MODULAR INDUCTION HEATING FOR COMPLEX MOULDS

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ABSTRACT

Heated moulds are frequently required to achieve optimal part quality in automated fibre placement using thermoplastic composites. However, attaining uniform heating of complex geometries is costly. Conventional heating elements do not adapt well to complex geometries, and adapting heating circuits to each geometry is expensive. Inductive heating using modular induction coils provides a viable solution to this challenge, though the design philosophies used for induction heating differ from those of other established methods. In particular thin-walled moulds are preferential as they can be heated more rapidly and efficiently than monolithic moulds. Expanding on developments from previous projects, chains of modular induction coils affixed to the rear surface of a thin-walled mould were developed, enabling heat to be applied uniformly and efficiently where required. The coil chains can be mounted on different moulds with varying geometric boundary conditions, requiring only calibration. The same coils were successfully applied to a mould machined from a monolithic steel block and to another mould formed from sheet metal.

1. INTRODUCTION

During thermoplastic Automated Fibre Placement (AFP) a heat source, e.g. a laser, melts the thermoplastic matrix of fibre reinforced tapes and applies them sequentially onto a mould to produce lightweight structures with complex geometries. [1] However, temperature management remains a central challenge for this process. [2] Studies have shown improved part quality on heated moulds in contrast to unheated moulds. Heating reduces the thermal gradient during the process and in the case of semi-crystalline matrix materials allows for longer and more thorough crystallisation. [3] [4] Common heating methods include conventional heating plates and cartridges, IR radiant heaters and integrated heating elements. These often need to be adapted and designed for each mould and pose limits on possible geometries. The required mould thickness for some of these also lead to high energy requirements and long heating times.

The development of a modular induction heating element provides novel solutions to this problem. By splitting the heating into small modular elements, the same heating can be applied to different moulds and be adapted to different geometries. By using induction heating, the required mould thickness is only limited by the forces applied during the process, so the mould can be thin enough to enable fast and economical heating.

Induction heating works by creating an oscillating electromagnetic field via induction coils, which in turn induces electric currents in the target structure. This is converted to heat by the electrical resistance of the material. Ferromagnetic materials, such as iron, are especially well suited for this procedure. However, achieving homogeneous surface temperatures using modular induction heating remains challenging. [5] Exact temperature measurements in different areas of the mould are necessary as input for control of the heating elements and ensure a homogeneous steady-state temperature distribution. Induction heating for moulds has already been applied in multiple forms. However, most applications adapt the heating to each mould separately. While this approach provides the technical benefits of induction heating, it imposes practical and economical limitations by fixing the heating elements to a given mould.

In a previous project the basic principles for flexible induction systems were developed. [6] The work presented here continues beyond these results, aiming for the development and refinement of modular induction heating for moulds used in AFP. Focus was placed on the heating rate, temperature homogeneity and energy consumption of the heated mould. The costs to manufacture the moulds were also taken into account. At the DLR Institute of Structures and Design in Stuttgart the moulds were designed and tested, with Msquare GmbH developing the induction heating system. [7]

2. EXPERIMENTAL SETUP

2.1 Heating system development

The development of the heating system was focused on three main goals: flexibility, modular heating, and digital monitoring and control. The flexibility was necessary to adapt the heating to different complex geometries, while the modularity enabled the system to add or remove sections depending on the heated area.

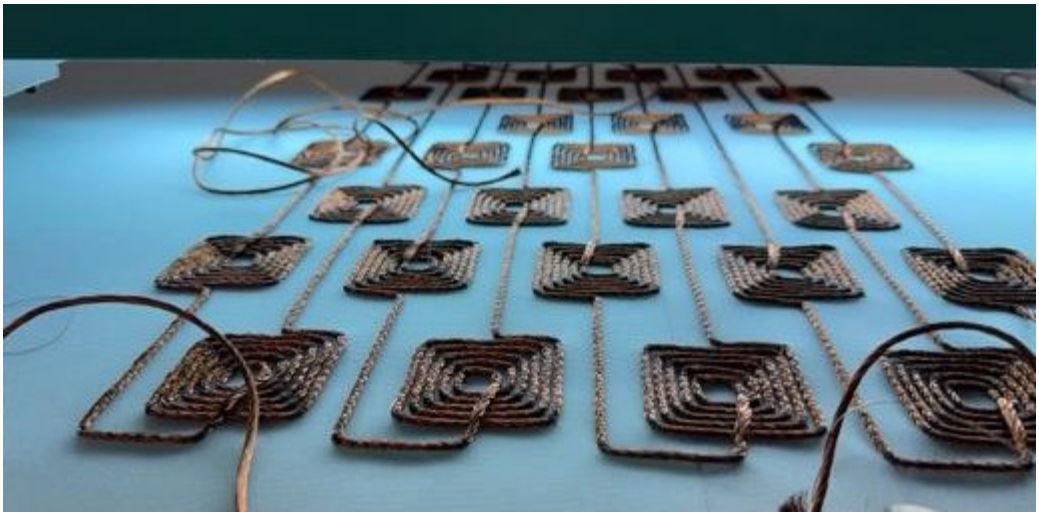


Figure 1: Manufacturing of induction coil elements

To satisfy the first two goals, an induction technology was developed that can be divided into any number of zones. Instead of a small number of large coils, a “chain coil” concept was designed in which multiple small coil elements are placed in series. These coil elements can be placed onto curved surfaces and apply heat homogeneously. The shape and size of the resulting heated areas can thus be individually adapted to different applications. The basic parameters of

the coil elements were derived from parameter studies using data from the mould design process.

The coils were manufactured on a CNC embroidery machine by stitching copper strands in square patterns onto a sheet of glass fibre fabric (see Figure 1). After that, the sheet was embedded into high temperature silicone to isolate the coils from external influences. The coils can be applied mechanically to the bottom side of the mould surface. In this case, threaded bolts were welded onto the surface and the coils were fixed using individual PTFE brackets (see Figure 2).



Figure 2: mounting of finished induction coil elements on a mould

An initial concept included individual plugs and sockets to connect the coil elements with each other. However, initial experiments showed severe efficiency reduction and heating in the contact areas due to the high power which is transferred from the induction generator to the coils. Additionally, creating an electrical contact at the coil tails posed an additional challenge. Each coil consists of copper strands containing 350 individual wires with a 0.1 mm diameter and individual coating. To ensure electrical connection, the coating of each wire must be removed at the contact area. This can be achieved by chemical, mechanical or thermal procedures. During experiments, a combination of thermal and mechanical procedures was found to be effective. First the coating is removed using a portable heat source. After that, the resulting soot is manually removed. The quality of the resulting contact is tested to ensure secure connection.

2.2 Mould design

To investigate the modular and flexible induction heating system on different moulds, two mould designs were chosen. The first was based on a pressure vessel dome mould and consisted of a monolithic machined spheric steel dome as shown in Figure 3 with a radius of 1120 mm and a square base area of 1010 mm x 1010 mm. The second mould consisted of a cylindrical sheet metal fixed upon an aluminium rib structure, also with a base area of 1010 mm x 1010 mm. Both moulds retain a positive curvature to facilitate usage with an AFP machine. These moulds are subsequently called “machined mould” and “sheet mould”. Both moulds were designed to accept the same heating system. To fill the area with coils, three heating areas were defined. Two zones consist of 33 coil elements each, the third 34 elements. Each zone supports up to two control thermocouples.

2.2.1 Machined mould

The mould was designed as self-supporting dome structure without further reinforcements to simplify production and prevent heat sinks. Accompanying simulations were conducted in Ansys 2023R2. The mould was designed to achieve the target geometry at 200° C.

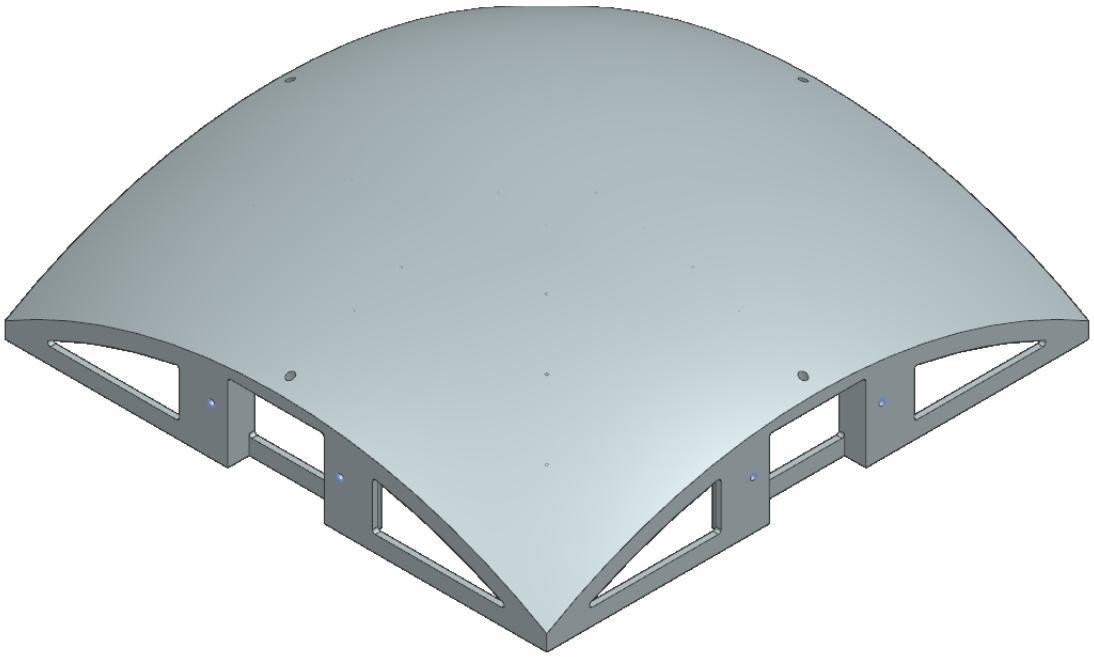


Figure 3: CAD of machined mould

To increase the efficiency of the induction heating system, a ferromagnetic material had to be chosen for the mould. Both unalloyed steel and invar were considered. Invar’s low thermal expansion at 200° C would pose an advantage, but the material expenses would increase significantly. Since the mould should also be used for post-consolidation processes in an oven at 400° C in another project, where the advantage of invar would decrease, unalloyed steel was chosen as material for the mould.

The design process was focused on five loading conditions. The first and second loading condition considered deformation due to the weight of the mould, both on an infinite flat surface and on a table smaller than the base area of the mould based on the mounting structure

of the AFP setup in Stuttgart. Loading conditions three and four added an additional small area pressure load to simulate the AFP roller. Loading condition 5 simulated the mould suspended from a crane. All loading conditions were simulated at room temperature and at 200° C except for condition 5, for which only room temperature was relevant. The maximum deformation in each case was required to be less than 1 mm. Additionally, a mesh convergence study was conducted to minimise the influence of the mesh elements. The necessary minimum thickness of the mould structure based on the simulations was determined to be 15 mm.

The base structure of the mould was machined by an external supplier and subsequently modified at DLR. Threaded bolts to install the coil elements were welded onto the structure and holes for control thermocouples were drilled.

2.2.2 Sheet mould

For the sheet mould, a contrasting design was chosen. The mould surface consists of a 1.5 mm thin steel sheet, which is supported by a separate aluminium rib structure. The necessary thickness was determined in a similar way to the machined mould. An optimisation was conducted to determine the optimum number of supporting ribs, with two cross-shaped central ribs emerging as a compromise between stiffness and potential heat sinks. A digital mock-up is shown in Figure 4. The steel sheet is designed to expand due to heating independent from the support structure within the design parameters and so the connection between both components was floating in nature. In a previous project a 2 mm thick layer of high temperature silicon provided this floating connection. [6] However, local failures were observed following testing and the choice of material decreased maintainability. For this mould, a different approach was chosen. Short sheet metal plates were cut and bent into the correct form. These sheet metal angles were modified with slotted holes in the expected direction of thermal expansion and mounted on the support structure. Using additional threaded bolts and nuts with PTFE washers, mobility of the steel sheet along prescribed paths due to heating was ensured. Additionally, threaded bolts for mounting the coil elements were added.

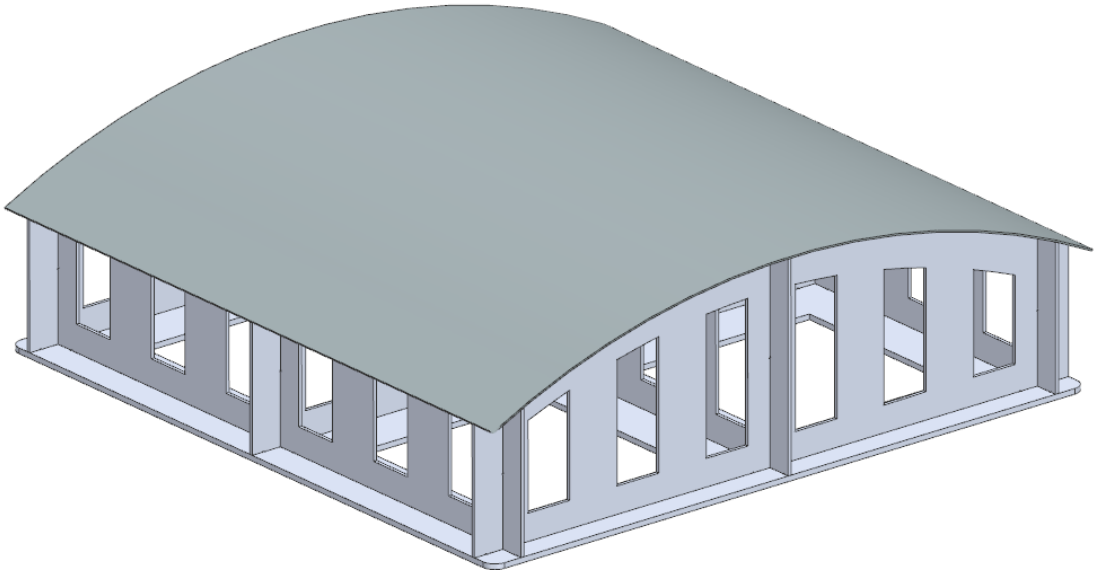


Figure 4: CAD of sheet mould

2.3 Heating experiments

After manufacturing both mould designs and the induction heating system, extensive tests were conducted. After mounting the heating system, each mould was fitted with at least nine thermocouples spread in a quadratic pattern over the top area to measure the temperature distribution (see Figure 5). The distance between each element was approximately 25 cm. Additional thermocouples might be added at strategic locations. The heating system was also set up to record the temperatures of the control thermocouples and the input power of the heating system.

The system was tested using multiple target temperatures and heating rates. For each setup the temperatures and power consumption were recorded. For a reference experiment, the moulds were heated with 5° C per minute up to 100° C and then held for 30 minutes. Temperatures up to 180° C and heating rates up to 15° C per minute were tested.

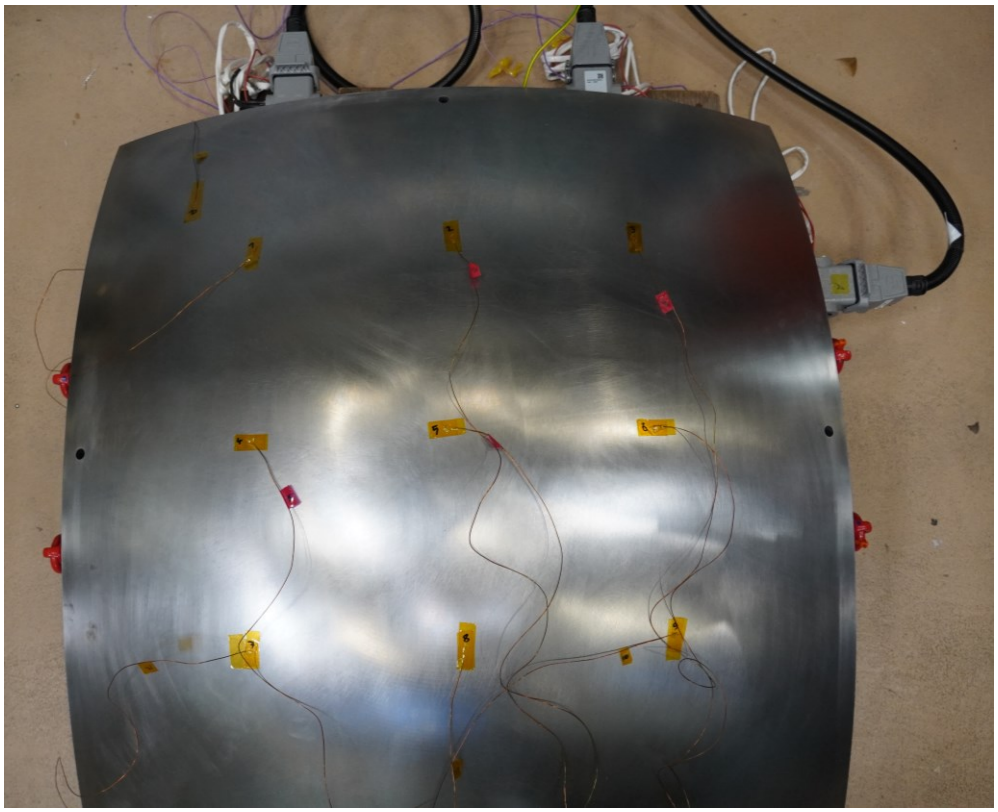


Figure 5: machined mould with heating and thermocouples

3. RESULTS

The tests of the machined mould showed significant hysteresis effects. The high thermal mass of the mould leads to a slow thermal response in both heating and cooling, leading to longer cycles. In contrast, the sheet mould in contrast reacted quickly to induced heat. The effect can be seen in Figure 6.

Temperature homogeneity was also different between the two designs. The standard deviation of all 9 thermocouples on the sheet mould was 7.4° C with a mean spread of 23.1° C between the minimum and maximum temperature, the machined mould reaches a standard deviation of

2.1° C with a mean spread of 6.3° C (see Figure 7). Both values can be further improved by calibrating the control parameters of the heating. The central thermocouple of the sheet mould showed the greatest deviation with an average temperature of 86° C during a 100° C hold phase. This position was located directly above an intersection of internal ribs, which acted as a heat sink and reduced the surface temperature. Thermally isolating the ribs from one another and the ribs from the mould surface should further improve temperature homogeneity for this design.

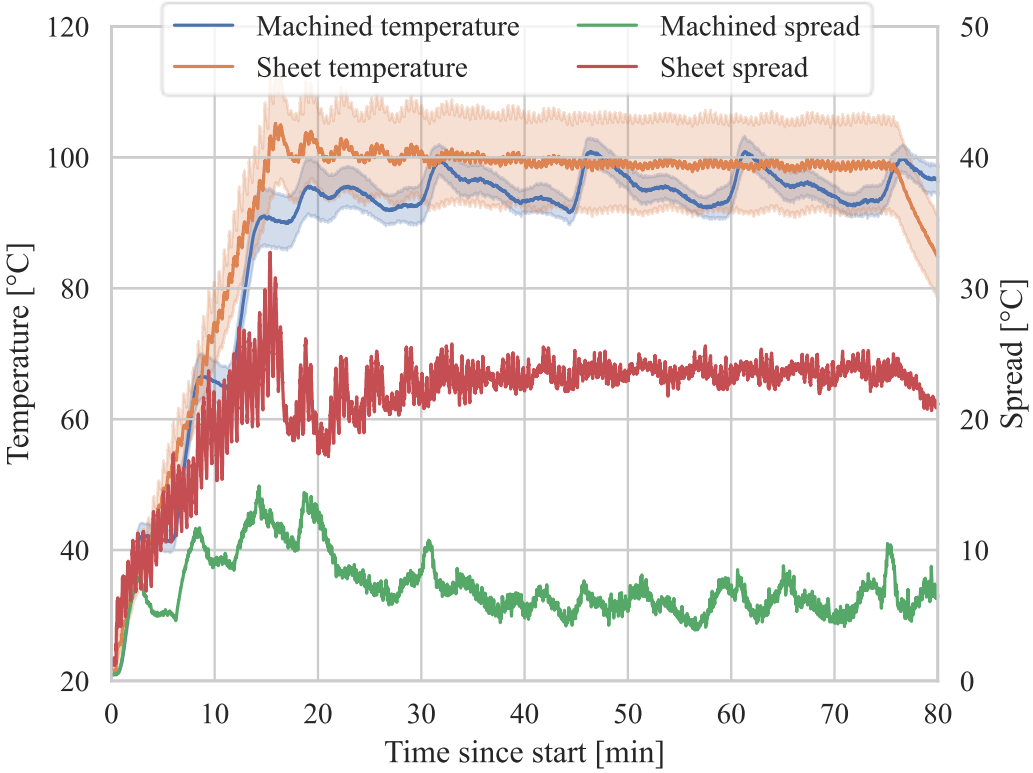


Figure 6: Example temperature history with standard deviation and spread of both moulds

The analysis of the cumulative energy consumption of both moulds can be divided between heating and holding phases. The heating phase at 5° C per minute reached 100° C after approximately 16 minutes. During heating, the sheet mould required significantly less energy than the machined mould, with a total of about 0.8 kWh at 100° C in contrast to 1.5 kWh at 100° C. During the hold phase, both moulds consumed about the same amount of energy. Figure 8 also shows the pronounced hysteresis effect of the machined mould, which results in significant steps during heating.

The final temperature measured on the surface of the moulds did not always conform to the temperatures measured by the control thermocouples below or inside the mould. The control thermocouples of the machined mould detected higher temperatures than those on top of the mould, while those on the sheet mould showed the opposite effect. Depending on the thickness and material of the mould and the calibration of the coils, heat is generated differently in each mould. Careful calibration is therefore necessary for each new mould heated by the same heating system.

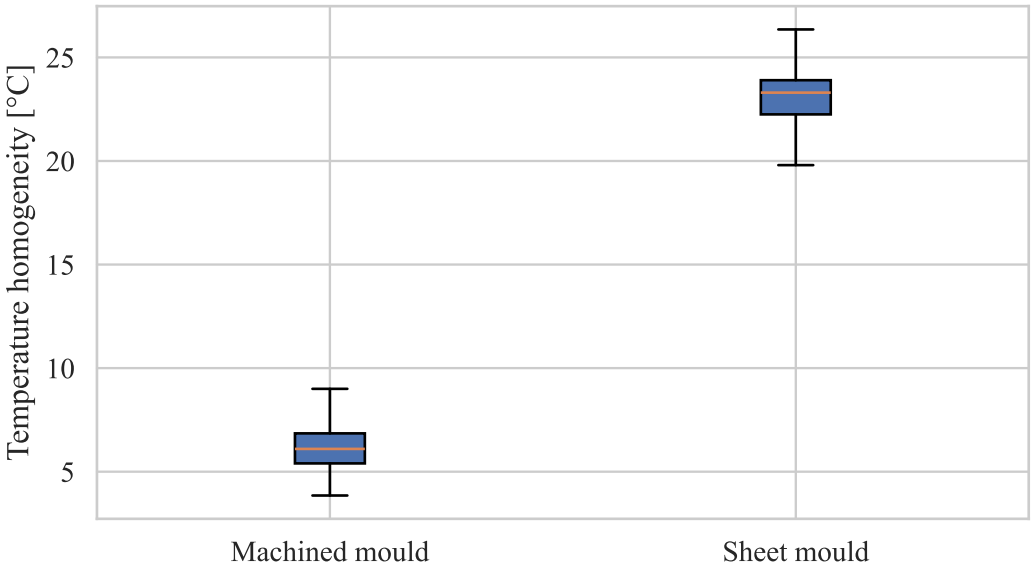


Figure 7: Temperature homogeneity during hold phase

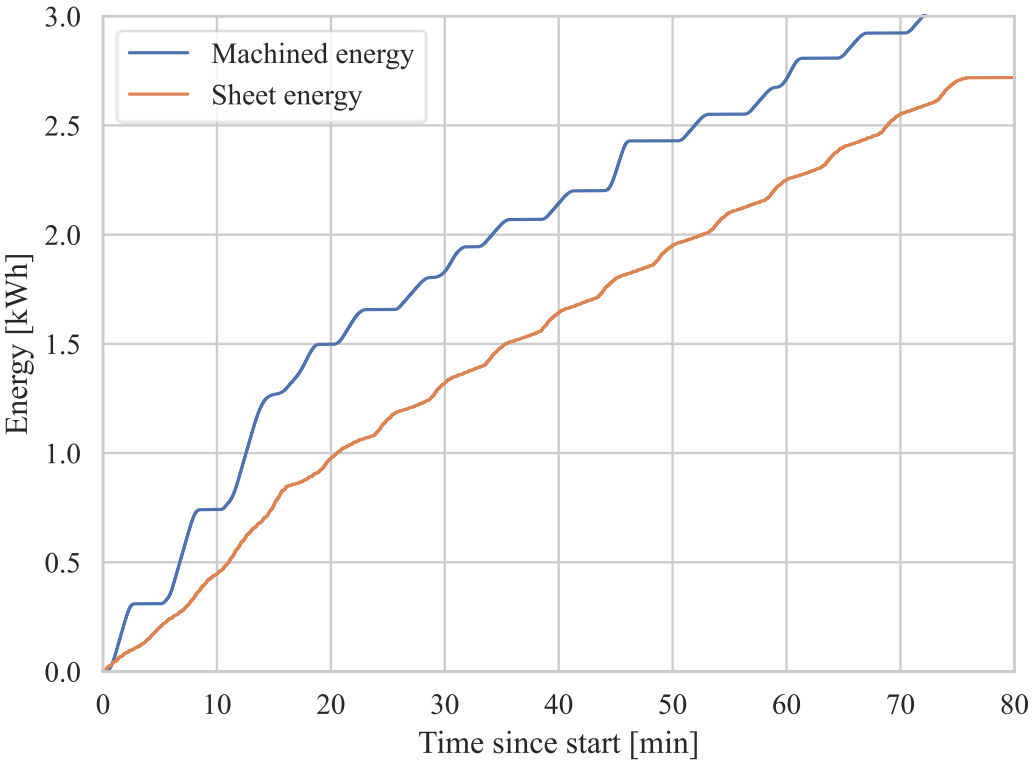


Figure 8: Cumulative energy consumption of machined mould

4. CONCLUSIONS

The heating system developed during this work could successfully be adapted to two different moulds with different geometry and manufacturing processes. The heating process worked for

different heating rates and holding temperatures. However, a few correlations and challenges were discovered.

The greater thermal mass of the machined mould was more challenging to heat up, requiring up to 87.5% more energy than the sheet mould. Additionally, significant hysteresis effects were detected due to the slow reaction time of the mould. However, once the hold temperature was reached, the high thermal mass of the mould equalised the temperatures across the surface and minimised hot and cold spots, allowing for much better temperature homogeneity. In contrast, the sheet mould showed noticeable hot and cold spots along the surface, both because of the low sheet metal thickness and the contact areas to the supporting rib structure, which acted as additional heat sinks.

To optimise usage of the same heating in both moulds, corrective measures are necessary. The machined mould would benefit from adapting the control parameters and increasing the number of the control thermocouples. Both measures can decrease the hysteresis effects. Additionally, a few calibration runs should be conducted to account for the temperature difference between control temperature and surface temperature for both moulds.

5. REFERENCES

[1] P. N. Dreher, A. R. Chadwick and S. Nowotny, “Optimization of in-situ thermoplastic automated fiber placement process parameters through DoE,” in *SAMPE Europe*, Nantes, Frankreich, 2019.

[2] M. A. Khan, P. Mitschang and R. Schledjewski, “Identification of some optimal parameters to achieve higher laminate quality through tape placement process,” *Advances in Polymer Technology,* vol. 29, no. 2, pp. 98-111, 2010.

[3] C. M. Stokes-Griffin and P. Compston, “The effect of processing temperature and placement rate on the short beam strength of carbon fibre PEEK manufactured using a laser tape placement process,” *Composites Part A: Applied Science and Manufacturing,* vol. 78, pp. 274-283, 2015.

[4] A. J. Comer, D. Ray, W. O. Obande, D. Jones, J. Lyons, I. Rosca, R. M. O'Higgins and M. A. McCarthy, “Mechanical characterisation of carbon fibre–PEEK manufactured by laser-assisted automated-tape-placement and autoclave,” *Composites Part A: Applied Science and Manufacturing,* vol. 69, pp. 10-20, 2015.

[5] M. Kaden and R. Keck, “Repair concept supported by laser removal and inductive heating,” in *28th International Congress of the Aeronautical Sciences*, Brisbane, Australia, 2012.

[6] D. Fricke and S. Tröger, “Induction heating for automated fibre placement tools,” in *SAMPE Europe Conference 2024 Belfast-United Kingdom*, 2024.

[7] M. Schneider and M. Kaden, “Efficient and flexible heating technology using induction,” in *SAMPE Technical Conference Series*, Long Beach, 2016.