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Optimized process chain for flexible and automated aircraft interior production

Henrik Eschen[a,*], Florian Kalscheuer[a], Thorsten Schüppstuhl[a]

[a]*Hamburg University of Technology, Institute of Aircraft Production Technology, Denickest. 17, 21075 Hamburg, Germany*

Abstract

The growing aviation market puts first tier suppliers of cabin interior under great pressure. Historically grown, poorly optimized manual processes limit the production rate of highly individualized interior components, required by the airlines. Different automated approaches offer solutions for high rate production of standardized lightweight structures. However, those solutions can not be adapted to individual sandwich panels. In this paper, first, the manual process chain is analyzed. Necessary components and features are identified and processes are evaluated with respect to automatability, accuracy, as well as flexibility and design freedom. Based on the analysis, a concept for the automated manufacturing of highly individual, flat sandwich panels with a standardized, digital process is developed. A discussion of the results shows that the presented process meets the targeted objectives, allows a simplified panel design and offers great potential for the development of digital assembly processes with low risk to fail aviation certification.

Keywords: process automation; flexible manufacturing; sandwich structure; aircraft interior

1. Introduction

1.1. Motivation and problem statement

The aviation market is constantly growing. The two biggest aircraft manufacturers Airbus and Boeing both predict a demand of 40.000 new commercial aircraft until 2038, resulting in an increase of the global aircraft fleet to then 50.000 aircraft [12, 2]. During the 25 year lifespan of an aircraft [2] the cabin interior is refurbished in intervals of five to ten years [11, 39, 50]. This results in an aftermarket that is typically two to three times bigger than the OEM market [44]. The combination of these trends will lead to a significant increase in the demand for aircraft interior in the upcoming years. To meet the increasing demand and remain competitive with low-wage countries, aircraft interior manufacturers need to increase the productivity of their manufacturing processes.

Aircraft interior manufacturers face various challenges. The aircraft interior is the main point of contact for the passenger. Therefore, the interior is not only of great importance for the travel experience itself [38, 44], but also a main factor for the brand images of the airlines [4, 50] and a major tool for the airlines to differentiate from competitors [38, 39]. This results in the demand for highly individualized aircraft interior. Combined with the large amount of aircraft types and variants, almost every aircraft cabin is unique [4, 43]. Although the interior component manufacturers differentiate their products to meet airline demand, the materials used for manufacturing are similar due to weight, crash safety, heat release, flammability, smoke and toxicity (FST) requirements [26, 25, 1, 44, 48]. Additionally, the introduction of new materials and designs is difficult due to time consuming and expensive certification processes [31].

Aircraft interior components are mostly made of composite sandwich structures with Nomex®honeycomb core and glass fibre facesheets with phenolix resin matrix [6, 11, 15, 36, 49]. This material combination is used for the lining components (e.g. hatracks, sidewalls, ceiling panels, light and airduct covers, door frames and dado panels), the monuments (e.g. galleys, lavatories, crew rest compartments, stowages and partitions), as well as floor panels and cargo space lining. These

* Corresponding author. Tel.: +49-40-42878-2504 ; fax: +49-40-42878-2500.

E-mail address: henrik.eschen@tuhh.de (Henrik Eschen).

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components differ greatly in terms of quantity, variety and manufacturing process. The lining parts are mounted in comparatively high quantity along the length of the aircraft and individualization is mainly achieved with different surface finish. Therefore, relatively well optimized manufacturing processes, mainly the crush-core process [11], as well as vacuum and hot press processes [6] are used. The number of monuments per aircraft is, compared with the lining parts, low. However, the monuments consist of much more different parts and are highly individual. Typical individualization options are: the amount and positions of the monuments inside the aircraft, the type, amount and position of equipment inside the monument (e.g. ovens, water heaters, standard units, mirror cabinet, sink) and additionally mounted crew seats. These options usually change the whole design of the monuments structure. The manufacturing processes used for the lining can not be used economically for the monuments, since they need expensive, component specific tools. Instead, the monuments are made mostly from flat sandwich panels that are cured in flat hotpresses [11, 34]. The processes for the manufacturing of aircraft interior from flat sandwich panels have grown historically. The high level of individuality is countered by a large amount of manual labor. In combination, this results in a poorly optimized process chain with redundant processes [22, 23]. This process chain will be described in more detail in Section 2. The automation and automation-compatible optimization of the process chain therefore offers great potential to achieve the productivity increase demanded by the market.

1.2. Related work

There are only a few works known regarding the automated manufacturing of cabin interiors. The most extensive work regarding the manufacturing of aircraft interior from flat sandwich panels was carried out in the research project MQS15. The main objective of this project was the increase of productivity for the manufacturing of floor and cargo lining panels [21, 45, 32, 34, 37]. Geis [32] improved productivity as well as quality of the machining process by optimizing of machining parameters and adapting a carving process from the furniture industry. Griefahn [33, 34] developed a referencing process based on thermography and principal component analysis to find the panel origin based on internal structures. The project made an important contribution to the production of sandwich panels for aircraft interior, but many parts of the process chain, in particular the layup of the sandwich package and the assembly processes, were not taken into account. Additionally, the floor and cargo lining panels considered in the project are less individualized than panels for cabin monuments. It is therefore questionable to what extent the results can be transferred.

Another approach to the automated manufacturing of aircraft interior was developed in the research project EFFKAB. Fette et al. [28] developed an automated process for the production of aircraft components from a combination of sheet moulding compound (SMC) and woven prepreg material. This approach was later adopted for the manufacturing of multi material overhead stowage systems [27, 29]. However, this approach uses part specific tooling and is therefore only suitable for large quantity interior parts, e.g. lining.

Other work regarding efficient manufacturing of sandwich structures, e.g. for automotive [52], furniture [41] or construction applications [17], as well as continuous produced honeycomb structures [40, 42, 30] can not be transferred, since the used materials do not meet the aviation requirements outlined in Section. 1.1 and the processes are not compatible with typical aviation materials.

Besides these general approaches regarding aircraft interior manufacturing, there are some contributions to the automation of composites and sandwich structure manufacturing, that offer great potential to be transferred to aircraft interior production. Great progress has been made in the automated layup of fiber materials, especially prepregs. Different flexible grippers for automated fiber handling were developed, e.g. [9, 8, 46]. Björnsson et al. [10, 7] combined automated gripping of prepreg with automated cutting and removal of backing paper. There are various approaches for automated sorting of prepregs directly from an ultrasonic cutting machine with a robot, e.g. [5, 3].

Another promising development is the automated introduction of potting compound into honeycomb panels. Potting compounds are usually epoxy materials with a high amount of filler and high viscosity. Normally, the potting compound is manually integrated in the honeycomb core during layup and co-cured with the sandwich panel [15]. Robot based, automated potting machines became available in recent years [23, 53]. However, these systems usually have a high amount of spillage, create air pockets and require manual rework. Harnisch et al. [35] solved these problems with closed loop control of potting pressure.

A third relevant field is the automated integration of inserts. Inserts are metallic or plastic elements that are integrated into the sandwich panel for load introduction [6, 55]. In aircraft interior mostly potted, threaded inserts are used [49], but a large variety of other inserts is available [20]. Usually, inserts are installed manually into machined pockets. While automation of this process is possible, special inserts for automated placement have been developed [13]. One example are so called TSSD-inserts. Thermoplastic TSSD-inserts are friction welded into the cured panel without any preceding machining, only by rotation and application of a preload force. This process can easily be integrated into a milling machine or a robotic system [54].

1.3. Outline

Although some approaches to the automated manufacturing of aircraft interior do exist and contributions to automated manufacturing of sandwich panels were made, no comprehensive optimization of the overall process chain for the automated production of highly individualized aircraft interior from flat sandwich panels exists. In order to develop an overall optimized and automated process chain, first the manual process chain will be described and used components will be analyzed. Afterwards, flat panel specific requirements are derived and the processes are evaluated based on the requirements. Based on the evaluation, a standardized, automation friendly process chain is developed and discussed.

2. Manufacturing of flat sandwich panels for aircraft interior

A large variety of processes for the manufacturing of sandwich structures is briefly described in the literature, most notably [6, 14, 15, 55, 34], including many processes used in aircraft interior production. However, these descriptions lack detail and a comprehensive overview over the process chain for the manufacturing of aircraft interior is missing. Therefore, the literature review was combined with a process analysis in the production environment.

The production of cabin interior is divided into the following steps: production of prepreg and honeycomb, raw panel layup, curing, machining, pre-assembly and final assembly (Fig. 1). Prepreg and honeycomb are usually produced by specialized companies and the machining of the cured panel is already well optimized (Section 1.2), therefore these steps will not be considered in the following.

Fig. 1. Conventional process chain for aircraft interior production

2.1. Raw panel layup

The production of sandwich panels begins with the layup of the raw panel. Besides the cutting and laying of honeycomb core and glass fiber prepreg facesheets, this step includes the integration of different inserts and inlays as well as potting compound (Fig. 2). Inlays in the facesheets usually consist of sheet metal or prepreg doublers. They are used to improve local pressure and impact resistance, pull-out strength of threaded inserts [18, 51], fatigue resistance [18] and overall stiffness and strength [6]. Inserts inside the honeycomb core, that are integrated during layup, are mostly monolithic blocks made of fiber reinforced plastics (FRP). Alternatively, potting compound is used. FRP-elments are commonly used for the transfer of high loads. Potting compound is used in combination with subsequent machining for multiple purposes (Section 2.3).

The production of raw panels starts with cutting of prepreg and honeycomb core. The continuous facesheet layers and simple shapes are usually cut manually with knifes and steel rulers. More complex prepreg pieces, e.g. doublers, are cut with automated cutting machines and then are transferred into the laying area on tray trolleys. The outer geometry of the honeycomb core is usually not machined. However, removing parts of the core is necessary to enable the integration of FRP-elements.

At the start of the layup process, an aluminum plate is brought into the laying area. This plate functions as a workpiece carrier during layup and curing. Afterwards, a layer of release film is cut, placed and fixed with adhesive tape. Then, the backing paper is removed from the prepreg and the lower facesheets are placed. During this step, metallic inlays and prepreg doublers are placed on or between the prepreg layers. The honeycomb core is laid on the lower facesheet afterwards. Next, FRP-elements are integrated into the core. Bonding between core and FRP-elements is usually achieved with foam adhesive, that is applied onto the edges of the FRP-elements. Afterwards, potting compound is pressed into the core. This is usually done by hand with spreaders or pneumatic dosing devices. For precise contours masking tape is used. After potting, the upper facesheet is laid in reverse order to the lower one. Finally, a second aluminum plate is placed on the raw panel before curing.

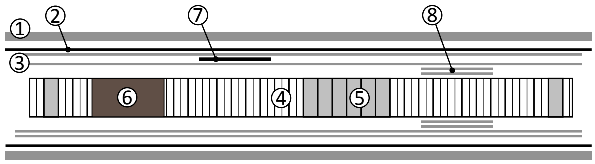

Fig. 2. Raw panel with different inserts and inlays: (1) aluminum plate, (2) release film, (3) prepreg layers, (4) honeycomb core, (5) potting compound, (6)FRP-insert, (7) metallic inlay, (8) prepreg doubler

2.2. Curing

After layup, the raw panels are co-cured in flat hot presses. During co-curing, the face sheets are consolidated, the potting compound is cured and the face sheets are bonded to the honeycomb core with the phenolic resin from the prepregs. Often, multiple presses are integrated into one frame and equipped with automated storage and transfer systems in order to achieve high productivity. The storage systems are used as a buffer storage, as well as for cooling of the cured panels. [6, 15, 11] The panels shift and distort between the aluminum plates during curing. According to Griefahn [34], the main reason for these distortions is the shrinkage of the phenolic resin matrix.

2.3. Pre-assembly

After curing, the panels are machined in milling machines. Afterwards, pre-assembly takes place. The pre-assembly phase can be further divided into two steps. First, all open honeycomb edges are closed to prevent moisture ingression, debonding of the top layers, as well as to enable load transfer at the panel edges [6]. In this process step different geometric features, e.g. pockets, are manufactured. Afterwards, inserts, as well as functional components and assemblies, e.g. retainer or lock fittings, are integrated into the panel. Depending on the panel joint design used during final assembly, one or both surfaces of the panel are finished during pre-assembly as well. This includes filling and sanding the surface, as well as the application of decorative films. However, most of the time surface finish takes place after the panels have been joined.

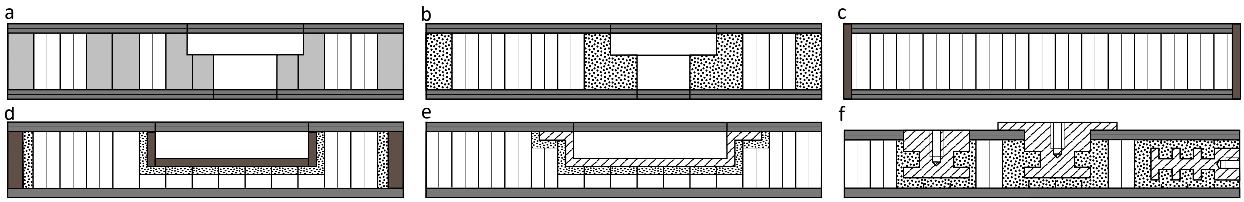

Fig. 3. (a) potting, (b) edge filler, (c) edge band, (d) FRP-closeout, (e) sheet metal, (f) inserts

2.3.1. Potting

One way to produce edge closeouts is the machining of potting compound, integrated during layup and curing. With this type of edge closeouts no further processes are required during pre-assembly. With the combination of potting and milling, closed edges can be manufactured in almost any geometry (Fig. 3 a). Potting compound is used for straight, curved and profiled closeouts of inner and outer panel edges, as well as pockets, insert mounting and free-formed elements.

2.3.2. Edge filler

Instead of the integration of potting compound into the honeycomb cells before curing, edge filler can be used (Fig. 3 b). Edge filler is, similar to potting compound, a thermoset, but usually cures at room temperature. For this process the panel has to be machined with oversize. Afterwards, the honeycomb core has to be removed between the face sheets, at the panel edges. This is usually done during machining, however manual rework is required to remove honeycomb residues from the face sheets. Afterwards, the edges are filled manually with the edge filler. After curing the filled panel, edges are machined to the final dimensions. Since the properties of cured edge filler are very similar to cure potting compound, the same structural elements can be manufactured.

2.3.3. Edge banding

Similar to wooden panels for the furniture industry, sandwich panels can be closed with edge banding (Fig. 3 c). Typically, cured glass fiber is bonded to the edges in edge banding machines with a polyurethane adhesive. To close multiple edges, the panel must be manually fed into the machine repeatedly. For the production of curved edges, special edge banding tools can be integrated into milling machines. However, even with these machines the maximum curvature of the edges is limited and only outer edges with a flat cross section can be produced.

2.3.4. FRP-process

For the edge closeout with FRP-strips (Fig. 3 d), first, the honeycomb core is removed between the face sheets at the panel edges. As for the edge filler, this is usually done during machining. However, manually operated table routers are also common. In both cases manual rework is required. Afterwards, FRP-strips are cut from cured plates or blocks with cotton or glass fibers inside a phenolic resin matrix. Subsequently, adhesive is applied onto the panel edges and the strips are placed and fixed with film adhesive. After curing, the strips are cut and sanded to length. Thicker material is used for higher strength. For the production of more complex shapes, e.g. closed pockets, multiple FRP-elements are combined. Manual machining of the core with pneumatic tools allows the integration of FRP-elements between core and face sheet. With this process inner and outer panel edges with limited curvature, as well as pockets can be closed. Similar to FRP-strips, edges need to have a flat cross section.

2.3.5. Sheet metal process

Sheet metal is mostly used to close pockets (Fig. 3 e). Therefore, the sheet metal is bend into Z- or U-shapes and, similar to the FRP-strips, adhesively bonded onto the core. If the core is manually machined, the metal elements can be integrated between core and face sheet for good load transfer. The design freedom of edge closeouts with sheet metal is very limited. It is usually only used for closed pockets and canals, e.g. for cable routing.

2.3.6. Insert placement

Various different types of inserts are available (Fig. 3 f). Most common are potted, threaded inserts in different sizes and from different materials. A variety of mounting options is used in order to transfer loads of different height and direction. These inserts are adhesively bonded to the panel. Therefore, the insert is placed and fixed into a machined pocket, with a mounting cap. Afterwards, the cavity between insert and panel is filled with adhesive through holes in the mounting cap. After curing, the cap is removed. Higher loads can be transferred if the inserts are mounted in areas filled with potting compound. If even higher loads occur, inserts with bonded flange are used at the panel faces and inserts with high length are used at the panel edges.

2.3.7. Functional component placement

Beside the inserts, functional components and assemblies, such as lock fittings, tubes for cable routing or guides for retainers are integrated into the panel. These processes are mostly component specific but share similarities with the integration of FRP-elements. First, some contour is machined into the panel, followed by manual rework. Then, the elements are adhesively bonded to the core and the face sheets.

3. Process chain optimization

3.1. Features and requirements

An optimized process chain must be compatible with the existing interior design. All features of the sandwich panels that were manufactured with the conventional processes must also be producible with the optimized process chain. Therefore, all panel features, produced with the manual processes were derived and categorized. An overview of the features is shown in Fig. 4. The features are further divided into the categories structure, edge closeouts and inserts.

During the raw panel layup the basic sandwich structure, consisting of core and top layers, as well as strengtheners in both, the top layers and the core, are produced. In the machining and pre-assembly processes, closed panel edges with a variety of geometries are manufactured. Closed panel edges can be further divided in outer and inner panel edges, pockets and free-form elements, including edges with a profiled cross section or mountings for components with complex geometry. The last group of panel features are inserts with varying strength. Low strength inserts are needed for installation of light accessories, e.g. cable clips. Medium strength inserts are needed for installation of e.g. mirrors, in flight entertainment systems or baby bassinets. High strength inserts are needed for panel connections, attachments to the aircraft structure, crew seats or retainers.

In addition, the processes must meet some basic requirements. In order to generate an automation-friendly process chain, all processes must be easy to automate without manual rework. To meet the demand for a high degree of customization, the processes should be highly flexible and allow maximum freedom of design without compromising efficiency. All processes must be highly accurate to enable efficient assembly without rework or tolerance compensation. These requirements are shown in Fig. 4.

3.2. Process evaluation

The different processes were evaluated in two steps. First, the required features were marked in an evaluation matrix. Afterwards the fulfillment of the basic requirements was evaluated for each process and marked in the evaluation matrix as well. The evaluation matrix is shown in Fig. 4. Automatibility was evaluated in two steps. First, the availability of ”off the shelf” solutions was checked. If off the shelf solutions were available the automatibility was rated as good. If no off the shelf solutions were evailable, the automatiblity was evaluated with a checklist proposed by Deutschländer [19]. Since some of the evaluation criteria proposed by Deutschländer were not applicable to the present process chain, these criteria were delted. The simplified checklist contained the criteria: number of parts, part complexity, dimensional stability, type of joining movement, accuracy requirements of joining movement, accessibility of joining location and gripping point, necessity of clamping, amount of rework and effort for sorting. Regarding the process accuracy, three main aspects were taken into account. Distortions during curing limit the accuracy of parts that are not machined after curing. Machined geometries are generally very accurate, however, machining of potted honeycomb is more accurate than non potted honeycomb, due to elasticity of the core and flagging effects. If elements of limited accuracy are adhesively bonded to machined surfaces, especially onto the honeycomb, some of the accuracy of the machining process is lost. The processes were considered flexible when they allow great variation in geometry with low additional effort and no additional process steps required. In general, processes are the most flexible that only require program changes to produce varying parts, e.g. prepreg cutting, potting and machining. Therefore, flexibility was rated good when only paramter chages are needed between differnt parts. Flexiblity was rated as medium when changing machine programs is required and as poor when part specific components or tools are needed.

3.3. Optimized process chain

The evaluation matrix was used to identify the most efficient process combination by choosing the subset of processes with the highest fulfillment of requirements that on the same time allow the manufacturing of all identified features. Therefore, the process with highest fulfillment of requirements was chosen for each feature separately (columns of evaluation matrix). Subsequently, these processes where connected, forming the process chain (blue line in evaluation the matrix). The optimized process chain is shown in Fig. 5 a. Layup of prepreg and honeycomb is inevitable to generate the basic sandwich structure. For face sheet strengtheners prepreg doublers are used. The combination of automated potting and machining allows the local strengthening of the core, as well as productuion of edge closeouts with the highest geometrical flexibility. TSSD-inserts are great for the production of mountings with low strength, since no machining is needed and cycle times are short. However, for higher loads, conventional potted inserts offer good overall flexibility due to the available variety of types and the standardized installation process. An example for the panel design resulting from this process chain, as well as the producible features are shown in Fig. 5-b.

4. Discussion

Compared to the existing process, the optimized process chain is greatly simplified. The elimination of redundant processes and manual rework leads to a significant reduction in the number of processes, without compromising producible panel features or design freedom. The standardization and simplification reduces the effort in production and manufacturing planning, simplifies the plant layout, simplifies material flow and reduces training costs. The elimination of materials and components simplifies the supply chain. Furthermore, the standardization allows a simplified design process. All processes are well automatable, robust and controllable. As a result, the productivity and the production rate are expected to increase. Regarding flexibility, the use of an automated potting process combined

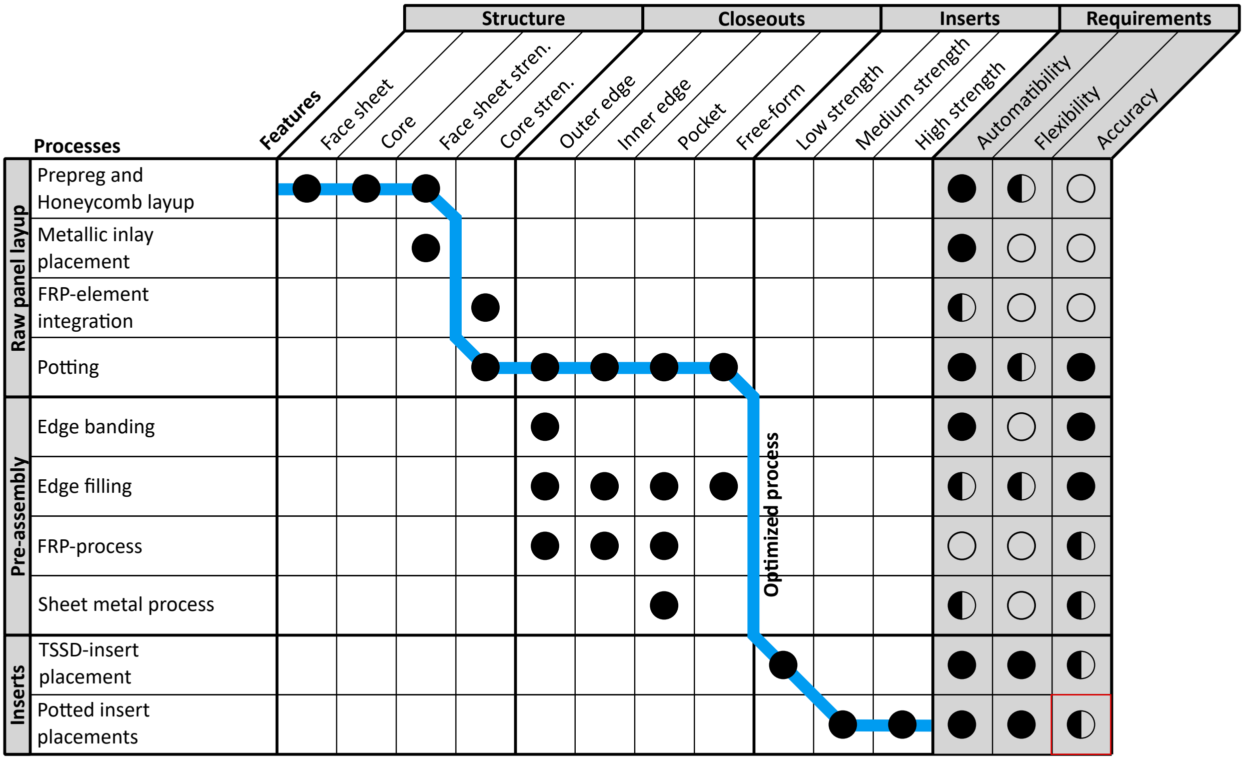

Fig. 4. Evaluation matrix

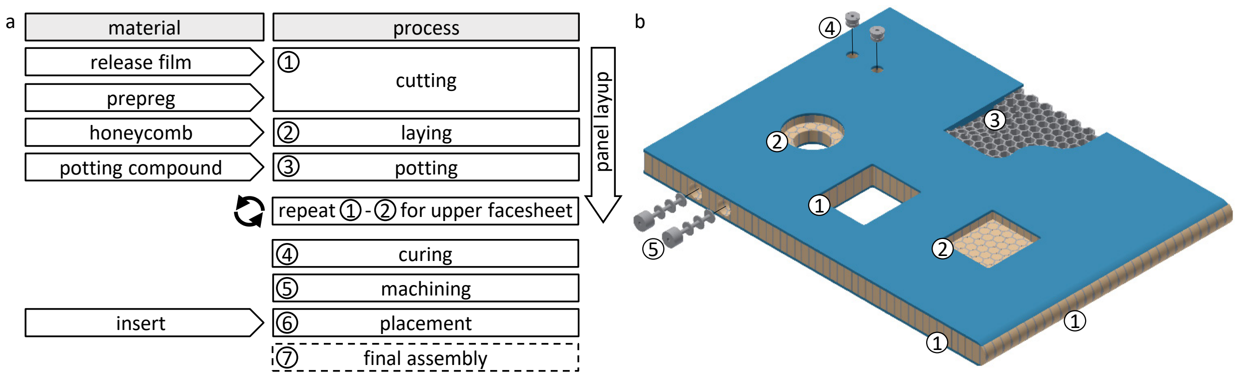

Fig. 5. (a) optimized process chain, (b) optimized panel: (1) inner edge, (2 pocekt, (3) facesheet strengthener, (4) low stength insert, (5) high strength insert)

with subsequent machining offers great freedom of panel geometry, only by changing machine programs. Thereby, the effort associated with individual parts and products is shifted to the digital domain. Machining programs can be easily generated with widely established CAM-software. Automated path planning for handling devices, such as industrial robots, is a current field of research. Due to the 2D-geometry of the raw panels, automated path generation for potting and cutting is comparably simple. The machining of potted honeycomb allows a higher accuracy, than machining of panels without potting. Therefore, the accuracy of the panels is expected to increase significantly. This enables precise insert placement, which is the foundation for the efficient mounting of components and sub-assemblies in subsequent assembly phases. However, since the potting compound is integrated before curing, it is effected by the panel distortions during the curing process. Although this does not alter the accuracy achieved during machining, panel weight might increase, if large safety margins have to be added to the potting paths. Therefore, further examination of the component distortions, especially in potted panels, is needed.

Besides these improvements during panel production and the first phase of pre-assembly, the introduced process chain yields potential for further improvements during subsequent pre- and final-assembly. It is expected, that the precise panel contours allow joining without further tolerance compensation. Furthermore, the amount of jigs required to position components in the raw honeycomb core during bonding will be reduced significantly.

The benefit of support systems for worker guidance, as well as automated assembly systems in the aviation industry has been repeatedly shown [16, 24, 47]. The shift to digital production processes enables the suppliers of aircraft interior to adopt such technologies, not only during manufacturing, but also throughout final assembly. Furthermore, it sets the basis for a consistent, digital process chain with digital product models for the entire development and production of aircraft interior.

5. Conclusion

In this paper an optimized process chain for the automated production of highly individualized sandwich structures for aircraft interior has been developed. To achieve this, a process analysis was carried out. Afterwards, necessary panel features where derived and the processes where evaluated regarding automatibility, flexibility and accuracy. The optimized process chain is based on automated cutting and layup of prepregs, as well as potting and machining of the sandwich panels. With this process combination the process chain was greatly simplified, due to the elimination of redundant processes and manual rework. The processes are easy to automate, highly flexible and accurate. This allows to manufacture all sandwich panels for aircraft interior, with highly individualized geometries and high quality, in a standardized, automated and highly productive process chain. Furthermore, this creates a basis for the standardization and automation of the subsequent assembly of interior components and leads the way for and end-to-end digital aircraft interior production.

6. Future work

In order to use the potential of the process standardization developed in this work, existing plant concepts for the presented process chain must be implemented. To achieve a complete digital interior production, first, the assembly processes have to be analyzed with respect to the optimized process chain. Integration of support and automation systems during assembly yields further potential for increased productivity. Afterwards a concept for continuous digital cabin production must be developed based on existing research on path planning, process digitization, CAM- and assembly-planning systems.

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