AN EXPERIMENTAL STUDY OF THE STRUCTURAL INFUSION$_{TM}$ PROCESS FOR MANUFACTURING OF AEROSPACE LOAD-BEARING STRUCTURES

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Keywords: *Composite, Thermoset, Aerospace, Structure, Infusion, Out-of-Autoclave*

ABSTRACT

Aerospace load-bearing structures manufacturing is a challenge for composite engineers. The main process used for this high requirement application typically is autoclave molding. A partnership between Bombardier and Centre technologique en aérospatiale [CTA] enhanced the development of a new infusion method to lower the cost of load-bearing aerospace composite structures. The experimental methodology started with the general infusion process as a baseline and studied the impact of infusion parameters such as the technique, materials, tooling and consumables. The infusion presents a high cost saving potential, but is limited in terms of thickness control, fiber volume fraction uniformity and toughened resin processability. Over 150 panels were done and inspected to complete this large study about the influence parameters of the infusion process. This work aims to develop the baselines of a new high end process, the Structural Infusion$_{TM}$. In this process, a new caul technology is used with state-of-the-art out-of-oven, out-of-autoclave tooling to process, at high temperature, a toughened liquid epoxy resin system. The resulting parts are uniform in fiber volume fraction, a project objective to manufacture load-bearing aerospace structures by infusion. This paper presents experimental results using Structural Infusion$_{TM}$ to manufacture several plaques and complex geometry fairings. The impacts of the main process parameters on fiber volume fraction uniformity will be presented.

1 INTRODUCTION

The Canadian aerospace industry is currently leaning towards new manufacturing processes in order to lower the weight of aircrafts and improve environmental impacts while actively reducing costs. World class aircraft manufacturers are investing in this orientation. The Advances Low-Cost Aircraft Structure project of Airbus involved 57 universities and partners [1]. The project resulted in showing which innovative technologies offer the best cost/weight advantages for load-bearing structures. The results supported the development of the Airbus A400M. The Action Plan 2013-2020 of the Quebec Aerospace Strategy on climate change launched in 2013 a mobilizing project for the Ecologic Aircraft named SA^{2}GE. In collaboration with Bombardier, a new R&D laboratory was setup at CTA, a unique applied research center in the Montréal aerospace cluster. Within this laboratory, a new team started its activities through the Industrial Research Chair for Colleges in Composite Aerospace Component Manufacturing. The main objectives of the team led by Robin Dubé is to **develop the local supply chain** of aerospace load-bearing structures, to improve and to **develop primary structures processes** and moreover, to **train highly qualified staff** for structural composite parts manufacturing.

The main process to manufacture primary structures in the commercial aerospace industry is autoclave molding. This high performance process involves the lay-up of pre-impregnated reinforcement on a tooling in a clean room, prior to an optimized cure cycle controlled in pressure and temperature within an autoclave. The pre-impregnated materials are highly controlled in quality and must be stored in a freezer under specified conditions. Therefore, this process implies inherent quality production and dedicated infrastructure. The most performant aircrafts, like the CSeries, Boeing 787 and Airbus A350, use composite structures that are mainly cured in an autoclave.

Many technological developments of novel processes to manufacture composite parts are being introduced. These imply a more competitive business case as compared to autoclave manufacturing where the total cost of parts is reduced. The Vacuum Assisted Process (VAP®) was developed by EADS a decade ago and has led to high quality liquid molded parts using a patented microporous membrane [2]. The membrane allows entrapped gas to be pulled out of the part, leading to a lower void content. The Airbus A400M cargo door was successfully manufactured using the infusion process [3]. Boeing patented the Controlled Atmospheric Pressure Resin Infusion (CAPRI®)[4]. This low-cost process aims to manufacture composite structures with low fiber volume fraction [V_f] variations. The main idea is to inject the resin at a lower pressure than the atmospheric pressure, thus limiting the compaction variation during the infusion. It also benefits from resin degassing during the process and ensures a lower pressure gradient, related to a lower thickness variation. Resin Transfer Infusion (RTI®) is another infusion derived process developed by Bombardier for the CSeries program. This process is a state-of-the-art infusion based technique where the main innovation is to use an autoclave to apply the pressure after the infusion resin transfer into the dry preform [5]. The infusion process has a high potential of reducing costs for large components relatively to the autoclave molding.

Hence, the Composites Chair at CTA took the challenge of improving the infusion process to address the requirements of aerospace load-bearing structures. CTA's Chair is lead in partnership with the main Canadian commercial aircrafts manufacturer, Bombardier, and the high-performance fiber weaver, Texonic. The infusion process involves low equipment investment, is achievable outside an autoclave using room temperature stored reinforcements and is a relatively well established process in Canada. Nevertheless, to address the high requirements of primary structures with this process is challenging.

2 CHALLENGES

Load-bearing structures in the aerospace industry are defined by several requirements, which are based on the aircraft loads, design and materials. Designers use physical properties of selected materials that have been established from measured experimental results implemented in theoretical stress models to evaluate the amount of material required to securely support a defined load. As a conservative approach, the material properties used to define the structure are based on the weaker results from the material tests [6]. Therefore, if the material used has high variations in performance, the impact of a design based on the materials performance leads to a heavier structure for safety purposes.

As most of the mechanical properties of the composite materials are linked to the ratio of fiber and resin, V_f is one of the most important requirements. The higher the V_f, the greater stress the structure will be able to sustain. However, V_f must stay under a certain limit, over which its impact resistance will become detrimental. Lowering the V_f to increase the after-impact resistance means heavier structures for the same load. Therefore, the fiber volume fraction needs to be optimized. The second main requirement is the uniformity of the material properties. V_f is not a unique value, but a range that is caused by inherent induced variations in the materials and processes. The bigger the range, the heavier the structure will become. Therefore, the uniformity of material properties is important.

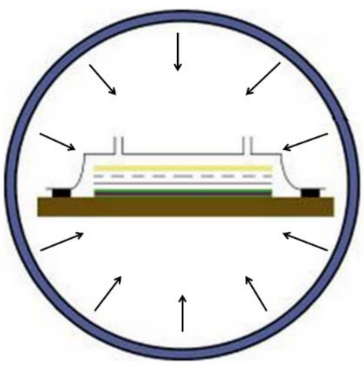

Figure 1. Autoclave Molding

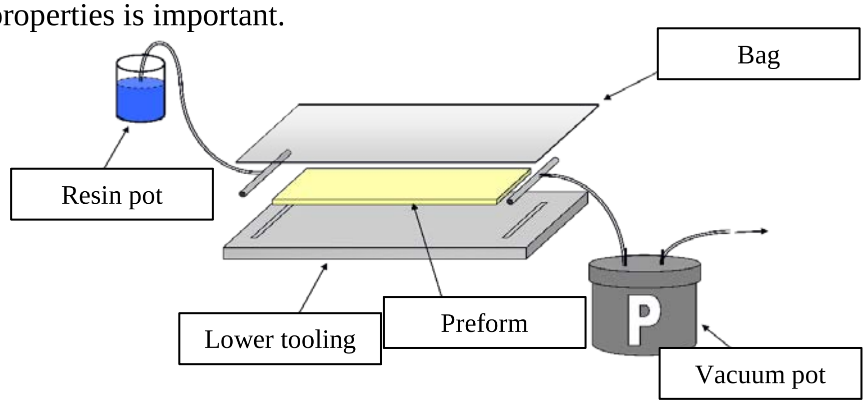

Figure 2. Infusion Molding [7]

Figure 1 shows the autoclave molding process, the blue circle representing a heated and pressurized vessel. In autoclave molding, the pre-impregnated reinforcement is laid up on a tooling over which a bag (flexible upper mold) is installed and sealed on the top of it along with other functional consumable layers. Then, the vacuum is applied within the bag to remove the air and compress the materials. After a vacuum integrity check, the setup is placed in the autoclave for a curing cycle controlled in temperature and pressure. Sometimes, the use of a caul between the laminate and the bag tends to enhance the final part bag surface quality. This molding technique is the one mostly used to manufacture composite structural components in aerospace.

In the infusion process, as shown in Figure 2, a dry preform made of layers of fiber reinforcements is positioned on a tool. Depending on the infusion strategy and material permeability, a flow media can be added on a peel ply over the preform to ease the resin flow. Then, a bag is installed and sealed on the top of it along with tubes and accessories planned in the liquid resin transfer strategy. Then, vacuum is applied in the bag and the reinforcement in compacted under atmospheric pressure. After an integrity check, the resin feeding line is opened and the liquid resin transfers into the preform. When the right amount of resin has entered the part, the resin inlet valve is shut off, the part is kept under vacuum until fully cured. The surface quality is controlled on the tool side, but is dependent on the bagging quality on the other side. Hence, this process is at first on the same surface control basics as autoclave molding. But nonetheless, the infusion process does have a huge disadvantage as compared to the autoclave molding process which is the maximum compaction pressure, limited to atmospheric pressure. This results in a weaker process when compared to autoclave molding in terms of V_f level and uniformity. This is a real challenge for the infusion process as currently known and a certification barrier for load-bearing structures manufacturing.

Typically, the general infusion process generates parts with good surface finish when planned properly. However, it also leads to parts with high variation in V_f, well over the target of the project. The resin feed lines show up as an imprint on the surface of the part. High permeability flow media zones compared to zones without flow media also show large thicknesses variation for an identical reinforcement areal weigh. And as the second image of Figure 3 shows, the tight radiuses are complex to address in infusion and are subject to high uncontrolled thickness variations. The main challenges of the infusion process are within the combination of atmospheric limited compaction pressure and flexible membrane upper mold surface.

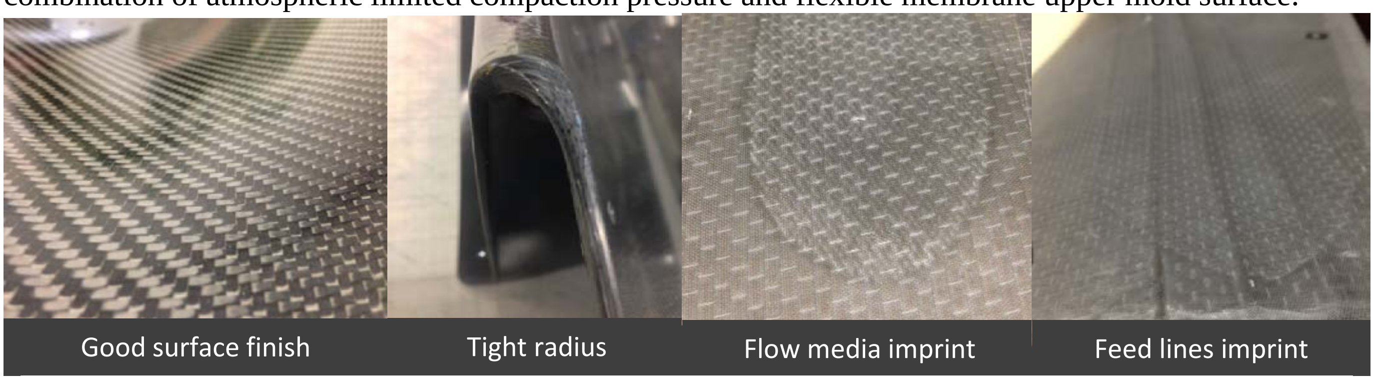

Figure 3: General infusion process results

3 DEVELOPMENT METHOD

The main objective of the project was to develop an infusion based process capable of producing composite load-bearing structures. It aims at a V_f of 58 % and variation within ±3 % with an overall part quality that is equivalent to parts molded with the autoclave process. Following the design of experiments, a test plan was set up to identify the main impact of the infusion process parameters on the fiber volume fraction. The first phase of the project lasted a year and a half and was focused on plaque manufacturing and measurements. The plaque experiments aimed to evaluate and select infusion materials and consumables compatible with the certification of the process for aerospace purposes. As the composite primary structures in aerospace manufactured by liquid molding are made of mono-component resins and combination of non-crimp structure reinforcement and surface layers, the infusion process needed to be adapted for it. Moreover, the process was meant for aircraft manufacturing and therefore needed to be sizeable to address large components.

Over 150 plaques were manufactured to identify the different parameter's influence on the fiber volume fraction and its uniformity. A detailed procedure was used for every infusion based on the aerospace industry manufacturing standards. Then, 100 points of thickness measurement were taken on each plaque using a coordinate measuring machine, as shown on Figure 4. The coordinated measuring machine (CMM) was used to measure flat panels to develop and validate a technique for thickness measurement of complex shapes without having to cut the part to measure thickness in isolated areas.

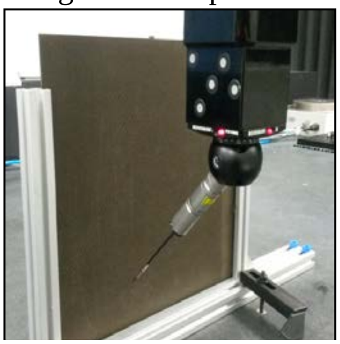

Figure 4. Thickness measurement by CMM measurement

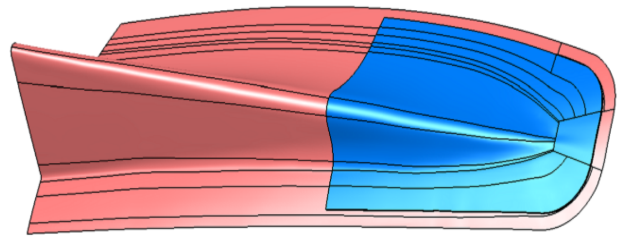

Figure 5. Complex geometry fairing

During panel manufacturing, the reinforcement layers were laid-up straight (not sheared). The reinforcements used were uniform over a plaque, and did not feature gaps or overlaps. This allowed to extract the Vf directly out of the thicknesses as detailed in equation 1, which shows the relation between the thickness of part and its Vf.

$$V_f(\%) = \sigma_{fabric} / \rho_{carbon} * t_{plaque} \tag{1}$$

where V_f = fiber volume fraction, σ = areal mass, ρ = density, t = thickness

The V_f values obtained by CMM were challenged against acid digestion tests per ASTM D3171 that were sub-contracted in an independent laboratory and were validated also in an industrial laboratory. This CMM technique was cheaper than acid digestion and significantly improved our capabilities to manufacture a large number of plaques and to measure all of them.

The second phase of the experimental plan was to adapt and validate the developed infusion process to a complex tri-dimensional geometry as shown on Figure 6. This geometry was chosen in partnership with Bombardier and Weber Manufacturing which provided a nickel shell tooling. The tooling was capable of 180 degrees Celsius curing with temperature control based on a pressurized water temperature control unit. The forward section (in blue) was selected as a first challenge to develop the process. The objective of this step of the plan was to identify the knowledge gaps of the technology and identify the performances of the process on a real complex geometry. Four fairings were manufactured using specific infusion tools and were inspected using microscopy, CMM and acid digestion.

4 STRUCTURAL INFUSION$_{TM}$ PROCESS

Caul technology adapted to infusion represents the core innovation of this process. Nevertheless, the materials, consumables and detailed procedures developed to laminate, preform, bag and infuse a load-bearing structure part are key to this novel process. The first main step of the process is to create a preform with the plies laid-up and compressed under vacuum as seen on Figure 6.

Figure 6. Preform

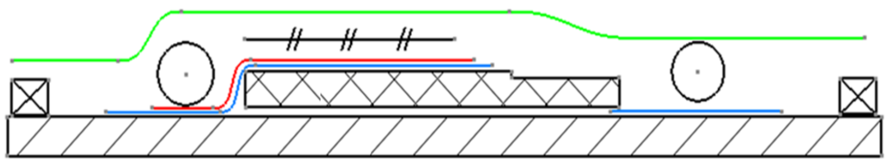

Figure 7. Structural Infusion$_{TM}$

This first step is critical for quality and drives the control of fiber orientation and position within a multilayers reinforcement stack that can easily be manipulated by technicians. This step also takes care of the compaction of the reinforcement layers, a control required to achieve high V_f. Moreover, the preform lowers the cycle time of the process because of the easiness in manipulating these preforms for storage or cleanliness of molding setup. The setup phase using the preform ( ) is shown on the schematic of Figure 7. This setup was quite simple for plaques, but fairing manufacturing required a bit more tooling ( ) solutions because of its complex double curvature. The tooling takes care of the surface of the part in contact with it.

To improve surface control on the bag side and ensure a higher thickness accuracy relying only on the atmospheric pressure, a novel infusion caul ( ) technology is used on the top of the stack up inside the bag. This critical features takes major functions as geometry control and resin injection points governing the infusion strategy.

Figure 8. Process setup

Figure 9. Positioning device

Figure 10. Infused fairing

Figure 8 shows an actual setup on a nickel shell tooling. The preform is under the caul, separated by a specific flow media and a peel ply. Tubes and resin inlet lines are also present and are included within the bag. The process was adapted for a tooling that was not designed for infusion purposes. Therefore, no locating features were included and a custom alignment and positioning device was designed and fabricated. Figure 9 shows this custom system that ensures an accurate position of the caul on the top of the stack-up. As in most of the molding processes, part release is followed by trimming and finishing steps to remove extra material molded. Figure 10 shows a picture of a finished fairing out of Structural Infusion$_{TM}$.

5 RESULTS

The first results for V_f from thickness measurements were obtained using the CMM. Then, plaques and fairing were cut into samples for microscopy, mechanical testing and acid digestion when required. The left side of Figure 11 shows a thickness scale, red being .0980 inches on average and hard blue being the thinnest section at .0792 inches on average. Note that this scale was selected arbitrarily. The plaques results shown on the second image of Figure 11 are from the tree independent plaques molding by Structural Infusion$_{TM}$. These plaques were specifically manufactured with the process specifications to validate the method in 2D. Fairing results, presented on the third image of Figure 9 were measured from the forth unit manufactured, the last part obtained at the moment.

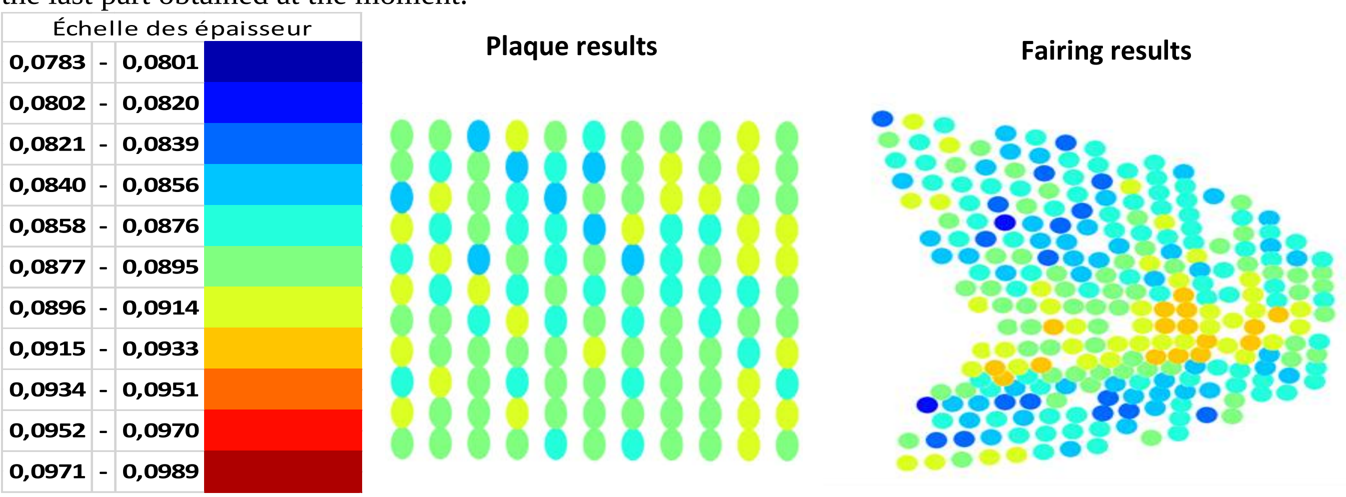

Figure 11. Thickness measurement results

The challenge with the fairing was that the fiber volume content was not measurable directly based on the thickness measurements. Indeed, the double curvature complex geometry was causing the reinforcement structure to shear and slightly change in areal density. To account for this, a parallel experimental plan was elaborated to determine the correlation between the shear angle and the fiber's density of the selected reinforcements. The correlation between the shear angle and the thickness was then used to calculate the real fiber volume content. Then, for the fairing, 3 different points of fibers volume content results were verified and validated using the acid digestion technique, the industry standard method. The Table 1 is a summary of the V_f results.

	Target	**General infusion**	**2D S. Infusion, Independent lab.**	**2D S. Infusion, Industrial lab**	**3D S. Infusion, Independent lab.**
Mean	58 %	53.4 %	59.9 %	59.9 %	62.2 %
err. +	3%	2.7 %	1.8 %	0.77 %	2.0 %
err. -	3%	1.9 %	1.4 %	0.75 %	1.2 %

Table 1. Vf results in function of process and testing laboratory

The target was set in the objective of the project for load-bearing structure applications. The general infusion results were the best results obtained by using best infusion practices, without preform and caul technology. The 2D Structural Infusion$_{TM}$ results were measured in an independent laboratory, the Centre de développement des composites du Québec (CDCQ) and in an industrial laboratory of Bombardier. As specified before, tree plaques were molded to validate the 2D results. The 3D Structural Infusion results are from the last fairing manufactures, measured at CDCQ. All the results in Table 1 were obtained by the acid digestion method per ASTMD3171.

6 ANALYSIS

The analysis of the results revealed an improved performance for the plaques manufactured by Structural Infusion$_{TM}$. The V_f achieved by tree different process validation plaques was 59,9 % with maximum variations of +0.77 % and – 0.75 %.

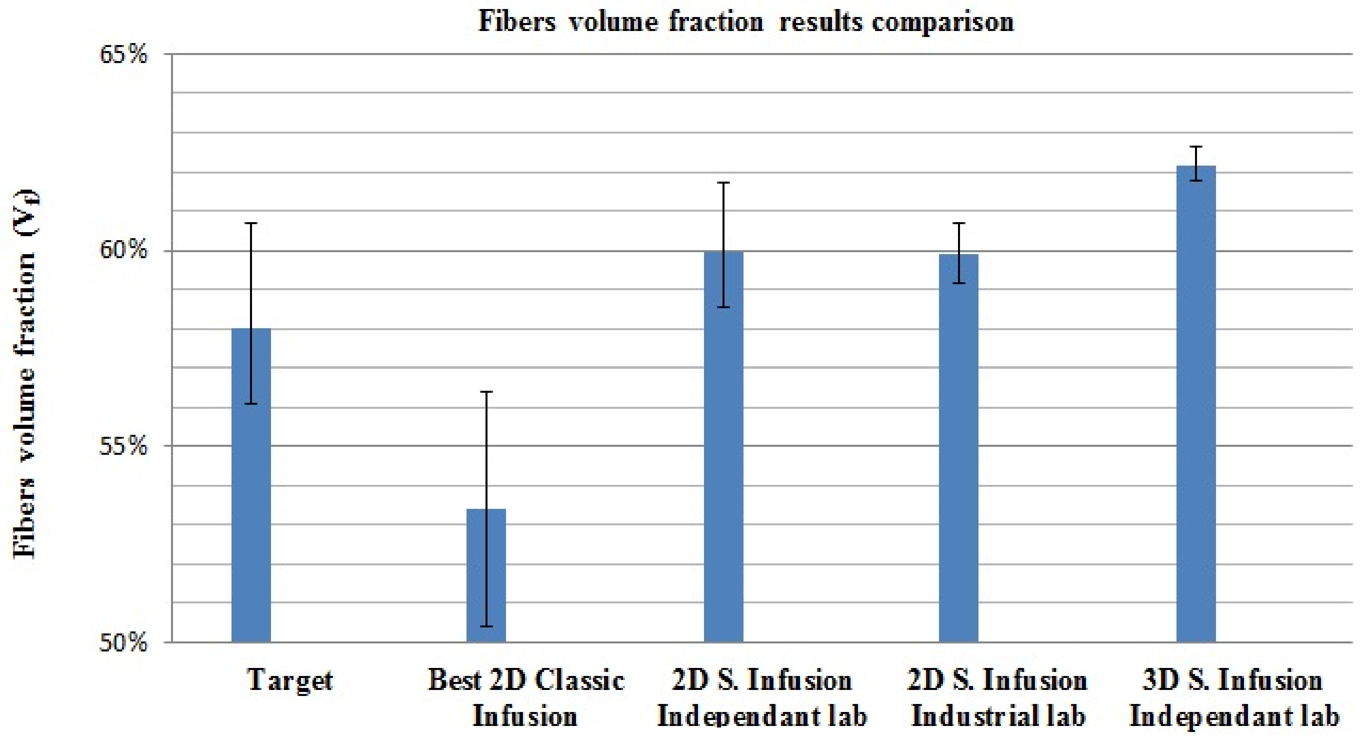

Figure 12. Fiber volume fractions results

Figure 12 shows a summary of the obtained results at the moment in this project. The plaque results were within the project targets in Vf with a maximum variability of ± 3%. The plaques gave promising results for the development of the infusion process to the required level for load-bearing structures manufacturing in aerospace. The fairing's analysis showed impressive results. But, only one fairing was measured meaning that a higher variation would be expected for tree independent fairing measurement. It is also noted that the range of V_f is very high and probably caused by the layer by layer preforming technique that had to be done to obtain a good preform quality. However, high V_f by state-of-the-art infusion if not uncommon, as mentioned by Larry R. Holmes from the U.S. Army Research Laboratory [8]. The main sources of variation were identified as: the reinforcement's natural variability, the tolerances on the material's specific density, the pressure equilibrium in the resin, the tolerance in position of the caul relatively to the tooling and consumables variability.

7 CONCLUSION

The main objective of the project was to develop a novel infusion based process capable of manufacturing primary aerospace structures with a fiber volume content of 58% and a variation within ±3 % with an overall part quality equivalent to parts molded by the autoclave process. The forecasted knowledge gaps to bring the infusion to a primary structure level were the maximum V_f achievable and its variability. On the other hand, the expected advantages were the lower manufacturing costs and the energy savings as compared to the autoclave process, the availability of the infusion materials within the local supply chain, and the low infrastructures required for the process.

A large experimental plan lasted over 2 years and covered different infusion techniques known in the industry to study the parameters of influence and their impact on part performance. More than 150 parts were rigorously manufactured, following the industrial standard required to supply load-bearing structures in commercial aerospace. Process validation plaques were manufactured and showed that the primary structure target in terms of fiber volume and void fraction were achievable. Moreover, they were manufactured with a 180 degrees Celsius curing temperature mono-component toughened epoxy resin system infused out-of-autoclave in a highly compact non-crimp carbon structure reinforcement. The process validation plaques (3) and the fairing measured demonstrated that infusion is of interest for the manufacturing of aerospace primary structures. A novel process was developed and relies on a good preform manufacturing procedure, a rigorous infusion setup procedure using a novel infusion specific caul technology and a combination of high temperature primary structure compatible consumables. Moreover, Structural $\text{Infusion}_{\text{TM}}$ is planned to be sizeable to address large structures.

8 FUTURE WORKS

The Structural $\text{Infusion}_{\text{TM}}$ process shows great performance for plaques and double curvature complex geometries. Other structural components, like stringers, frames and braces would be interesting to experiment. Moreover, a complete mechanical performance test plan would be required and a study of the impact of thickness and materials on process performance. The infusion process is ready to manufacture secondary structure and this would give access to more data to evaluate its performances. Finally, the process is expected to match the requirements of other industries where a need for low cost composite parts with high fiber volume content and uniformity are of concern.

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