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DEVELOPMENT OF A RAPID PROTOTYPING METHODOLOGY FOR WIND TUNNEL TEST MODEL DESIGN

Bruno R. M. Padilha
Guilherme N. Barufaldi
Roberto Gil A. da Silva
Instituto Tecnológico de Aeronáutica, Praça Mal. Eduardo Gomes, 50, Vila das Acácias, CEP: 12228-900, São José dos Campos - SP - Brazil
brunomassucatto@gmail.com, guilherme.barufaldi@protonmail.com, gil@ita.br

Abstract. *The use of rapid prototyping tools has shown promise in many engineering and academic areas. Currently, the qualities of these tools for building complex geometries are remarkable, combining low cost and fast production. Among the wide range of 3D printing technologies, the fused filament fabrication (FFF) stands out. In this technology, models are built by filament deposition, layer by layer until the complete generation of the final 3D geometry. This paper focuses on the aeronautical use of such tools, specifically the fabrication of models for wind tunnel testing. Such models are usually made with machined aluminum, by an expensive and slow machining process. We applied the FFF technology to build wind tunnel airfoil and wing test models, with Polylactic Acid (PLA) as raw material, obtaining a cheaper and faster process. The prototypes were tested in the Transonic Pilot Tunnel (TTP), a transonic wind tunnel located at the Institute of Aeronautics and Space (IAE), in São José dos Campos, Brazil. During the tests, the models were subjected to high aerodynamic loads, proving their structural strength. The pressure distribution on the surface of the models was investigated with Pressure-Sensitive Paint (PSP), and the experimental data were compared to that of models manufactured with traditional methods. The results allow both qualitative and quantitative analyses, leading to the identification of several characteristics of the transonic behavior, such as shock wave formation. The outcomes of the fabrication and test campaign suggest that this methodology could become a powerful tool for productivity in aerodynamic research and development, especially concerning the creation of complex geometries.*

Keywords: *Additive manufacturing, 3D printing, wind tunnel testing, transonic aerodynamics, pressure-sensitive painting*

1. INTRODUCTION

In Aerospace Engineering, wind tunnel testing is an essential part of research and development, allowing engineers and scientists to capture and analyze physical phenomena in the air flow over different geometries. However, due to issues related to wind tunnel test section size and available power, the vast majority of tests require the development of scale models, smaller than the actual body (Barlow *et al.*, 1999).

In many cases, the bodies and models have a complex geometry, with surfaces having multiple curvatures and details. This complexity increases manufacturing costs and time, and sometimes, depending on the type of surface and available resources, the fabrication can be unfeasible. Scale problems also appear, because some details simply cannot be replicated by machinery in reduced dimensions. Wind tunnel test models are usually made with machined aluminum, by expensive and slow machining processes. With these difficulties in mind, we have developed a methodology for manufacturing wind tunnel models by applying rapid prototyping techniques, with the goal of reducing costs, fabrication time, and facilitating the production of more complex geometries.

The increasing popularity of 3D printing and other rapid prototyping tools indicate that these technologies will be increasingly present in aerospace engineering, both in industry and academia, acting as a means to facilitate the creation and materialization if ideas and concepts. The developments in this area have produced tools and techniques of remarkable quality, combining low cost and fast production. However, the usage of this technology within the environment of the Institute of Aeronautics and Space (IAE) and the Technological Institute of Aeronautics (ITA) is recent.

Among the wide range of 3D printing technologies, the fused filament fabrication (FFF) stands out. In this technology, models are built by filament deposition, layer by layer until the complete generation of the final 3D geometry. This additive manufacturing process allows the production of complex geometries with relative ease, and FFF printers are now compact and accessible. We applied the FFF technology to build wind tunnel test models, using Polylactic Acid (PLA) as raw material for the printer, and steel and aluminum for internal reinforcements. The result is a faster and significantly less costly process. This work is a contribution to the implementation of 3D printing in IAE and ITA.

2. MATERIALS AND METHODS

2.1 Fused filament fabrication

FFF is one of the most widespread 3D printing technologies, due to its low cost, and ease of raw material storage and handling. Its operation principle is quite simple: a filament of raw material is unwound from a coil and supplied to a heated printer extruder head; inside the head, the material is softened by heating, and deposited on the part being manufactured, layer by layer. As the piece grows, it is moved away from the head, in order to keep a constant distance between the head nozzle and the surface receiving material. Because of this form of operation, the surface of the prototype is usually rough.

Two different raw materials were tested: acrylonitrile butadiene styrene (ABS), and polylatic acid (PLA). ABS is a copolimer thermoplastic, very popular for use in 3D printing. It has good impact absorption capacity and limited elastic characteristics. However, this material has poor thermal dissipation properties, which can result in contractions and cracks. The first airfoil prototype was manufactured in ABS but showed cracks caused by material contraction, due to the aforementioned issues, as can be observed in Fig. 1. This problem was not encountered in prototypes manufactured with PLA, which proved to be a better material and, therefore, was selected.

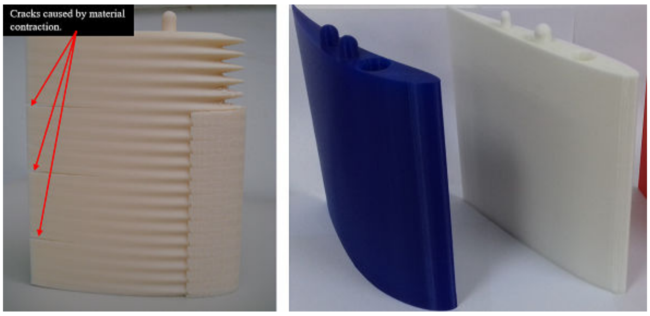

Figure 1. Comparison between airfoil prototypes manufactured with ABS (left) and PLA (right). Note the cracks caused by material contraction on the ABS prototype.

2.2 Test model design and internal structure

In order to be used in a wide range of dynamic pressure values, the airfoil test models must be able to withstand the loads in all aerodynamic range. Since the plastic has a limited mechanical resistance, a reinforcing internal structure was conceived. Consisting of a spar made of steel SAE 1020, this structure substantially increases not only the maximum allowed load, but also the stiffness, so that the bending and twisting deformations are negligible. It also acts as a support for the fixation clamps. The airfoil test model is illustrated in Fig. 2.

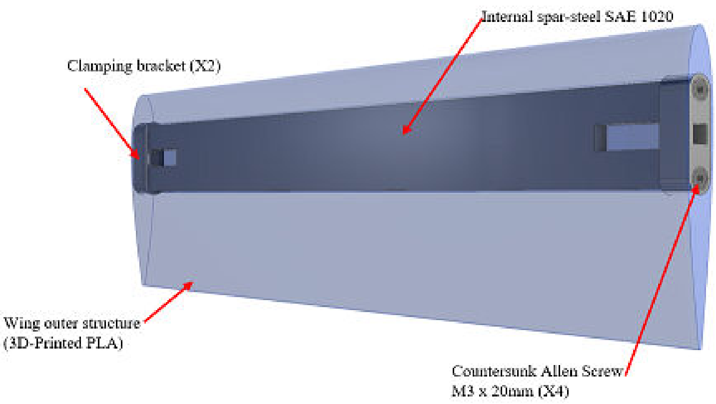

Figure 2. CAD drawing of the airfoil test model, showing the outer structure, manufactured in PLA, and the inner structure, manufactured in steel SAE 1020.

Due to the pioneering character of the proposition and the newness of the technology, there were very few reliable bibliographical references at the time this method was developed by Padilha (2017), between 2016 and 2017. The test models were employed in wind tunnel test campaigns, for evaluating the method itself in the transonic regime, and for the work developed by de Paula (2016), which employed a complex airfoil geometry. The wavy leading edge of the airfoils and wings could hardly have been manufactured with other methods with the available budget and time frame.

2.3 Surface roughness correction

Objects manufactured with FFF technology present small residual marks from the layer deposition process. Small differences between each deposited layer appear due to many factors, mainly because when one layer is being deposited, the previous one has already hardened and cooled a little. Therefore, the surface finishing is not smooth, but slightly rough. For many applications, this roughness does not cause issues, but in the case of wind tunnel models, surface roughness can produce undesired aerodynamic interference. The usage of PSP also requires a smooth surface, otherwise the infrared radiation will be emitted in scattered fashion, impairing data acquisition.

The printed test models were subjected to surface measurement, made with an optical profilometer, and the average surface roughness measured was 10.55 microns. For comparison, an aluminum baseline model, manufactured by a traditional machining process was subjected to measurements in the same equipment, and the average roughness measured was 0.83 micron. In order to obtain a similar surface finishing, the models external surfaces were covered with a thin layer of epoxy resin. This substance was chosen because less material is added and, therefore, less geometrical distortion is produced. Directly sanding the surface of the models would cause excessive wear and distortion.

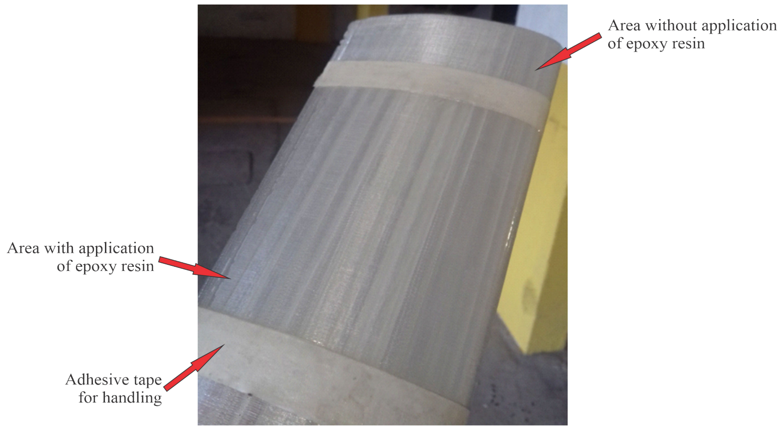

Figure 3. Test model with partial application of epoxy resin for surface roughness correction. The area where the resin was applied is more shiny.

The epoxy resin was applied with a brush, by hand, which requires a certain level of manual skill. Due to the relatively high viscosity of the resin, only one layer was required. In order to obtain a smoother finishing, the models were sanded with fine grain sandpaper after the resin was cured. The epoxy also increased surface strength, so that the risk of surface damage during sanding was diminished. Optical profilometer measurements revealed that the average roughness was reduced to 0.53 micron after the application of epoxy resin and sanding, a significant improvement.

2.4 UV transparency correction

An unanticipated problem encountered during the wind tunnel test campaign was the transparency of the test models to UV light. Since UV is used to excite the pressure-sensitive paint (PSP), the models are constantly subjected to this radiation. The PSP absorbs UV and emits infrared radiation, as explained in Section 2.5 However, if the model is transparent to UV, not only a significant part of the radiation will pass through the model, it will reflect on the other surfaces and cause interference, greatly affecting the pressure measurements. Figure 4 shows the models exposed to UV radiation, and how transparent they can be to this type of radiation. Even if the raw material is pigmented, UV light is still capable of passing through the structure.

In order to block UV transmission, a finishing material with UV-blocking properties and capable of being applied in very thin layers was needed. After testing some different types of paints and thin resins, we discovered that the best results were achieved with polyurethane (PU) paint, sprayed over the surface. The spraying process and paint properties guaranteed a very thin layer – no significant geometric distortion –, and a very smooth finishing, with no need for surface roughness correction (sanding). As can be seen in Fig. 4, the PU paint is able to completely block the UV radiation.

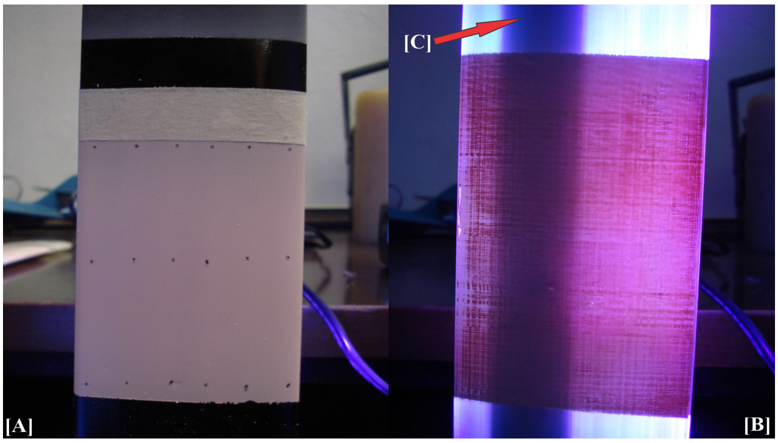

Figure 4. Test models exposed to UV light. On the right-hand side is the test model without PU paint (B) – notice the UV penetration on (C), where the spar can be seen. On the left-hand side (A), the same test model after application of PU paint: the UV light is completely blocked.

2.5 Wind tunnel testing

The Transonic Pilot Tunnel (TTP) at IAE was chosen for the tests. This wind tunnel is a Brazilian project, developed at ITA and IAE with help from Sverdrup Technology Inc., from Tullahoma, Tennessee, in the USA. This company specializes in the development of industrial scale wind tunnels. Due to the high costs and budget limitations, the original design had to be resized, resulting in the current dimensions. The TTP is a closed circuit tunnel, with a test chamber cross section of 250 mm $\times$ 300 mm, and an operation Mach number ranging from 0.2 to 1.3 (Falcão Filho and Mello, 2002).

Figure 5. The Transonic Pilot Tunnel, located at IAE. The tunnel is currently operating in open circuit form, as can be seen in the photograph.

The TTP was conceived for testing aerodynamic profiles, wings, model vehicles and bodies. Airfoil models are mounted vertically, fixed to the upper and lower walls by clamps, which allow the angle of attack to be adjusted. Inside the tunnel, the air is circulated by axial compressors, and additional air is pressurized and injected by radial compressors. Even though the TTP was designed to function in closed circuit form when operating conditions are normal, the tunnel can be operated in open circuit form in case of damage to the axial compressors or any abnormal functioning condition.

Due to electrical problems, the wind tunnel tests in (Padilha, 2017) were conducted using the "blow down" technique, with the TTP operating in open circuit form. With the experiment setup ready inside the test chamber, the tunnel is opened in the sections before and after the chamber. The pressurization system compresses a great air volume and discharges it into the chamber using solenoid valves, and the air mass flows through, leaving the tunnel through the rear opening. This is a degraded mode of operation, since there is much less control over the airflow. Due to the "blow down" condition, fluctuations in the Mach number appear, causing the results to be noisy, as shown in Sec. 3.

To measure the pressure distribution on the airfoil test model surface, we employed the pressure sensitive paint (PSP) method. This paint presents luminophores in its chemical composition, which absorb light, in wavelength of 400 to 460 nm, and emit infrared radiation due to chemical reactions. The chemical equilibrium is modified by alterations in oxygen concentration, which is related to the local air pressure on the surface (Bell, 2011). By using special equipment to emit ultraviolet light of 400 nm, and a CCD camera to capture the infrared frequency emitted by the paint, we obtained a digital image of the pressure distribution on the airfoil upper surface. The experimental apparatus is shown in Fig. 6.

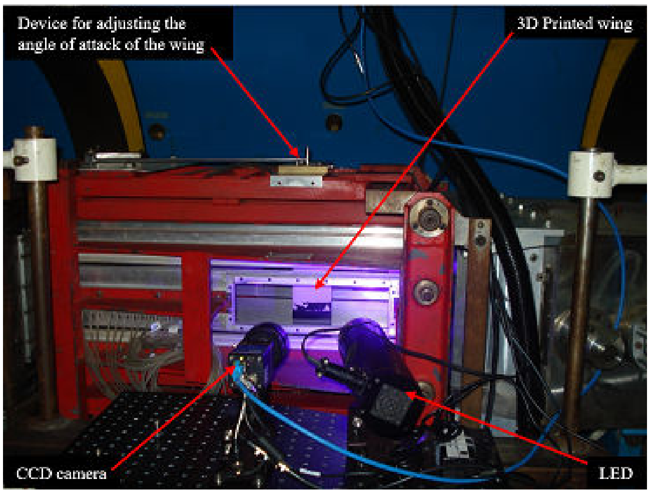

Figure 6. PSP equipment disposition for the experiment at the TTP. The equipment with a ultraviolet LED emits radiation and the CCD camera captures the infrared radiation emitted by the PSP on the model inside the tunnel.

3. RESULTS AND DISCUSSION

The experiments were conducted using an airfoil test model for the NACA 0012 profile, which presents a wealth of experimental data from many different sources. The wind tunnel test campaign was composed by 12 runs, for three different Mach numbers - all runs were performed using the "blow down" operation. In this article, we show comparative results for two experiments, which consisted of observing the airfoil at an angle of attack of zero degrees, and Mach 0.8 and 0.7, respectively. Despite the noisy measurements caused by the "blow down" condition, the results show that the test models manufactured with the method presented in this article have aerodynamic characteristics very similar to those manufactured with traditional machining methods. The pressure field over the model upper surface was measured with PSP method, with the set up shown in Fig. 6.

Figure 7 shows the results for the first experiment – Mach 0.8, angle of attack 0º. The chart presents the dimensionless pressure coefficient C_P on the upper surface of the airfoil as a function of the dimensionless chord coordinate x/c, with x being the distance along the chord line with respect to the leading edge, and c being the average chord. Three C_P curves are presented: in blue is the result for the test model prototype, manufactured with the method presented in this article; in yellow is the curve obtained by Goffert (2012), with an aluminum model (baseline), and the tunnel operating in closed circuit; the green curve was also obtained from a baseline test model, manufactured in aluminum, but subjected to the "blow down" conditions, in which some Mach fluctuations appear, causing the measurements to be noisy.

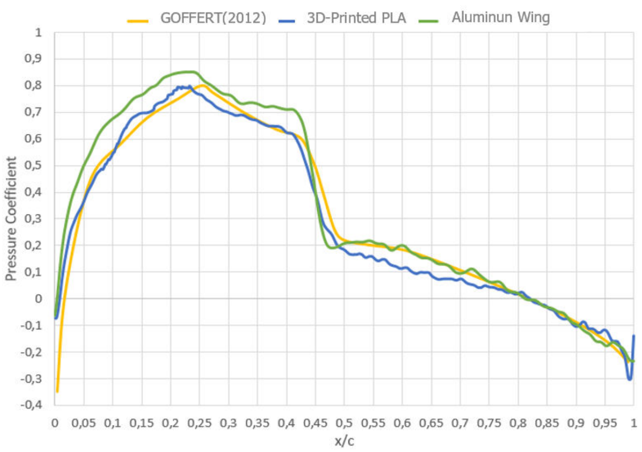

Figure 7. Comparative results between the prototype (3D printed), the model from (Goffert, 2012) and a baseline aluminum model subjected to "blow down" conditions. Dimensionless pressure coefficient versus dimensionless chord coordinate x/c. Mach 0.8, angle of attack 0°.

Figure 8 shows a PSP photography for the first experiment, with the pressure field corresponding to the chart in Fig. 7. The colors correspond to values of the dimensionless pressure coefficient over the test model manufactured with the methodology presented in this article. The region highlighted by the red rectangle shows an abrupt change in colors (cyan to yellow), which corresponds to an abrupt increase in pressure, i.e., a shock wave. As seen in Fig. 7, the shock position is consistent to that found in other experiments, highlighting the similarity of the test model.

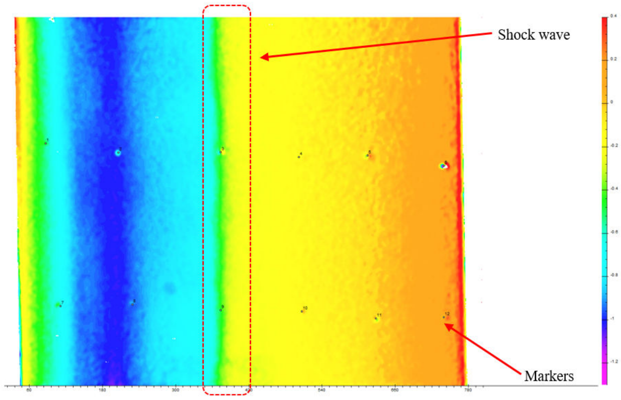

Figure 8. PSP photography of the test model upper surface for the experiment in Fig. 7. Mach 0.8, angle of attack 0°.

Figure 9 shows the results for the fourth experiment – Mach 0.7, angle of attack 0º. The chart presents the dimensionless pressure coefficient C_P on the upper surface of the airfoil as a function of the dimensionless chord coordinate x/c. Again, the three C_P curves correspond to the results for the test model prototype, and the same references presented in Fig. 7. The measurements taken during "blow down" conditions present Mach fluctuations that cause the results to be noisy.

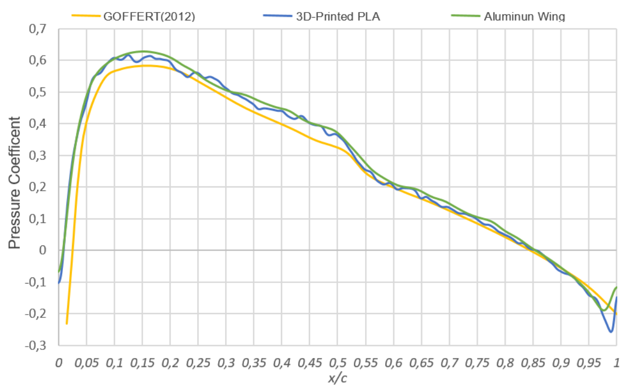

Figure 9. Comparative results between the prototype (3D printed), the model from (Goffert, 2012) and a baseline aluminum model. Dimensionless pressure coefficient versus dimensionless chord coordinate x/c. Mach 0.7, angle of attack 0°.

Figure 10 shows a PSP photography for the fourth experiment, with the pressure field corresponding to the chart in Fig. 9. The colors correspond to values of the dimensionless pressure coefficient over the test model manufactured with the methodology presented in this article. The region highlighted by the red rectangle shows a softer and more gradual change in colors (cyan to green), which corresponds to a weak shock wave. As seen in Fig. 9, the pressure distribution is consistent to that found in other experiments.

To illustrate the Mach fluctuations caused by the "blow down" operation, a chart of the free stream Mach number versus time is exhibited in Fig. 11. The time frame for image capture is shown inside the red rectangle. Within this window, 100 images are captured by the CCV camera. Due to the higher fluctuations in the beginning and the end of the window, the images corresponding to those intervals must be discarded. The fluctuations introduce noise to the pressure measurements, even when within acceptable levels. This effect is produced because the Mach number oscillation causes the pressure to also oscillate, thus varying its distribution over the test model surface.

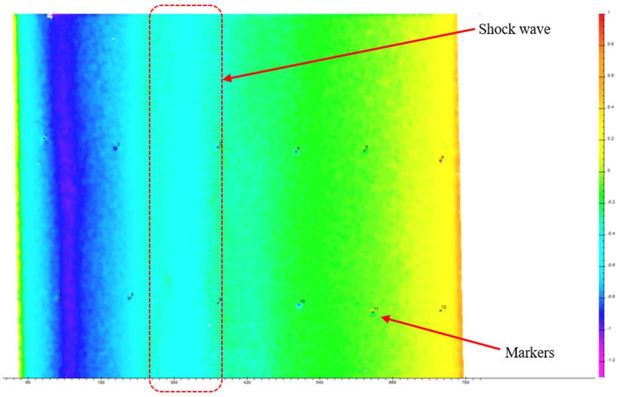

Figure 10. PSP photography of the test model upper surface for the experiment in Fig. 9. Mach 0.7, angle of attack 0°.

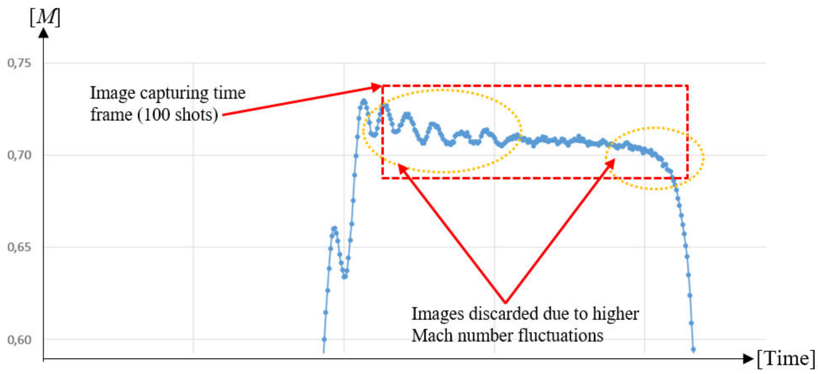

Figure 11. Example of the Mach number for the free stream ahead of the wind tunnel test chamber, illustrating the data acquisition time frame and the fluctuations caused by the “blow down” operation.

4. CONCLUSIONS

In this paper, a new method for manufacturing wind tunnel test models using additive manufacturing was presented. The method is based on 3D printing (FFF technology), with internal structural reinforcements made of steel. Solutions for correcting surface roughness and transparency to UV radiation were presented. To test the method, test model prototypes were subjected to wind tunnel testing in a transonic wind tunnel located at IAE, in São José dos Campos, Brazil. Pressure measurements were taken with PSP technology, and the results were compared to other references.

Post-experiment analyses show that the results obtained with the test model prototypes manufactured with the presented method agree very closely to results obtained with aluminum test models manufactured with traditional machining methods, including the position of shock waves. The method presented in this paper allows a substantial reduction in manufacturing costs, which can be very useful for increasing productivity.

Regarding the financial aspect, the methodology also shows promise. The estimated cost to produce a simple wing test model, with the proper dimensions to fit in the TTP test chamber, using traditional manufacturing methods – such as CNC machining – 800 to 950 USD. The cost to manufacture the same test model with the methodology presented in this paper is around 50 USD, a cost reduction of about 95%. However, it is necessary to consider factors such as the longer time required for the manufacture and assembly process, and the manual skill required during the resin application and sanding. Considering all these factors, we believe that the methodology presented in this work can be very useful to reduce costs and help researchers to manufacture complex geometries.

5. ACKNOWLEDGEMENTS

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