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Elastomer coating selection for AFP compaction rollers: A dual numerical-experimental approach.

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Abstract

Automated Fiber Placement (AFP) is a manufacturing technology widely used to produce lightweight composite structures, especially for aerospace and energy applications. The compaction roller is a critical component of the process because it applies pressure to prepreg tapes during material deposition. However, resin adhesion to the roller surface can compromise laminate surface quality, promote material buildup, and reduce process continuity. This study presents the experimental selection of an elastomeric coating for an AFP compaction roller using silicone rubber, nitrile-butadiene rubber (NBR), and neoprene as candidate materials. The evaluation integrated thermogravimetric analysis (TGA), wettability tests (WT) based on the sessile drop technique, a Graeco-Latin square design of experiments (DoE), and analysis of variance (ANOVA). In addition, a CAD model of the compaction roller was developed, and its mechanical performance was validated through finite element analysis (FEA) and analytical calculation of the Hertzian contact pressure. CAM toolpaths and CNC programs were subsequently generated for prototype manufacturing. The results showed that silicone rubber showed the best overall performance with an initial thermal degradation temperature of 440 °C, residual mass of 56%, and average contact angles close to 75°, which indicated a lower surface wettability and less tendency of the resin to stick to the surface. Mechanical validation confirmed the structural feasibility of the proposed design with Von Mises stresses of around 3 MPa, localized equivalent strain of approximately 0.5 mm/mm in the elastomeric contact region, and a maximum Hertzian contact pressure of around 1.83 MPa.

Keywords: AFP, ANOVA, FEA, Hertzian contact pressure, CAD/CAM/CNC.

1. Introduction.

Automated Fiber Placement (AFP) is a manufacturing technology widely used to produce high-performance composite structures, particularly in the aerospace, wind energy, and automotive sectors, where lightweight components, complex geometries, and high process repeatability are paramount [1], [7], [8]. The process enables the controlled deposition of prepreg tapes or tows on flat or curved surfaces, with advantages in productivity, placement accuracy, and laminate quality [1], [2]. However, the quality of the manufactured component strongly depends on the compaction conditions applied during deposition since non-uniform pressure may lead to defects such as voids, delamination, fiber waviness, and surface imperfections [2],[5].

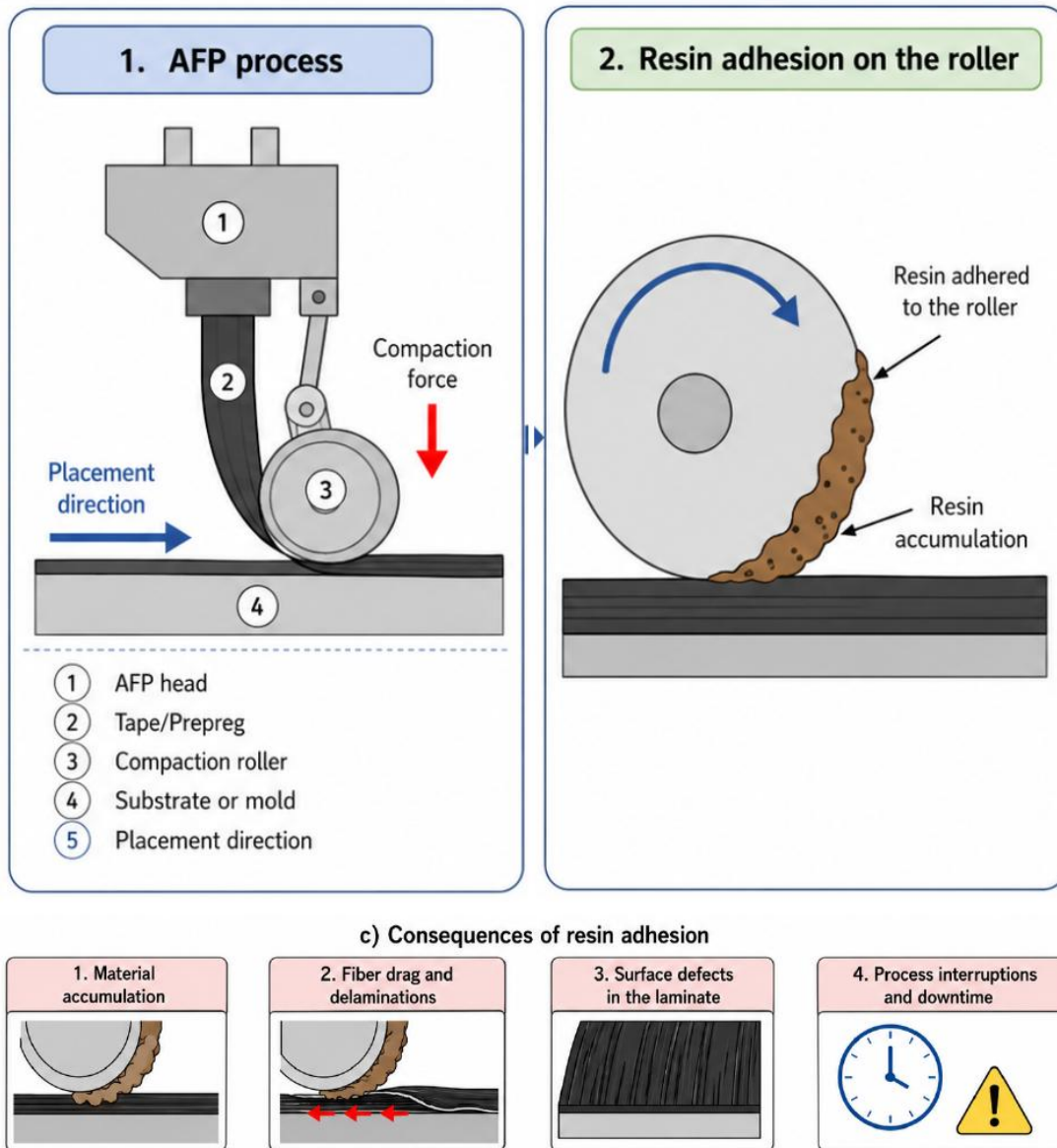
The compaction roller is one of the most important mechanical components of the AFP deposition head, as it provides the pressure required to consolidate the material during placement [2], [6]. The pressure distribution of the roller directly influences contact uniformity, interlaminar bonding, and laminate quality. Therefore, the geometry and the mechanical design of the roller have been the subject of much research [3], [6]. However, in addition to these problems of structure and pressure distribution, a constant practical problem is posed by the continual contact of the roller with the polymeric resins, which adhere to the roller surface (Fig. 1). This leads to resin accumulation, material drag, degradation of the laminate surface finish, and interruptions in process continuity.

One solution to this problem is to apply elastomeric coatings to the outer surface of the compaction roller to reduce the surface wettability while maintaining a sufficient mechanical performance at the operational conditions. Thermal stability and contact angle are the key material properties in this context, since they are indicative of the resistance to the thermal conditions encountered during the processing and the tendency of the surface to interact with liquids or polymeric resins [9][14][17][20]. Most of the prior studies have been focused on pressure

distribution and the effect of the compaction roller on laminate quality [2][6]. In contrast, the experimental selection of roller coating materials as well as their integrated mechanical validation has been paid relatively little attention.

The present work details an experimental approach for the selection of elastomeric coatings and mechanical validation of an AFP compaction roller. The three elastomers, silicone rubber, nitrile-butadiene rubber (NBR), and neoprene, were characterized by TGA, wettability tests (WT) using the sessile drop technique, and a Graeco-Latin square DoE with ANOVA [9][17] [21][23]. Then the compaction roller was modeled in CAD and validated mechanically by finite element analysis (FEA) and Hertzian contact theory [24]–[27]. Finally, the manufacturability was assessed by a CAD/CAM/CNC workflow [28–31]. The main contribution of this work is the combination of experimental selection of the coating material with structural validation of the prototype, providing a technically supported solution to the resin adhesion problem in compaction rollers for AFP processes.

AFP compaction roller: process, resin adhesion, and effects



Resin adhesion on the roller compromises laminate quality, reduces process efficiency, and increases operating costs.

Figure 1. Schematic representation of resin adhesion on the AFP compaction roller.

2. Materials and Methods

2.1 Materials first evaluation

Three commercially available materials were tested for elastomeric coating of the AFP compaction roller, namely silicone rubber, nitrile-butadiene rubber (NBR), and neoprene (see Figure 2). The selected elastomers are industrially available, elastic, easy to manufacture, and potentially suitable for use as surface coatings in contact with polymeric resins.

Elastomers are polymeric materials that can undergo a reversible deformation under fairly small loads, because of the mobility of the molecular chains and their lightly cross-linked structure. This property is particularly important for a compaction roller since the coating must conform to the deposition surface without sacrificing the dimensional stability of the assembly. The selection criterion was not limited to the elastic properties of the material but to the overall performance with respect to three main requisites, namely thermal stability, low surface wettability and mechanical suitability within the design of the roller. Thus, TGA, wettability tests and statistical evaluation by DoE were performed on the three elastomers.



Figure 2. Elastomer samples evaluated as coating materials for the AFP compaction roller.

2.2 Thermogravimetric characterization

The thermal stability of the candidate elastomers was assessed using Mettler-Toledo TGA/DSC+3 equipment. Through this method, the mass loss of a specimen (due to the temperature increase) is measured, enabling the detection of the temperature corresponding to the start of thermal degradation, the degree of mass loss, and the ultimate mass remaining of the material, respectively. TGA measurements were carried out not only on a sample of silicone rubber, but also on a piece of nitrile-butadiene rubber (NBR) and neoprene. The main factor considered was the temperature at which a material starts to thermally deteriorate, because an AFP compaction roller coating needs to be capable of maintaining its performance during exposure conditions where localized heat from the composite material deposition process might be present.

The mass loss was calculated using (Equation 1):

$$\text{Mass loss (\%)} = \frac{m_i - m_f}{m_i} \times 100 \quad \text{Equation 1}$$

Where:

m_i = initial sample mass (g).

m_f = final sample mass after the thermal test (g).

The residual mass percentage was determined using (Equation 2):

$$\text{Residual mass (\%)} = \frac{m_f}{m_i} \times 100 \quad \text{Equation 2}$$

These parameters were used to compare the thermal resistance of the three elastomers and to identify the material exhibiting the highest thermal stability under increasing temperature.

2.3 Wettability tests

The surface wettability of the materials was evaluated through a contact angle meter by means of a Goniometer model VCA Optima (AST Products Inc.). Basically, the procedure includes putting a liquid drop on the material and measuring the angle at which the liquid meets the solid and gas surface. The liquids that were used were water, ethylene glycol, and ethanol. The measured contact angle θ gave an idea about the ability of the material to be wet by the liquid in question. Overall, a high contact angle value corresponds to low surface wettability and vice versa (see Equation 3).

$$\cos(\theta) = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \quad \text{Equation 3}$$

Where:

γ_{SV} =solid–vapor surface tension

γ_{SL} =solid–liquid interfacial tension

γ_{LV} =liquid–vapor surface tension.

2.4 Design of Experiments and ANOVA

A Graeco-Latin square DoE (statistical experiment design) was utilized to determine how the coating material affected the surface wettability. This research design allowed the researchers to see the results of the coating material alone while taking away the possible influences coming from the probe fluid, day of experiment, and measurement shift factors. Table 1 shows the different variables considered for this experiment.

Table 1. Experimental factors considered in the Graeco-Latin square DoE.

Factor	Levels
Material	silicone rubber, NBR, neoprene
Liquid	water, ethylene glycol, ethanol
Day	Monday, Thursday, and Friday
Measurement shift	morning, afternoon, night

The statistical analysis was performed using ANOVA, with a significance level of $\alpha = 0.05$.

The F-ratio was calculated as seen in Equation 4.

$$F = \frac{MS_{factor}}{MS_{error}} \quad \text{Equation 4}$$

Where:

MS_{factor} = mean square of the evaluated factor.

MS_{error} = mean square of the experimental error.

Statistical significance was determined according to the p-value, which is considered statistically significant if $p < 0.05$. On the contrary, when $p \geq 0.05$, we believed it to have no statistically significant effect.

2.5 Methodological workflow and software declaration

The methodological workflow used in this study was structured to connect the experimental selection of the elastomeric coating with the digital design, mechanical validation, manufacturing, and prototype testing of the AFP compaction roller. First, three candidate elastomers were evaluated through thermogravimetric characterization and wettability measurements. Then, the contact angle response was analyzed using a Graeco-Latin square design of experiments and ANOVA. Based on the experimental and statistical results, silicone rubber was selected as the coating material for the compaction roller.

The design process started by defining the main functional requirements of the roller: contact with the prepreg tape, compaction force transmission, compatibility with bearings and shaft assembly, and the integration of an elastomeric outer coating. The CAD model was developed in SolidWorks by defining the central shaft, aluminum core, bearing seats, and external silicone rubber coating. The assembly was then checked for component compatibility, internal clearances, and complete roller geometry before mechanical validation.

The finite element analysis was performed using SolidWorks Simulation. The numerical model considered the applied compaction load on the external roller surface, while the equivalent Von Mises stress and strain distribution were evaluated to verify the mechanical response of the assembly. The numerical validation was complemented with Hertzian contact theory to estimate the contact pressure between the cylindrical roller and the deposition surface. Finally, the manufacturing stage was developed using NX CAM, where machining operations, toolpaths, and CNC programs were generated for prototype fabrication.

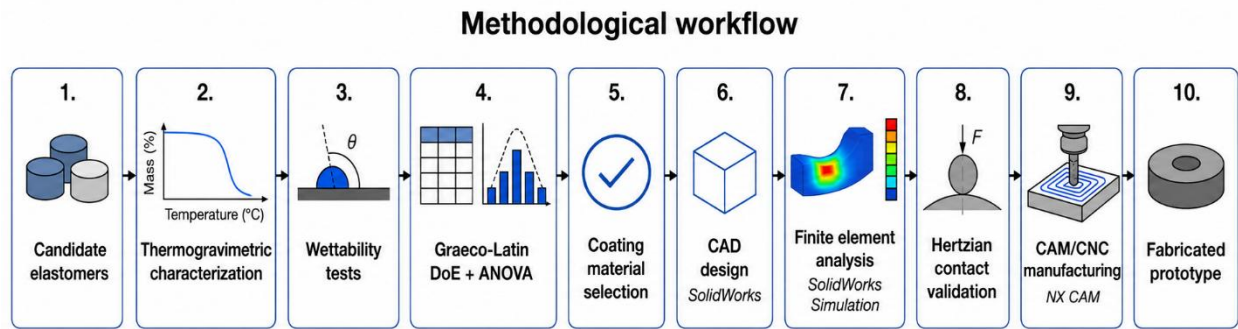


Figure 3. Methodological workflow for elastomeric coating selection, mechanical validation, and prototype manufacturing of the AFP compaction roller.

Finally, after prototype manufacture concluded, validation tests were performed first by manually fiber placements. Finally, the prototype was mounted on a Schunk® robotic arm and performed some basic routines to visually evaluate the quality of fiber placement.

3 Results

3.1 Thermal Stability of the Elastomers

The TGA results gave insight into a comparison of the three kinds of elastomers regarding their thermal stability (see Table 2). Silicone rubber was found to have the best thermal properties; its thermal degradation began at 440°C, the mass loss was 44%, and the ultimate mass left was 56%. The starting point for NBR's degradation was 325°C, and for neoprene, the initial phase of thermal decomposition was observed at 320°C (see Figure 4).

Table 2. Comparative results of the TGA analysis.

Material	Onset of thermal degradation	Mass loss	Residual mass
Silicone rubber	440 °c	44%	56%
Nbr	325 °c	45%	55%
Neoprene	320 °c	41%	58%

These findings show that silicone rubber is a far better choice when it comes to heat resistance. Among the tested elastomers, it can withstand much higher temperatures, which is very significant for an AFP roller as a compaction means of a resin transfer mold because the coating has to stay in good condition while in operation of the laying head and during possible exposure to the heat points that might emerge at any stage of the production process.

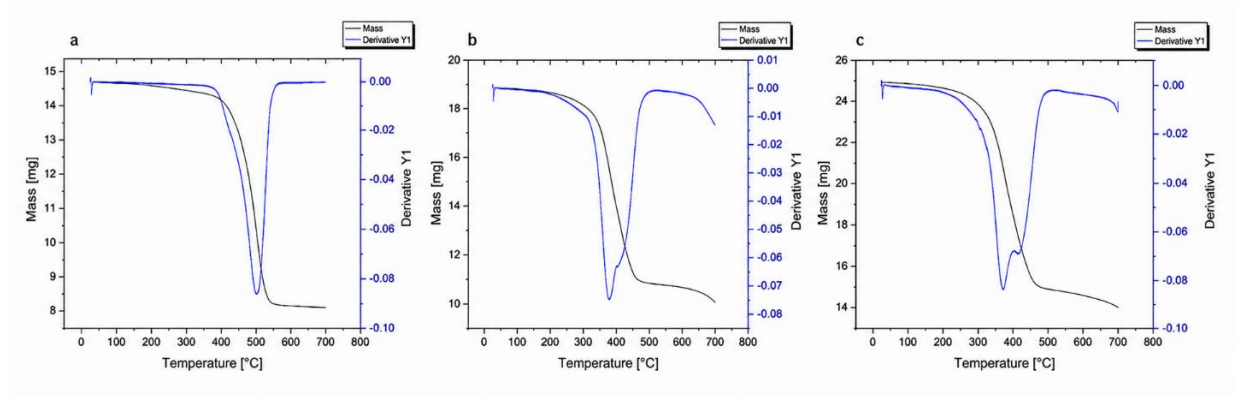


Figure 4. Thermogravimetric characterization of the evaluated elastomers: (a) silicone rubber, (b) NBR, and (c) neoprene.

3.2 Wettability and Coating Material Selection

The results of the wettability tests showed evident differences between the materials under study (see Figure 5). Silicone rubber presented the highest average contact angle, about 75°, followed in order by NBR and neoprene with relatively lower contact angle values. It suggests that the surface wettability of silicone rubber is less than that of the other candidate elastomers

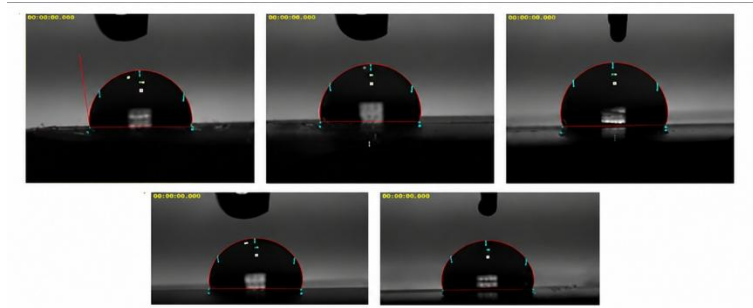


Figure 5. Wettability test using the sessile drop technique: (a) optical goniometer and (b) contact angle measurement sequence.

From the point of view of function, the reduction in the surface wettability is favorable as it reduces the tendency of the liquids or polymeric resins to spread out on the surface of the coating. Therefore, silicone rubber was considered the best option for reducing the resin adhesion on the AFP compaction roller surface (see Figure 6).

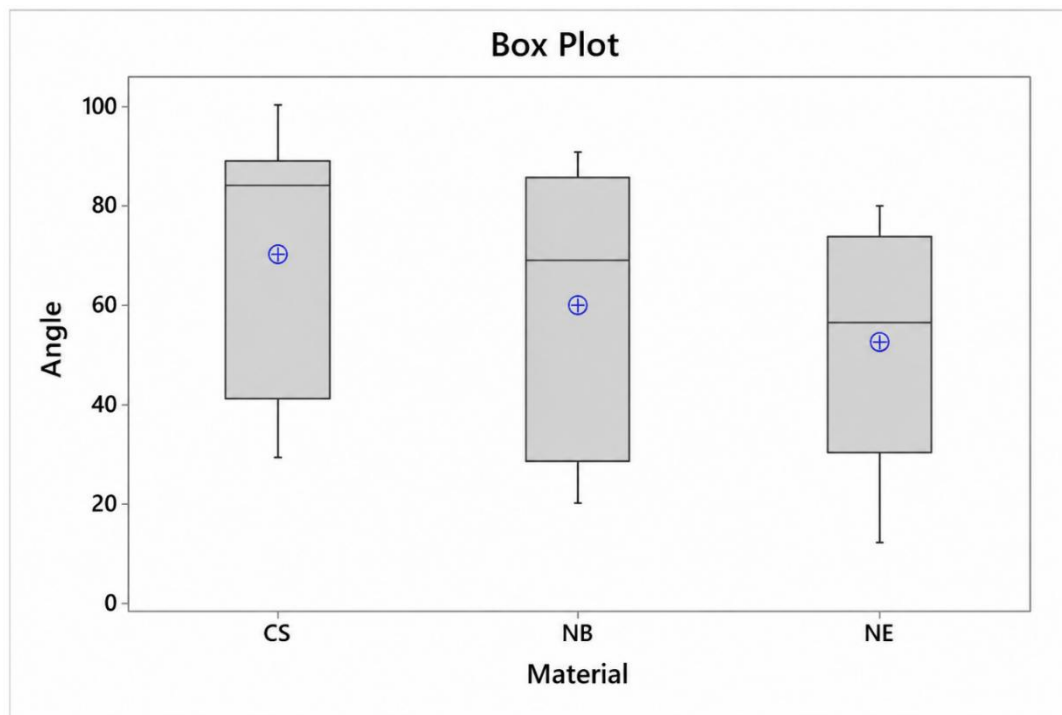


Figure 6. Comparison of the contact angle measured for silicone rubber, NBR, and neoprene.

3.3 Statistical Validation by ANOVA

Analysis of variance (ANOVA) was carried out to assess the impact of each factor considered in a Greco-Latin square Design of Experiment (DoE) on the wettability response. The analysis showed that the use of different materials, days, and measurement shifts as factors resulted in p-values equal to zero, which means these factors were statistically significant, as they passed the test that $\alpha=0.05$ is the threshold for significance. On the other hand, probe liquid as a factor resulted in a p-value of 0.354, which means the probe liquid had no statistically significant influence on the wettability measurement under the conditions of the experiment.

Table 3. ANOVA results for the contact angle.

Factor	Df	Sum of squares	Mean square	F-ratio	P-value
Material	2	2456.7	1228.3	39.36	0.000
Day	2	952.7	476.4	15.26	0.000
Measurement	2	24498.3	12249.1	392.46	0.000
Liquid	2	66.7	33.4	1.07	0.354
Error	36	1123.6	31.2	—	—
Total	44	29098.0	—	—	—

The ANOVA results (see Table 3) indicate that material, day, and measurement shift had a statistically significant effect on the contact angle response ($p < 0.05$). In contrast, the probe liquid did not show a statistically significant effect under the evaluated experimental conditions ($p = 0.354$). Therefore, the surface material was confirmed as a relevant factor affecting wettability. These results support the use of contact angle as a valid criterion for coating material selection and reinforce the selection of silicone rubber as the best-performing elastomer among the evaluated materials. The ANOVA diagnostic plots (see Figure 6) showed that the residuals remained within acceptable limits, supporting the validity of the statistical interpretation of the experimental results.

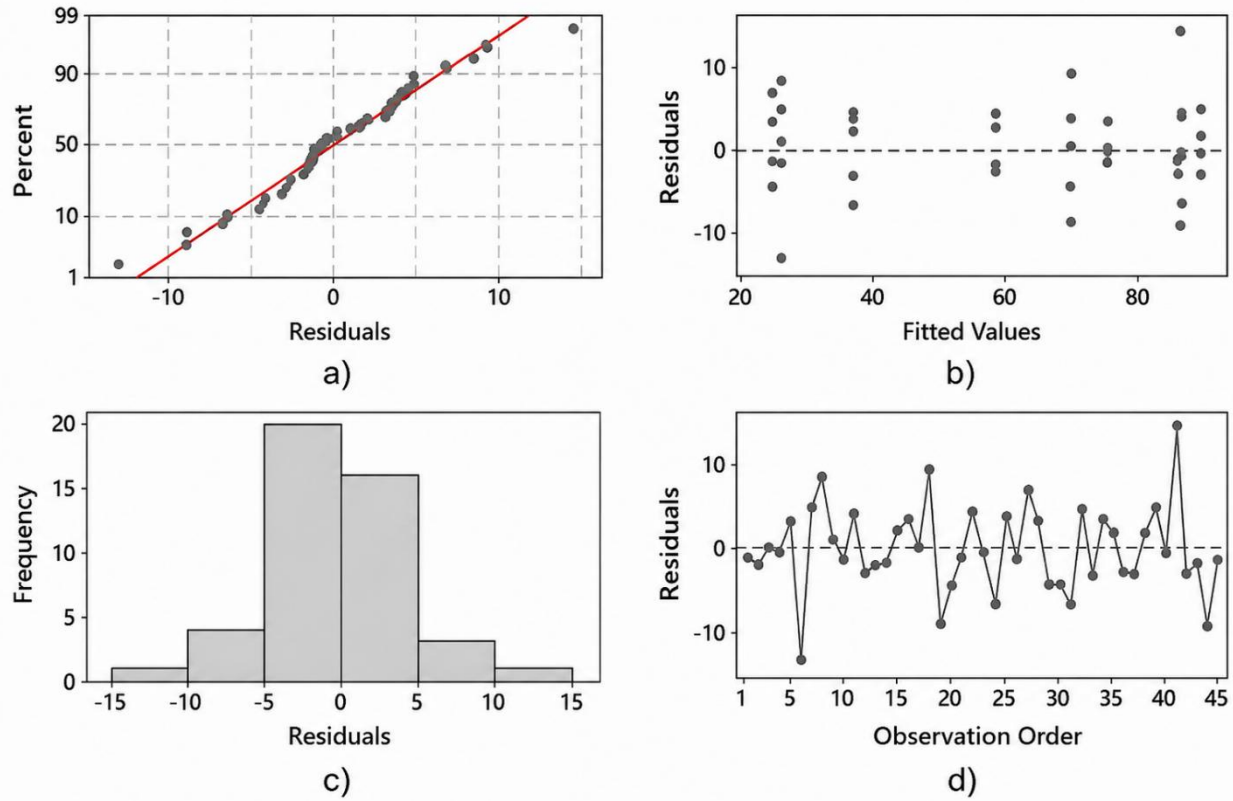


Figure 7. ANOVA model diagnostic plots: (a) normality, (b) constant variance, (c) independence, and (d) histogram of residuals.

3.4 CAD Design of the Compaction Roller

The compaction roller was developed as a CAD model after selecting silicone rubber as the coating material. The main components of the assembly were the central shaft, the aluminum core, the bearings, and the outer elastomeric coating. The CAD model allowed the component compatibility, internal clearances, and complete roller geometry to be verified before mechanical validation. The resulting assembly in Figure 7 shows the material distribution and the functional arrangement of the roller components, including the aluminum core, steel shaft, SKF bearing, and silicone rubber coating.

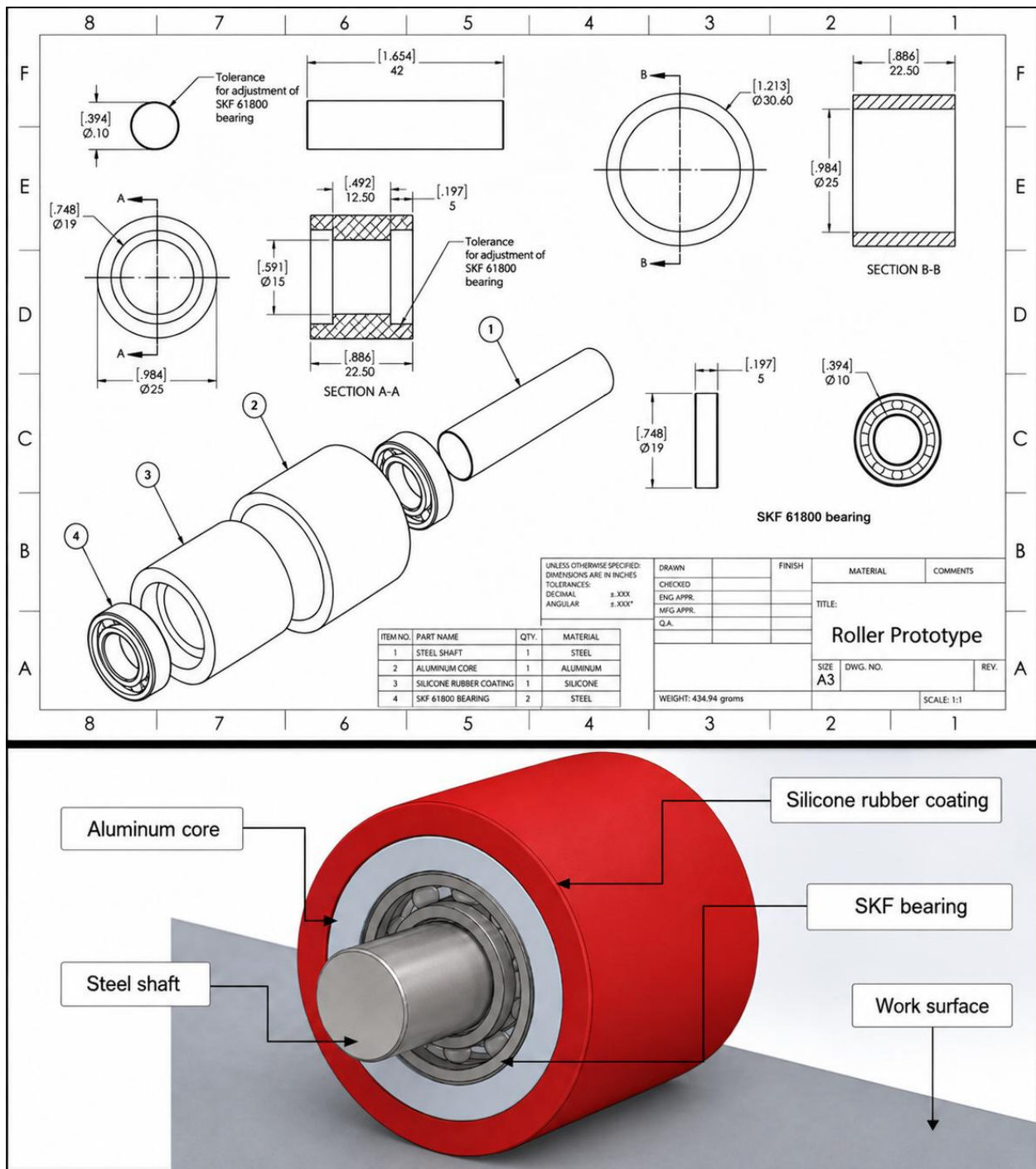


Figure 8. CAD model of the AFP compaction roller and the main components of the assembly.

3.5 Mechanical Validation by FEA and Hertzian Contact Theory

Finite element analysis and Hertz contact theory were combined to mechanically validate the compaction roller. According to the finite element analysis, the maximum von Mises equivalent stress under the applied compaction load of 20 N/mm² was approximately 3 MPa. The local deformation of the elastomeric coating in the contact region was primarily responsible for the maximum strain, which was approximately 9×10^{-6} mm/mm. This behavior aligns with the purpose of the coating, as the metal core and shaft preserve the structural integrity of the roller assembly, while an elastomeric layer must deform locally to conform to the deposition surface. Consequently, the finite element analysis results show that the proposed design can withstand the evaluated loading condition, while allowing the coating to provide the necessary resistance.

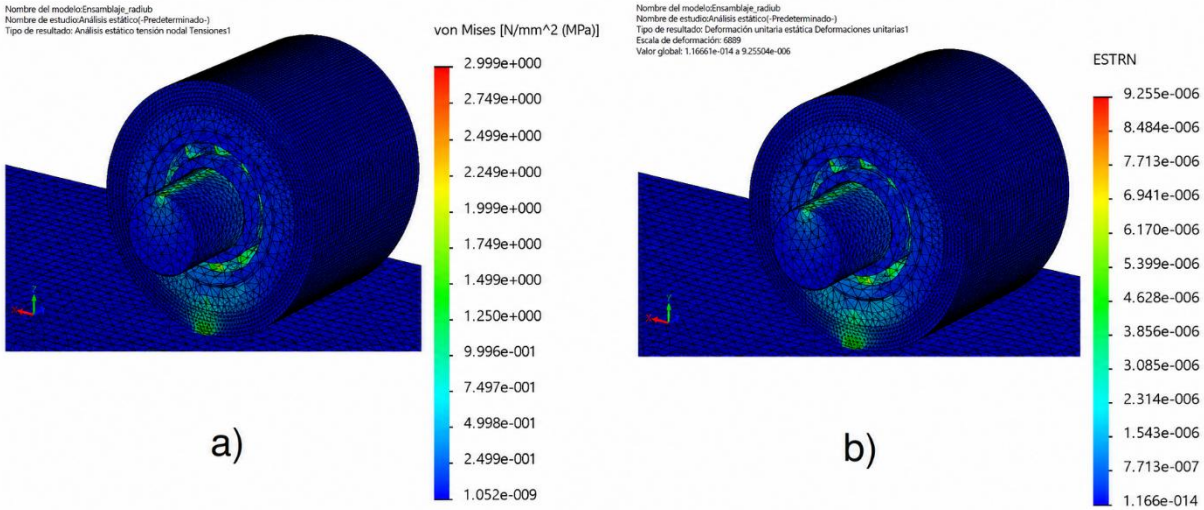


Figure 9. Finite element analysis (FEA) results for the compaction roller: (a) equivalent Von Mises stress and (b) strain distribution.

The analytical validation using Hertzian contact theory was used to estimate the contact behavior between the cylindrical compaction roller and the deposition surface. For the cylinder-on-flat contact configuration, the contact half-width, b , was calculated using Equation 5:

$$b = \sqrt{\frac{2F}{\pi l}} * \frac{\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}}{\frac{1}{d_1} + \frac{1}{d_2}} \quad \text{Equation 5}$$

where **F** is the applied force, **l** is the contact length, **E₁** and **E₂** are the elastic moduli, **v₁** and **v₂** are Poisson's ratios, and **d₁** and **d₂** are the diameters of the contacting bodies. For the flat surface, **d₂** was assumed to be infinite.

The maximum contact pressure was calculated using Equation 6:

$$P_{max} = \frac{2F}{\pi bl} \quad \text{Equation 6}$$

The Hertzian calculation estimated a maximum contact pressure of approximately 1.83 MPa and a contact area of approximately 13.84 mm² (see Figure 9). These values were used as reference parameters to compare the analytical contact behavior with the numerical simulation.

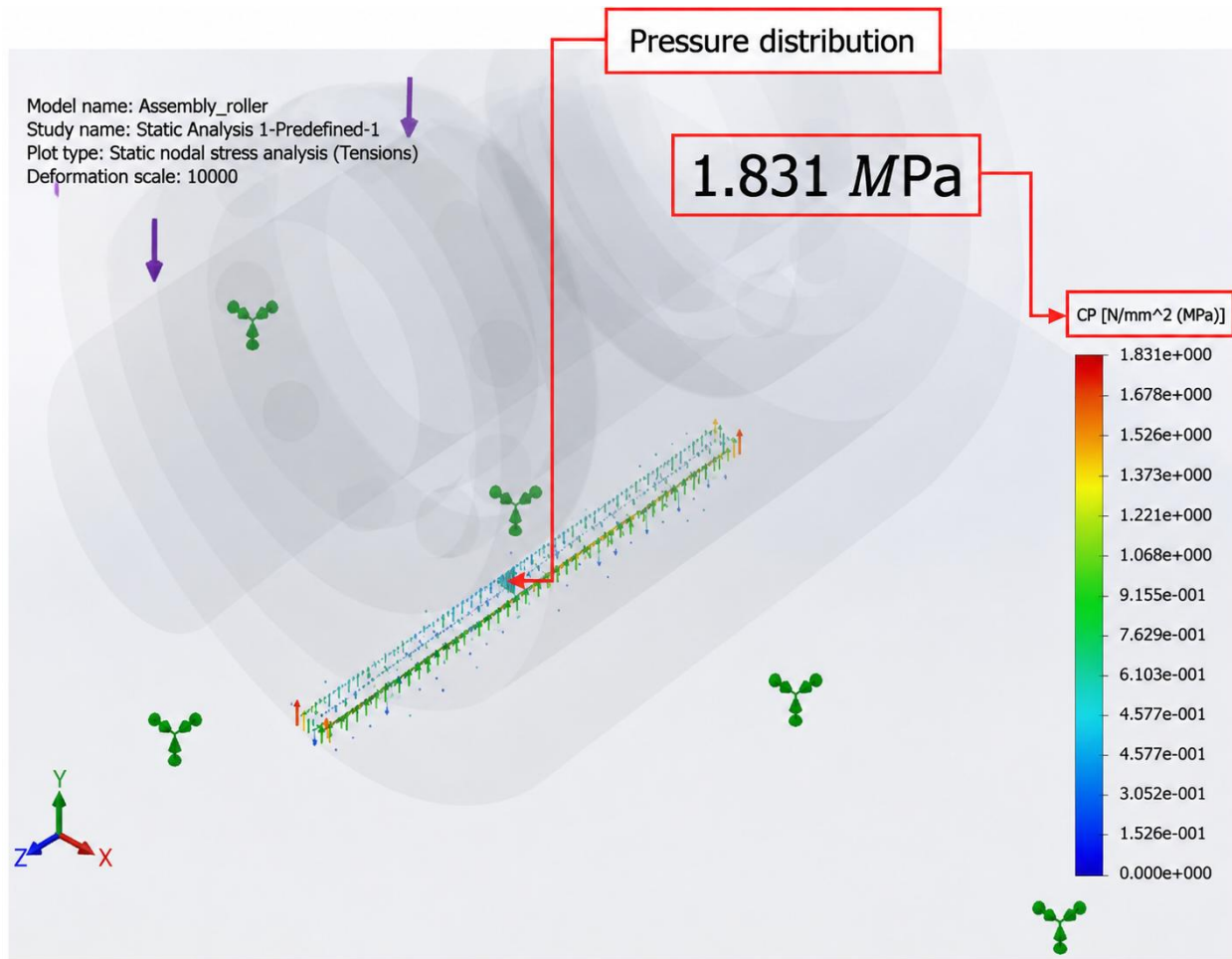


Figure 10. Hertzian contact pressure distribution between the compaction roller and the deposition surface.

Table 4. Comparison between numerical and analytical validation.

Method	Main result
Fea von Mises stress	≈ 3 mpa
Fea strain	$\approx 9 \times 10^{-6}$ mm/mm
Hertz maximum contact pressure	≈ 1.83 mpa
Hertz contact area	≈ 13.84 mm ²

The numerical and analytical results support the mechanical feasibility of the proposed compaction roller design. The low Von Mises stress indicates that the structural components

remain within a safe stress range, while the localized strain response is mainly associated with the elastomeric coating and its ability to adapt to the contact surface. In addition, the Hertzian contact pressure estimation was consistent with the pressure distribution obtained from the numerical simulation, providing additional support for the structural and functional validity of the roller design.

3.6 CAM/CNC Manufacturing and prototyping.

After mechanical validation, the manufacturing process was evaluated through CAM/CNC programming (see Figure 10). The machining stage was developed to verify the feasibility of producing the metallic components of the compaction roller by CNC turning and milling. The CAM setup included the definition of the workpiece coordinate system, stock geometry, cutting tools, and machining operations. The generated manufacturing strategy included roughing, finishing, and drilling operations. After post-processing, the corresponding G-code and M-code programs were obtained for component manufacturing. The complete CNC code was not included in this article because the scientific contribution is focused on the material selection, mechanical validation, and manufacturing feasibility of the compaction roller.

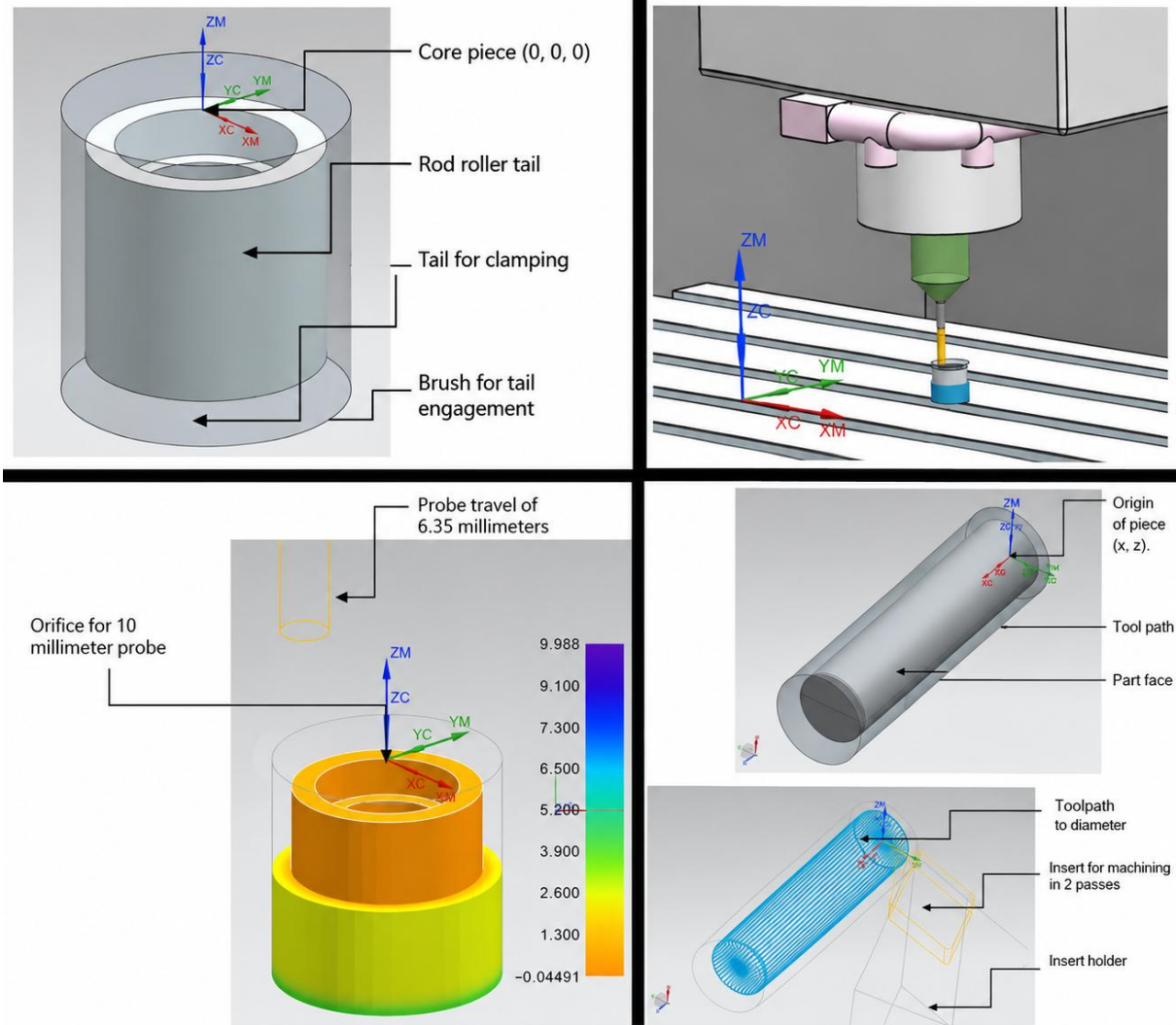


Figure 11. Digital manufacturing process of the compaction roller: (a) raw material preparation, (b) CAM simulation, (c) machining toolpaths, and (d) machined component.

3.7 Prototype

After the experimental characterization, statistical analysis, mechanical validation, and CAM/CNC manufacturing stages, the compaction roller prototype was fabricated and assembled (see Figure 7). The final prototype consisted of the main shaft, aluminum core, bearings, and the selected silicone rubber coating. The fabricated prototype confirmed the transition from the digital design stage to the physical implementation of the AFP compaction roller. This result demonstrates that the proposed workflow integrates material selection, mechanical validation, and prototype manufacturing into a complete development route for AFP compaction roller applications.

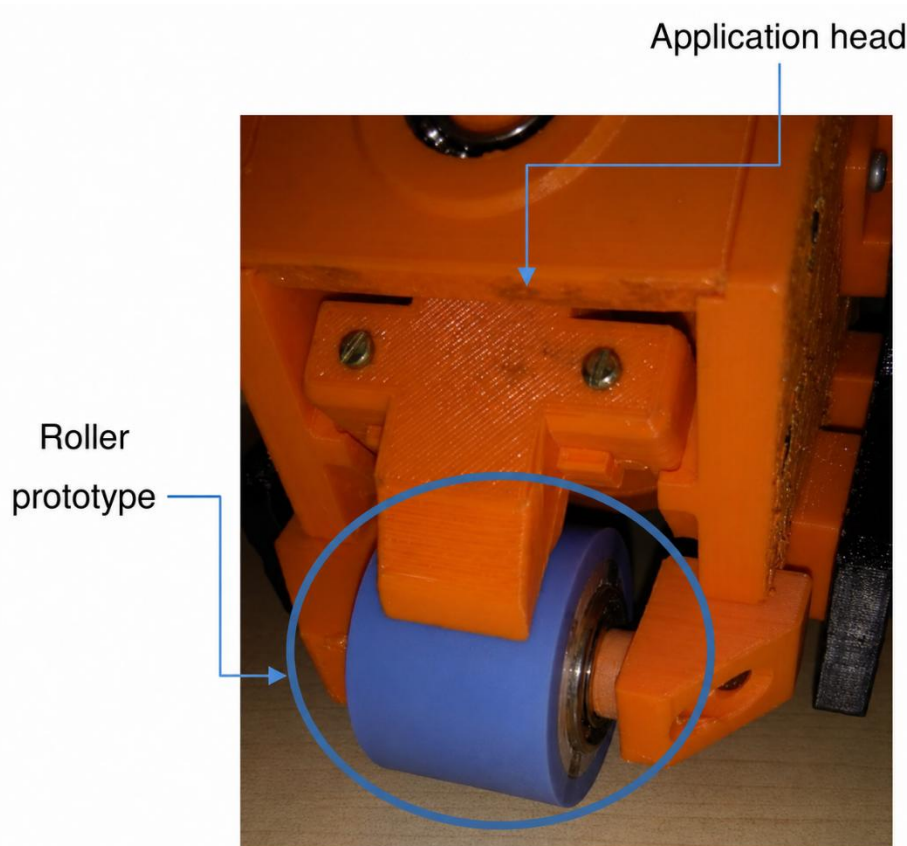


Figure 12. Final physical prototype of the compaction roller mounted on the AFP application head.

Figure 13 shows the prototype validation in two different materials. Figure 13a shows the Figure 12 prototype following some trajectories along a balsa wood wind turbine mold, while Figure 13b shows the linear placement of wet carbon fibers along a plane balsa wood mold. Figures 13c-d show the wet carbon fiber placement along a linear aluminum mold. In both molds, the visual inspection did not reveal flaws, heterogeneities, or detachments in the fiber depositions, thus yielding significant and good results that were published in governmental portals. Further information can be found in the following reference [32].

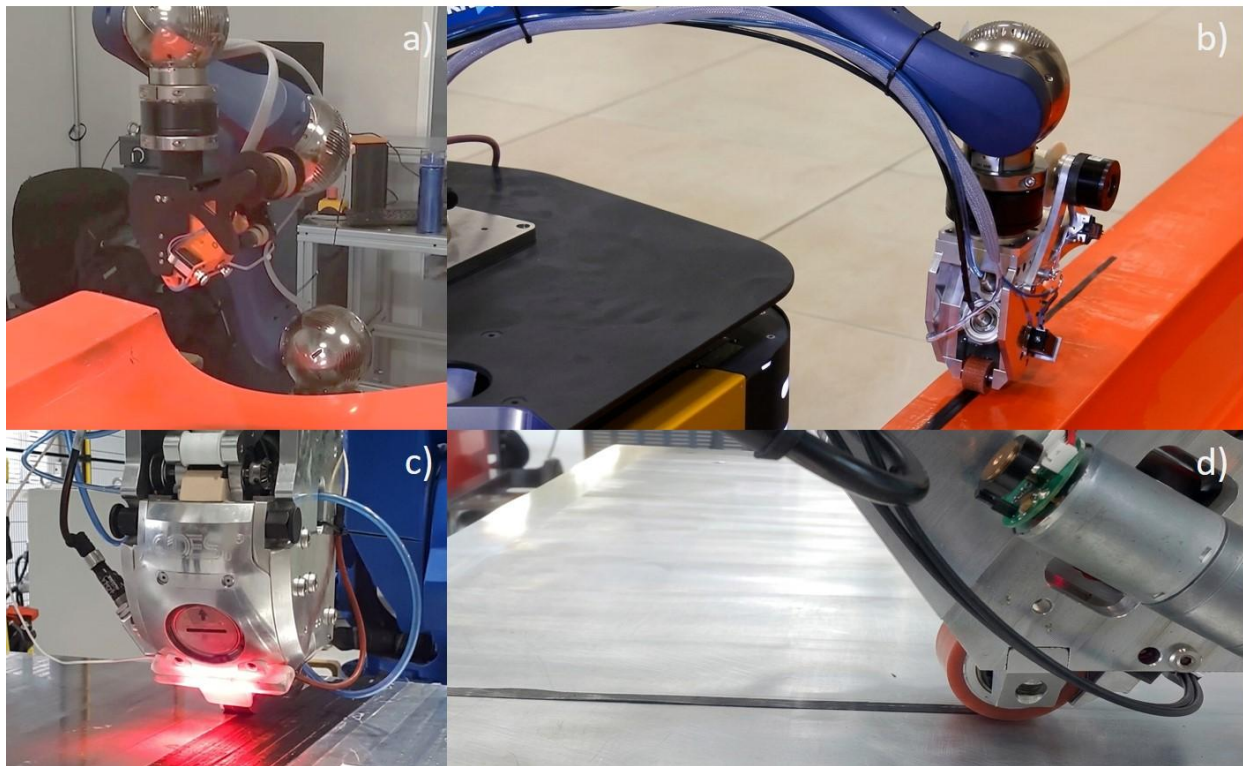


Figure 13. a) First prototype testing, b-d) roller testing on an AFP head-machine.

4. Conclusions

Three types of commercially available elastomers were assessed for their suitability as coating materials for an AFP compaction roller, namely, silicone rubber, nitrile-butadiene rubber (NBR), and neoprene. The conclusions are drawn based on the results of thermal analysis, wetting tests, statistical analysis, mechanical verification, and prototyping.

1. Silicone rubber was found to demonstrate the most advantageous thermal properties among the examined substances, with its thermal degradation beginning at 440 °C and its final residual mass reaching 56%. This indicates that silicone rubber is thermally more stable than NBR and neoprene in high-temperature settings.
2. The tests performed on the wettability of the materials have shown that silicone rubber reached the highest average angle of contact, that is about 75°, which means that silicone rubber has less wettability and hence a lower possibility of adhesion of the resin to the surface of the roller.
3. The use of the Graeco-Latin square design of experiments with the help of ANOVA proved the significance of the material of the roller influencing the wettability. The conducted experiments proved the positive effect of the material of the roller, while there was no effectiveness of the probe liquid used.
4. The mechanical investigation of the proposed compaction roller design was performed using FEA and Hertzian contact theory. The simulations showed Von Mises stresses of approximately 3 MPa and localized equivalent strain of approximately 0.5 mm/mm in the elastomeric contact region, supporting the structural feasibility and compliant behavior of the proposed roller design.
5. The combined use of CAD/CAM/CNC technology made it possible to successfully move from digital design to physical prototyping. This process involves the

combination of some trials in coating selection, testing of mechanical conditions, and actual manufacturing.

Finally, the presented methodology shows how to select and design a coating for the AFP process, where a practical utility was fully demonstrated through a real industrial application. Thus, this procedure can help to designers or users of AFP technologies to develop AFP components like the one exposed within this work.

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Declaration of Conflicting Interests

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