Die-Less Forming of Fiber-Reinforced Plastic Composites

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Abstract. Fiber-reinforced plastics (FRP) are increasingly popular in light weight applications such as aircraft manufacturing. However, most production processes of thin-walled FRP parts to date involve the use of expensive forming tools. This especially hinders cost-effective production of small series as well as individual parts and prototypes. In this paper, we develop new possible alternatives of highly automated and die-less production processes based on a short review of current approaches on flexible thin-walled FRP production. All proposed processes involve robot guided standard tools, similar to incremental sheet metal forming, for local forming of the base materials. These include woven glass fiber fabrics which are locally impregnated with thermoset resin and cured using UV-light, woven commingled yarns made out of glass fibers and thermoplastic fibers which are locally heated and pressed, as well as pre-consolidated thermoplastic organo sheets which require selective heating for forming. General applicability of the processes is investigated and validated in practical experiments.

Keywords: Automation · Composite · Die-less forming · Fiber-reinforced plastic · Incremental forming

1 Introduction

Due to their high structural strength-to-weight-ratio, fiber-reinforced plastics (FRP) are exceedingly popular in aircraft manufacturing, medical and other lightweight applications. Basic manufacturing steps of FRP are shaping of the structure, impregnation of reinforcement fibers with resin, consolidation and curing/solidification. While thermoset polymer matrices are cured through chemical crosslinking, thermoplastic polymers can be softened and reshaped with the aid of heat [1]. Most FRP-production processes such as injection molding or thermoforming rely on solid molding tools, whose design and fabrication is time-consuming and costly. As a consequence, these processes are not economical for prototyping and small batch production, which is in conflict with the general trends of higher variant diversity and increasing cost pressure. Therefore, a reduction of the tooling effort up to die-less forming would be beneficial [2, 3].

For metal sheets, incremental sheet forming (ISF) is a flexible and die-less process for the production of individual parts and small series. Simple forming tools, usually with

K.-Y. Kim et al. (Eds.): FAIM 2022, LNME, pp. 3–14, 2023.
https://doi.org/10.1007/978-3-031-18326-3_1

hemispherical tool ends or rotating balls, moved by CNC-machines or robots form the sheet. The workpiece is clamped by blank holders, so that the tools progressively introduce strains into the material. Different process variants include singe-point incremental forming (SPIF) with just one standard tool and double-sided incremental forming (DSIF) using two tools, one on each side of the sheet. Heat-assisted ISF has been demonstrated for the forming of thermoplastic sheets at research level [4, 5].

Due to the benefits of ISF, its application to FRP forming would be desirable. However, with high tensile strength and limited strain of the reinforcement fibers, deformation mechanisms of endless-FRP are significantly different to metal or pure thermoplastic sheets, and direct application of ISF is not possible [6, 7]. Instead, the main draping mechanisms of bending and shear of the fibers and the weave must be realized for forming. Thus, local deformation of the fabric in the current forming spot is only possible through fiber movement in adjacent regions of the weave. However, already generated final part geometries need to be maintained. Therefore, the development and evaluation of new processes for the die-less forming and production of FRP is focused in the joint research project iFish – incremental Fiber shaping.

The remainder of this paper is structured as follows: First, we review existing approaches on flexible and die-less forming of thin-walled, shell-shaped FRP components. Afterwards, we list requirements for die-less forming processes and conduct a functional analysis of material types and matching processing functions for a flexible production process similar to ISF. In basic experiments, we investigate the general applicability of the process ideas and discuss the results.

2 Related Work

Flexible forming can be classified into processes with rapid tooling, with flexible molds and without molds. Production of temporary molds for prototyping is often a manual process conducted by experts, although other rapid tooling processes such as additive manufacturing or the forming of metal molds by ISF have been used [7, 8].

A flexible molding method is multi-point forming, which uses a geometrically adjustable tool consisting of an array of pins whose lengths can be changed independently. Diaphragms can be used to smoothen the mold surface [9, 10]. For long endless-FRP parts with variable cross section, a patented concept describes the local forming of a pre-impregnated and consolidated solid thermoplastic FRP sheet (organo sheet) by heating the whole width but only a certain length of the sheet and subsequently forming the area in a modular press. As neighboring sections of the laminate are solid, strains are introduced and later released when the process is repeated in the respective sections [11]. Local curing of thermoset prepreg with pressure and heat was demonstrated by Cedeno-Campos et al. [12], however not forming the material.

Processes that do not require a mold at all include additive manufacturing. Extrusion-based processes such as Fused Deposition Modeling (FDM) have been used for FRP fabrication with short and long fibers, giving the possibility to arrange the fibers in the load path direction. However, several limitations prevent industrialization of fiber-3D-printing, including limited homogeneity and fiber volume content of the material, low productivity and challenging processing [3, 13]. Miller et al. [6] conceptualized and tested a flexible roll-forming process where thermoplastic FRP were passed through an array of individually controllable rollers, creating long, singly curved shapes with variable cross-section. Localized heating was accomplished by induction [14].

Few approaches were made to develop ISF-like processes for FRP production: Fiorotto et al. [7] applied a metal diaphragm and a nylon film to a woven thermoset prepreg via a vacuum bag in order to maintain the deformation during SPIF. Al-Obaidi et al. [15] sandwiched unidirectional basalt fiber laminates with polyamide matrix between aluminum sheets, globally heated them by hot air and applied conventional SPIF for forming using an additional steel sheet between the FRP-aluminum sandwich and the tool. The authors also used the same setup to form woven glass fibers with polyamide matrix sandwiched between metal sheets. Defects occurred, especially with higher wall angles [16]. A similar approach was made by Ambrogio et al. [17] who, however, only used short-fiber-reinforced polyamide and formed it together with an aluminum sheet by SPIF. Ikari et al. [18] used a round tool tip in an ISF-like setup to incrementally form short-fiber-reinforced organo sheets. Forming was conducted by successively moving the tool in x-y-direction, locally heating the thermoplastic by an infrared spot heater and pressing the tool onto the sheet to the target z-coordinate. Resulting shape accuracy and part quality need to be improved.

To conclude, no genuinely die-less process for the forming and production of doubly-curved, shell-shaped woven FRP without a metal sheet as support exists.

3 Process Analysis for Die-Less Forming

3.1 Materials

The aim of this project is to investigate and develop die-less forming and production of woven FRP without the use of metal support sheets. Woven fabric is targeted because of its high tailorable reinforcing effect as well as relatively good drapability [19]. As matrix material, thermoset as well as thermoplastic polymers are considered, which can be initially separate from the reinforcement fibers or already included in a semi-finished product. Separate matrix can either be initially liquid (thermoset) or solid (thermoplastic). Similarly, pre-impregnated fabrics are either formable (thermoset), semi-formable (thermoplastic semi-pregs, not considered here) or rigid (thermoplastic organo sheets) at room temperature. A special semi-finished and formable product are weaves of commingled yarns with reinforcement and thermoplastic fibers. Table 1 gives an overview of the described matrix materials and product types.

3.2 Requirements and Functional Analysis

The die-less forming processes shall make use of just two robot guided standard tools similar to DSIF, which form and solidify small areas of the FRP while moving along tool paths determined according to a forming strategy published elsewhere [20]. The paths follow the required fiber orientations from an already rigid starting point until the edge of the fabric. The forming sequence is based upon the required shear distribution as shear is the main draping mechanism for surfaces with double-curvature. Starting with

Table 1. Classification of matrix materials and product types

		Product type		
		Separate	Commingled	Pre-impregnated
Matrix material	Thermoset	A: liquid matrix		D: formable
	Thermoplastic	B: solid matrix	C: comm. weave with matrix fibers	E: pre-consolidated solid organo sheet

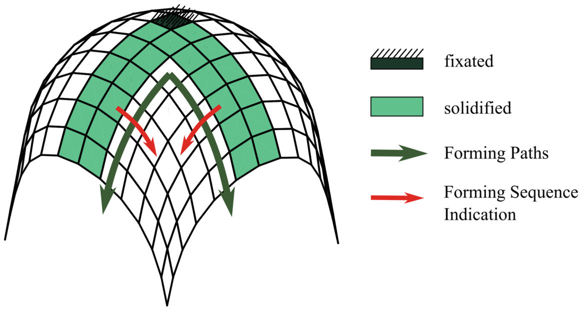

Fig. 1. Forming paths & forming sequence for a hemisphere

the forming paths requiring least shear, the desired geometry is formed and the FRP part produced adding a solidified path next to another, as indicated in Fig. 1.

Thus, depending on the materials used, the following functions must be fulfilled for forming and producing a FRP with just two robot guided standard tools:

1. Fixation of the fabric. According to the forming strategy, clamping of the fabric or laminate is primarily required in the starting point of the first forming paths, which is very likely in the midst of the fabric. For stability and realization of the clamping through mechanical elements, the FRP must be already cured/solidified in the starting point. Highly flexible dry fabrics (used in A & B in Table 1) require extra attention and possibly additional fixations on the edges in order to prevent unpredictable and undesirable draping before and during the forming process. A tacky pre-impregnated thermoset (D) could additionally stick onto itself when unwillingly folded. Thermoplastic fibers are usually less flexible than reinforcing fibers, so that commingled weaves (C) are more stable and less likely to deform extremely undesirably when fixated.

2. Acquiring formability of solid matrix material. Separate (B) or pre-consolidated (E) solid and non-deformable thermoplastic matrix materials need to be heated above melting temperature. This can be realized by multiple different heat sources including electrical resistance heating with contacting elements or heat guns, gas torches, infrared heating, laser light sources as well as ultrasonic elements or induction heating. Heating of separate matrix (B) is easier than of a flat or even already deformed organo sheet (E), especially when considering the need for targeted heating of a delimited area changing in size after each forming step. This is an essential basis for organo sheet forming without metal support sheets, as already formed areas need to be cold and solid while others need to be warm and drapable. While the first forming paths require heating of a major part of the sheet, areas to be heated are getting smaller during the process.

3. Local forming. For highest flexibility, two standard forming tools, one on each side of the fabric, should be guided by two individual industrial robots in a setup similar to the concept sketch in Fig. 2. Following the developed forming strategy, shear is introduced into the fabric only by out-of-plane deformation inducing compressive stresses in-plane in between the formed rigid areas. Thus, the forming tools do not need to introduce tension into the fabric directly by pulling a fixated point. In order to enable a time-efficient continuous processing while minimizing friction and undesired movement of fibers or matrix material, rotating ball or roller tool tips are desirable. The radius of the balls or rollers depends on the minimal edge radius to be formed. Flat tool tips or inflatable bladders can be considered as well, especially for processes requiring the application of pressure onto the composite in a comparably bigger area. The forming path would then consist of adding one individual pressed area after another, moving the tools to the next forming point while not in contact with the laminate. Regarding accessibility with industrial robots, rotationally symmetric tools are advantageous.

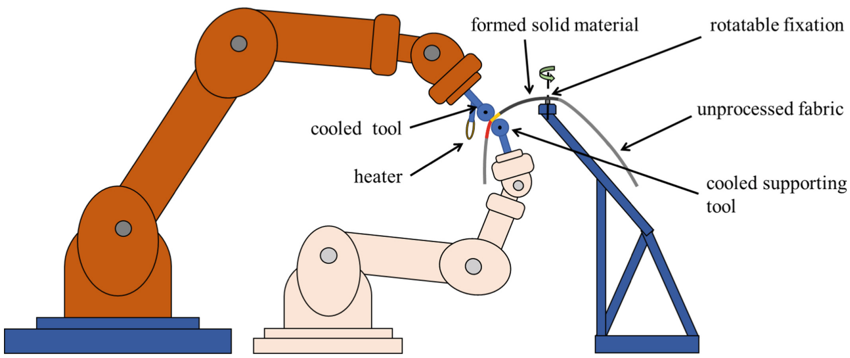

Fig. 2. Concept sketch for robotic die-less forming of thermoplastic co-weave

4. a) Impregnation. Unlike thermosets, thermoplastic polymers must be first heated above melting temperature in order to impregnate dry fiber fabrics. While impregnation immediately starts after heating woven commingled yarns (C), separate thermoplastic (B) or thermoset (A) polymers need to be handled and transferred to the reinforcement fabric which can be challenging. The former has higher viscosity and is therefore likely to deform fibers or fiber bundles rather than impregnating each individual fiber. Additionally, it easily solidifies if the required temperature is not maintained, which could be prevented by pre-heating the fabric.

4. b) Consolidation. Subsequent consolidation removes voids out of the matrix by applying pressure on the composite. The required pressing force between the tool ends must be generated by the handling devices. With higher matrix viscosity, higher pressure is required to fully impregnate the fabric and consolidate the FRP [21]. Especially in the case of thermoplastic matrices (B & C), this pressure needs to be maintained for a certain time. Not only prepregs, but even pre-consolidated organo sheets (E) need a certain but comparably lower pressure in order not to de-consolidate when heated above melting temperature for a specific time [22].

5. Curing/Solidification. Each forming path follows the final part geometry and curing/solidification while forming ensures that the acquired geometry is maintained. Thermoplastics (B, C, E) solidify during cooling, preferably under pressure to maintain consolidation, which can be supported by air jets or otherwise cooled tool ends. Thermoset polymers (A & D) need to build chemical crosslinks in order to cure. Depending on the resin, this curing process can for example be initiated thermally or by UV-radiation. The latter process, called photopolymerization, is significantly faster, allows easier resin handling, processing at atmospheric conditions and produces less styrene emissions. Selective curing is possible using either a laser or a conventional UV-light source in combination with local impregnation. However, in contrast to glass fibers, carbon and aramid fibers block UV-light, so that thermo-curing in a second processing step is necessary [23].

3.3 Allocation and Evaluation of the Processing Functions

Table 2 shows an allocation of the described processing functions to the material types of Table 1. In addition, feasibility of the matches is rated from *1* (feasible) to *3* (hardly feasible). If a material type does not require a certain processing step, the corresponding cell in the allocation matrix is empty and counted with *0*. The sum for each material type represents its unfeasibility. As a result, the three material types with least points, liquid separate thermoset (A), organo sheet (E) and woven commingled yarns (C), are further considered and evaluated for die-less forming.

Table 2. Matching material types and processing functions

		Fixation	Formability	Forming	Impregnation	Consolidation	Curing/Solidification	Total unfeasibility
		1	2	3	4 a)	4 b)	5	
Liquid separate thermoset	A	*2*		*2*	*1*	*2*	*1*	8
Solid separate thermoplastic	B	*2*	*1*	*2*	*3*	*2*	*1*	11
Commingled weave	C	*1*		*1*	*1*	*2*	*1*	6
Thermoset prepreg	D	*3*		*3*		*2*	*3*	11
Organo sheet	E	*1*	*2*	*2*		*1*	*2*	8

4 Preliminary Practical Experiments

4.1 Liquid Separate Thermoset Processing

Setup. Feasibility of local thermoset impregnation and UV-curing while forming a hemisphere according to the forming strategy was investigated using glass fiber twill weave with an areal weight of 160 g/m^2 and a size of 30 × 30 cm^2. Its center was fixated to a pole using a tack and the remainder of the fabric hanging freely. A handheld 2D quarter circle tool with a radius of 12 cm and a thickness of 1 cm was coated with release agent and manually positioned under the fabric. The so defined forming path was impregnated with UV-curable 3D-printing resin (PrimaCreator, Sweden) using a brush. Subsequently, a handheld laser with a wavelength of 405 nm and a power of ~600 mW was moved along the forming path, curing each spot for approximately 4 s. Afterwards, the tool was moved to the next position according to the forming strategy. In a further setup, in order to investigate die-less forming, the 2D tool was replaced by a rotatable metal ball as a standard "1D" ISF-tool, which was manually movable in fixed increments along a hemispherical surface around the fixation as the highest point of the hemisphere. In a forming path, the tool was moved to the desired point and the fabric manually impregnated and cured. Both setups are shown in Fig. 3.

Results. Both tools enabled the generation of hemispheres as depicted in Fig. 4. However, the surfaces show imprints of the respective tools so that overall part quality is not yet satisfactory. With a curing time of 4 s per forming point, sufficient part stability was achieved but surfaces were still tacky. Light conductivity led to undesired curing of already impregnated areas surrounding the laser spot, which was problematic especially when the metal ball was contacting the respective resin, leading to adhesion.

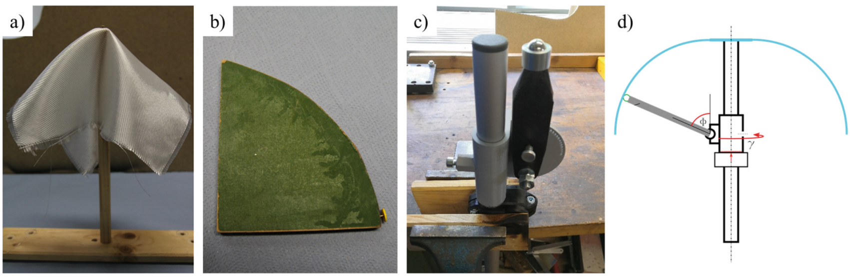

Fig. 3. a) Fixated glass fiber twill weave fabric, b) 2D quarter circle tool, c) Setup with rotatable metal ball ISF tool, d) Working principle of the metal ball tool setup

4.2 Organo Sheet Forming

Setup. Two-layered twill weave carbon fiber organo sheets (INEOS Styrolution, Germany) with styrene-acrylonitrile matrix, an areal weight of 245 g/m^2, 45% fiber volume

Fig. 4. a) Forming sequence and results of thermoset resin UV-curing using a 2D-tool, b) Result of thermoset resin UV-curing using a metal ball tool

content and a thickness of 0,6 mm were used to investigate the die-less forming process. The organo sheet sized 25 × 25 cm^2 was clamped at one or more rigid edges not requiring fiber movement in the respective forming step. Thus, also the starting point of the forming paths was fixed due to the rigidity of the organo sheet. Localized heating was acquired by using one infrared heater on either side of the sheet and masking areas not to be heated with reflective aluminum foil, shown in Fig. 5a). Temperature was measured using a thermography camera. After reaching 180 °C, the heating was disabled and the corresponding path was formed. Thereby, a handheld rotatable ball used in the setup in Fig. 3c) followed the forming path and pressed the sheet onto the 2D quarter circle tool of Fig. 3b) positioned under the sheet. While following the path, an air jet was directed onto the organo sheet exiting the forming zone for instant cooling.

Results. Shielding with aluminum foil enabled a clearly localized heating of the desired area as demonstrated in Fig. 5b), where only the upper side of the sheet was heated and temperature measured on the lower side. With double-sided heating, the target temperature of 180 °C was reached after around 40 s. The air jet enabled rapid localized cooling and solidification of the formed path. However, the resulting hemispherical frustum as depicted in Fig. 5c) showed large wrinkles mainly due to inhomogeneous and insufficient heating of already deformed areas by the stationary infrared heaters.

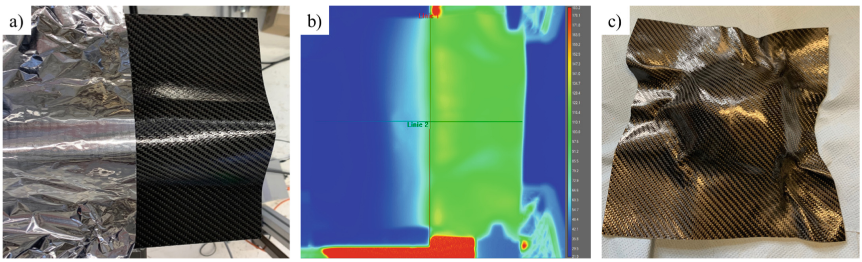

Fig. 5. a) Clamped organo sheet with aluminum foil shield, b) Resulting temperature distribution during infrared heating, c) Generated hemispherical frustum

4.3 Woven Commingled Yarn Processing

Setup. Glass fiber/polypropylene commingled twill weave (COMFIL, Denmark) with an areal weight of 700 g/m^2 and 60% reinforcement weight fraction was used to investigate the feasibility of local forming, impregnation and consolidation. The fabric of size 30 × 30 cm^2 was fixated to a pole, the 2D quarter circle tool was protected with release film and placed under the fabric to support the respective forming path. Local heating of the forming area to a temperature of ~190 °C, measured with a pyrometer, was accomplished by a hot air gun set to ~500 °C within 6 s. Moving along the forming path, the heated fabric was pressed onto the 2D-tool using a handheld roller protected by separating foil. The roller as well as the fabric exiting it were cooled by an air jet. The setup is depicted in Fig. 6.

Results. The performed process produced rigid material in each forming step and generated the desired hemispherical geometry as shown in Fig. 7a). Although the roller tool initially created relatively smooth surface in each forming path, the finally resulting surface quality of the whole part is inferior and individual forming paths are visible. As heating with the hot air gun is not as localized as required, material surrounding the forming path which already has been processed is heated and melted again, but not consolidated by the tools.

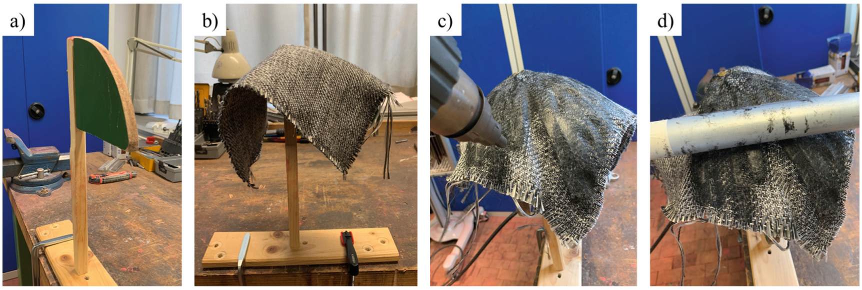

Fig. 6. a) Pole & 2D quarter circle tool, b) Commingled weave fixed to the pole, c) Heating with hot air gun, d) Forming, impregnation & consolidation with a roller

5 Discussion and Outlook

Die-less forming with two simple standard tools, each individually guided by a handling device such as an industrial robot, can be a solution to reduce cost, time and effort of prototype and small batch FRP production. Through a systematic functional analysis, material types and processing options for die-less forming were described and compared. Out of these options, local thermoset photopolymerization, organo sheet forming and local commingled weave processing have most potential and were investigated in preliminary experiments using 2D quarter circle tools. Furthermore, a rotating ball tool was used in local thermoset photopolymerization, die-lessly forming the material.

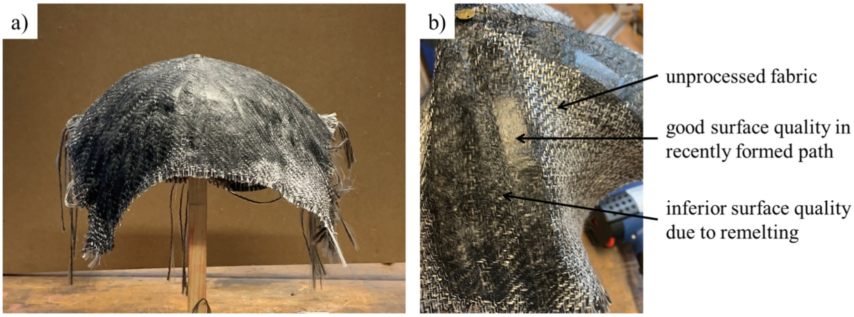

Fig. 7. a) Generated hemisphere, b) Surface quality in an intermediate forming step

Although UV-curing of thermoset resin showed good results and curing was relatively quick, processing was intricate. High resin viscosity led to easy wetting of the used tools, resulting in adhesion when the resin was cured. Due to toxicity of the resin and danger of the laser radiation, high safety measures are required. Furthermore, the process is limited to glass fibers. As curing takes place under atmospheric conditions, the process is simpler but part quality comparably poor. Consolidated organo sheets are advantageous in terms of stability while clamped as well as final part quality when carefully formed and not de-consolidated. However, uniform local heating proved difficult especially when the targeted area is already deformed and not perpendicular to the incoming infrared radiation. Other heating options such as movable laser or inductive heaters were considered but dismissed as too expensive and impractical. In addition, multiple repeated heating and/or a long time above melting temperature can lead to deconsolidation and decreased mechanical properties of the material. For commingled weave processing, heating is required for impregnation only in a small area the size of the tools. However, different heating options such as induction heating need to be further investigated as the heat-affected zone of the hot air gun used in the preliminary test was too big. Achieving a sufficient level of impregnation and consolidation in the FRP is one of the most challenging tasks in die-less forming. This is especially problematic with commingled weave processing as the pressed area might be too small and consolidation time too short. Thus, it may be reasonable to first create a semi-consolidated part with the desired geometry and outsource possible further consolidation to a downstream process step with different, comparably larger tools. Nevertheless, the processing of thermoplastic co-weaves is the overall most feasible option and will be further pursued and investigated in the project. This includes studies on heating methods, the influence of the tool type on part quality and optimal processing parameters.

Acknowledgements. Research was funded by the German Federal Ministry for Economic Affairs and Climate Action under the Program LuFo VI-1 iFish with project partners CompriseTec GmbH and carat robotic innovation GmbH.

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