Finite Element Prediction of Surface Waviness in Membrane-assisted Rigidized Preform-based Composite Molding

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Abstract

Silicon Carbide (SiC) Ceramic Matrix Composites (CMC) frequently require rigidized three-dimensional (3D) woven preforms. These preforms can suffer from geometrical variation, necessitating clearance in traditional rigid molds. That ultimately leads to excess thickness in the final CMC part, which contribute to non-functional weight and increase the risk of fracture initiation. Correcting the resulting surface finish through machining at the end of the manufacturing process is both difficult and costly. The use of an inflatable membrane to conform the mold to the preform presents a potential solution to this issue. However, depending on the membrane geometry and material properties, there is a risk of imprinting the woven surface features of the preform onto the final part, preventing its net-shape surface finish. A Finite Element Analysis (FEA) model is developed and validated against experimental results to predict the surface waviness of injected CMC parts. The preform surface is first characterized using structured light 3D scanning, showing a maximum height of waviness $W_z^{Preform}$= 55.56 µm and total height of the waviness profile $W_t^{Preform}$ = 140.36 µm. Paraffin is then injected into the preform, and a silicone membrane is inflated at 0.7 bar. After pressure release, the residual paraffin layer reflects the expected surface finish of the final CMC part. The waviness post-injection shows a two-fold reduction compared to the preform with W_z^{Exp} = 21.19 µm and W_t^{Exp} = 67.73 µm. In the FEA model, the scanned preform surface is imported as a rigid body and the membrane is modeled as a Mooney-Rivlin solid. Material parameters are identified via a bulge test as C_{10} = 0.07 MPa and C_{01} = 0.221 MPa. The FEA model predicts a post-injection waviness of W_z^{Num} = 25.30 µm and W_t^{Num} = 58.96 µm, corresponding to deviations of 19.4% and 10.3% from experimental measurements for W_z and W_t, respectively. Overall, the results demonstrate that the proposed FEA framework provides a reliable predictive tool towards optimizing mold design and fabrication processes in membrane-conformed CMC.

1. Introduction

To meet the new environmental standards, aircraft manufacturers are turning towards Ceramic Matrix Composites (CMC) as they could improve the fuel efficiency by 10-25% [1–4]. Among the matrix densification methods for complex CMC parts, the injection-filtration (IF) process, is particularly attractive. The IF uses a Chemical Vapor Deposition (CVD) consolidated 3D woven preform placed inside a mold cavity equipped with filtrating surfaces. As a pressurized aqueous suspension of ceramic micronic particles is injected into the mold, water flows through the filtration surfaces leaving a powder cake within the porous network of the preform. After thermal treatment, this powder cake becomes the ceramic matrix [5–7].

Figure 1 presents an example of a typical preform used for the IF. The preform is a square sample of dimensions 50 by 48 by 3 mm. 3D preforms are reinforcements used in complex composite parts requiring high mechanical properties along different directions. Most of the time the preform is soft while the mold used for the matrix densification of the composite is rigid. However, IF-manufactured SiC CMC use rigidized preforms [6, 7]. When rigid molds are used, the loose dimensional accuracy of the consolidated preforms, coming from the CVD step, necessitate clearances, which in turn result in excess raw matrix material accumulating on the part surface [7]. For aircraft engine parts such as turbine blades, limiting non-functional weight is essential. Moreover, those raw matrix areas are prone to cracking while drying and can facilitate fracture initiation. Correction of this excess thickness near the end of the industrial range, while possible, requires long and costly specialized machining [1, 8–10].

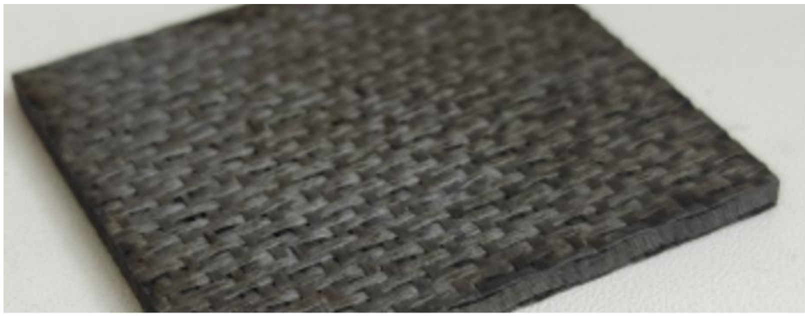

Figure 1. Global view of a square plane CVD consolidated 3D woven preform used for this study.

This motivates the use of membrane-assisted IF processes to conform to the preform geometry and achieve a near-net-shape surface finish. In this context, the inflatable membrane must effectively act as a low-pass filter on the surface profile, introducing a tradeoff: it must be sufficiently compliant to conform to the preform and prevent excess matrix accumulation, while retaining enough stiffness to ensure that the resulting surface waviness remains within specified tolerances. The experimental studying of the deformation and conformation of a soft or foamy material in contact with a rigid smooth surface is documented [11]. In some extent, the modeling of this kind of contact with a textured surface [12] or with complex shapes [13] has also been studied. However, the experimental surface acquisition of an inflatable membrane pressed against a textured finish part seems unaddressed in the literature. To experimentally study this phenomenon a 3D imprint taking solution is envisaged. Despite its thermal retraction, paraffin wax seems promising instead of sand derivatives or specific metrology reproduction pastes [14, 15]. The paraffin allows for an easy injection due to its high fluidity and low melting point, is easy to clean, show low adhesion to mold parts and membranes, and is inexpensive. The objective of this study is therefore to develop an experimentally validated Finite Element Analysis (FEA) model capable of predicting the final surface finish of an IF-densified SiC CMC component as a function of the initial preform surface state, membrane thickness and material properties, and processing conditions.

2. Experimental Methods

2.1. Membrane hyperelastic properties determination

The membrane used in this study is cut from a 1.7 mm thick 50 Shore A silicon sheet. A bulge test recreating a biaxial stress state on the membrane [13, 16, 17] is used to fit Mooney-Rivlin constitutive model parameters C_{10} and C_{01}.The supports to clamp the membrane are designed in the Computer Assisted Design (CAD) software (SolidWorks 2024, Dassault Systemes) and produced using Stereolithography (SLA, Photon M3 Max, Anycubic), using Water-Wash ABS-like V3 resin, and Fused Filament Fabrication (FFF, Prusa XL, Prusa) with Polylactic Acid (PLA) and Polyethylene Terephthalate Glycol (PETG). The membrane is air-tightly sealed in the setup which is connected via tubing and push-to-connect fitting to a pressurized tank. The pressure in the tank is set with a compressed air network, a manual regulator and a digital manometer (LC-189B, Lycebell) with an accuracy of ± 0.001 bar. The deformation under pressure of the membrane is acquired by structured light 3D scanning (Atos Core 200, GOM) allowing for a minimun points spacing of 0.08 mm. The deformation is measured for three pressures aiming respectively to 0.70 bar (10 psi), 0.46 bar (6.66 psi) and 0.23 bar (3.33 psi). The resulting scan files in STL format are then analyzed in CAD to extract the maximum deflection at each pressure. Finally, the inflation of the membrane is simulated via FEA (Abaqus 2024, Dassault Systemes) for values of C_{10} and C_{01} between 0 and 0.850 MPa. The couple C_{10} and C_{01} that minimizes the root mean square error (RMSE) of the experimental vs FEA deflections is selected.

2.2. Preform surface waviness measurement

Figure 2 illustrates the steps of the 3D scanning based waviness metrology analysis workflow used in this study. Figure 2 a) shows the 3D scanning of a CMC square plane woven preform . The scan file obtained, presented in Figure 2 b), is cleaned, cropped and repositioned in SolidWorks, using the ScanTo3D module. Figure 2 c) displays the heatmap obtained in the software MountainMap (Digital Surf) by applying the following protocol. In the software, after importing the STL mesh file of the surface, a z-height heatmap is extracted manually, aiming for an initial positioning of the surface mean plane the closer possible to the screen plan. After removing the micro rugosities (< 2.5 µm), the surface mean plane position is then leveled with the least squares method. The shape inaccuracy of the surface, resulting from the fabrication process, is removed with a 6th order polynomial. Five 10 mm long profiles, such as the one shown in Figure 2 d), each centered on a yarn and avoiding the singular areas, are extracted from the surface. Waviness parameters, W_z (the maximum height of waviness) and W_t (the total height of the waviness profile), are calculated on each profile following the ISO 4287 standard, using five base lengths and a cut-off filter of 0.8 mm. Final results are mean values for Wz and Wt of the five extracted values.

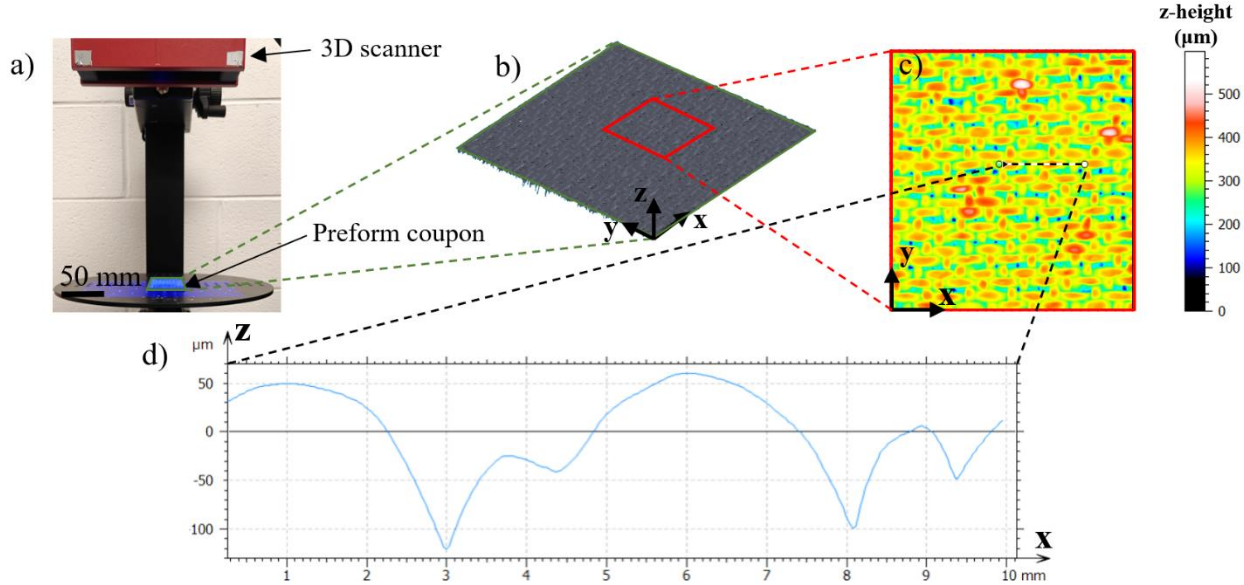

Figure 2. Illustration of the surface waviness metrological workflow used in this study. a) 3D scanning of the preform coupon. b) Meshed surface resulting from the 3D scan. c) the z height variation heatmap obtained. d) profile extracted from the surface.

2.3. Inflated membrane and woven preform contact experimental validation method

Figure 3 shows the concept of the conformation gap imprinting and its setup. Figure 3 a), b) and c) show the different steps of the process, explained below, and the Figure 3 d) shows the elements of the setup with Figure 3 e) a detailed view of the main body of the mold lodging the preform coupon. The mold is CAD designed and SLA 3D printed with directly printed thread for the screws and the NPT push-to connect fitting used. The different parts of the mold and the coupon, minus the membrane, are heated at 70°C in an oven and the paraffin melted in a beaker at 110°C. After coating the contact face of the membrane with a thick silicon oil (helping with the release), the mold is assembled. It is connected, without valve opening, to a pressurized tank at 0.7 bar (10 psi) and positioned on a tailored stand with its vent up. The paraffin is injected into the mold via a syringe, fitted in a cone-cone contact with the mold, until the paraffin level reaches the entrance of the vent which is then obstructed. The mold is then moved with the syringe up to allow for a better handling and the membrane is pressurized. After approximately 1 min, the syringe and the plug of the vent are disengaged and, after 15 min of cooling, the mold can be disassembled and the result 3D scanned (after talc mattifying) with the protocol detailed in Section 2.1.

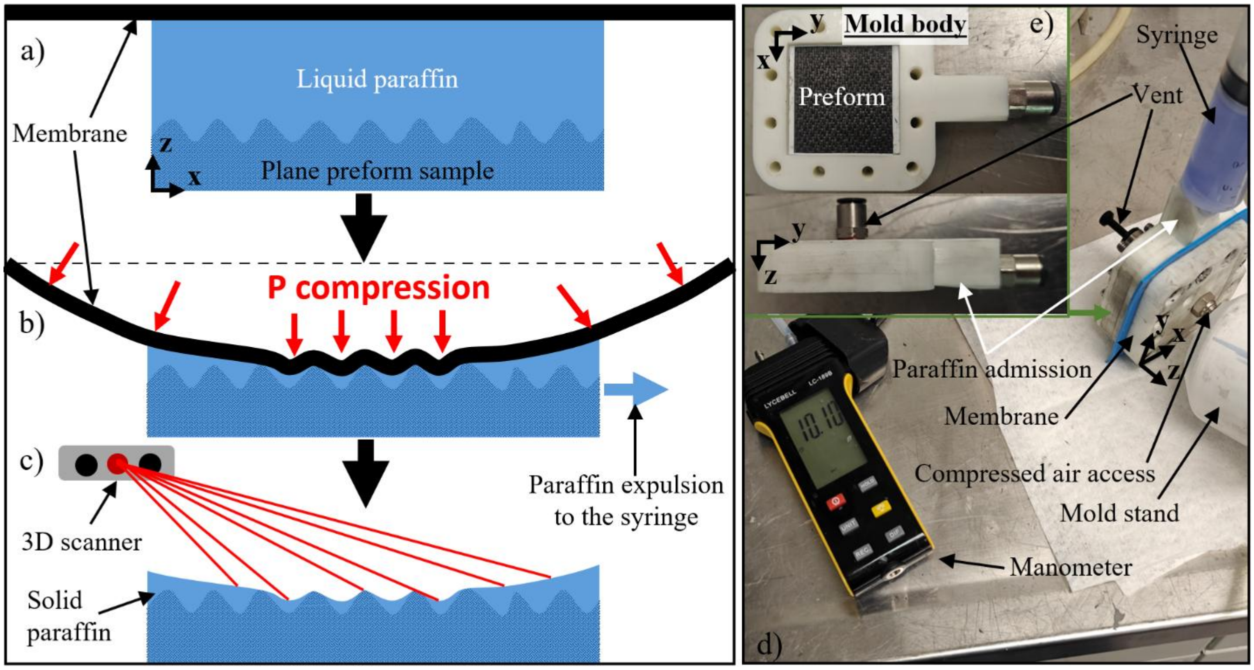

Figure 3. Conformation gap imprinting approach to characterize the waviness of membrane-assisted IF of a CMC. a), b) and c) illustrate the concept, starting with the paraffin injection, followed by the compression of the membrane and finishing by the 3D scan of the resulting surface. d) the setup during a test and e) Two detailed views of the mold main body.

3. Numerical Methods

Figure 4 shows FEA model used to predict the surface waviness in membrane-conformed CMC. Figure 4 a) displays an isometric view of the setup and Figure 4 b) a cutting view extracted following the blue lines displayed on a). The preform is modelled as a fixed rigid shell divided in two areas. A 30 x 30 mm centred square, representing a section of the preform 3D scan, and flat 10 mm wide horizontal border aligned 0.3 mm under the highest peek of the preform 3D scan (lowered to reduce convergence troubles at the transition between woven texture and plan). Membrane is modelled as an homogenous solid part solid with a surface area of 50 x 50 and a thickness of 1.7 mm. The membrane material is modelled as a Mooney-Rivlin hyperelastic solid with C_{10} = 0.07 MPa and C_{01}= 0.221 MPa (these values are fitted from the bulge test described in Section 2.1). The membrane is clamped on all side and positioned parallel with the plane border of the coupon with its lower face at 5 mm on z from the highest peak of the coupon.

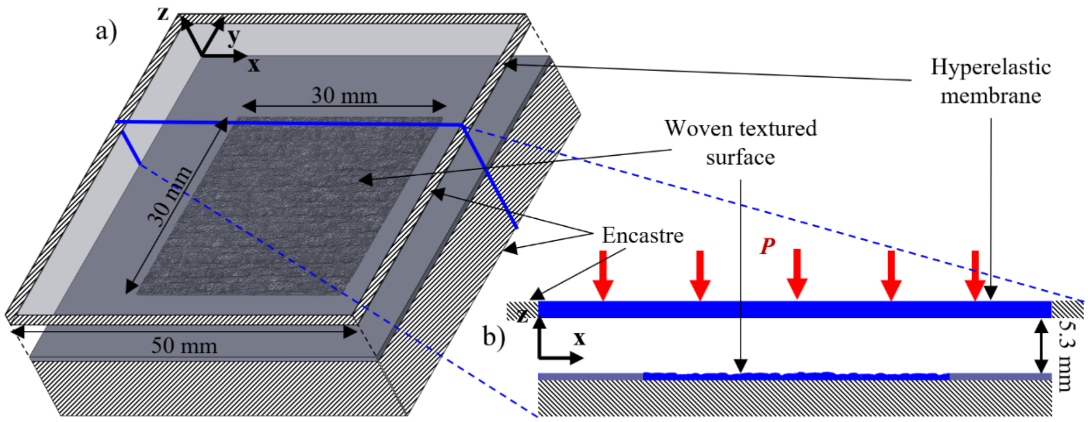

Figure 4. FEA model used to predict the surface waviness in membrane-conformed CMC. a) an isometric view showing the main dimensions and b) a cut view corresponding to the blue lines in a) and presenting the boundary and load conditions.

The FEA is carried in Abaqus 2024. The CAD model is created and parametrized in Solidworks. The CAD is then transferred to Abaqus using the Solidworks-Abaqus Associative Interface. The contact interactions between the membrane and the rigid preform are of the type general contact – all with self. The normal contact setting is “hard contact” (no penetration). The tangent contact setting is frictionless. The load is a pressure ramp with a final pressure of 0,7 bar (10 psi) applied on the face of the membrane opposed to the coupon. The structured mesh used for the membrane is made of approximately 10000 C3D8H elements with a 12 by 12 mm centered square using 0.4 by 0.4 by 1.7 mm elements and the rest of the mesh using varying size elements (with a seed of 0.8 mm for the plane and of 1.7 mm for the Z axis on the border). The coupon uses its native 3D scan mesh for the textured part and a structured mesh with elements of approximately 0.8x0.8 mm for the border surfaces.

4. Results and discussion

Figure 5 shows the results of waviness qualification of the preform coupon at a non-injected state, and at an injected state both for the FEA and for the experimental testing. Figure 5 a) display the z-height heatmap of the native coupon surface finish. Figure 5 b) presents the z-height heatmap of the coupon surface finish according to the FEA. Figure 5 c) present a XZ cut view of the membrane in contact with the textured surface. It displays the Z displacement of the membrane, illustrating its local thinning when conforming to the peaks of the texture. Figure 5 d) shows the z-height heatmap resulting from the conformation gap imprinting test. Figure 5 e) displays the top view of the coupon’s surface post paraffin injection (before the mattifying allowing for the 3D scanning).

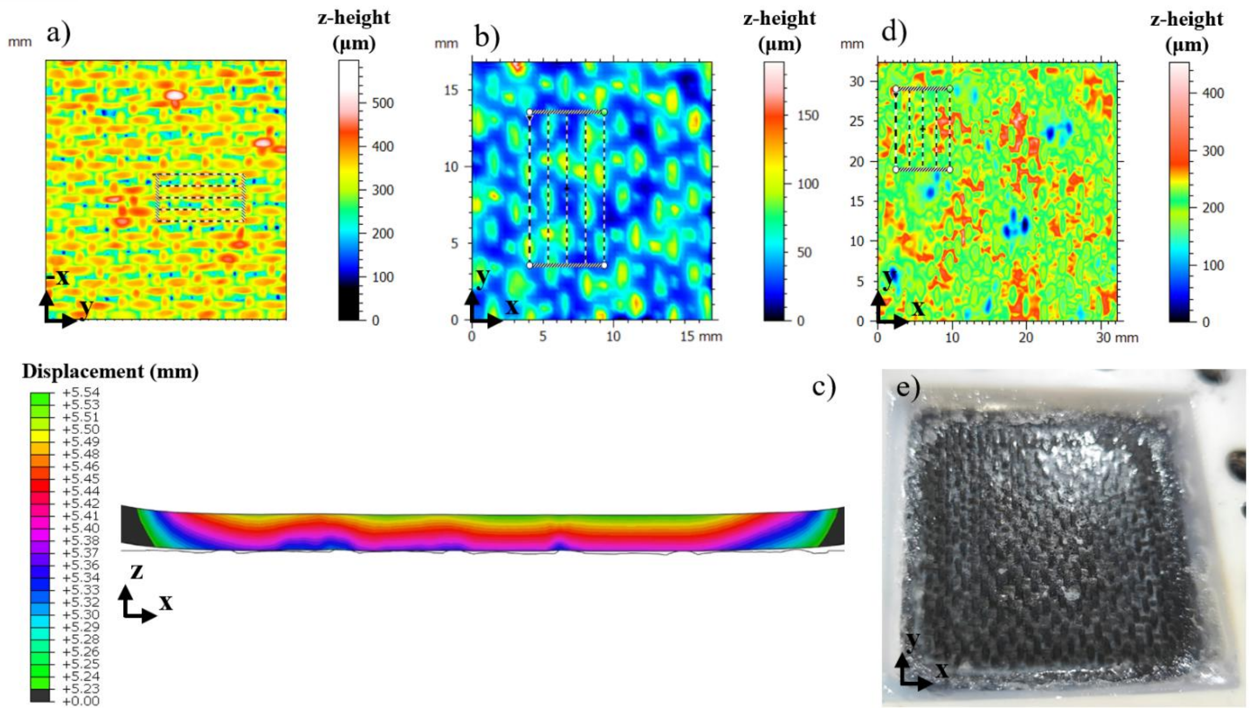

Figure 5. Results for the preform coupon surface finish in the initial, FEA and experimental cases. a), b) and d) the z-height heatmap of the initial, FEA and experimental cases respectively. c) a cut view showing the contact of the membrane with a profile of the woven surface. e) a picture of the surface state of the coupon after wax injection and membrane conformation.

Table 1 summarizes the mean values of W_z and W_t of the study. For the initial preform, the means of the measured values are $W_z^{Preform}$ = 55.56 µm and $W_t^{Preform}$ = 140.36 µm. Respectively, that gives an error of 6.8% and 3.2% compared with the reference values of W_z^{Ref} = 52 µm and W_t^{Ref} = 145 µm given by Safran Ceramics for the full plate and determined with a 3D microscope (Infinite Focus SL, Alicona). Those results confirm the adequacy of the used 3D scanner to qualify the surface waviness of the woven SiC preform considered. After extracting the deformed membrane from Abaqus, a negative is made to produce the theoretical surface finish of the coupon. Table 1 show the FEA waviness results, with W_z^{Num} = 25.30 µm and W_t^{Num} = 58.96 µm, and experimental results, with W_z^{Exp} = 21.19 µm and W_t^{Exp} = 65.73 µm. For the W_z, the experimental result poses a 2.62 reduction of the initial W_z of the coupon compared to a 2.20 reduction for the FEA results. For the W_t, the experimental result presents a 2.13 reduction of the initial W_t of the coupon while the FEA results show a 2.20 reduction. Also, the FEA model matches the experimental result with an error of 19.4 % for W_z and of 10.3% for the W_t.

Table 1. Reference values for the preform waviness and mean values results for the initial waviness and experimental and FEA results values.

Case	Wz (µm)	Wt (µm)
Reference value for the initial sample	52	145
Mean initial sample	55.56	140.36
Experimental case	21.19	65.73
Simulation case	25.30	58.96

5. Conclusion

This study compared experimental measurements and FEA predictions for the surface waviness of SiC CMC parts consolidated on woven preforms. Both approaches indicate a reduction in waviness amplitudes by approximately a factor of two after processing. The FEA model shows reasonable agreement with experiments, with errors of 19.4% for Wz and 10.3% for Wt, demonstrating its capability to capture the main features of surface smoothing induced by membrane-assisted IF. These discrepancies can be attributed to several factors. In addition to the inherent spatial dispersion of Wz and Wt across the coupon surfaces, the current model neglects key physical phenomena, including paraffin phase change, thermal shrinkage, and frictional effects at the interfaces between the membrane and the preform. Despite these limitations, the proposed modeling framework could be leveraged to guide the tuning of membrane material properties and geometry to improve the surface finish in CMC.

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