1. INDUCTION HEATING FOR AUTOMATED FIBRE PLACEMENT TOOLINGS

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ABSTRACT

While Automated Fibre Placement is a versatile process for manufacturing composite parts, the rapid heating and cooling inherent to the process results in high temperature gradients. When thermoplastic composites with a semi-crystalline matrix are used, high cooldown rates also impede crystallisation processes. Heated toolings can alleviate the problem, but including heating technology in toolings with complex geometries while ensuring a homogeneous temperature distribution is often difficult and requires tools with high thermal mass, which also require more energy to heat and can only achieve slow heating rates. By using flexible induction coils fixed to a thin ferromagnetic metal sheet, a double-curved tooling with induction heating was developed and successfully used in manufacturing composite skin panels. Compared to traditional heating technology, higher heating rates and better energy efficiency could be achieved. The process was accompanied by AFP simulation to predict process induced warping, achieving this with 90% accuracy in the planar regions of the tooling.

2. INTRODUCTION

The usage of fibre reinforced plastic (FRP) in aviation has been increasing for the last couple of decades. However, manufacturers have been hesitant to use FRP in primary structures due to the high mechanical requirements. High performance thermoplastic matrix materials like Polyetheretherketone (PEEK) or Low-Melt Polyaryletherketone (LM-PAEK) can achieve the necessary strength and stiffness, though standard autoclave consolidation of these materials demands more energy compared to equivalent thermosets. Out of Autoclave (OoA) manufacturing processes like Automated Fibre Placement (AFP) can theoretically forgo autoclave consolidation and produce primary structures in a one-step process, but in practice require heated toolings to achieve satisfactory part quality. Many parts in aviation have complex geometries, which complicates the implementation of traditional heating methods like heating cartridges. This can be alleviated by designing toolings with high thermal mass, which are beneficial for a homogeneous temperature distribution but have the drawback of slow heating rates and high energy requirements. In this work, a novel tooling configuration of flexible inductive coils applied to a thin ferromagnetic material is presented to enable AFP of complex geometries without compromising part quality.

2.1 Automated Fibre Placement

By using thermoplastic AFP with in-situ consolidation (ISC), complex FRP parts can be manufactured. A focused heat source, e.g. a laser, melts the thermoplastic matrix of a composite tape and fuses it onto the target structure. The part is built consecutively in multiple additive iterations by means of a high degree-of-freedom robot setup. The highly dynamic nature of the process combined with the inhomogeneous temperature distribution and semi-crystalline matrix material behaviour pose challenges to overcome in order to achieve acceptable part quality. In multiple studies the influence of different manufacturing parameters has been examined [1] [2] [3] [4], with a high tooling temperature shown to significantly improve the part quality.

Toolings for AFP must be accessible by the robot arm which limits the kind of heating which can be used. Infrared heating for example interferes with the space required by the robot. Heating cartridges in contrast require massive toolings and are challenging to adapt to different geometries. Heating blankets are more flexible, but suffer from efficiency issues due to depending on convection to transfer heat to the tooling. Designing an integrated heating inside the tooling conforming to the geometry is very expensive.

2.2 Flexible induction heating

This challenge can be overcome by using flexible induction coils on a thin metal sheet. Induction heating uses an electromagnetic field created by a metal coil to induce electric current in a conductive susceptor material which in turn gets transformed into heat. The heat is created directly in the susceptor structure. The coils themselves only suffer from waste heat.

For optimum efficiency, the coils need to be placed with constant distance to the susceptor, which itself should be designed with a homogeneous thickness. These characteristics usually pose strict design limits on the heating and require a separate heating design process for different toolings. By using a flexible sheet composed of many small induction coils instead of a single large coil, the heating can be draped around arbitrary geometries and can be scaled to different sizes. Previous works on thermoplastic composite repairs focused on developing such a flexible induction heating technology [5]. This work has been expanded upon to develop a method for heating arbitrary large and complex surfaces [6].

3. EXPERIMENTATION

3.1 Demonstrator geometry

To test the viability of the flexible induction heating for AFP toolings, a representative geometry was chosen for the initial tooling. The geometry had to be complex, e.g. multiaxially curved, with an edge length of about 0,9 m. The curvature of the tool must be achievable by the AFP robot. The geometry chosen for the demonstrator represents a skin panel of a generic UAV, shown in Figure 1.

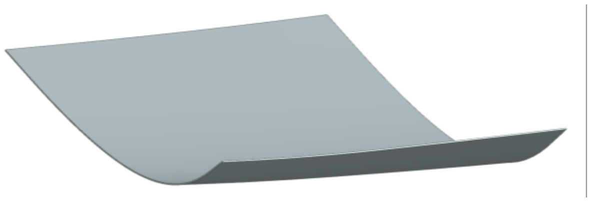

Figure 1: skin panel for the demonstrator geometry

For the usage with AFP, the geometry has been expanded on each side by 100 mm. The path of the robot must not interfere with this extension, so the geometry of the AFP cell had to be taken into consideration.

3.2 Induction coil

The induction heating was developed by msquare GmbH and was initially designed for composite repairs. The initial heating system has been scaled for usage in heated toolings. To adapt the system for this tooling, the coil geometry and the control electronic system have been varied inside defined parameters. The components of the system are shown in Figure 2.

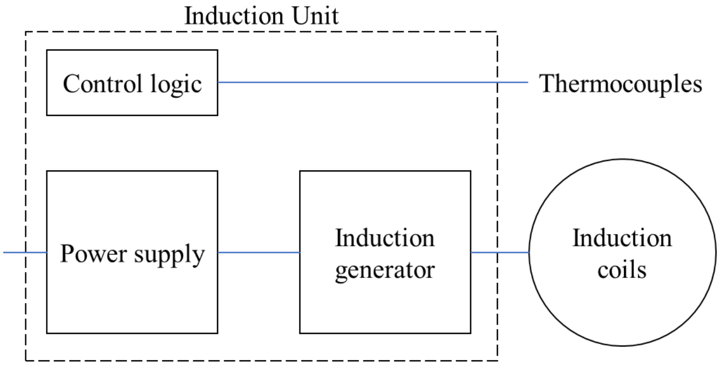

Figure 2: Induction heating schematic

For the tooling, five different coil configurations have been designed and tested. The frequencies of the induction system were varied from 20 kHz up to 400 kHz. The goal of this parametric study was maximisation of heat transfer efficiency and temperature homogeneity. The coils consist of insulated copper wires stitched onto a flexible fabric, e.g. glass fibre fabric.

Figure 3: top: manufacturing of induction coils on glass fibre fabric; middle: induction coils, bottom: infrared camera view of heated structure

Afterwards, the coils were coated with silicon on one side to insulate the coils from the heated structure. To attach the coils on the toolings, a hole was left in the centre of each coil. With the help of threaded rods and nuts, the coils can be fixed onto the structure. However, the corners of the coils also need to be pressed onto the structure to achieve minimal distance between coils and susceptor and improve efficiency and homogeneity. Therefore, a cross-like structure has been designed and manufactured from PTFE to press the corners onto the structure even with curved surfaces. Holes with threads have been added to the fastening elements to add screws in case of a smaller curvature radius. The result is shown in Figure 4.

Figure 4: induction coils with PTFE fastening elements

Each set of coils uses its own induction unit (compare Figure 2). Control over the heating process is achieved with PID-controllers and checked with type E thermocouples, which are more resistant to the EM-fields of the induction coils. Each set of induction coils covers an area of similar thermal behaviour.

3.3 Susceptor structure

3.3.1 Tooling panel

The chosen structure represents a skin panel of a generic UAV. In addition to the requirements mentioned in 3.1, the structure must also be able to withstand temperatures of up to 500° C while also be thermally isolated from the support structure to minimise heat sinks. The mechanical connection between tooling surface and support structure must be flexible enough to allow for different thermal expansions while also supporting the surface against the process loads. Finally, to achieve a homogeneous temperature distribution, the thickness of the tooling surface also must be homogeneous and an even distribution of induction coils must be ensured.

To determine the thickness of the tooling panel and the distance between the necessary support structures, a simple FE-simulation was set up in Ansys 2021R1 and designed around a design-of-experiments-analysis. The FE-model consisted of a rectangular panel which was fixed on two sides and loaded with a representative robot force on the opposing corner. The setup is shown in Figure 5.

The thickness and the size of the panel were varied with the goal to minimise system mass while simultaneously minimising warping. The resulting parameters were applied to the real geometry and verified in additional simulations.

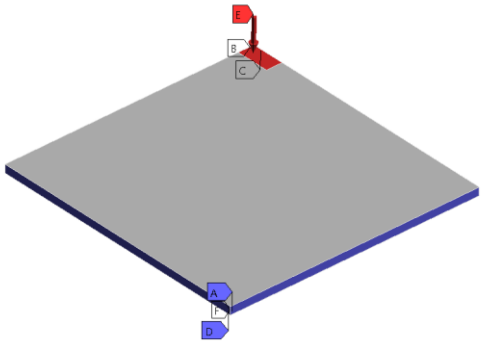

Figure 5: screenshot of FE-simulation setup in Ansys 2021R1

A thin panel with complex geometry poses additional challenges to the manufacturing process. Classic metal sheet forming is optimised for simple geometries like cylinders and cones. To achieve complex geometries, multiple small sheets can be welded together. An example is shown in Figure 6 with a combined cylinder-cone-tooling. However, welding might decrease the tooling quality and geometric accuracy in the transition area between two sheets.

Better results can be achieved with casting and machining. However, the effort and cost to manufacture toolings this way is very high and often not an economic alternative in composite manufacturing. Thin, large area toolings also pose challenges during manufacturing due to oscillations.

The final chosen process is called incremental sheet forming. A negative die was machined from wood. On this die, a flat metal sheet was fixed and slowly pushed on single points against the die by a robot. Slowly, the sheet was formed onto the die and into the desired geometry. The result is shown in Figure 6.

Figure 6: left: complex AFP tooling made with metal sheet forming; right: tooling panel manufactured with incremental sheet forming on a wooden die

3.3.2 Support Structure

For the support structure a set of aluminium ribs mounted on an aluminium frame was chosen. To manufacture these ribs, the actual geometry of the tooling panel was determined using a

GOM Atos 5 3D-scanner. The ribs and the frame were fitted to the panel geometry and cut from flat aluminium sheets by using a water jet cutting machine. The finished ribs were glued into a rectangular structure using epoxy glue.

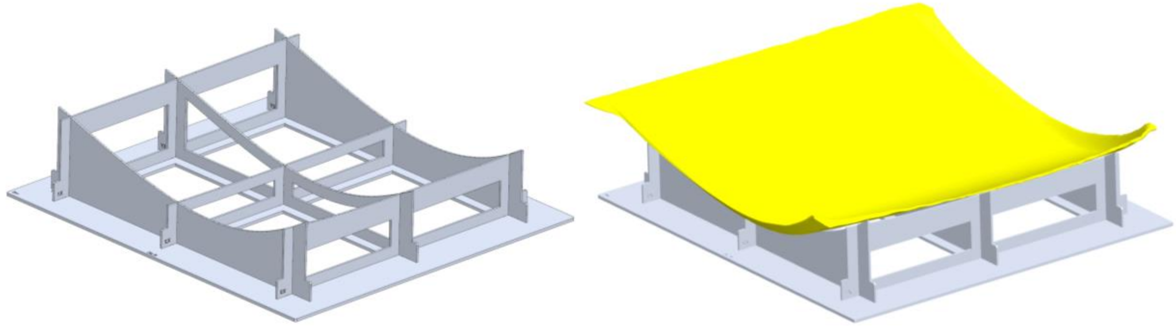

Figure 7: CAD of the support structure without (left) and with the tooling panel on top

The flexible mounting of the tooling panel onto the support structure was achieved by using a high temperature silicon with a 2 mm gap. A high-temperature silicon was used, which can withstand temperatures up to 300° C according to the manufacturer. The gap ensures the stability of the structure against process loads while still allowing slight shearing due to thermal expansion. Figure 8 shows the combined tooling structure. Finally, the induction coils must be mounted under the tooling panel. Threaded bolts were welded in a uniform pattern under the tooling panel. The coils were mounted onto the bolts, as described in chapter 3.2.

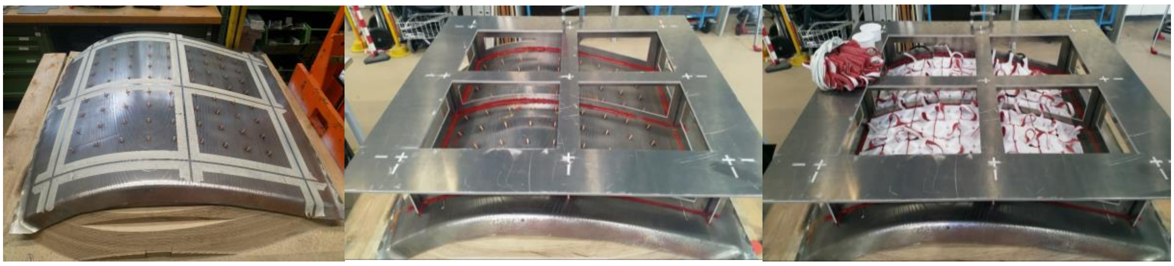

Figure 8: tooling panel with welded threaded rods (left), combined with support structure via silicon layer (middle) and with induction coils (right)

After mounting the final tooling in the AFP machine and ensuring functionality and temperature homogeneity, a demonstrator panel was manufactured. The manufacturing process was accompanied by a process simulation to predict the process induced warping, as demonstrated in [7].

4. RESULTS

The tooling was designed as described in chapter 3. For the induction coils, the final design consisted of induction units with 23 coils, each with 7 windings. These parameters were the optimum to heat the designed 3 mm thick steel sheet. The optimum distance between the reinforcement ribs were 360 mm, which were adjusted to be compatible to the dimensions of the induction coils.

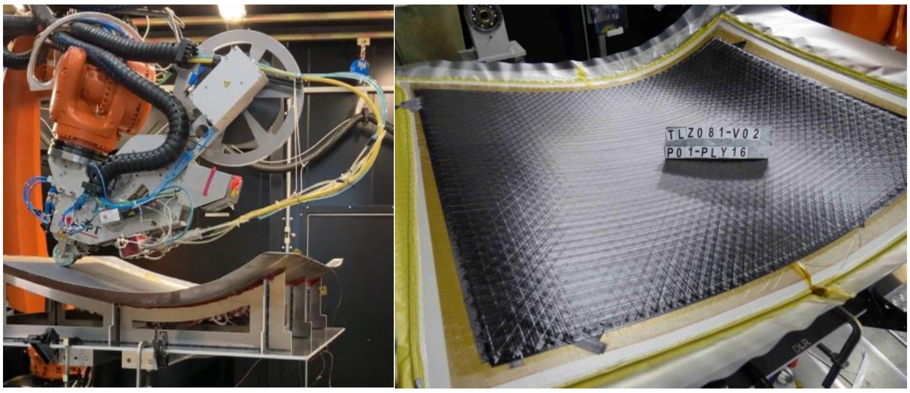

Figure 9: manufacturing process (left) and final part on tooling (right)

The tooling was heated to 200° C with a heating rate of 10° C/min and used to manufacture a demonstrator panel of CF/LM-PAEK (Figure 9). The first layer was placed on a neat matrix foil, which was fixed onto the tooling using a vacuum pump. A quasi-isotropic layup with 16 layers was chosen for simplified warping calculation and to minimise problems during the process. The manufacturing was conducted without major problems. Additional tests verified that heating rates of up to 15° C/min were possible.

Figure 10: tooling with induction heating and demonstrator panel

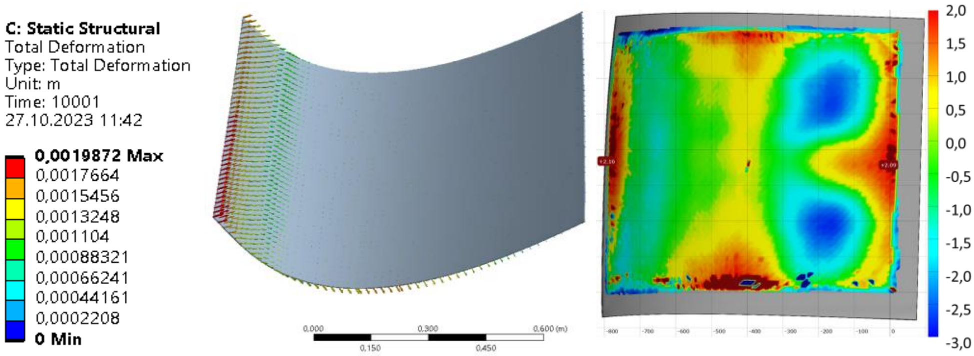

Figure 11: predicted process-induced warping (left) and measured warping (right) of the demonstrator panel

The part was measured with a GOM Atos 5 3D-scanner and compared to the ideal geometry and the predicted warping from the process simulation. The prediction of a spring-in of 1,9 mm was met with a measurement of 2,1 mm. However, additional warping was detected in the area between the ribs (Figure 11).

5. CONCLUSIONS

During the project, a tooling with complex geometry and induction heating for AFP was successfully designed and built. The final tooling was tested by manufacturing a panel. The scanning of the final panel showed some additional warping which was not predicted.

The location of this warping indicates a connection with the location of the support structure ribs. Thermal expansion of the tooling panel was considered during designing the interface between the tooling panel and the support structure. However, the scans show that the mechanical decoupling of both components was incomplete. The cause of this is still to be investigated but is likely a result of changes in material behaviour of the tooling panel due to the forming process.

However, the goal of a tooling with induction heating was achieved (Figure 10). Experiments showed a stable heating rate of 15° C/min with a homogeneous temperature distribution of ±5° C. During a follow-up project the interface will be investigated in more detail.

6. REFERENCES

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