INVESTIGATIONS OF VARIOUS SANDWICH MATERIALS AND PROCESSES WITH RESPECT TO AEROSPACE APPLICATIONS

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Abstract
Composite sandwich structures offer excellent lightweight properties for the aerospace industry. Up to today most sandwich structures are based on fibre reinforced thermoset composite skins, which are adhesively joined to core structures. Among these sandwich structures the most common combination are carbon-fibre reinforced epoxy based prepreg skins, which are adhesively bonded to an Aramid/Phenolic honeycomb core by means of an epoxy film. However, the production cost of prepreg and honeycomb based sandwich structures are high, since the production is time consuming and the production method requires high machine investments such as an autoclave.
In this study two different production approaches, namely the resin infusion technology of thermoset materials and fusion bonding of thermoplastic materials, are introduced, which show high potential to lower the manufacturing costs while featuring sufficient performance for certain aerospace applications. The different sandwich structures are compared and evaluated in terms of performance to weight ratio. In addition, production-time estimations are performed according to laboratory scale results.

1. Introduction

Due to the excellent performance to weight ratio, a wide range of sandwich structure is applied in the aerospace vehicles of the Airbus Group. In aircrafts typical external sandwich structures are aerodynamic fairings, covers and doors (1,2). Some examples are radomes, belly fairings, leading and trailing edge fairings, engine cowlings and landing gear doors. Applications in the inside of an aircraft are fairings and floor panels (3). Figure 1 shows exemplary sandwich applications in the A380 aircraft (2).

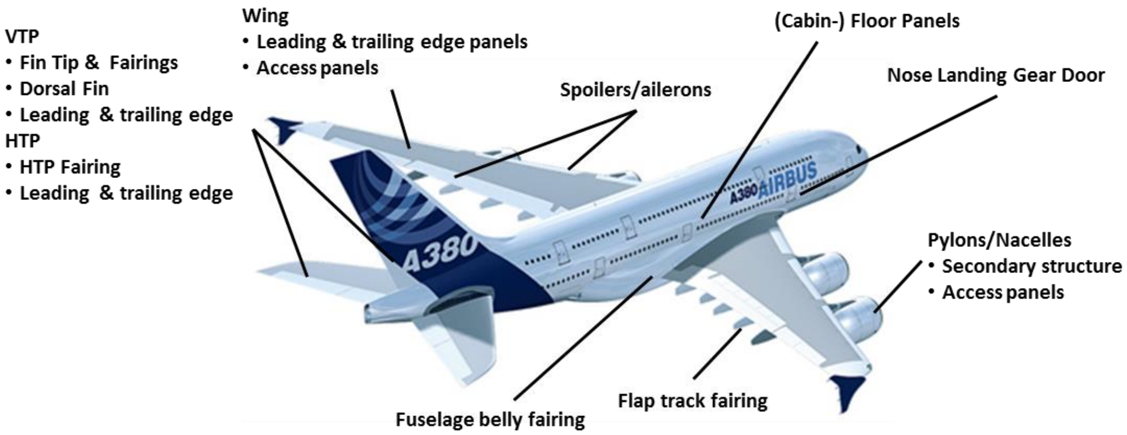

Figure 1: Sandwich structures in the Airbus aircraft A380 (2)

In helicopters sandwich structures can be found for example in floor panels, cowling, beams and frames and rotor blades (4).
As displayed with these examples, the requirements for sandwich structures in aerospace vehicles are diverse. External structures have to withstand high operational temperatures and high aerodynamic loads. Exemplarily radomes and fairings face local impacts such as bird strike, hail, etc. (2).

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Internal structures must mainly meet the FST (Fire Smoke Toxicity) requirements, though they also have to withstand discrete loads caused by passengers such as high heel shoes (2).
To fulfill each specific requirement different materials can be combined and the sandwich structure can be customized for the application. Skin materials can be metal, aluminum or fibre reinforced materials. For the core, structures such as foam, balsa wood, textile, corrugated and honeycomb structures can be applied (2,5). However, up to today predominated skin materials are glass fibre or carbon fibre reinforced prepreg (pre-impregnated) materials with epoxy or phenolic resins. As the core material mostly honeycombs, especially Aramid/Phenolic honeycombs traded as Nomex®, are applied even though they are overdesigned and too costly in some cases.

1.2 Sandwich structures with honeycomb cores

Nomex® honeycomb cores are most prevalent in aerospace applications (2–4,6). They consist of Aramid paper which is impregnated with a phenolic resin (1,6). Nomex® honeycomb cores feature excellent stiffness and strength characteristics and have positive FST properties for interior applications (3). In spite of the excellent performance and the wide background of knowledge about handling these core structures, honeycombs also bring various drawbacks along. Due to the hexagonal structure honeycombs feature an anisotropic behavior, which can lead to a loss of the superior performance to weight property if filling or potting is necessary (3). In addition an adhesive film or surplus resin needs to be applied to ensure a strong bond between core and skins leading to a further weight increase. Besides the high raw materials prices (3), honeycomb structures require costly and frequent maintenance since the honeycomb may fill up with water under certain circumstances such as porous surface skins (1,4). The water freezes and expands at low temperatures in high altitude and can thereby damage the honeycomb cells (1).
In addition, surface recesses, referred to as telegraphing, can be caused by the hexagonal structure of the honeycomb cores and therefore production times and costs are increased since extremely thin skin surfaces (for example in interior applications) have to be prepared additionally (3).
Moreover, the production of honeycomb core sandwiches is time and cost intensive. Already the first production step, forming of the core, is labor intensive. Since honeycombs are hard to form into complex parts they have to be shaped or machined respectively (3). After preparing and draping the prepreg stacks and adhesive layers, a vacuum bag-set up, has to be installed in a manual labor step. The production process is followed by the curing cycle, which is mostly done in an autoclave and takes up to 6 hours (see Figure 2).

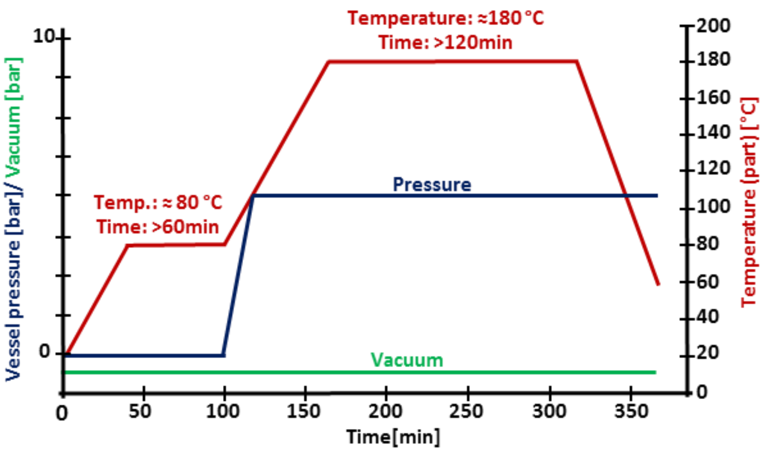

Figure 2: Autoclave cycle for manufacturing of Nomex® based sandwiches

2. Goal

Hence, it is not surprising that there is an increasing demand for new cost-effective production technologies for sandwich structures which are suitable for aerospace vehicles.
In this paper Airbus Group Innovations is presenting two different approaches based on foam cores, which are seeking to be alternatives for Nomex® honeycomb sandwiches in certain applications.

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Since Nomex® honeycomb core sandwiches are performance-wise hard to beat (7), the two approaches aim to realize sandwiches, which are suitable for given aviation application where Nomex® sandwich structures are overdesigned and too costly.
Therefore, the focus of these investigations is to manufacture sandwiches which fulfill the requirements of certain aviation applications while reducing the cycle times and the sandwich weight. As a first step to evaluate the quality of the sandwiches only the skin to core adhesion strength is tested in this study. The focus of the evaluation of the sandwiches lies on the production cycle time, which influences the manufacturing costs significantly.

3. Sandwich structures with foam core

Foam cores are already used in the aviation industry, though they find fewer applications than honeycomb structures. A good example for a successful application of foam cores are Polymethacrylimide (PMI) foams in rotor blades (4). In general, foam cores feature a lower mechanical performance than honeycomb structures but they are in general cheaper as displayed in the Figure 3. In (7) a detailed comparison of some foam and honeycomb sandwiches for aviation applications, all produced by means of an autoclave, is given.
Besides the lower price, foam core structures offer further advantages. Closed cell foam cores feature an even distribution of pores leading to an isotropic behavior. In addition the closed cell structure leads to minimal water absorption. Moreover, foam cores can be shaped easily and in case of thermoplastic materials even thermoformed.

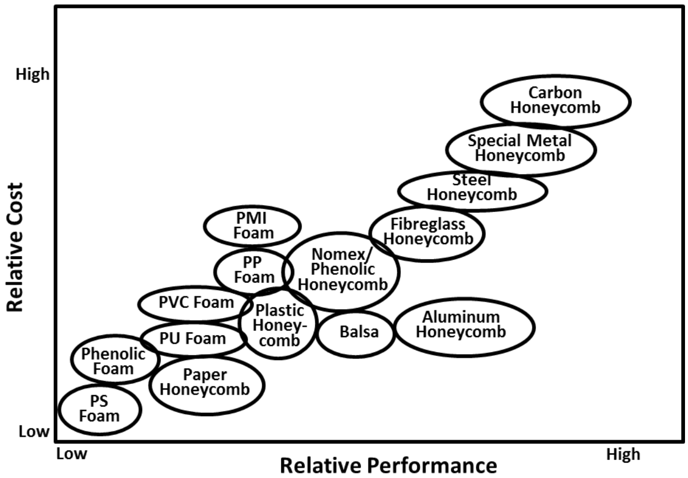

Figure 3: Cost vs. performance of core materials (6)

There is a wide range of different foam cores available, though only a few are suitable for the aviation industry. In the following sections two manufacturing approaches are presented, which make use of PMI foam cores and Polyetherimide (PEI) foam cores, both suitable for the aviation industry.

3.1 Resin infusion sandwich structures with a PMI foam core

Resin infusion technologies offer the possibility to produce monolithic composite parts and composite sandwich structures with a high quality, while reducing production and investment costs compared to the prepreg technology. Today, novel and modern infusion technologies enable the production of composite structures, which feature a similar quality as achieved with prepreg technology (8,9).
There is a wide range of infusion technologies, which only differ slightly. In general, the dry fibres are draped into the mould, followed by the infusion of the resin. Often a binder material is applied to keep the draped fibres or textiles, referred to as preform, together. A distinguishing mark of infusion technologies is the design of the mould. Infusion technologies can be realized with an open or closed mould (8,9).
In this investigation a closed mould infusion technology, namely resin transfer moulding (RTM), is used. RTM is mostly used when smooth surfaces on both sides are required (e.g. aerodynamic or interior parts). In addition, higher pressure compared to an open mould technology can be applied

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allowing a speed up of the infusion. Moreover, due to the both-sided formative mould smaller and more reproducible tolerances and part thicknesses can be achieved (8–10).
It is the goal of these investigations to establish the RTM process for the production of sandwich structures with reproducible and high quality. To investigate and evaluate the quality, the sandwich structures are tested mechanically and compared to Nomex® based sandwich structures produced by autoclave curing. In addition, the process shall be optimized with respect to manufacturing time and cost. Therefore a production cycle time comparison is carried out.

3.1.1 Materials

The skins consist of three plies of a plain fabric by Hexcel Corporation, which are stabilized both-sided by 5g/m² binder. The plain fabric is characterized by the use of 12K spread carbon fibre tows, so that undulations are reduced. The fabric's areal weight is 220g/m². An epoxy based thermoset by Hexcel Corporation is used as matrix resin. Epoxy based resins are common for aviation applications and often used for infusion technologies since it is features a high glass transition temperature of about 183°C. For the core two different versions (see Table 1) of the PMI foam (Rohacell®) by Evonik Industries AG are used. The foams feature closed cells and show a high elongation at break. A foam height of 15mm is chosen.

Table 1: Densities of Rohacell® foams

Typ	Density [g/dm³]
Rohacell® Typ1	82.7
Rohacell® Typ 2	67.2

Nomex® based sandwiches are selected as reference. The skins are made by stacking of three epoxy based prepreg plies by Hexcel Corporation. The prepreg plies consist of a satin fabric with a fibre areal weight of 220g/m² and an epoxy based matrix. The fibre volume content amounts to 55 %. For the core, a Nomex® honeycomb by Euro-Composites®, featuring a density of 48kg/m³ is chosen. The height of the core materials is 15 mm, as well. The skins are adhesively bonded by means of an epoxy based film by Cytec industries Inc.

3.1.2 Manufacturing process

In the first step, the fabrics are cut and then draped manually and kept in position by means of a vacuum bag. Then the preform is stabilized in an oven for approximately 20 min at 120°C to activate the binder. Subsequently, the polymer and the mould are heated. Then the preform and the core are placed into the mould. By means of 3 bars pressure and a preheat temperature of 140°C the matrix polymer is injected, before being further heated up to 180°C for curing. Finally, the mould is cooled down for demoulding. In Figure 4 the process cycle is displayed. The infusion process takes around 3.5 hours. For the preform process, additional time for cutting the plies, stabilization of the preform and machining the core has to be added. Moreover, labor time for installation of the tool and post-processing has to be considered.

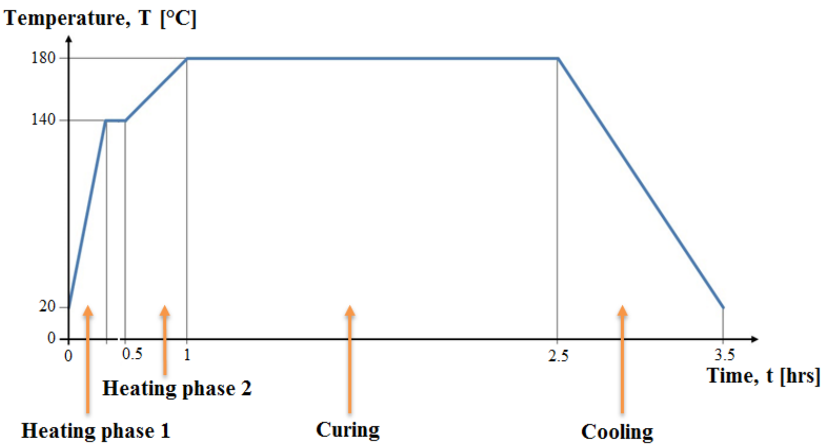

Figure 4: Cycle time for the infusion process

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The manufacturing of the reference sandwiches based on Nomex® honeycomb cores are performed according to Figure 2, which takes up to 6 hours. Times for cutting, draping the plies and machining the core can be assumed to be equivalent to the preparation times for the infusion sandwiches except stabilizing the preform is not necessary.

3.2 Thermoplastic composite (TPC) sandwich structures with a PEI foam core

The introduction of thermoplastic materials for sandwich structures seems promising due to lower manufacturing costs, a better environmental sustainability and better mechanical properties such as damage tolerance (11–13). In order to produce TPC sandwich structures of sufficient quality, a good bond between skins and core needs to be achieved (13). An appropriate joining method for thermoplastic materials is fusion bonding, which is based on intermolecular diffusion of the polymers of the components, also referred to as adherents, to be joined (14). A fusion bonded joint can compete with the bulk properties of the adherents (15,16). Additionally, fusion bonding can be performed in short cycle times and requires only minimal surface treatment (17). In theory, fusion bonding of thermoplastic composite skins and thermoplastic core structures of the same polymer should be readily possible according to the autohesion theory (18). However, several researchers have highlighted some challenges such as core collapsing or skin lofting (13,19).

Compression moulding of composite sandwich panels with fibre reinforced polyethereterketone (CF/PEEK) skins to a PEI foam core is the subject of present investigations. Due to its good mechanical properties and excellent chemical and high temperature resistance, the polymer PEEK meets most of the requirements for the aviation industry (20). PEI, employed as the foam core polymer, also offers excellent mechanical properties, though some drawbacks concerning chemical resistance (e.g. against Methylethylketone) exist (20). PEI is also suitable for high temperature applications. According to the literature PEEK and PEI can form a fusion bond since they are compatible on molecular level (21).

3.2.1 Materials

The considered skin material consists of two CF/PEEK 4HS fabric (220g/m²) plies by Porcher Industries and two plies of CF/PEEK UD tapes (145g/m²) by Toho Tenax. The surface is enriched with a 125µm thick PEI film by Lipp Terler. For the core structure, PEI foam provided by Gaugler and Lutz oHG is used. The foam features a density of approximately 64 kg/m³ and the chosen height is 19 mm.

3.2.2 Manufacturing

For manufacturing of sandwich structures by fusion bonding, the skins as well as the core, precisely the core surface, need to be molten and joined under pressure. However, at temperatures above 343 °C the CF/PEEK skins tend to deconsolidate and deform and the core collapses. At temperatures below 343°C fusion bonding is not taking place and the bonding strength is insufficient.

To enable the fusion bond between these two adherents the sandwich manufacturing by compression moulding is adapted to the idea of the “thermabond process” according to (22). The basic idea of the thermabond process is that thermoplastic (preferably semi-crystalline polymer) composite parts are bonded by the aid of a second polymer system (preferably amorphous). However, the second polymer is not applied as a hot melt film, but rather a cohesive bond between the two polymers is created. Therefore the thermoplastic composites skins (CF/PEEK), which shall be joined to the core, are superficially enriched with the second polymer system (PEI). This can be done during the consolidation process of the skins, taking up approximately 3 hours, including material preparation, tool installation and post-processing.

In the following step the two parts are to be joined are fusion bonded by means of heat and pressure. The surface-layer (PEI layer) is heated sufficiently above the softening temperature ($T > T_g$(PEI)) to enable molecular diffusion, but still below the melting temperature of the composite polymer ($T < T_m$(CF/PEEK)). The physical and mechanical properties of the composite are therefore not compromised. The joining process is illustrated in Figure 5.

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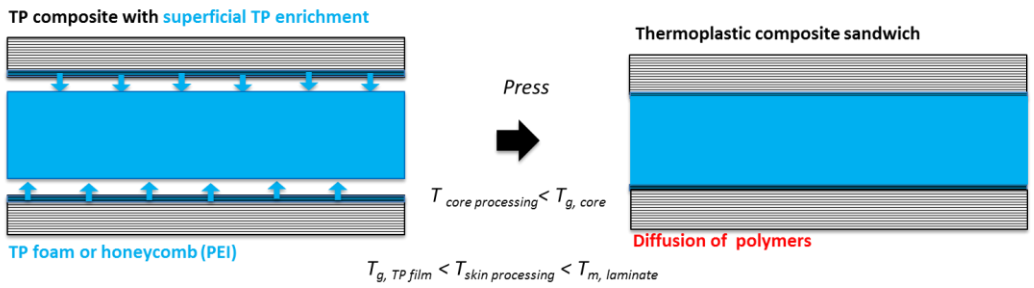

Figure 5: Fusion bonding process of CF/PEEK - PEI Sandwiches

By adapting the “Thermabond” process, CF/PEEK skins and the PEI core can be joined in the temperature range T_g(PEI) < 300°C – 335°C < T_m(PEEK). The viscosity of PEI is low enough for molecular diffusion. PEEK still shows a high form-stability in this temperature range and the mechanical properties are not compromised. The core is compressed during the process by 2 mm on each side resulting in a final core thickness of 15 mm. The fusion bonding process takes around 3 minutes and heating of the skins depending on the heating process between 5 and 45 minutes.

4. Testing

To determine the skin-to-core bond quality of the sandwiches, two mechanical tests are performed. First the tension test in flatwise plane according to DIN 53292 is conducted. Second the drum-peel strength according to DIN EN 2243 is determined.

5. Results

In Table 2, the areal densities of all investigated sandwiches are presented. Although the densities of the Rohacell® foam cores are higher than of the Nomex® core density, the foam based sandwiches feature the lowest overall areal density (reduction of up to 15%). The higher mass of the Nomex® based sandwich can be explained by the need for the application of the adhesive film. The thermoplastic sandwiches feature an even higher areal density (increase of 11% compared to the Nomex), which is caused by the application of the UD plies, the PEI film and the core compression.

Table 2: Areal densities of sandwiches

Skin	Core	Areal density [kg/m²]	
Epoxy prepreg	Nomex	3.382	100 %
Dry fabric + epoxy resin	Rohacell® Typ 1	3.125	92 %
Dry fabric + epoxy resin	Rohacell® Typ 2	2.861	85 %
CF/PEEK fabric + UD	PEI foam	3.775	111%

The results of the mechanical testing are presented in Figure 6 and Figure 7. The Nomex® based sandwiches feature the best tensile strength, but only a slightly higher tensile performance compared to the foam sandwiches. However, all tested sandwiches failed within the core, which indicates that, the skin-to-core-bond is stronger than the core itself.

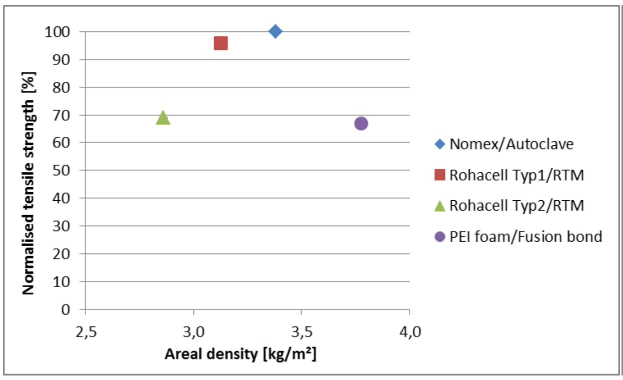

Figure 6: Tensile strength

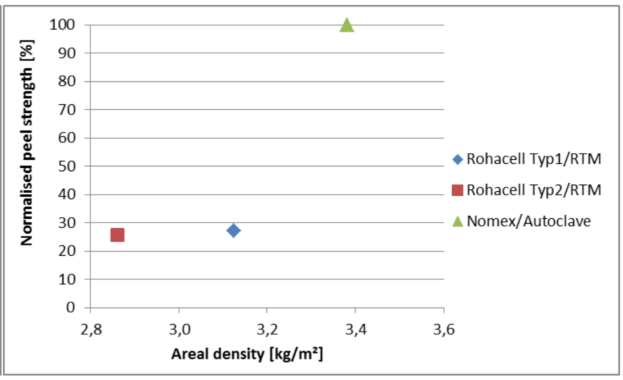

Figure 7: Drum-peel strength

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The skin to core bond quality is therefore sufficient. The drum peel test results show the superior performance of the Nomex® based sandwiches compared to the foam sandwiches. The peel strength is approximately five times higher than for the Rohacell® foam sandwiches. However, the peel strengths of the Rohacell® sandwiches fulfill the requirements of given sandwich applications and are therefore sufficient for the application. Due to a machine failure, TPC sandwiches unfortunately could not be tested.

In Figure 8 the cycle times for the production of the sandwiches by means of the different approaches are displayed. The investigations show that by application of the two approaches the cycle times can be decreased significantly. The infusion approach leads to a reduction of the cycle times of up to 24%. By applying thermoplastic materials a cycle time reduction of 46 % can be achieved. The results are based on a laboratory scale, which means that most steps are performed manually and some deviations are expected when the approaches are adapted for a serial production. In addition, some manufacturing steps such as cutting fabric plies or shaping the core are assumed to be equivalent for all approaches. By taking a deeper look into the single manufacturing steps it is noticeable, that for the prepreg and the resin infusion approach the "Manufacturing process" is the most time-consuming step. During this step, the resin has to cure at a high temperature. For the TPC approach, the sandwich "Manufacturing process" is done in a couple of minutes, since the skins only have to be heated up, stacked with the core and joined under pressure. The fusion bonding process, performed non-isothermally in this case, runs in a matter of seconds. For the TPC approach the consolidation of the skins is the most time-consuming step, since the material placed in a heavy metal tool has to be heated up to 400°C, held for some minutes and then cooled down.

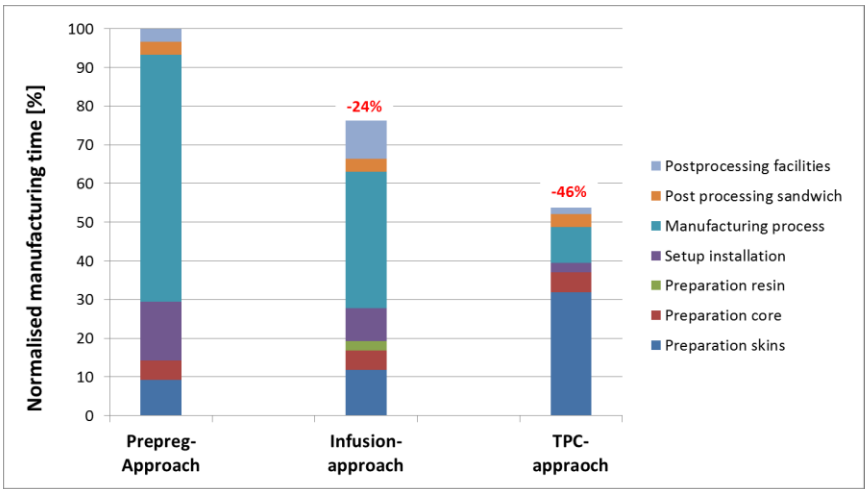

Figure 8: Comparison of manufacturing cycle times

6. Conclusion

Sandwich structures find a wide range of applications in the aerospace industry. The most prevalent sandwich structures are based on carbon fibre reinforced prepreg skins and Nomex® honeycomb cores. In some published investigations it was shown that sandwich structures with a Nomex® honeycomb core are weight-performance-wise hard to beat. However, for some applications, the Nomex® based sandwiches are overdesigned and therefore too heavy and too costly due to their manufacturing times. In this paper two approaches, taking advantage of foam cores, were presented. Sandwiches are realized on the one hand by resin infusion and on the other hand by fusion bonding of thermoplastic materials. Both approaches lead to high quality sandwiches, which are characterized based on the skin-to-core bond strength in a first step. Tension testing in flatwise plane showed that all foam sandwiches fail within the core structure, drum peel testing lead to sufficient peel strength results, although the peel strength is significant lower compared to honeycomb sandwiches. In addition, the infusion process enables the reduction of the areal density of up to 15% and of the manufacturing cycle time of up to 24%. The application of thermoplastic materials leads to a cycle time decrease of up to 46% due to the omission of the time consuming resin curing step. However, up to now the manufactured TPC sandwich structures feature an increased areal density.

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