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To cite this article: Riccaro Angiuli *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1024** 012024

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SPARE project – improvement of continuous compression moulding process for the production of thermoplastic composite beams

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Abstract. In recent years, thermoplastic matrix composites have seen an increasing interest from the research and development sector due to the versatility of use and the wide potential in sectors such as automotive, aeronautics and transport. Furthermore, the thermoplastic matrix allows the use of simpler, faster and automatable production cycles and joining systems. As part of the SPARE project, the continuous compression moulding process (CCM) was upgraded using as numerical simulation, monitoring via infrared thermography and induction welding. Thanks to these innovations, the CCM process can ensure savings in terms of production costs, reduction of waste and a higher level of automation, the proposed work will illustrate the activities carried out during the project. The numerical simulation was used to analyze the heating process and verify its uniformity in order to identify the best configuration to obtain uniform heating, infrared thermography, on the other hand, was used to continuously monitor the temperature of the laminate at the entrance and exit of the compaction zone and to measure the process temperature and the degree of uniformity.

Finally, at the end of the production process, a tool was developed for the induction welding of the laminates for the construction of complex beams with a T or H cross section.

1. Introduction

SPARE is the acronym of Full scale innovative composite pax and cargo floor grids for regional Aircraft Fuselage barrel on ground demonstrators. The Project addresses the manufacturing of 2 full shipsets of pax and cargo floor grids for regional Aircraft Fuselage barrel on ground demonstrators using thermoplastic resin reinforced with carbon fiber. During the project the use of manufacturing technologies with a lot of potential for automation have been explored (i.e. Progressive Roll Forming, or continuous compression moulding and Induction welding) in order to be competitive in terms of weight saving and recurring cost reduction. Floor beam, object of the work, has a double T or H cross and Progressive Roll Forming (PFR) process, will be used as fabrication process. PPS thermoplastic matrix and T300J 5HS carbon fiber are the baseline for production but also PEI, PEEK and PEKK will be investigated as alternative materials; the choice of the thermoplastic matrix is dictated by the growing demand for environmental sustainability of the materials used for the production of aircraft. Most of the



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commercially available manufacturing technology for thermoplastic composites was adapted from methods for processing thermoset composites. There are several methods of manufacturing with thermoplastic composites currently in use. Some of the most common processes include compression molding, injection molding, and autoclave processing. Less common methods for process thermoplastic composites include pultrusion, vacuum forming, diaphragm forming and hot press techniques. PRF can be compared with Continuous Compression Moulding (CCM). Induction welding of thermoplastic composites for the manufacturing of H-Shapes can ensure high mechanical properties, high efficiency and reliability together with high flexibility and good applicability at an industrial level [2][3]. In the induction welding process, the material is heated by means of a high-frequency alternate magnetic field generated by an induction coil. This magnetic field produces eddy currents within the conductive composite material, which heat the material due to the Joule effect. The main disadvantage of the induction welding technique applied to composite materials is the difficulty to optimize the temperature distribution through the thickness of the joint and to avoid, for example, too high temperatures on the surface directly exposed to the induction coil and near the edges of the joint (due to current concentration by “point effect”). CETMA developed and patented a new machine for continuous welding of advanced composite materials. The innovative aspect of this machine is the integration of a new control and tuning system to allow optimized temperature distribution for different materials and geometries to be welded. In addition to the induction coil for material heating, one or more nozzles were introduced to cool the composite on its surface or near the edges, thus allowing optimized heating of the joining surface. The cooling process is adjusted by a software unit and the temperature on the upper surface of the joint is controlled by means of a thermo-camera. In addition, full automation of the welding process is possible because the surface temperature and the cooling velocity are controlled by the software (Figure 1).



Figure 1 View of the induction welding equipment developed by CETMA

As in other sectors [4], process temperature monitoring can improve process knowledge and increase product quality. Since the temperature is one of the most critical parameters in the PFR process, an in-line monitoring procedure by InfraRed Thermography (IRT) could be useful in order to check the quality of the process. With respect to traditional tools for the on line monitoring and measuring of temperature in composite manufacturing processes (e.g. thermocouples, pyrometers, etc.), IRT is a recently developed technique (with respect to traditional techniques) able to provide the following measuring capabilities which make it quite unique in the field of processes monitoring and control: a) it is contactless thus it does not affect the object and the measure at all (e.g. thermocouples have to be installed in close contact to the monitored component thus affecting the reliability of the measurement), b) it allows fast scanning to monitor fast temperature variation (e.g. acquisition rate up to 100 Hz), c) it is real time and 2D, thus allowing the monitoring of the whole component in the same thermogram (e.g. it works like thousands of traditional sensors without the need of complex wiring) and, at the same time, a real time comparison of different zones of the area under investigation. Such complex manufacturing processes can also be simulated to identify what changes to make to the equipment to achieve a uniform

temperature range. Process modeling involves the discretization of all elements and the replication of all heat transmission phenomena and process parameters. Finally, the comparison between experimental data and numerical model allows to refine the model itself up to a high degree of confidence.

2. Improvement of CCM process

2.1. CCM process simulation

To simulate the PRF process, a numerical model need to be set up, the main objective of the model is to reproduce the thermal field inside the prepreg during the heating phase up to the point where pressure is applied to induce consolidation on the material. In order to model the process, the conservation equations of mass, momentum and energy are to be solved, along with the calculation of irradiation between involved surfaces. A Finite Volume Method has been set up by realizing a simplified geometry and its discretization and inputting all the needed information about materials and physics phenomena involved. A sensitivity analysis has been carried out to establish the correct discretization of the computational domain, before moving to the calibration phase, needed to set up some unknown parameter. After the calibration, temperature field will be shown and analyzed in order to assess the reliability of the numerical model. A “strip” of prepreg moves in a rectangular duct and is heated by ceramic infrared heaters. At the end, the duct opens up in a greater cavity in which pressure is applied by two heating rotating metallic rollers. The equipment is shown in Figure 2; on the left-hand side, the ceramic heaters are visible since the duct is open, while on the right-hand side the cavity in which the rollers apply the pressure on the prepreg can be viewed.



Figure 2: PRF equipment

Equations of mass, momentum and energy conservation are solved using the Finite Volume Method, thus obtaining a CFD (Computation Fluid Dynamics) model of the considered domain, which will be now described. The modeled geometry is shown in Figure 3.

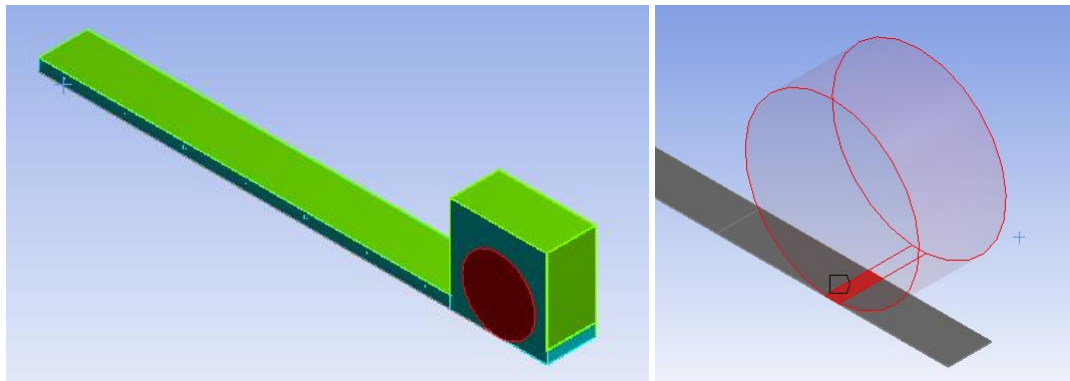


Figure 3: Geometry of the CFD model - isometric view and detail, contact between roller and prepreg

The CFD model includes the following list of physics phenomena involved in the heating of the prepreg strip:

- heat conduction inside the prepreg strip and the steel walls of the duct;
- forced convection due to the air flowing inside the duct;
- natural convection around the external walls of the duct;
- irradiation between all the solid walls inside the duct, which means the heaters, the prepreg and the internal walls of the duct;
- relative motion of the prepreg strip, which induces a convective effect in the heat transfer equation for the solid.

All these phenomena are included in the numerical model.

A procedure based on the Mean Field Homogenization Theory [5] has been carried out to determine the matrix of thermal conductivities, starting from the basic material (carbon fibers and resin), the volume of the fibers and the lamination sequence. Other solids included in the numerical model are the walls of the duct and the rollers, which are considered isotropic. Finally, the only fluid included in the CFD model is the air, modeled as an incompressible ideal gas. Turbulence of the fluid is accounted for by including in the numerical model the two equations of the realizable k - ϵ model. As already stated, the finite volume method [6][6] is applied to solve a series of equations in the computational domain, namely:

- mass conservation
- momentum conservation
- energy conservation
- turbulence model equations

A system of radiosity equations is coupled to the conservation equations in order to model the heat exchange due to irradiations inside the cavity [6]. The most important boundary conditions imposed are here briefly reported. A mass flow rate is imposed on the inlet; its intensity is calculated on the basis of the flow rate of the fan taking into account the density of the air. The flow rate and the temperature are two unknown parameters to be estimated. Heaters are included in the model as empty spaces. The face that irradiates is kept at a fixed temperature of 870 K that gives a total irradiated power of 400 W, which is the power of each heater. The face of the prepreg at the entrance is kept at an ambient temperature of 295K, while the exit face is considered adiabatic. Finally, a translational velocity of 1 m/min is imposed into the prepreg, while a rotational velocity of 0.111 rad/s is imposed to the roller. A grid convergence study has been performed in order to establish a sufficiently accurate discretization of the computational domain. Three different grids of increasing size were involved in heating simulations, each with a finer discretization of the composite tape and the air in the duct; rollers were neglected for simplicity. Monitored outputs to assess the grid convergence were the average temperature of the entire composite strip and the average temperature of the exit surface of the strip. Applying the same discretization

parameters to the complete model with rollers, we obtain a mesh of about 1.35 million cells, which is shown below.

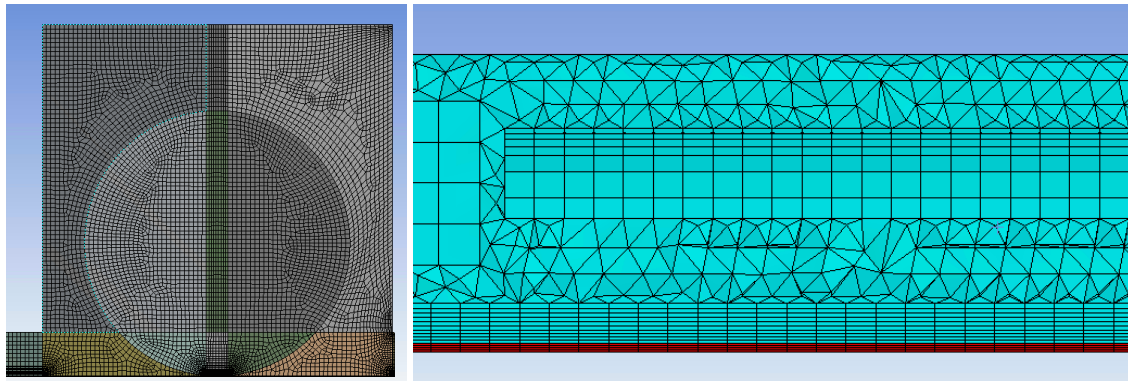


Figure 4: CFD model mesh - detail of rear portion near roller and longitudinal section at first heater

Preliminary analysis were carried out to obtain a roughly estimate of the sensitivity of composite temperature to changes of the air temperature. Technical data of the fan have been retrieved, which give a flow rate in a range between 0.3 m³/s and 0.6 m³/s, while temperature data were not available. For this reason, an optimization procedure has been set up to estimate these quantities. The procedure is divided in three steps:

1. execution of a Design of Experiment, varying the unknown parameters into a specific range;
2. fitting of a surface response, based on the results of the preceding DoE;
3. parameter identification, minimizing the deviation between numerical and available experimental outputs.

The optimization process allowed to obtain values of the output temperature very close to the target desired. We can conclude that a flow rate of 0.582 m³/s and a temperature of 434 K are the calibrated quantities of the unknown model parameters. In Figure 5 isometric views of the prepreg strip are reported; rollers and heaters are shown in transparent mode.

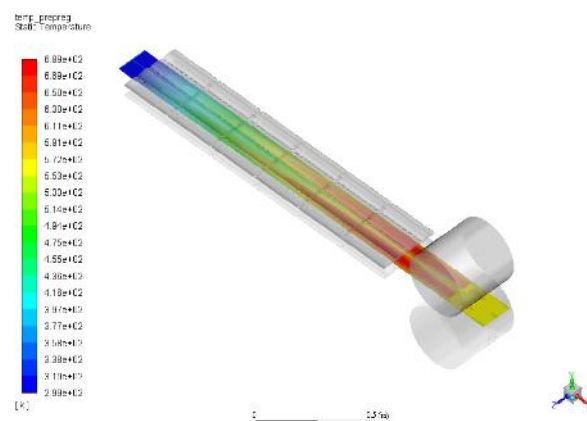


Figure 5: CFD model results - Temperature on prepreg

2.2. Real time monitoring of process temperature by infrared thermography

Thermographic technique provides a thermal map of object without any physical contact and without affecting the surface temperature of the radiant source or altering its integrity and operating conditions in any way. The advantage of infrared thermography is the ability to measure the surface temperatures of objects with a much greater accuracy than all other temperature sensors that provide data, even

precise, but referring to a single point. In addition, at the current state of development of thermographic equipment, editable control software are already available and capable to record, monitor and report any exceedances in comparison with target values. The main challenge was to find the most suitable thermographic equipment, to design the monitoring system (Figure 6) and its communication with the data collection system. To achieve this goal, once scenarios and application cases have been identified, preliminary tests has been carried out in order to identify the setup, the equipment and the architecture of the acquisition system.

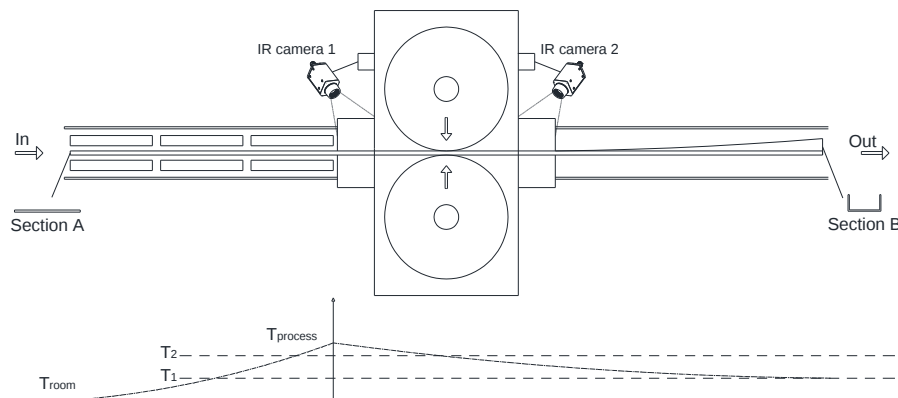


Figure 6 Position of the IR cameras and Temperature variation during the PFR process

During the tests, the typical process conditions of the material and parameters were reproduced by observing, through an infrared camera, the temperature distribution on the material and its evolution over time as some process parameters change. The acquisitions activities were conducted in the area before the compacting rollers (Zone A) and at the exit from them (Zone B); the test saw a first initial phase of static heating (up to the process temperature) and a subsequent forming phase in which the material, driven by a double track, flowed continuously in the heating area and in the compaction area.. The thermographic equipment, on the other hand, was positioned using magnetic hooks and in such a way as to have an almost perpendicular view of the processed material. The processed material is a carbon based composite with a thermoplastic matrix, the emissivity of the material (indispensable for performing quantitative tests) has been calculated on material samples with the comparison technique using a calibrated thermocouple and was equal to 0.94. During the test, the static heating phase and the process phase were monitored, in the other two tests only the process was monitored by varying the processing speed. The test was carried out in two phases, first the material was heated to the target temperature (about 320°C), measured by thermocouples, and then, by activating the double mechanical track, the continuous rolling process was started.

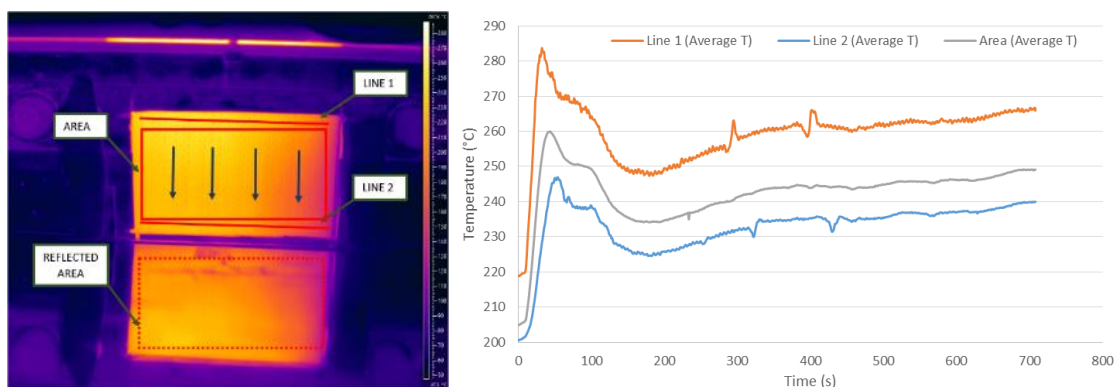


Figure 7 IR view with ROI identification (left), average T during Test 1 (process): line 1, line 2 e area (right)

In the Figure 7 (right) the average temperature relative to line 1, line 2 and the entire area, detected during the process itself, are shown; the line 1, closer to the heating zone has an average temperature always higher than the line 2 (close to the compression zone). The results of the surveys show how, during the continuous forming process, the passage from the heating zone to the compression zone involves a cooling of the processed material, at when the process becomes stable, equal to about 25°C. The temperature profiles recorded show that the temperature of the external areas of the laminate is lower than in the central area, in both profiles, this leads to uneven heating and therefore to different mechanical properties of the material. In order to better understand the temperature distribution on the inspected area a 3D surface of the temperature values recorded through the IR thermographic equipment is shown in Figure 8.

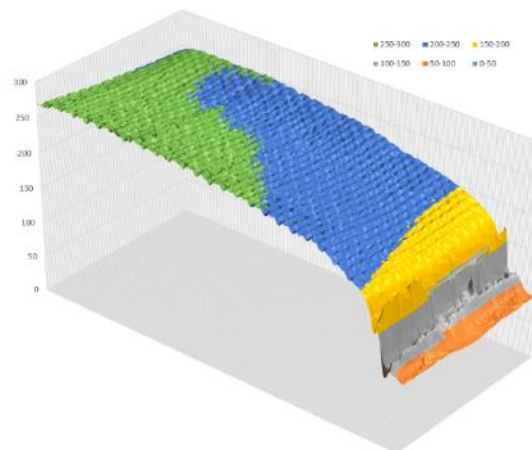


Figure 8: 3D superficial temperature distribution during the PFR process

2.3. Induction welding

In order to create the two floors, object of the project, it is necessary to build the beams with H and T section in thermoplastic composite. The sections are made by welding C, L and flat profiles according to a predetermined sequence and in order to facilitate the welding process, using the robot shown in the figure, a special tool for beading the elements has been designed.

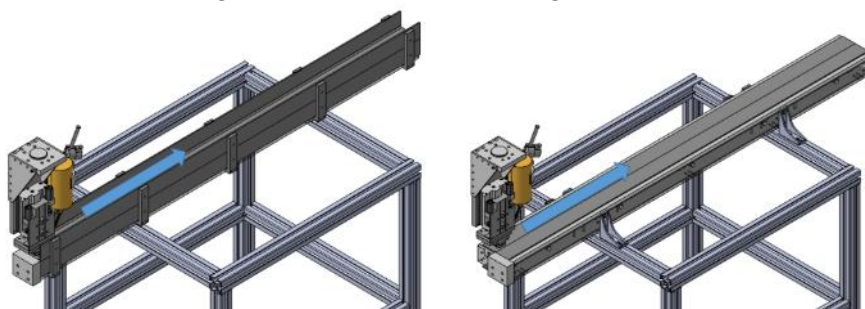


Figure 9: Welding sequence: welding of the web (left), welding of the caps (right)

The process parameters to be considered during welding process are as follows:

- Power to be supplied to the welding head circuit;
- Rolled- welding head distance;
- Surface temperature monitored by the pyrometer;
- Air flow insufflated from the cooling outlet;
- Pressure applied by the roller;
- Speed of movement of the welding head.

During the preliminary welding tests a thermocouple is positioned between the two laminates in order to control the temperature at the interface and to identify the correct parameters

3. Project next step

The next steps from now until the end of the project (that will be in April 2021) will be the validation of the temperature monitoring system. The system, in fact, already tested, will be used to monitor a continuous extended process to identify the operating temperatures once the production parameters have been optimized. Induction welding will be performed on the components for the construction of the beams for the two floors using the parameters already identified and finally the assembly of the two floors will take place by the topic leaders of the project.

4. Conclusion

A thermographic procedure for monitoring the process temperature to be used during the continuous forming process on thermoplastic matrix composites was developed. The procedure developed, which can be integrated into the production process itself, is able to monitor the process temperature allowing to act on the production parameters, so as to guarantee a constant and adequate temperature during the process. The results of the experimental tests conducted have allowed us to evaluate the influence of some process parameters such as: temperature set by thermocouples, drag speed and compaction force on the average temperature trend on the belt being processed. A numerical model for the simulation of the PRF process has been set up. The main goal of the model was to reproduce correctly the thermal field inside the prepreg before the consolidation, the model could be further improved after the installation of an on-line system for the monitoring of the process. The setup of the IW process has been completed, the optimized IW process parameters have been identified and a specific tool has been created for welding beams with different cross sections using a high degree of automation.

Acknowledgment: This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 820840

References

- [1] J. Zhang, V. S. Chevali, H. Wang, C. Wang "Current status of carbon fibre and carbon fibre composites recycling" Composites Part B: Engineering Volume 193 2020 ISSN 1359-8368 - <https://doi.org/10.1016/j.compositesb.2020.108053>
- [2] N. Banik "A review on the use of thermoplastic composites and their effects in induction welding method" Materials Today: Proceedings Volume 5, Issue 9, Part 3 2018 Pages 20239-20249 - ISSN 2214-7853 <https://doi.org/10.1016/j.matpr.2018.06.395>
- [3] F. Lionetto, S. Pappadà, G. Buccoliero, A. Maffezzoli "Finite element modeling of continuous induction welding of thermoplastic matrix composites" Materials & Design Volume 120 2017 Pages 212-221 ISSN 0264-1275 <https://doi.org/10.1016/j.matdes.2017.02.024>
- [4] R. Angiuli R., M. Giannuzzi, G. Papadia "Experimental thermographic investigation for a dry and highspeed turning of SAF2507 Steel" Proceeding of 22nd International Conference on Material Forming (ESAFORM 2019) Vitoria-Gasteiz 8th-10th May 2019
- [5] MSC Digimat®
- [6] Ansys® CFD Theory Guide