# VACUUM ASSISTED INDUCTION WELDING FOR ALL-THERMOPLASTIC SANDWICH PANELS ASSEMBLY

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## ABSTRACT

Vacuum assisted induction welding (Vac-IW) method for the assembly of all-thermoplastic sandwich panels is presented, providing a new method to produce lightweight, high-performance, and thermally insulative sandwich panels. Samples are placed in a vacuum bag to ensure constant and homogeneous pressure application during the welding process. An induction coil moves at fixed speed above the sample to perform induction welding. Heat at the welding interface is generated by direct heating in CF/PEEK skins, or by placing a susceptor material at the skin/core interface when using GF/PEEK skins. PEI films are co-consolidated at the surface of PEEK skins to facilitate welding with the 3D-printed PEI honeycomb core. Welded samples are tested using the flatwise tensile (FWT) test to assess the skin/core strength. For both types of skins, samples welded at the optimal speed reached strength between 5 and 7 MPa, which surpasses the FWT strength reported in the literature for polymeric honeycomb sandwich panels. Vac-IW method can be used with both heating mechanisms, depending on the electrical nature of the laminate reinforcement, and is promising to assemble all-thermoplastic sandwich panels for various applications.

## 1 INTRODUCTION

The goal of reducing the mass of structures is one of the reasons for the increase in use of composite components. In automotive and aeronautic applications, the main objective is to reduce fuel consumption and the associated pollution and $CO_2$ emissions. In the space industry, minimizing the mass helps to reduce the launch cost. Composite materials are good candidates for these applications, especially composite sandwich structures, which offer high flexural strength and compression resistance for a minimal mass.

### *1.1 Sandwich structures*

A sandwich panel is made of a low-density core – a polymeric foam or a cellular structure made of aluminium, Nomex or polymer – placed between two high-strength skins (or facesheets) – typically in aluminium or in fibre-reinforced thermoset composites [1]. The parts are typically bonded together with an oven-cured adhesive film. Recently, an increasing interest is observed in thermoplastic composites, because of their high toughness and impact resistance, their unlimited shelf life, and their weldability [2]. They also present a good potential to be recycled [3] and repaired [4]. These materials can be used in sandwich panels to replace metallic parts. All-thermoplastic sandwich panels cumulate the presented advantages of the classical sandwich with those of thermoplastic materials [5]. The use of thermoplastic-based cores also allows for alternative manufacturing methods, such as additive manufacturing [6].

Compared to thermoset composites, the assembly of thermoplastic composite parts can be challenging, as adhesive bonding typically requires extensive surface preparation to reach limited mechanical strength [2]. When it comes to all-thermoplastic sandwich panels, fast and reliable skin/core assembly methods must be developed. Thermoplastic welding can be used as an alternative to adhesive bonding, thanks to the fusible nature of thermoplastic polymers. Various thermoplastic welding techniques have been developed, relying on thermal, friction or electromagnetic heat dissipation mechanisms [7].

### *1.2 All-thermoplastic skin/core welding*

To assemble all-thermoplastic sandwich panels by thermoplastic welding, the skins are typically pre-heated in an oven and then transferred in a vacuum bag or a hot press where they are placed on the core and where the required welding pressure is applied on the structure [8]. The use of a hot press is advantageous as it can reach higher pressures, it can pre-heat the core and/or maintain heat on the parts during joining, and the transfer can be more easily automated, which minimizes temperature losses [8]. The heat lost during parts transfer requires overheating the skins to maintain a sufficiently high temperature when the sandwich panel is assembled; this overheating however can lead to laminate deconsolidation. Double-belt lamination is another method to manufacture thermoplastic composite sandwich panels. In this method, the sandwich parts are guided through heating elements by two belts and the joining interface is heated up by conduction through the skins [9]. The advantage is that the process is continuous, but the temperature must be closely monitored to avoid core crushing.

Thermal welding methods present challenges, mostly caused by the fact that the heat source is located outside of the sandwich panel, requiring to heat up the whole part to reach the desired temperature at the joining interface. To better localize the heat dissipation, it is interesting to explore other methods such as induction welding.

### *1.3 Induction welding*

One of the commonly used thermoplastic welding methods is induction welding, which relies on the application of an alternating magnetic field on the joining interface to melt or soften the surrounding thermoplastic and consolidate a bond under pressure. Heat is generated at the welding interface through two mechanisms: induced eddy currents in electrically-conductive materials, which heat up by the Joule effect, or hysteresis losses in a magnetic material called a susceptor.

When electrically-insulative materials such as glass fibre (GF)-based composites are used as sandwich skins, the use of a susceptor is required to dissipate heat at the joining interface. It can be either a conductive mesh that will experience induced eddy currents, or magnetic particles dispersed in a thermoplastic polymer film [10]. The magnetic susceptor is less invasive than the continuous mesh, is typically lighter, and exhibits a coefficient of thermal expansion closer to the surrounding parts.

On the other hand, carbon fibre reinforced composites can be welded without using a susceptor due to their electrically-conductive nature [11]. This process is known as susceptor-less welding. As an alternating magnetic field is applied to the laminate, eddy currents are induced in the carbon fibres, which heat up due to the Joule effect. This heat dissipation can be used to melt the polymer at the skin/core interface and perform welding. However, when eddy currents are induced in an electrically-conductive material, the current paths form loops. As the induction coil approaches the edges of the material, these loops are compressed, locally increasing the current density, therefore inducing large heat generation [12]. This phenomenon causes non-homogeneous heating at the joining interface and must be minimized.

This paper aims to demonstrate the use of a novel vacuum assisted induction welding (Vac-IW) method to assemble all-thermoplastic sandwich structures with either electrically-conductive or insulative composite facesheets. The present paper highlights the working principle of the method and how it can be used with both types of fibre reinforcement in the laminate skin. It then validates the quality of the welds by flat wise tensile tests to obtain the strength of the skin/core interface.

# 2 METHODOLOGY

## 2.1 Samples manufacturing

Composite laminates are manufactured using carbon fibre reinforced poly-ether-ether-ketone (CF/PEEK) unidirectional tape (Tenax®-E TPUD PEEK-HTS45 from Teijin), and glass fibre reinforced PEEK (GF/PEEK) unidirectional tape (APC-2/S2 Glass from Solvay), both in a $[0,90]_{2S}$ lay-up sequence. A 100 µm thick layer of poly-ether-ether-imide (PEI, ULTEM 1000) is added at the surface of the laminate before consolidation, following the Thermabond process [13], which allows for the weld to be conducted at the PEI welding temperature, which is lower than the melting point of PEEK, avoiding the risk of deconsolidation in the laminate. Consolidation of the laminate is conducted in a hot press for 20 min at 380°C and 2 MPa. The resulting 8-plies laminates exhibit a total thickness of 1.1 mm, with a co-consolidated surface layer of PEI allowing welding to occur with PEI honeycomb cores. The GF/PEEK laminates are cut in 5 cm x 5 cm squares to be used as sandwich skins. As CF/PEEK laminates experience edge effects on the side edges in presence of the magnetic field, they are cut into 5 cm x 6.25 cm rectangles to be used as skins. Excess material is trimmed after welding to obtain the final 5 cm x 5 cm sandwich sample.
The honeycomb cores are manufactured by 3D-priniting using an AON3D M2 printer equipped with a 0.4 mm nozzle. They have a surface of 5 cm x 5 cm and a total height of 11 mm, including a 1 mm thick bottom skin, also 3D-printed in PEI. Hexagonal honeycomb cells have a side length of 4 mm and cell walls thickness of 0.8 mm (Figure 1). The material used for 3D-printing is an ULTEM 1010 filament (3DxTech).
To weld the GF/PEEK facesheets, a PEI/Ni-10%vol susceptor is produced [14]. PEI pellets (ULTEM 1010 from Sabic) and Ni particles (from Sigma-Aldrich, mean diameter 5 µm) are mixed in an internal mixer for 5 min at 320°C after having been dried for 4 h at 150°C. The compounded material is then pressed into films using a hot press at 320°C. The resulting films (approximately 0.6 mm thickness) are cut into 5 cm x 5 cm squares to be placed between the skins and the core to perform the induction welding process, as presented in Figure 1.

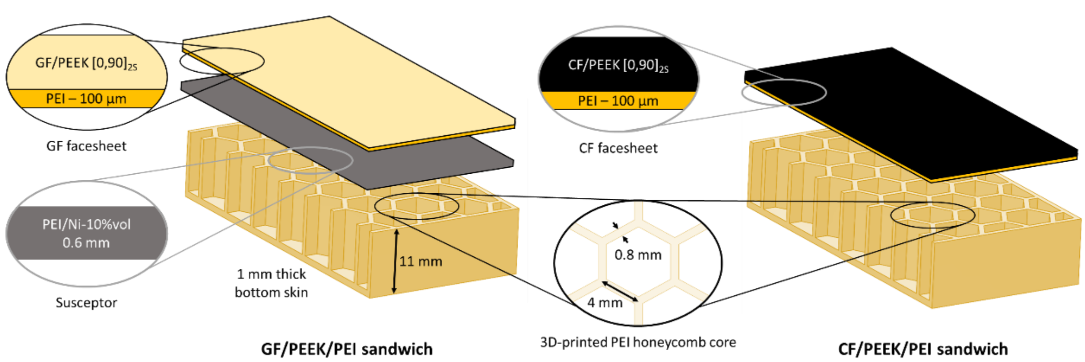


Figure 1. Schematics of GF/PEEK/PEI and CF/PEEK/PEI sandwich samples.

### 2.2 Continuous induction welding setup

To weld GF/PEEK and CF/PEEK skin to 3D-printed honeycomb cores, pressure must be applied on the sample during heating and cooling to ensure the complete development of the welding degree. To ensure the continuous application of pressure throughout the process, the sample is placed inside a vacuum bag, as presented in Figure 2. Then, the induction coil moves relative to the sample in a linear movement at a constant speed. The skin progressively heats up along with the core located close to the interface. The sample is kept under pressure after the passage of the coil until it cools down. This vacuum assisted induction welding technique (Vac-IW) is a continuous process allowing to weld by induction the sandwich panel under a homogenous and constant pressure.

### 2.3 Sandwich structures characterization

Skin-core strength of the welded sandwich samples is characterized by performing flatwise tensile (FWT) tests, following standard ASTM C297. Steel blocks are adhesively bonded to each side of the sample and fixed to the testing jig mounted on the tensile test machine. Stress at failure, obtained by dividing the at failure by the sample's surface area, is reported as the skin/core strength. Fractured samples are then observed to determine the dominant failure mechanism.

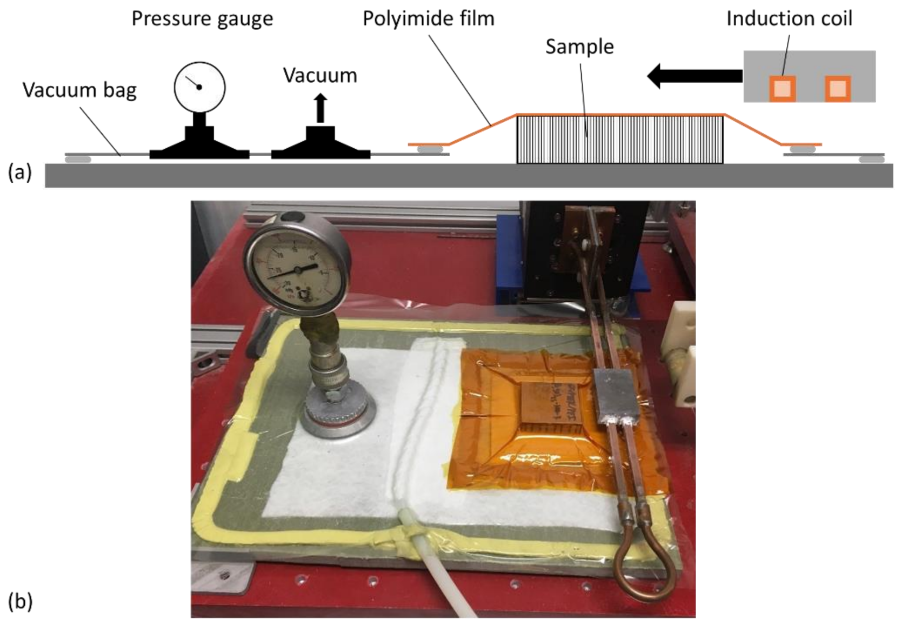


Figure 2. (a) Schematic and (b) picture of the vacuum assisted induction welding (Vac-IW) setup. Reproduced from [14].

## 3 RESULTS

### 3.1 GF/PEEK skins

Skin/core strength of sandwich samples made of GF/PEEK skins is reported in Figure 3a. The strength increases when the welding speed decreases, which is explained by the fact that the sample remains longer under the coil when moving slower, giving it more time to heat up. Strongest samples were welded at 0.5 mm/s and reached around 6 MPa in FWT tensile strength, which is higher than what is reported in the literature for adhesively-bonded sandwich panels with polymer cores (around 5 MPa [15]). The skin/core welding properly occurred and can be used as an alternative to adhesive bonding. In Figure 3b, one fractured sample welded at 0.5 mm/s is presented, showing a cohesive failure inside the susceptor layer. This indicates that welding occurred, reaching skin/core strengths equivalent to the core failure strengths observed hereafter for the CF/PEEK samples. In Figure 3c, a sample welded at 0.9 mm/s is presented, exhibiting mostly adhesive failure between the susceptor and the core, indicating that the weld could not be achieved at that speed.

### *3.2 CF/PEEK skins*

Similar relationships between the skin/core strength and the welding speed are observed for CF/PEEK skins as for GF/PEEK skins, although it looks less linear in this case. Overall, it appears in Figure 4a that the welding speed range is higher than in Figure 3a, indicating that the direct heating mechanism seems slightly more efficient. The optimal welding speed is 0.7 mm/s, resulting in skin/core strength up to 7 MPa. It must be noted that lower welding speed resulted in core crushing caused by overheating. In Figure 4b, the presented fractured sample welded at 0.7 mm/s shows a failure in the printed core, indicating that the welded interface is stronger than the tensile strength of the printed honeycomb core. On the other hand, at higher welding speeds, adhesive failure is observed, highlighting that the weld did not occur between the skin and the core (Figure 4c).

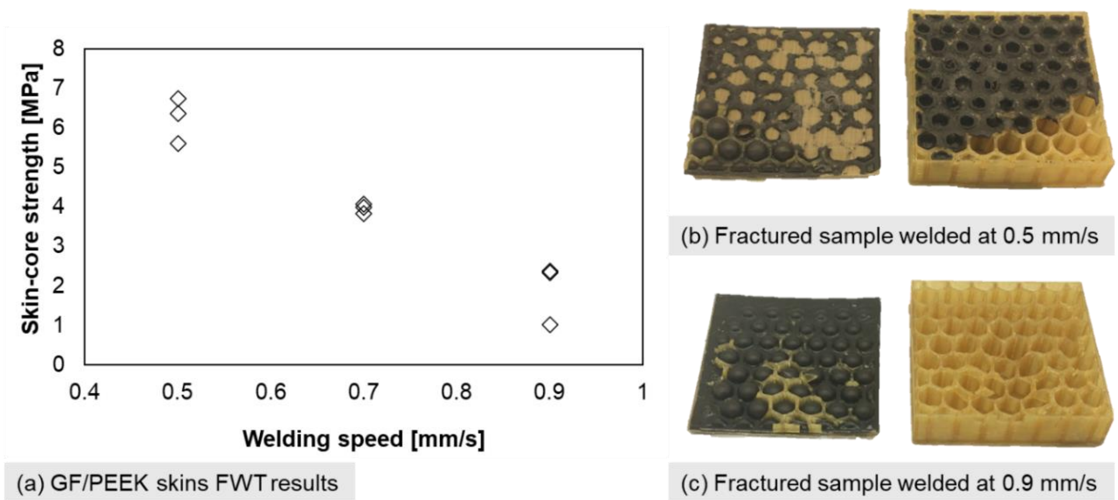


Figure 3. (a) GF/PEEK FWT test results. Fractured samples welded at (b) 0.5 mm/s and (c) 0.9 mm/s are presented.

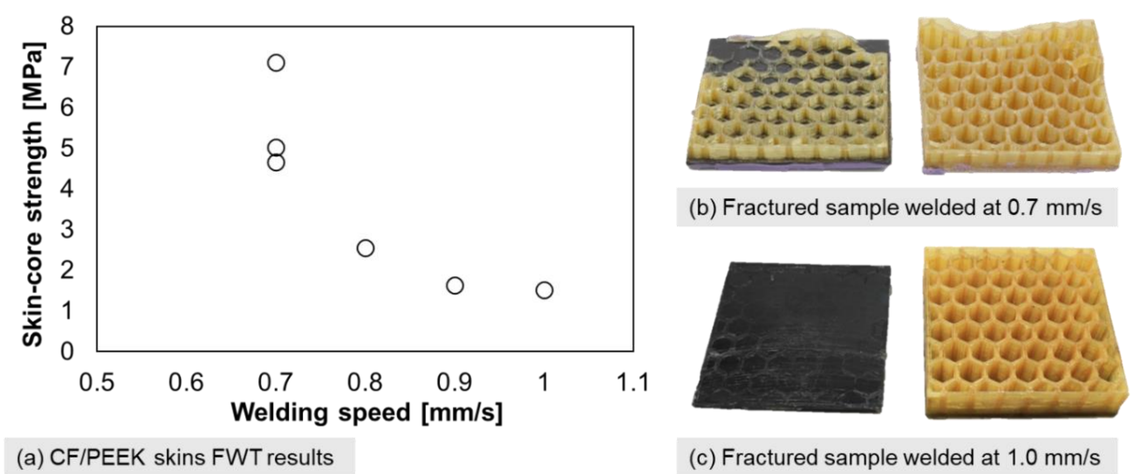


Figure 4. (a) CF/PEEK FWT test results. Fractured samples welded at (b) 0.7 mm/s and (c) 1.0 mm/s are presented.

# 4 CONCLUSION

This paper presents a method to join fibre reinforced thermoplastic skins to honeycomb cores produced by 3D-printing using the vacuum assisted induction welding technique (Vac-IW). The method can be adapted to all-thermoplastic sandwich panels made of electrically-conductive and insulative composites skins. A magnetic susceptor is used with the GF/PEEK skins to generate heat at the welding interface while direct heating of the carbon fibre was used in CF/PEEK skins. FWT tests showed that at the optimal welding speed, both types of sandwich samples achieved a FWT strength of over 5 MPa.

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