COMBINING FUSED GRANULAR FABRICATION AND AUTOMATED FIBRE PLACEMENT FOR THE RAPID PRODUCTION OF COMPLEX SANDWICH-STRUCTURES

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Keywords: Thermoplastic composites, in-situ bonding, PEEK

ABSTRACT

Extrusion-based additive manufacturing methods like Fused Granular Fabrication (FGF) have made significant progress in recent years for their application in industrial processes. But these technologies still fall short of being usable for load bearing structures. A combination of FGF and automated fibre placement can be used to achieve a manufacturing process for parts with the strength of continous fibre reinforced laminates and freedom of design which is offered by FGF. Additionally, 3D-printing the tooling for a PAEK laminate using FGF is a cheap alternative to traditional subtractive manufacturing methods. Using incompatible polymers for the mould and the laminate allows to design a bond between those polymers is strong enough to hold the tapes during the AFP secure in the mould while still being weak enough to allow a demoulding of the laminate. To adjust the bonding strength appropriately for a given part, the influence of certain process parameters of the AFP was investigated in this study. These results were than used to demonstrate the new cooperative form of manufacturing thermoplastic sandwich structures using FGF and AFP by producing a 600 mm × 800 mm sandwich structure with integrated conduits in a short time frame.

1 INTRODUCTION

Additive manufacturing (AM) has found more applications in industrial processes in recent years. Using high performance thermoplastics like polyether ether ketone (PEEK) enables the manufacturing of load bearing structures while being able to design complex geometries which would not be manufacturable using traditional technologies. However, 3D printed structures alone can not be used to manufacture primary structures for use in aerospace applications since their mechanical properties are still below, e.g., injection moulded parts [1].

The in-situ bonding of 3D printed PEEK on thermoplastic laminates is one approach to overcome those limitations. A thermoplastic laminate can have a high tensile strength while being light weight and thus is suitable for aerospace applications. Automated fibre placement (AFP) is a method of producing thermoplastic laminates which is already widely researched for its used in the aerospace industry. In-situ AFP eliminates the need for autoclave processes. Therefore, it is suitable for the combination with other processes and its automation. Extrusion-based AM, like Fused Granular Fabrication (FGF), can be used to manufacture complex parts out of thermoplastic materials. The combination of automated fibre placement (AFP) and fused granular fabrication (FGF) allows a high-performance structure and the use of complex geometries. When 3d printing directly onto a thermoplastic laminate where the feedstock for the 3d printer is the same as the matrix of the laminate, a durable bond can be formed. The bond of PEEK onto PEEK laminates was demonstrated in a prior study [2]. Complex sandwich structures can be created when AFP is used to lay another laminate on the 3d printed structure after it was printed onto the first laminate.

When manufacturing complex structures, such as curved sandwich panels, the manufacturing of a tooling in which the part can be laminated, significantly increases the over-all cost of a part.

Furthermore, the production of a tooling using traditional subtractive manufacturing technologies increases the production time.

By 3D printing a tooling on which a laminate can be laid, production time and cost can be reduced significantly. A study by Allen et al. [3] already demonstrated the use of 3D printed support structure for the manufacturing of complex, 3D printed sandwich panels. For the separation of the support structure and the part, a buffer layer out of a thermoplastic elastomer was used. This is not employable when processing high temperature thermoplastics such as PEEK.

This study investigates a holistic process chain for the production of complex thermoplastic composites by combining in-situ AFP and FGF printing. By using an incompatible thermoplastic polymer, the tooling can be 3d printed while allowing a part to be demoulded. Due to its good workability, polyamide 6 (PA6) could be suitable for this application. In the first part of the study, the bonding between 3d printed PA6 and LM-PAEK tapes is investigated to define the process parameters for the AFP when tape laying on PA6 moulds. Using these results, a process chain for the production of complex thermoplastic sandwich structures is shown and demonstrated.

2 MATERIALS AND METHOD

2.1 Manufacturing Facilities

The 3D printing process is performed using the FGF facility of the DLR in Stuttgart, Germany. It consists of a six-degree-of-freedom robotic arm with a single screw extruder as its endeffector. The facility is produced by Hans Weber Maschinenfabrik GmbH and has a build volume of 1200 mm x 800 mm x 1200 mm. The manufacturing of CFRP laminates took place in the AFP facility of the DLR in Stuttgart, Germany. Laminates can be laid up using a Multi Tape Laying Head (MTLH) mounted on a six-degree-of-freedom robotic arm. The MTLH is produced by the company AFP GmbH.

2.3 Materials

For the AFP of CFRP laminates a Cetex TC 1225 prepreg is used. These carbon fibre reinforced tapes have a matrix out of low-melting poly-aryl-ether-ketone (LM-PAEK).
To 3D print a core structure onto a laminate, TECACOMP PEEK 150 CF30 by the company Ensinger, a carbon fibre reinforced PEEK granulate, is used. For the 3d printing of toolings and specimens for the investigation of the bond between LM-PAEK tapes and PA6, the granulate carbon fibre reinforced Polyamide 6 CF 30 with a fibre mass fraction of 30 % compounded by the company AKRO-PLASTIC was used.

2.2 Testing

To investigate the bonding of LM-PAEK tapes on 3d printed substrates out of PA6, peal tests were performed which were designed with the standard DIN EN 28501-1. For the specimen production a one-walled part, like shown in Figure 1, was 3d printed out of PA6. Planar sheets could be separated out of the part using a disk saw. On those sheets, tapes were laid using the AFP facility of the DLR. Five Specimens were produced and tested for each variation of process parameters. The single specimens were than separated from the whole sheet using a disk saw. The specimens were tested using a universal testing machine RetroLine 1475 build by the company ZwickRoell GmbH & Co. KG. The peal force was measured and the arithmetic mean calculated for each variation of parameters. The laser power of the AFP facility and the position of the laser (weather it points on the substrate or the tape before the nip point) were each tested on 3 levels. Thus, nine Variations of parameters were investigated.

After testing the surface roughness of the specimens were measured in three locations: the substrate where the tape was laid on, the tapes surface on the side which was bonded to the substrate and the other side of the tape. For the measurements the profilometer Keyence VR-5000 was used.

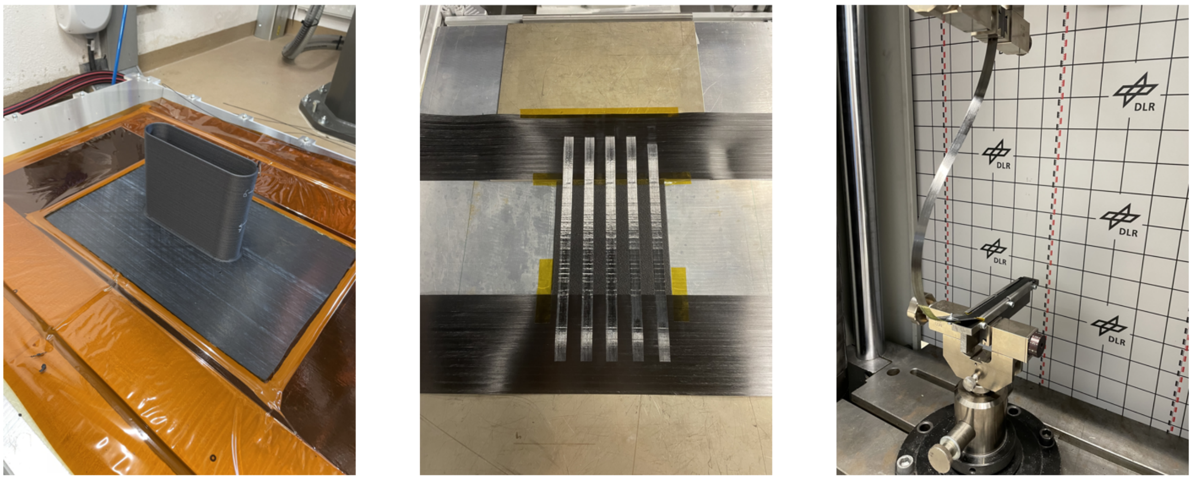

Figure 1: Specimen preparation for peal tests. 3d printing of one-walled part to separate PA6 sheets out of (left), tape laying on PA6 sheets with LM-PAEK tapes (middle), testing of specimens in universal testing machine (right)

3 RESULTS

The results are divided in those of the investigation of the bonding between LM-PAEK and PA6 and the presentation of the developed process chain.

3.1 Laying of CF/LM-PAEK tapes on a CF/PA6 substrate

The testing of the peal specimens shows the influence of the process temperature of the AFP process on the bonding strength of LM-PAEK tapes on PA6 substrates. Higher process temperatures result in higher bonding strength. Additionally, heating the tape earlier before consolidation improves the bonding strength, compared to heating just before the nip point. These results can be seen in Figure 2.

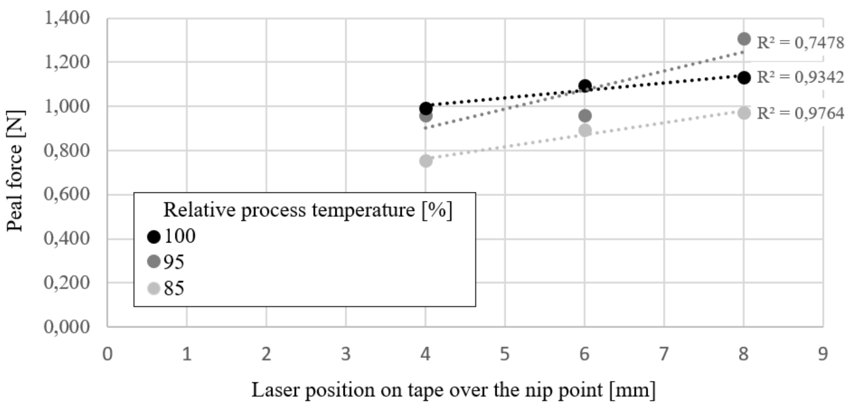

Figure 2: Peal force in N over laser position in mm of different specimens with variation in process temperature

Also, an influence of the process parameters on the surface roughness of the tape and the tooling could be observed. Earlier heating of the tape results in a higher roughness of the substrate after demoulding and a lower roughness of the Tape, like it is shown in Figure 3.

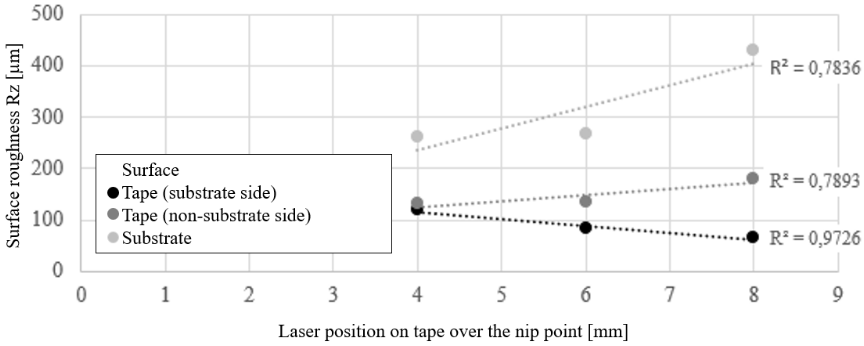

Figure 3: Surface roughness Rz of Peal Specimens after testing over laser position. Specimens where produced with process temperatures at 100 %

3.2 The process chain

To manufacture complex composite sandwich structures, a tooling out of PA6 can be manufactured using FGF. The tooling should be designed to be stiff enough to withstand the orthotropic stress which will be caused by tape laying onto the tooling's surface.

Tape laying onto the tooling using in-situ AFP produces one of the skins for the sandwich structure. Reducing the process temperature and consolidation pressure compared to those parameters used when laying tape-on-tape can reduce the strength of bonding between LM-PAEK and PA6 and thus improve the demouldability of the part. This modification of parameters is not necessary for other plies.

After the layup of the first laminate is completed, the part can be transferred to the FGF facility where it can be overprinted with PEEK to create the core of the sandwich structure. The bonding of the core to the laminate is formed in-situ during the printing. In prior studies, the shear strength of this bonding was found to be up to 25 MPa. By 3D-scanning the laminates surface, a digital twin of the laminate can be created. This digital model can then be used to adjust the core geometry to account for surface defects in the laminate. The core can be designed to fit individual requirements and loads. Multi-material Extrusion can be used to implement functional parts, such as conductive segments. Further, conduits can be integrated in this step to allow later integration of cables or pipes for fluids or gases, like seen in Figure 2. The integration of functionality was described in [4] and [5].

The part can then be transferred back to the AFP facility after the core structure is completed. Tape

Figure 4: tapes laid onto 3d printed honeycomb structure with 100 % (upper) and 50% (lower) consolidation force

laying onto a non-continuous substrate, like a honeycomb core, is challenging. Process parameters of the AFP need to be adjusted since the consolidation force is spread on a significant smaller area of substrate. Further, the process temperature and the position of the laser need adjustment to achieve a load bearing bonding of tape and core. The consolidation force was found to have the most impact on the laminate's quality. By reducing the consolidation force to 50 % of the usual force used for the process, significant improvement in the flatness of the laminate was seen, which is shown in Figure 4. The strength of the bonding between tape and core was stronger than the bonding strength of single layers of the 3d printed structure.

The described process chain is shown in Figure 6 and was demonstrated by manufacturing a complex curved sandwich structure with a size of 600 mm × 800 mm. The steps of the manufacturing of the demonstrator are also shown in Figure 3.

It was possible to demould the demonstrator after its completions. The finished demonstrator can be seen in Figure 5.

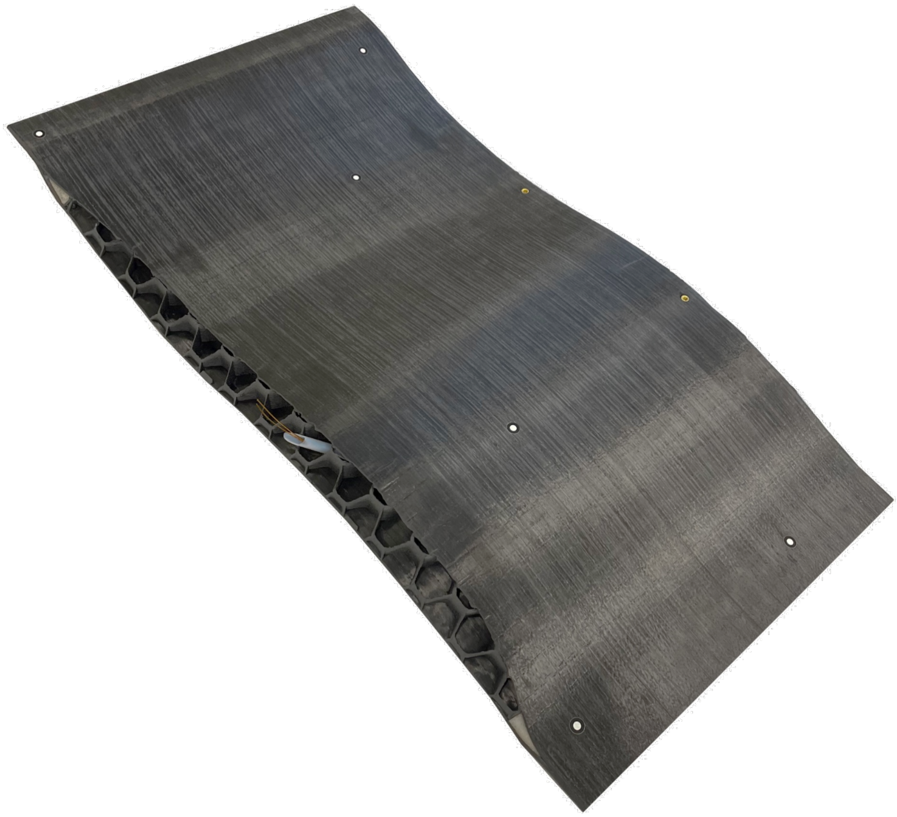

Figure 5: Demoulded demonstrator

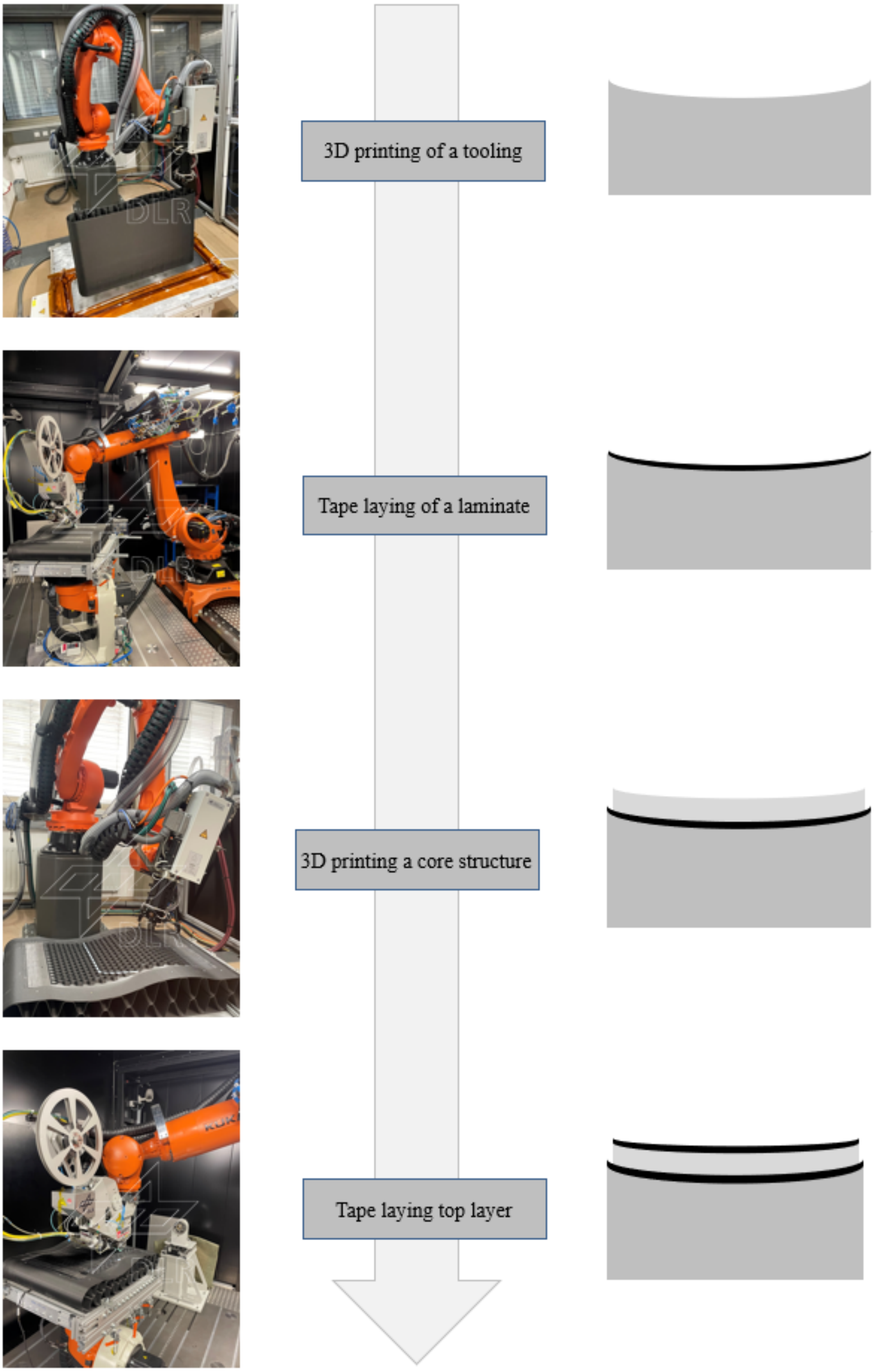

Figure 6: Process chain combining Fused Granular Fabrication and in-situ Automated Fibre Placement: Divided in 1) 3D-printing of a tooling out of PA6, 2) in-situ AFP onto tooling, 3) in-situ bonding of PEEK on AFP laminate in the FGF process, and 4) in-situ AFP

4 DISCUSSION

The principle suitability of the developed process chain was demonstrated.
The manufacturing of toolings for the AFP of LM-PAEK tapes proved to be promising. Tapes were held in the mould during manufacturing but the weak bond allowed a demoulding after the production. It is possible that the necessary bonding strength is highly dependent on the geometry of the part. Thus, further investigations on the influence of process parameters of the AFP are required.
The influence of the laser position on the bonding strength and the surface roughness can be explained with an earlier heating of the tape leading to an accumulation of LM-PAEK on the side of the tape which later will be in contact with the tooling. In this case the substrate will not be heated as much as a later heating of the tape would result in. Thus the original structure of the substrate is more preserved. An accumulation of LM-PAEK on the contact side of the tape may result in a weaker bond between the first ply of the laminate and the second ply because the lower content of LM-PAEK may impair the bonding of the tapes to each other. Further investigations on this topic need to conducted.
Since, the surface roughness of the produced laminate is an important property in aerospace applications, the influence of the tooling's surface should also be investigated.

5 CONCLUSION

It was demonstrated that CF/LM-PAEK tapes can be laid onto a tooling out of PA6. A concave/convex tooling on which an 8-layer laminate was laid, was used as a demonstrator. On this laminate a honeycomb structure with integrated conduits was 3d printed. A second laminate which was laid on the honeycomb structure formed the second skin of a sandwich structure. Using AM to produce a tooling significantly reduces the manufacturing costs compared to subtractive manufacturing methods. Additionally, the production time and the time between the design of a part and its manufacturing can also be reduced significantly. The used combination of materials and technologies enables rapid production of aerospace-grade and lightweight structures.

Due to the usage of industrial robots in this study, the applicability of the proposed process chain on an industrial scale was demonstrated. The combination of both robots in one facility could further speed up production time and eases the automation of the process as a whole.

ACKNOWLEDGEMENTS

This work is financed by the Ministry of Economic Affairs, Labour and Tourism Baden-Württemberg reference numbers 3-4332.62-DLR/59 (IRAS III) and WM3-4332-157/68 (IRAS IV).

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