloss* or *Haze*, in optical design polishing terms are standardized in the *ISO10110* norm, which defines the allowed imperfections. In the mould making industry it refers to both the *VDI34000* and the *SPI* standard for surface finishing.

However, in this report the focus is set on "generalized" surface definitions, most often quantized as roughness (Ra) and waviness (Wa) parameters given in micrometers. The usage of these parameters has been standardized in *ISO1302*.

3.3.1.1 Surface profile definitions

In general, a measured surface profile results in "raw profile" data. This data contains information about the geometry, the geometric tolerances, and the "primary profile" of the surface. This primary profile can be split up into the low-frequent "waviness profile" and high-frequent "roughness profile".

Unless otherwise stated, the split between roughness and waviness is dependent on the roughness upper limit cut-off value; this means that the lower the roughness, the lower the waviness threshold is. Regarding polishing, one can imagine that a large initial roughness (e.g. Ra=30[um]) can be polished to a very low roughness (e.g. Ra=0.01[um]) while maintaining the initial roughness, calling it "waviness" (Wa=30[um] in this example).

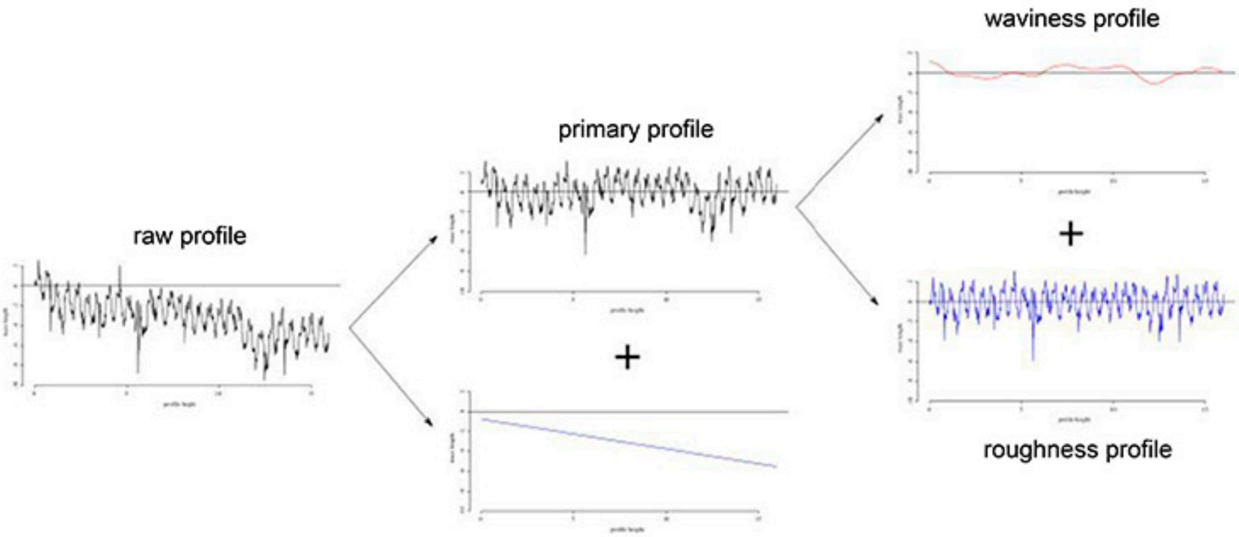


Figure 42- http://www.renishaw.com/cmmsupport/knowledgebase/en/surface-finish-measurement--22135

Figure 43 shows a close-up of a roughness profile. The Ra value is defined as the average deviation from the mean of the roughness profile.

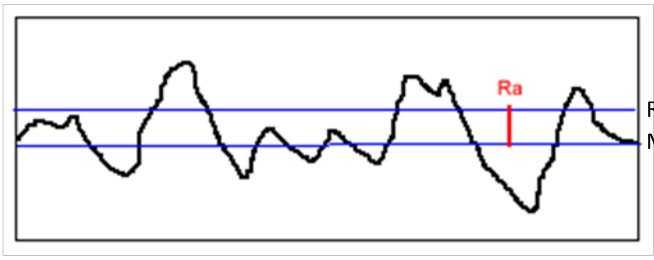


Figure 43 - Indication of Ra value and the mean of the roughness profile [Misumi]

3.3.1.2 General surface treatments

The surface of a product (primary profile / surface profile) can have varying requirements regarding roughness. To meet those requirements four general groups of roughness altering surface treatments can be defined, see below.

1. **Removal of material**
2. **Redistribution of material**
3. Adding of material
4. Conversion of material

All four groups of surface treatments can apply to either an entire surface, or macro/micro/nano geometry. The latter set comes with either masking or local application techniques.

Polishing techniques specifically are used only for the removal- and redistribution of materials in the roughness profile on the micrometer-scale, as shown in bold above.

3.3.1.3 Definition of polishing

Polishing is the process of *smoothening* the surface roughness profile such that certain *optical* or *functional properties* are obtained.

Smoothening can be by redistributing and/or removing surface material in the (sub)micrometer range. Optical properties can be e.g. aesthetics, translucence (lenses) or reflection (mirrors). Functional properties can be e.g. sliding properties, cleanability or improved strength of the product.

3.3.2 Surface Requirements

The surface requirements defined for polishing within the 3D&FPP project are based on various User Cases. These User Cases are subject to updates and can be found in the latest edition of the requirement document.

Currently the surface requirements are split into different categories: material, dimensions, interfaces, external geometry, internal geometry and the general surface profile.

Note that not all of these requirements need to apply to a single polishing technique.

ID	Category	Description	Value	Unit
Req.Pol.250	materials	corrosivity	-	-
Req.Pol.251	materials	metal	-	-
Req.Pol.252	dimensions	max dimensions	100	mm
Req.Pol.253	dimensions	min dimension	10	mm
Req.Pol.254	Interface	clamping	-	-
Req.Pol.255	External geometry	surface roughness Ra	0,1	um
Req.Pol.256	External geometry	Geometric tolerance (form)	0,2	mm
Req.Pol.257	External geometry	Geometric tolerance (position) refd. E.g. ABC	0,2	mm
Req.Pol.258	Internal geometry	surface roughness Ra	1,6	um
Req.Pol.259	Internal geometry	piping diameter	2	mm
Req.Pol.260	Internal geometry	Geometric tolerance (form)	0,2	mm
Req.Pol.261	Internal geometry	Geometric tolerance (position) refd. E.g. ABC	0,2	mm
Req.Pol.262	Surface profile	Cleanliness	-	-

Table 4 - Overview of requirements on polishing from [RD02]. The requirements are subject to change, check latest version.

3.3.3 Roughness 3D Printed Objects

The initial roughness of a 3D printed metal part varies as used within the 3D&FPP project depends largely on the build direction. And vary greatly too among producers of 3D printed objects.

- Stratasys [LS49] indicates approximately Ra=9[um] (~350 Ra uinch).
- Bell Air Finishing supply [LS50] indicates a roughness between Ra=2.5-26[um] (~100-1000 Ra uinch) within one part.
- 3T RPD Ltd. presented a more conservative estimate of Ra=20-30[um] intended for this research and their experience.

All producers emphasiz the respective values to be a very approximate estimation, dependent on the material, shape, orientation and angle of measurement and various other parameters. The spread of the roughness therefore gives an indication of the numerous challenges for 3D printing companies have today.

Note: Ra as defined by the mentioned producers are based on different definitions and are therefore hard to compare.

Regarding polishing the spread in roughness of the 3D printed objects presents a big challenge for the result of polishing is greatly dependent on the initial state of the surface.

Galvanic polishing for instance can to reduce the surface roughness by only 50%. Abrasive polishing would need to abrade down to the deepest surface valley, which is a time consuming and therefore expensive process.

As polishing is focused on local roughness, strict geometric tolerances can be lost for the waviness profile of the surface profile becomes undefined when excess polishing is to be applied.

Limiting the polishing action will therefore result in a smooth part with local remaining roughness. Hence, designing 3D printing parts with post processing in mind, i.e. polishing [LS50], the added cost and effort in either smoother printing or post-processing should be weighed.

An overview of available polishing techniques is presented in Figure 31. In the next sections more details on rating these techniques are given.

3.3.4 Rating Polishing Techniques

For a polishing technique to be interesting in the context of the 3D&FPP project, the technique should meet the following requirements:

- The technique must be able to process free-formed surfaces.
- The technique should be flexible i.e. varies forms should be able to be processed without extensive preparation measures.
- The technique should in some way be automated.

Within the 3D&FPP project the various polishing techniques were benchmarked against her respective T_p - value. This value expresses the repeatability of surface matter removals of the polish technique. (Ref. O2.1 Par. 3.3.1 for more detail).

The achievable T_p – value associated to the polishing process should be 0.4 mm or at least lie in that range. It is an advantage if the polishing treatment can be used for a broad range of materials, but at least the polishing techniques should be usable for the materials applied in the User Cases: mould steel 1.1730, Ti6Al4V and AISI 316L. Two other materials which are very common in the metal printing industry are Inconel718 and AlSi10Mg. The selected polishing processes should at least be able to process these 5 mentioned print materials.

For the purpose of rating the polishing techniques different initial surface categories are introduced. These surface categories are based on the requirements of the User Cases Per category some specific surface requirements should be met:

Category 1:
Starting from a initial surface roughness of Ra = 1,6 which is typical for milled products.

- A roughness of Ra= 0.4 um should at least be achievable.

Category 2:
Based on a initial surface roughness which is typical for 3D printed objects.

- A roughness of Ra = 6,4 should be attainable.
- Multiple surfaces or parts should be able to be processed at the same time.

Category 3: Base on the initial roughness of the internal geometry of 3D printed objects

- An channel should be polishable
- Starting from an un-processed printed surface, a roughness of 1.6 should be attainable.

Polishing techniques discussed in [RD02] that (potentially) fulfill these requirements are listed in table 2.

	Category 1	Category 2	Category 3
Brush honing	✓	✗	✗
Robot finishing	✓	✗	✗
Laser polishing	✓	✗	✗
Fluid jet	✓	✗	✗
Wet blasting	✓	✓	✗
Dry blasting	✓	✓	✗
Reverse drag finishing	✓	✓	✗
Barrel finishing	✓	✓	✗
Isotropic super finishing	✓	✓	✗
Plasma-electric polishing	✓	✓	✓
Chemical polishing	✓	✓	✓

Table 5 - An overview of polishing techniques that are suitable for category 1,2 or 3 types of cases.

3.3.4 CURRENT EMPLOYED POLISHING TECHNIQUES

Multiple companies merely indicate their post-processing steps in order to obtain better surface quality after 3D printing of metals. These companies indicated the following common polishing techniques used on 3D printed products, sometimes after processing such as CNC milling:

- Lapping (manual)
- Honing (manual)
- Dry blasting (Glass bead blasting) → roughness reduction to Ra=2.5-6[um]
- Barrel finish → roughness reduction to Ra=0.8-3.2[um]
- Electro polishing

The first four techniques in this list are most common. Logically, their main advantage is their universal approach to most products, regardless their material. Barrel finishing and dry blasting can be used on virtually any part without strict geometric tolerances. Lapping and honing present the best mirror like finish, where specialist craftsmen are able to process intricate, delicate and unique products. These techniques are however reproducible badly and therefore not suitable for the tightest geometric tolerances.

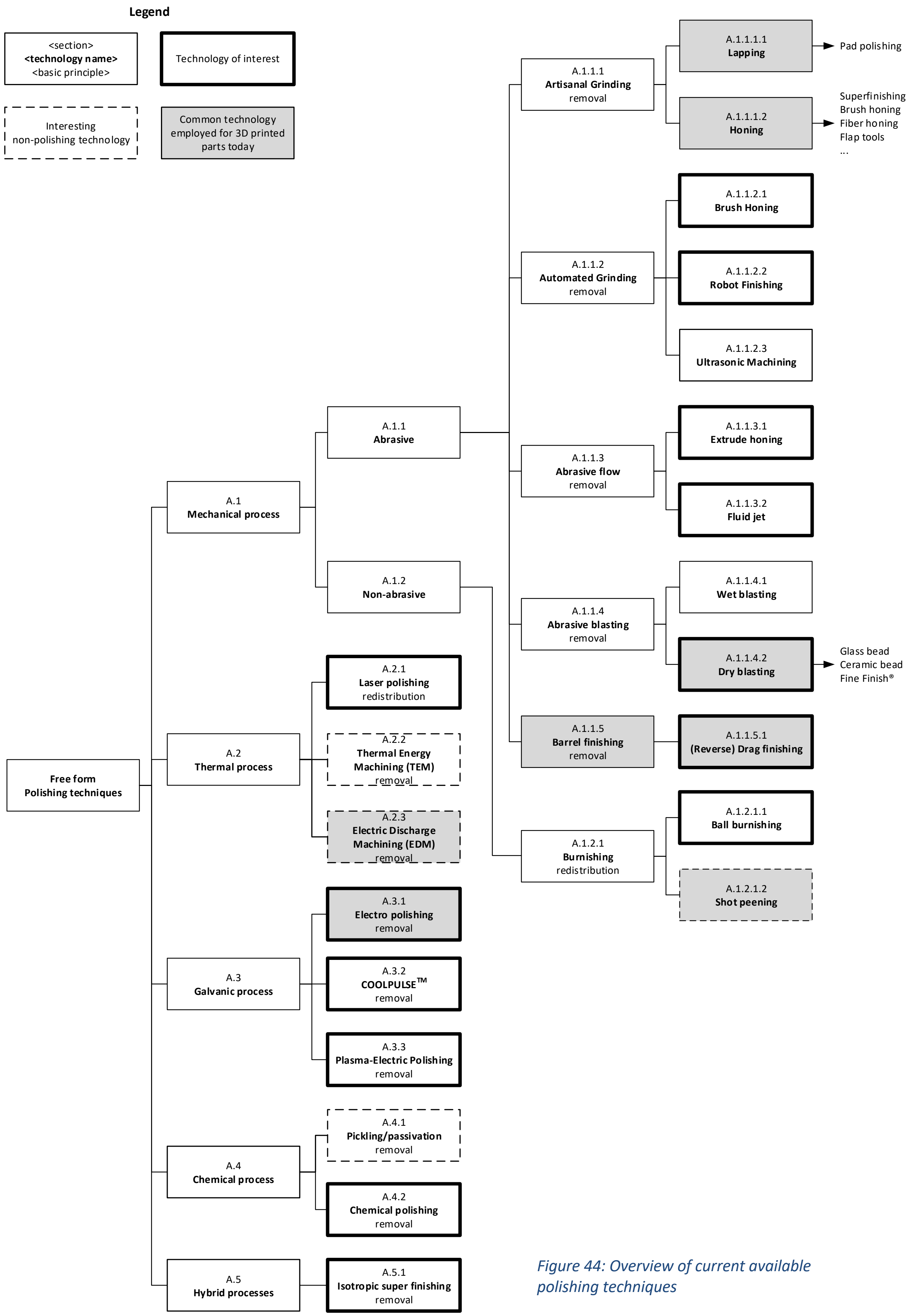


Figure 44: Overview of current available polishing techniques

Electropolishing and alike plasma-electric polishing are mostly equivalent to the first four technologies.

In contrast, the basic galvanic process is reproducible and because of this nature applicable for strict geometric tolerances when the design is iteratively adjusted based on the galvanic polishing result. This process however is limited to a maximum roughness reduction by a factor 2 and can therefore require initial processing by one or multiple of the alternative methods – incorporating their down sides such as non-reproducibility.

Please notice that the list of common polishing methods mentions abrasion/removal of material technologies exclusively, and also that it does not implement a technology which is able to process internal surfaces and/or piping, such as extrude honing and chemical polishing.

3.3.4.1.1 External geometry

All selected technologies are suitable for free formed external geometry. The large list of applicable technologies with a diverse fundamental background indicate difficult choice for an engineer, and the subtle differences between them. Out of all the technologies mentioned, most of them are able to create a surface roughness lower than Ra=0.8[um] – apparently this roughness value is safe to assume feasible. Their effect on geometric tolerances and general shape of the product will vary per technology and can be significant.

Three technologies are experts in external geometries – **Robotic finishing, Laser polishing and Fluid jet polishing** – which allow maintaining and/or creating of tight geometric tolerances. Notably these three technologies have closed the loop between integrated measuring and processing. The technologies are however recent and have not yet found their way into the general market.

Robotic finishing has been proposed and trials in 2013 seem promising though with limited action.

Laser polishing has recently been introduced – though deemed not profitable back in 2013 – and machines can be purchased from two manufacturers.

Fluid jet polishing has been around somewhat longer and is currently marketed as a free form lens polishing apparatus. Note that Laser polishing is the only technology where material is redistributed, not removed.

Barrel Finishing , which is a generic term for using small solid objects to polish a surface. A vibrating barrel is the most commonly used. Somewhat more expert barrel finishing types are: **Isotropic super finishing** is a semi-expert in external geometry. The method will preserve geometric features, though geometric tolerances will be affected by the material removal of over 50[um] on 3D printed parts. The process is however repeatable, allowing process tuning to achieve geometric tolerances.
Domeless round vibrator submerges objects in a bed of fine granula which through vibrations applied polishes the surface of the object.

The other technologies are less suitable for strict geometric shapes and tolerances. Out of these technologies we have **brush honing, extrude honing, (reverse) drag finishing, (plasma) electro polishing and chemical polishing** which are reproducible, allowing for process fine-tuning. Commonly these processes can be controllable within multiple micrometers on the larger geometries, whereas they will (significantly) round edges, indicating these methods are less suitable to thin features.

Dry blasting is a manual coarse processing step, with a removal rate depending on the crafts man. COOLPULSE^{TM} is dependent on the produced work piece (anode) and tools (cathodes) and how these are assembled. This method is therefore less suitable for work pieces with a defined geometric tolerance. Process parameters can have a large influence as well; e.g. the shape and location of the cathode in galvanic processes w.r.t. the work piece.

Ball burnishing is based on burnishing, which redistributes material over the surface. The main characteristic of this method is the peening effect; creating compression forces in the surface and allowing for improved fatigue properties. As a side effect the geometry is polished, and as such less documented, to a reflecting level.

3.3.4.1.2 Internal geometry /piping

In the list of *commonly* used additive-manufacturing polishing techniques no technique suitable for internal geometry is presented. The expert techniques which are able to process internal piping situations are **chemical polishing** and **extrude honing**. Both are reproducible and suitable to a variety of internal structures. Extrusion honing uses an input and output and polishes the flow path in between. Chemical polishing can be used identically and is suitable for blind holes. The obtainable roughness of chemical polishing is however unknown at the moment. Extrusion honing is applicable to a wider range of materials, as its basic principle is abrasion.

Generic inside geometry, such as a box with a small opening can be processed using chemical polishing, ball burnishing and isotropic super finishing – methods which effectively inserts the tool into the product. The same holds true for generic tumbling (barrel finish).

Simple internal geometry, such as the inside of a cup, can be processed by a wider range of techniques as more tools are able to enter the product. Brush honing, robot finishing, dry blasting and galvanic processing are suitable processes. Laser polishing can be suitable, depending on the focus distance and the depth of the 'cup'. When the cup becomes a free formed pipe with two large openings, (reverse) drag finishing becomes of interest.
Fluid jet polishing is mainly dependent on the length of the jet, similar to laser polishing. The documentation in the literature study however presented a short "jet length", making this method unrealistic for most internal geometries.

3.3.5 Observations

Most polishing techniques have to various extends an effect on the geometry shape and geometric tolerance.

Regarding external surfaces 3 polishing techniques are however able to maintain geometry shape within tolerance. These are Robotic Finishing, Laser Polishing and Fluid Jet polishing. These technologies use automated measurement and polishing to maintain geometry, in contrast to most other methods.

These techniques are not applicable to internal geometry. Internal requirements thus need to be relaxed regarding geometric tolerances. Expert processing of internal geometry and piping can be done using either chemical polishing or extrude honing. Extrude honing polishes the path of flow between input and output, whereas chemical polishing can be used for blind holes as well.

In terms of obtainable surface roughness a roughness lower than Ra=0.8[um] is viable w.r.t. the information found in the Literature study. The impact on other geometric tolerances is mostly dependent on the input state of the product as the polishing is generally not able to correct initial imperfections.

Laser polishing is most promising regarding the elimination of surface defects, as the surface is processed using a re-melt technique. This technique can be used in conjunction with other polishing techniques, where laser polishing would pre-process the material in order to eliminate the larger surface defects in the micrometer scale.

All polishing techniques are highly dependent on initial surface quality. The higher the ratio between initial roughness and requested roughness, polishing will be time consuming and most techniques available today will result in a loss of geometric tolerance or general shape. Main difficulty in this process is the initial surface quality, which varies strongly over a single printed part – resulting in either local remaining roughness, or local loss of geometry shape and tolerance using most polishing processes.

3.4 Selection of 3D&FPP polishing methods

As can be read in previous paragraphs there is no polishing process available which can be integrate to the 3D&FPP to fulfil all requirements. All techniques have their own advantages and off course, disadvantages. If just the reduction of roughness level as apolishing requirement of were compared, this would lead to a reduction to a view solutions. For only current polishing techniques can be compared. Whereas the near- and feature techniques as well as more diverse requirements such as flexibility, education level employee, automation level and investment has to be taken in to account within the 3D&FPP project.

When looking closely at the current state of art: present, near future and point at the horizon (future), polishing techniques the following techniques are selected as the most promising:

1. Domeless round vibrators (current state of art)
2. Robotic supported polishing (near feature)
3. Laser polishing (future)

The following table give a overview of the specific capabilities per selected polishing technique with respect to a number of key requirements. A rating is added per item. The averaged total end score (bottom) is the mutual relationship.

Category		Domeless round vibrator		Robotic supported polishing		Laser polish	
Capability		score		score		score	
	reduction of roughness	5	depending on time / abrasive. but in basis no constraints up to Ra 0,2um. Aspect ratio depending on level of material removal.	4	time consuming/separate tooling required. Aspect ratio depending on level of material removal	3	max aspect in order of 3 to 10 times / almost none removal due to local melting.
	complex geometries	5	interaction with all surfaces	3	difficult programming/ complex movement of tooling	4	difficult programming (automated in future, CAM)
	selective surfaces	2	only solution by covering surfaces	4	program requested surfaces	5	only program requested surfaces
	rounding of corners (undesired)	3	rounding corners due to abrasive depending on total removal of material (limited to 0,2mm)	4	selective/guided programming	5	selective programming
	deburring	4	proces parameter see above	5	programmable/ sanding / fast	3	programmable, because of re-melting results poor
	internal structures (eg. bore holes)	2	depending on stone size / les impact in blind holes	3	separate tooling required	1	laser beam must acces location
	geometrical stability of original part	2	depending on level of material removal	3	depending on removal. Active adjustment possible	5	almost no removal due to local melting
	processable materials	5	wide varity of materials possible	5	wide varity of materials possible	2	Poor results at number of materials. Eg. Aluminium in research stage.
	add functioniality	1	increase corrosion resistance by polishing	1	increase corrosion resistance by polishing	5	- surface structuring - engraving additional info - local hardening
Automation							
	level of automation	4	Not, but is autonomous process at itself.	5	fully integrated in 3D&FPP	5	fully integrated in 3D&FPP
	human intervention during process	2	black box	4	easily start and stop. direct view on process.	3	dangerous, covered in protective atmosphere?
	process optimizing during process	2	start stop only	5	automated in scanning cell	5	automated in scanning cell
	predictability	3	based on experimental numbers	4	depending on basic settings/ dependency of compliance	4	based on experiments / store experience settings/ alloy dependency
	complexity	4	few parameter settings/ lots of abrasives available	3	programming en setup fairly complicated	1	complex programming and process control
Time							
	programming	5	Almost zero	2	CAM or teach-in.	2	CAM programmable
	clamping	4	part must be connected to base plate	3	the parts must be connected to a stable carrier (with a known reference) forces + elastic def product.	4	the parts must be connected to a stable carrier (with a known reference)
	time of processing	3	Depending of used abrasive material but approx. 12 hours. More pieces per batch possible	4	Highly depending on used abrasive material.	2	due to a small spot size and power, time consuming
Costs							
	Investment hardware	4	20k	3	80k	1	200k
	education	5	low level education / quick operational	3	First programming by engineer (CAM). Teach in by technician	2	Programming by engineer (CAM)
	cost of employee (proto part)	4	moderate knowledge	2	expert	1	expert
	cost of employee (series)	3	moderate knowledge	5	fully automated	5	fully automated
Total (averige)		3,4		3,6		3,2	

Table ##. Comparison of the 3 different polishing techniques. Legend: 5 = excellent, ... , 1 = poor

3.4.1 CONCLUSION

After carefully weighin alle the polishing techniques, the respective ratings applied on the various techniques bases on the established requirements within the 3D&FPP project, the selected of polishing techiques for further testing are addressed in more detail below.

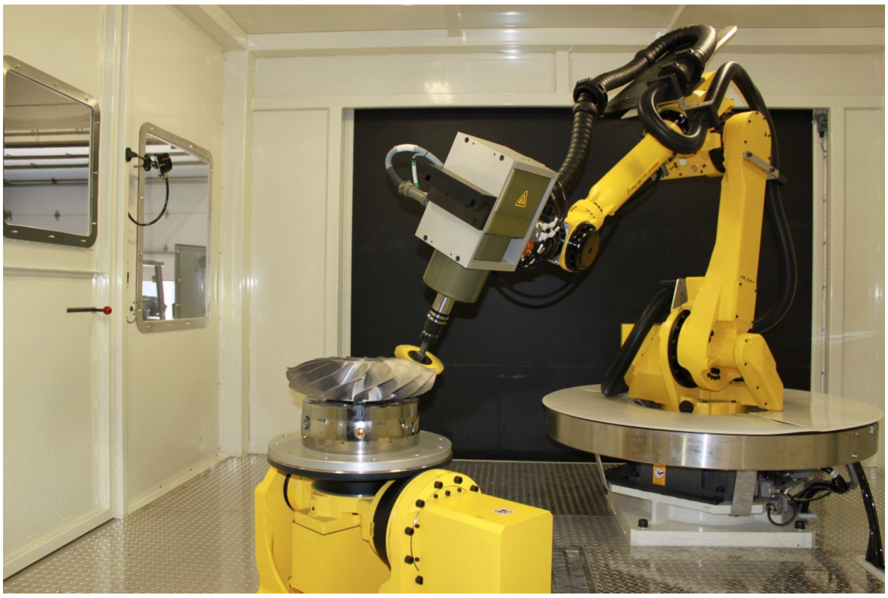
Domeless rotory vibration

[*Source: https://us.rosler.com/us-en/products/aerospace/domeless-round-vibrators/, 17/11/2017*]

When looking at the comparison table, this technique is easy to implement. It's an off the shelf solution, readily available. Therefore an field test is planned to invest the possibilities with this polishing techniques.

It's the current state of art and the most convenient way to reduce roughness.

Robotic supported polishing



[*Source: http://avr-aerospace.com/polishing/, 17/11/2017*]

Robot assisted polishing is a compromise between fully autonomous polishing and craftsmanship. Lessons learned in practice will be feed into a CAM program. Programming a robot is often a complex technical matter but the industrial robots and human interfaces are changing rapidly. Nowadays the first teach-in programmable robots are available which eases programming and tweaking a program dramatically.

In a few key words, robot assisting polishing:

- Is capable of targeting polishing
- has the possibility to automation
- requires a complex clamp
- needs complex programming time

However the results of robotized polishing are more or less predictable (because the copying capability), the automation bit of implementation of robot assisted polishing is very interesting for the 3D&FPP project.

Laser polishing

Laser polishing is expected to be in the start-up phase of its lifecycle. The expectations of laser assisted polishing are high, but nowadays far from direct implementation. Different large institutes and universities try to tackle the current large drawbacks, and is progressing rapidly.

At a high level laser polishing can be summarized as given below.

Laser polishing:

- Requires very specific knowledge,
- Can run fully automated,
- Requires a complex clamp,
- Needs expert programming skills
- Can add future features

Due to the fact that automation and "adding future features" are possible, the process itself fits perfectly within the 3D&FPP project en will be investigated in more detail.

3.5 CAD-CAM Integration

3.5.1 Introduction/Scope

As an emerging advanced manufacturing method, Metal Additive Manufacturing (MAM) presents new challenges for the post-processing of printed parts while offers advantages for the fabrication of complex metal parts. Two of the most challengeable problems are how to ensure the printed part can be cut into the final expected shape and how to properly position the printed part onto a CNC machine to apply the design CAM strategies. Such problems may cause additional cost and time due to the failure of post-processing either because of the printed part without enough cutting allowance or the position of part is not correct.

The potential benefits by integrating many of separate techniques from design, printing, to post-processing into one CAD/CAM platform could be the improvement of success rate which will significantly save time and costs, reduction of manual work, and the shorting of whole production cycle. Currently, there are lots of commercial available CAD/CAM products already provide functions for the edit of CAD model, apply CAM strategies and generate NC code for CNC machine. However, regarding to the characters of MAM, some additional techniques, such as 3D scanning and design rules for post-processing, are needed to gain efficiency and reduce cost to drive this project. Based on the state of the art investigation and the objective of the 3D&FPP project, we would like to propose an integrated CAD/CAM solution as shown in Figure 45.

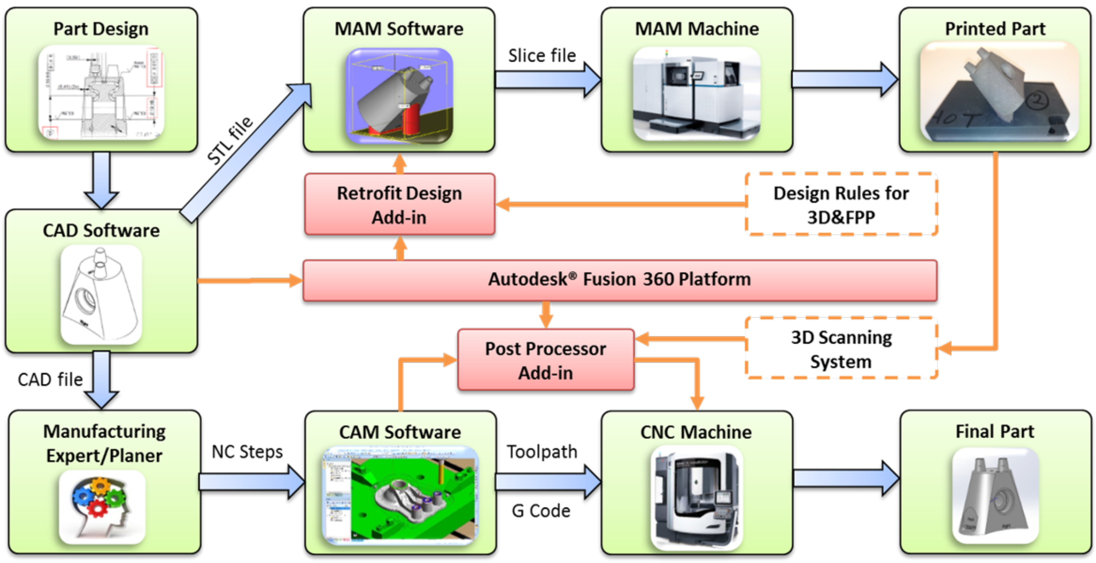


Figure 45: Integrated CAD/CAM solution for 3D&FPP

The two work flows, MAM and post-processing with CNC machine, will be integrated into one system by employing two innovative techniques:

- **Retrofit design based on design rules for 3D&FPP**
  Retrofit design of the original CAD model before printing will increase the success rate of post-processing printed parts with CNC machine by considering properly cutting allowance

on selected features. Also, it will facilitate the clamping as well as scanning procedures by considering additional reference features.

- **Customized CAM post-processor based on 3D scanning system and model comparison algorithm**
  A relative position relationship between the original CAD model and scanned 3D model (either for printed part after or before being clamped) can be achieved by comparing these two models. And then, the comparison result can be used to generate the NC code/function which will be written into the final NC code with a customized CAM post-processor. Alternatively, the comparison result can be used to position the stock model (scanned 3D model) and the target model (original CAD model) in CAM software before apply CAM strategies. By doing so, it will save significant time during the preparation of the CNC machining job by reducing the requirements for measurements.

3.5.2 CAD/CAM Integration Concepts

The integration of design rules for the retrofit design of original CAD model will be implemented before 3D printing by considering cutting allowance as well as the references for clamping and scanning. After that, the printed part should be scanned and properly positioned onto the CNC machine to make it ready for performing the NC code, in other word, the integration with CAM/CNC system. For the integration, it can be implemented through one of the two operations (concepts).

- **Integration with CAM**: import the scanned 3D model into CAM software as a stock and compare with the original CAD model to align the two models. Then the programme zero (workpiece zero) could be located on the stock model and the CAM strategies (tool paths) could be applied based on the original CAD model.
- **Integration with CNC:** the CAM strategies (tool paths) can be applied based on the original CAD model and a block stock before comparing with the scanned model. Then a translate matrix will be generated through comparing the scanned model with the original CAD model. After that, the tool path / NC code file could be modified by adding specific NC code/function to apply the tilting of work plane and the offset of workpiece coordinate system.

3.5.2.1 Concept one: Integration with CAM

A flow chart for the concept of integration with CAM system is shown in Figure 46: flow chart for the integration with CAM system.

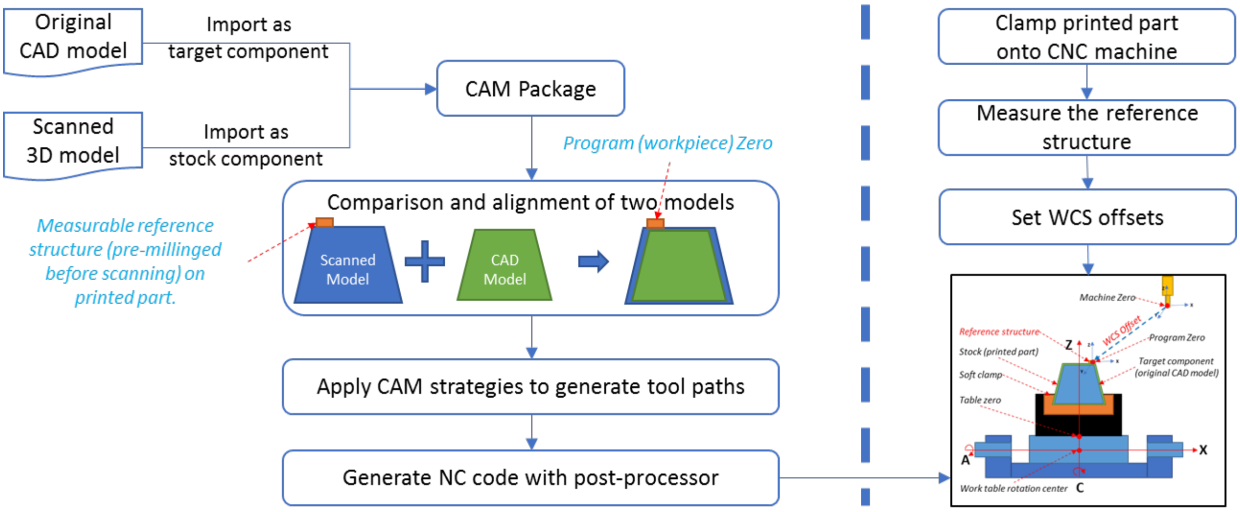


Figure 46: flow chart for the integration with CAM system

In this concept, the printed part (after removing the supports and heat treatment) will be scanned to generate a 3D mesh model (STL) which then will be imported into a CAM software work as the stock model. Also, the original CAD model will be imported into CAM software work as the target component. Before applying the CAM strategies, the original CAD model and the scanned 3D mesh model will be compared for alignment, and then, the program zero (workpiece zero) will be assigned on the stock model (scanned 3D mesh model).

It is important to note that, for this concept, the printed part needs to be measured after clamped onto the machine for setting of the WCS (Working Coordinate System) offsets. Therefore, to facilitate the setup of the machine, it is necessary to print a reference structure on the part. The reference structure could be pre-milled to make it measurable before 3D scanning. By doing so, the CAM programmer could locate the program zero (workpiece zero) on a surface (work plane) the pre-milled reference structure.

After setting of the program zero and work plane, the CAM programmer could apply CAM strategies with conventional methods to generate tool paths and convert the tool path into NC code with the post-processor for specified CNC machine.

On the other side, the printed part (with pre-milled reference structure) could be clamped onto the CNC machine. To set the WCS offsets, the CNC machine operator could measure the location of the program zero related to the machine zero with conventional CMMs (Coordinate Measuring Machine) devices such as a probe system. Finally, the operator could set the WCS offsets on the CNC machine to make it ready for performing the NC code generated with CAM software.

3.5.2.2 Concept two: Integration with CNC

A flow chart of the concept of integration with CNC system is shown in Figure 47.

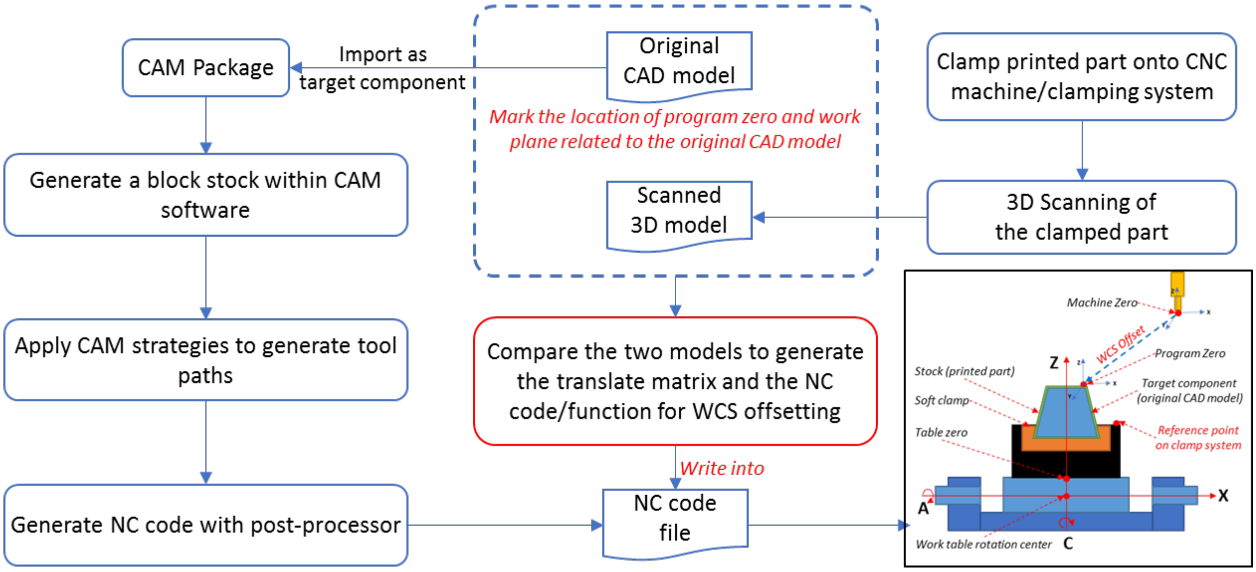


Figure 47: flow chart for the integration with CNC system

In this concept, the NC code can be generated with a CAM software package independently. The only input for the CAM software is the original CAD model. To apply CAM strategies, the CAM programmer could select a block stock automatic generated by the CAM software or design a fake stock model to assign a work plane and locate the program zero.

On the machine side, the printed part (after removing supports and heat treatment) could be either clamped onto an offline clamping system with standard interface to the CNC machine or directly clamped on to the CNC machine. And then, the clamped part can be 3D scanned to generate a 3D mesh model (STL) for the comparison with the original CAD model.

To generate a practical translate matrix, the work plane and the location of program zero related to the original CAD model used in CAM software have to be known before performing the model comparison. The purpose of model comparison is to align the original CAD model within the scanned 3D mesh model and generate a translate matrix between the coordinate system of the two models. Also, a reference point will be marked on the clamping system or the work table of the machine. By doing so, the relationship between the work plane assigned in CAM software and the surface of clamping system/machine's work table can be calculated to generate NC code/function for the tilting of the work table to make the work plane orthogonal to the cutting tool. After that, the position of the new program zero can be calculated based on the reference point marked on the work table or clamping system to generate the values for WCS offsetting.

Finally, the generated NC code/function for work table tilting and WCS offsetting will be written into the NC code generated with CAM software previously. And then the modified NC code file can be uploaded onto the CNC machine for the post-processing of the printed part.

3.5.3 CAD/CAM Concepts Trade off

To select the most promising concept, the pros and cons of the two concepts in time and cost saving are compared as shown in Table 6.

Table 6: CAD/CAM Concepts Trade Off

Concepts	Integration with CAM system	Integration with CNC system
Pros	• No specific requirement for clamping • No need to modify the NC code • Take the full advantages of commercial CAM software	• No additional structure needed to be printed • CAM programming can be independent • Model comparison can work as a universal tool for the generation of final NC code
Cons	• Additional reference structure need to be printed • CAM programming only can be start after printing and scanning • Measurement is needed during setup of the machine • Model comparison algorithm need to be integrated with different CAM system	• The location of program zero and work plane required to be input manually for model comparison • Reference point need to be marked on the clamping system or work table of the machine
Time factor	The total time of the production depends on the sum of printing time, support remove and heat treatment time, scanning time, CAM programming time, and machine setup time.	The total time of production depends on the sum of the longer of the printing time plus support remove & heat treatment time or the CAM programming time, the scanning & model comparison time, and the machine setup time.
Cost factor	Cost reduction depends on the total production time and success rate of post-processing compared with the traditional methods.	Cost reduction depends on the total production time and success rate of post-processing compared with the traditional methods.

According to the comparison of the two concepts, the second concept looks like to be better than the first concept due to the potential benefits it will deliver:

- The model comparison algorithm/method for NC code modification can be integrated with the 3D scanning system to develop a universal tool for automatically positioning of the printed part onto an offline clamping system or the work table of a machine;

- The reference point is located/marked on the surface of the clamping system/work table where the surface can be the reference of work plane. This will make it be universal for any printed parts.
- With this concept, the CAM programming can be earlier or synchronized with the printing procedure which will significantly reduce the total time of the production.

The feasibility test will be further described in output document O2.1.

4 Conclusion

This report concludes the initial phase of the 3D&FPP project. Focus during this initial phase has been identifying the 3D printing and post-processing production chain, as well as investigating the various techniques involved in the separate process steps.

It has been shown that in the opinion of the partners, the integrated post-process flow contains the following steps:

- Clamping the 3D printed product in a flexible manner;
- Scanning the printed product while it is clamped;
- Comparing the scanned data of the actual printed product with the desired end result of the customer, and;
- Converting the scanned data to be used in the subsequent milling and polishing steps.

Research on clamping has indicated several interesting technologies. These technologies have been scored on several aspects, and it has been shown that the following technologies look most promising:

- Printing of additional features which can be clamped;
- The use of Hot melt;
- The use of a bed of pens.

Some of these solutions are more suitable for a series product, while some excel for prototype products. The technologies will be further investigated and tested during the next phase.

Scanning of the product was initially regarded to serve 2 purposes: 1) inspect the orientation of the printed product with respect to the clamp, and 2) perform the final quality check. It has been found however that a quality check with the required resolution and accuracy is not feasible for stringent accuracy requirements with current state of the art scanning systems. Therefore, the focus has been on using scanning technology to define the orientation of the product with respect to the clamp, such that this info can be used in a later stage of the process to for instance re-orientate the CNC machine bed.

Investigation has shown that the following technologies look most promising for this purpose:

- Prototype / one-off: The use of a 3D Structured light system;
- Batch process: For the batch process a conclusive system could not be identified.

The 3D structured light system will be further tested and investigated during the following phase. Focus will be on aspects such as repeatability and accuracy, balanced with cost price.

Integrating the various fabrication steps showed several integration concepts:

- Integration with CAM;
- Integration with CNC.

These 2 concepts differ fundamentally, and both have pros and cons. Integration with the CNC system looks most promising for the 3D&FPP project and will be further investigated in the next phase.

Three polishing techniques have been identified which are suitable to be integrated in the new manufacturing flow. These are:

- Domeless vibratory polishing;
- Robotic supported polishing;
- Laser polishing.

The techniques differ in their suitability to be used either for prototypes / one-off products on the one hand, and a series product on the other hand. The techniques are subject to testing, resulting in O2.1. A clever way of integrating all the separated process steps results in a reduction of production time and costs.

Above mentioned concept solutions have been found with various concept generation techniques, literature studies and retrieving information from discussions with observers / market parties. The concepts have been scored with the aim to reduce production time with 50% production cost with 30% with respect to current manufacturing time and cost. Validation the reduction of time and costs will be part of the following phases of the project.

Based on this document and the feasibility test the most promising post processing process will be selected that will be further tested in the following phases of the project.

5 ANNEXES

5.1 LIST OF FIGURES

5.2 LIST OF TABLES