Fabrication of Temperature Sensitive Paint Applied to Polyvinyl-Chloride Adhesive Films for Global Surface Temperature and Heat Flux Measurements

Sophia Edwards*, Rachel Constantin†, and Mark Gragston‡
The University of Tennessee-Knoxville, Knoxville, TN, 37995, USA
The University of Tennessee Space Institute, Tullahoma, TN, 37388, USA

Temperature sensitive paint (TSP) was applied to a polyvinyl-chloride (PVC) adhesive film, which enabled a more efficient application and removal process of the paint for testing of aerospace models. This approach is especially useful when damage occurs to the TSP in facilities like shock-tunnels and expansion tunnels since it can reduce the repainting time significantly while maintaining consistent TSP properties. Initial characterization experiments indicate that painted TSP film is comparable to traditional TSP application. This was verified through static and dynamic calibrations. It was also determined that the TSP could be applied to the PVC film before its placement on the model without leading to damage or inconsistencies on the TSP film. Overall, the developed TSP film method can enable easier use of TSP and potentially better measurements of surface temperature and heat flux.

I. Nomenclature

I_{TSP} = Local Measured TSP Image Intensity
I_{Ref} = Local Measured TSP Image Intensity at Room Temperature
T = Temperature
T_{Ref} = Room Temperature

II. Introduction

Surface heating is a critical consideration in the design of high speed vehicles. The frictional forces the flow experiences near a surface causes a boundary layer to form, which corresponds to the velocity slowing to zero at the wall. This decrease in kinetic energy is balanced by increasing thermal energy, resulting in significant surface heating. Furthermore, the rate of heating is dependent on the presence of unsteady flow features such as turbulence and shockwave-boundary layer interactions (SBLI). Modern computational tools used for designing hypersonic systems struggle to match experimentally observed heat transfer rates and are therefore seeking high-quality heat transfer measurements for validation purposes. Schramm *et al.* goes into more detail about the motivation behind the experimental aspect of testing high temperature effects [1].

Temperature sensitive paint (TSP) is a non-intrusive optical diagnostic technique capable of measuring global surface temperature and heat flux values. Although IR thermography provides similar information, IR cameras are currently incapable of acquiring high-speed information and usually have specialized windows that restrict the use of other optical techniques at the same location. This makes TSP the preferred diagnostic when high temporal responses are desired for global temperature measurements. The comparison between the two diagnostics is talked about more by Lorenz *et al.* [2].

TSP contains a luminescent molecule called a luminophore, which is raised to an excited state upon ultraviolet (UV) illumination. The luminophore then spontaneously decays back to its ground state, emitting photons which provide the observed fluorescent signal. Radiationless downward transitions are also possible and become more likely with increased temperature, resulting in a inverse relationship between surface temperature and emission intensity levels.

*Undergraduate Researcher, Department of Mechanical, Aerospace, and Biomedical Engineering, AIAA Student Member
†Undergraduate Researcher, Department of Mechanical, Aerospace, and Biomedical Engineering, AIAA Student Member
‡Assistant Professor, Department of Mechanical, Aerospace, and Biomedical Engineering, AIAA Member

This phenomenon is called thermal quenching. A detailed discussion on the modeling of the TSP fluorescence is provided by Nagai *et al.* [3].

Many researchers have utilized TSP in various ways [4–6]. For instance, Ozawa *et al.* used TSP to to measure heat-flux associated with the transitional boundary layer on a 7-degree cone [7]. This gives insight on some considerations associated with this diagnostics capabilities, but ultimately confirms its ability to obtain heat flux distributions in high speed flow. TSP Tests have also been done by Laurence *et al.* in a hypersonic shock tunnel [8]. Emphasis was put on TSP time response capabilities as well as obtaining information regarding boundary layer transition.

Many hypersonic ground tests are done in impulse facilities that utilize diaphragms which have the tendency to fragment during wind tunnel testing. Those fragments often then strike the model and damage the paint layer, resulting in the paint needing to be removed and reapplied after a single run if drastic enough. It would also likely need to be re-calibrated due to inconsistencies in paint layer thickness to allow for data consistency. In some cases, the removal of the model can be exceedingly tedious if other sensors are present. Therefore, there is a need for an efficient application and removal process of TSP to manage these occurrences.

In order to address this problem, TSP was explored in conjunction with adhesive surface strips that enable the strips to be quickly placed or removed. A similar approach is already used for IR imaging [9]. The work detailed in the following sections shows that polyvinyl chloride (PVC) sheets suffice as an affordable adhesive material and still enable quantitative use of TSP. Comparisons are also made to a typical TSP application.

III. TSP Formulation and Application

Traditional TSP application consists of two layers: commercially available white polyurethane paint as the base coat and then the TSP layer as the top coat, in this case a ruthenium-based TSP was used following the work of Smith *et al.* [10, 11]. This formulation, discussed by Ozawa *et al.* [12], is created by dissolving the luminescent molecule in a binding agent, and then using ethanol to dilute it. Ikami also discusses some important considerations during the application process [13]. The white polyurethane paint, used as base coat in many TSP applications, takes a minimum of three hours to dry before the top coat can be applied, which can hault experimentation time.

The adhesive film used in this work is made from polyvinyl chloride (McMaster-Carr (# 8590K21)). This material was chosen due to its well characterized thermal properties, its affordability, and its availability. Well characterized thermal properties and low thermal diffusivity are both necessary for TSP to work correctly and to properly determine heat flux from the temperature data. The PVC film had a density of 1384 kg/m^3 and a thickness of 0.1143±0.013 mm per the vendor provided data.

This experiment tested five different TSP applications. First, the control group consisted of the traditional base coat and top coat application. Second, both top coat and base coat were applied to the PVC adhesive film that was then placed on the model. The last three variations all consisted of top coat applied directly to PVC film after the film had been sanded by a different grit sanding to promote binding. The film on the third, fourth, and fifth variation had 400 grit, 1000 grit, and Scotch Brite sanding, respectively. For each test, the model was first cleaned with methanol and then the paint was applied using a paint gun, allowing time for the base coat to dry when used.

IV. Experiment Setup

A. TSP Calibration in Static Heating

Since a key aspect of TSP is the mapping of image intensity ratios to a temperature ratio, testing was done to find the calibration curves for each TSP configuration. Figure 1 displays the experimental setup used for this process. A steel plate containing one of the paint variations was placed on a hot plate and heated to a steady temperature. The steel plate temperature was measured with an IR camera and a surface mounted thermocouple attached to the unpainted portion of the steel plate. The IR camera was also used to record surface temperature values of the model as well, particularly the painted regions. A Photron FASTCAM Mini AX camera was used to to collect the visible fluorescent emission from the paint, which was illuminated by a continuous 405 nm LED. The camera had an exposure of 50 μs and a frame rate of 2 kHz. A long-pass filter was used with the camera to block wavelengths lower than 575 nm while allowing light at greater wavelengths to pass through.

For all five paint application variations, the hot plate started at room temperature and was increased to approximately 383 K over eleven increments. At each temperature, the thermocouple value was recorded, as well as two IR camera temperature values. The IR camera took values from the surface of the hotplate, as well as the painted surface of the

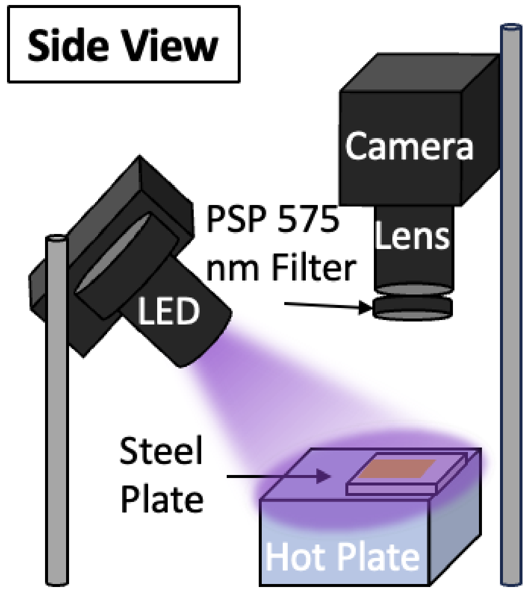

Fig. 1 An illustration of the setup used for determination of calibration curves for mapping TSP emission to temperature.

steel plate. After the first set of temperature measurements were gathered, a video was taken of the TSP emissions followed by more temperature measurements. The temperature measurements before and after the video were averaged to get more accurate temperatures to represent when the image was taken.

The temperature ratios were obtained by dividing the measured paint temperature values by the paint temperature at room temperature, and the TSP intensity ratio was obtained by dividing the pixel intensity at various temperatures by the pixel intensity at room temperature over a designated area. The temperature ratio was plotted against the intensity ratio and curve fitted using the quadratic form in Eq. 1, which provided calibration curves to convert TSP images to temperature maps.

$$\frac{T}{T_{Ref}} = A\left(\frac{I_{TSP}}{I_{Ref}}\right)^2 + B\left(\frac{I_{TSP}}{I_{Ref}}\right) + C \tag{1}$$

B. Dynamic Calibration

A simple dynamic response test for TSP was done by examining the time response of the paint to a heat impulse. Figure 2 shows the experimental set up for these dynamic calibration tests. The TSP was illuminated with near UV light while the camera was set to have an exposure of 48.29 μs and a frame rate of 20 kHz. This setup also utilized a long-pass filter like the previous test. In this setup, a butane blowtorch was used to provide the impulse.

This test was completed for the control group as well as the two paint variations that were determined to be the most similar to the control based on examination of the static calibration tests. The dynamic tests were done three times for each paint variation for consistency.

C. Vacuum Testing

Testing that the painted PVC film would hold in a vacuum without substantial bubbling or peeling was an important part of its characterization, since vacuums are utilized by many ground testing facilities. The film was tested by placing it on a cleaned model into a vacuum chamber. The vacuum chamber used in this test was an Ideal Vacuum that was brought to an approximate pressure or 2 Pa using a vacuum pump (# P107304). Piezo Vacuum Transducer from MKS Instruments (# 902B-11024) with an accuracy rating of ± 1 % was used to specify this pressure.

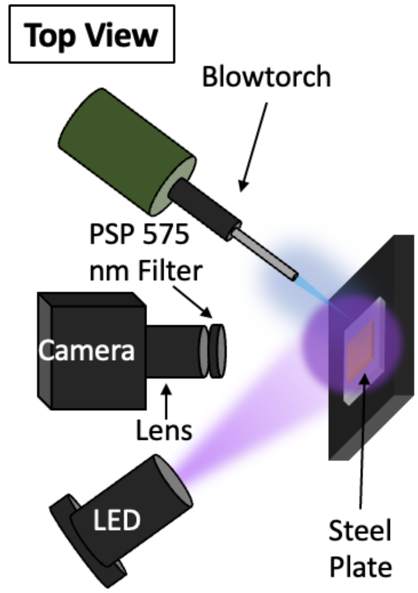

Fig. 2 An illustration of the dynamic response test experimental set up.

V. Results and Discussion

A. Static Heating Calibration Results

The eleven images that were taken at increasing temperature increments were used to correlate temperature ratios with pixel intensity ratios. These are displayed in Fig. 3 using five different subplots for each paint variation type. Each graph displays two sets of data points for two different pixel locations that follow a quadratic trend. Figure 4 indicates the respective pixel region used for each subplot. The coefficients from Eq. 1 for each of the curves on this graph are displayed in table 1.

Table 1 Using Fig. 3, the coefficients for Eq. 1 were determined.

Equation: $\frac{T}{T_{Ref}} = A\left(\frac{I_{TSP}}{I_{Ref}}\right)^2 + B\left(\frac{I_{TSP}}{I_{Ref}}\right) + C$

Case	Region	A	B	C
Control: Base and Top	1	1.308	-3.125	2.841
	2	1.276	-3.086	2.836
PVC Base and Top	1	1.181	-3.031	2.869
	2	1.197	-3.049	2.869
PVC 400 Grit	1	1.565	-3.613	3.063
	2	1.526	-3.853	3.07
PVC 1000 Grit	1	0.9542	-2.525	2.59
	2	1.033	-2.564	2.555
PVC Scotch Brite	1	1.295	-3.1	2.82
	2	1.325	-3.175	2.863

The coefficients displayed in table 3 for test two through five, were used to take the percent change relative to the control group coefficients. Table 2 shows these relative percent change values. It is apparent that the application of TSP

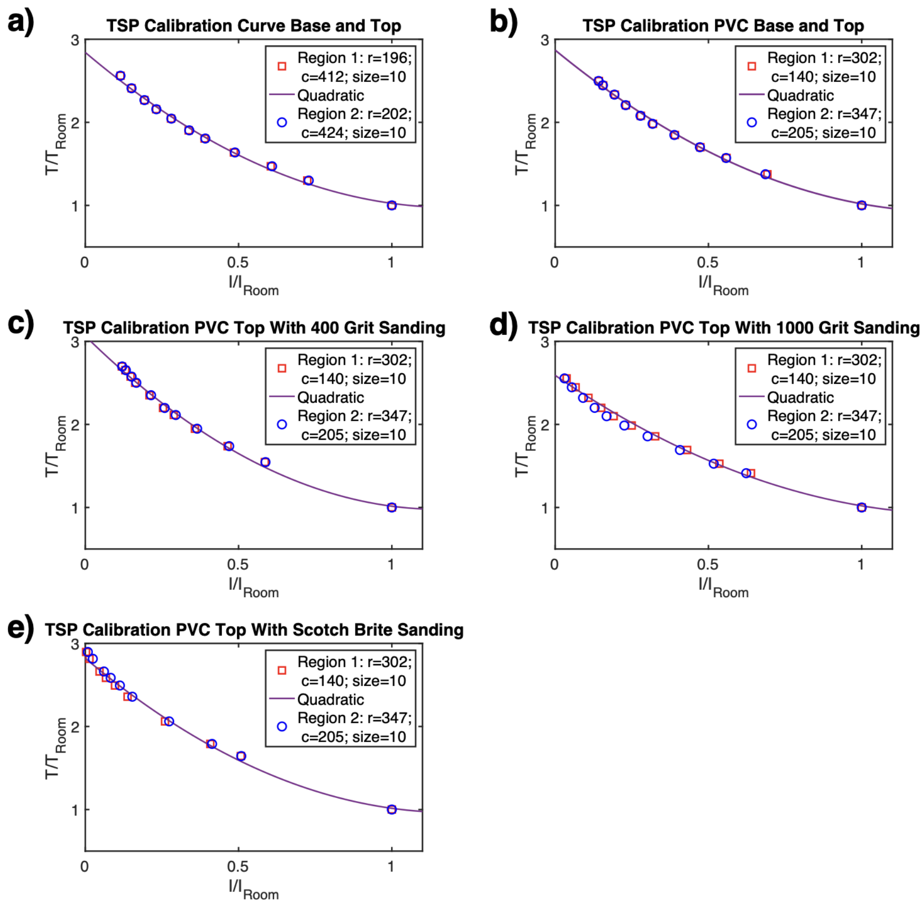

Fig. 3 Static calibration curves: a) Control: base coat and top coat applied to the model b) base coat and top coat applied to PVC tape c) top coat applied to PVC tape with 400 grit sanding d) top coat applied to PVC tape with 1000 grit sanding e) top coat applied to PVC tape with Scotch Brite grit sanding.

Table 2 The relative percent change of fit coefficients in Table 1 based on Eq. 1.

Case	A	B	C
Control: Base and Top	–	–	–
PVC Base and Top	7.97	2.11	1.07
PVC 400 Grit	19.62	20.21	8.03
PVC 1000 Grit	23.10	18.06	9.37
PVC Scotch Brite	1.39	1.03	0.11

on PVC adhesive film does not show significant interference with its capability to obtain quantitative responses. The base coat and top coat applied to PVC as well as top coat applied to PVC with Scotch Brite sanding were shown to have the lowest amount of percent change.

The control group and the two cases with the lowest relative percent change were displayed in Fig. 4 to demonstrate the pixel regions that were used to determine the calibration curves. In these images, the temperature was increased from room temperature to approximately 375 K. As the temperature increased, a decrease in pixel intensity resulted, demonstrating the effect of thermal quenching. This proves that TSP applied to a PVC film is capable of yielding a quantitatively useful response.

Using the control group, Fig. 5 demonstrated how selecting different pixel regions should result in very similar calibration curves. The selected regions are depicted in Fig. 6. The plot demonstrates that responses for multiple pixel locations are virtually the same.

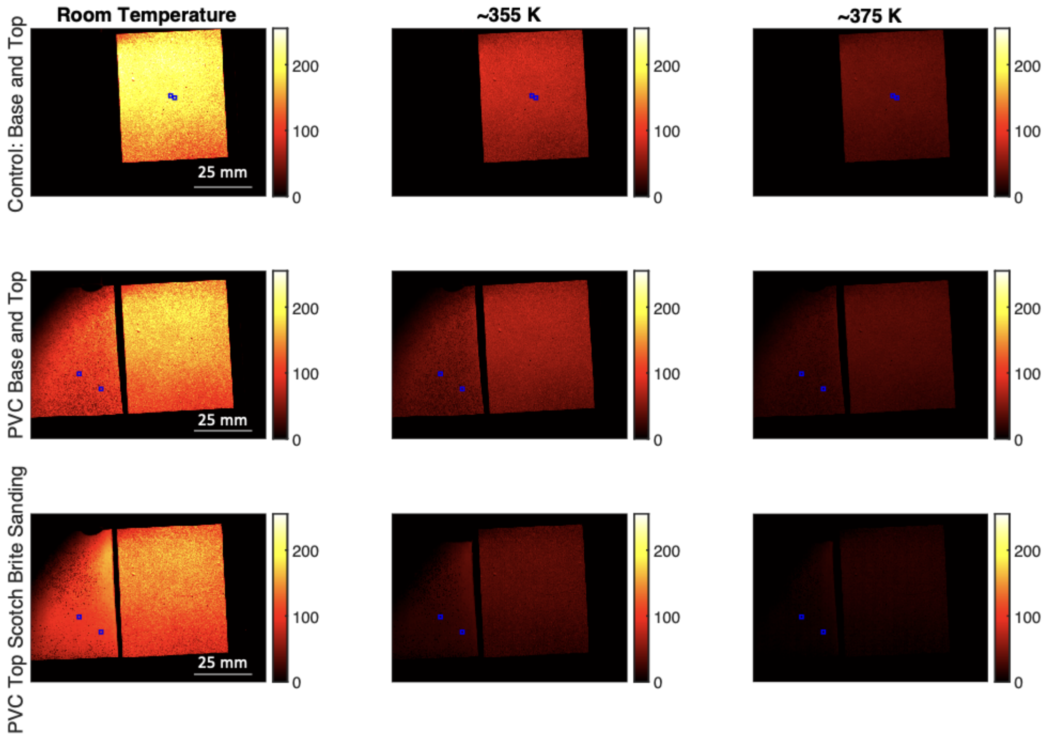

Fig. 4 Images of three variations in paint application at a range of temperature values. The region of boxed in pixels were used in the calibration curves.

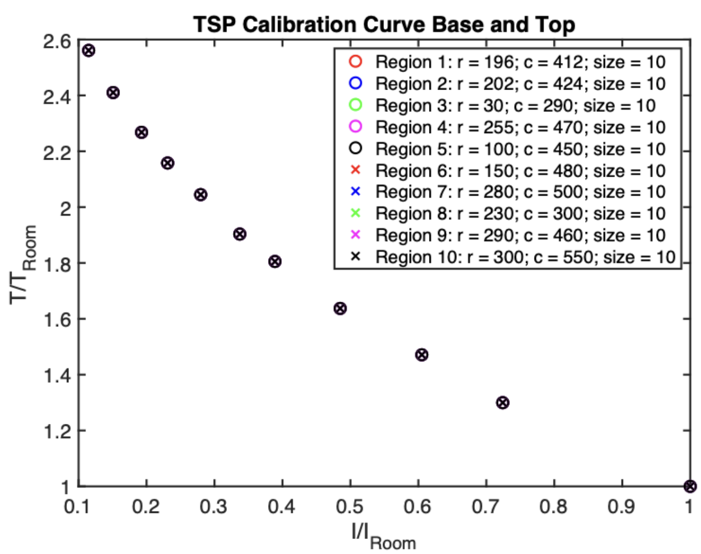

Fig. 5 The curve fit shown in Eq. 1 was applied over ten different pixel regions.

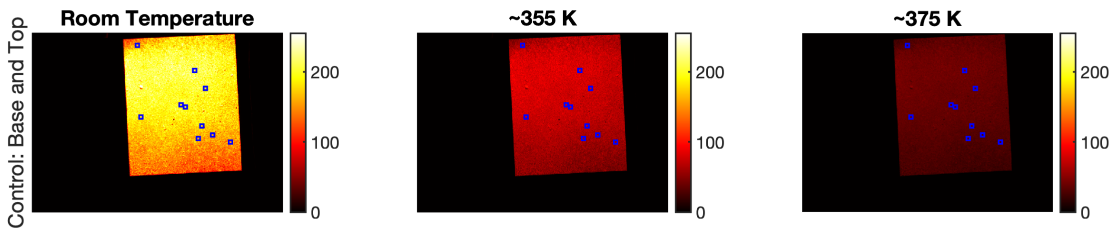

Fig. 6 The ten pixel regions used to determine the curves in Fig. 5.

Through comparison of static calibration curves to traditional TSP application, it is validated that TSP applied to a PVC adhesive film is capable of resolving qualitative data.

B. Temporal Response of the TSP

Figure 7 displays the dynamic response for the three paint samples that were tested. Each graph contains three of the same tests on the same paint variation to ensure repeatability and consistency. In each graph, there is a steep drop in pixel intensity near the beginning of the test. This represents the impulse from the blow torch. It can be concluded that each paint sample is capable in achieving a time response. It should also be noted that the initial downward slope of each line is roughly the same for each test, indicating that TSP applied to PVC adhesive film is capable of yielding time resolved data. Variances in line trends are largely associated with inconsistencies in blowtorch impulse.

An important consideration in these tests is base layer thickness which acts as an insulator, interfering with the heat transfer rate. The control group's base layer consists simply of the white polyurethane paint. The second test contained the polyurethane paint and the PVC adhesive as the base layer, acting as a double layer of insulation. The third test's base layer just consisted of PVC adhesive. The increased insulative layers in the second test resulted in elevated surface temperature over a longer duration since thermal diffusivity is much slower in those layers than the steel plate. This is reflected in the trends displayed in Fig. 7. The similarity between the first and third test should also be noted.

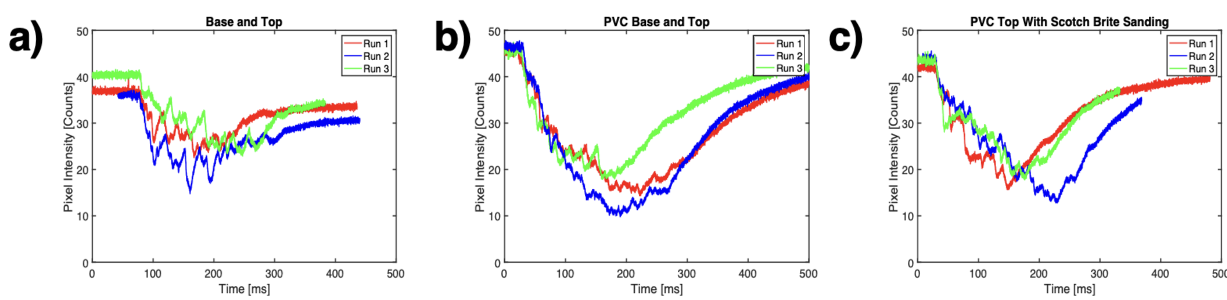

Fig. 7 Dynamic calibration curves: a) Control: base coat and top coat applied to the model b) base coat and top coat applied to PVC tape c) top coat applied to PVC tape with Scotch Brite grit sanding.

C. Vacuum Testing

After completing the vacuum testing, it was apparent that the surface needed to be cleaned well before adhesive film application, or it would result in bubbling at that location. The surface of the model was not cleaned all the way in the first test. This caused the air to expand in any location that dust or debris was present when the pressure was decreased, which led to bubbling. This can significantly impact the results of TSP testing because a drastic intensity difference will appear where the confined air is located in comparison to places were the film was properly adhered.

During the second test, the model was cleaned with methanol before applying the adhesive film. Cleaning the surface of the model eliminated any air bubbles. In both cases, there was not any visible peeling occurring at any point. The vacuum was pulled to approximately 2 Pa, which was determine to be sufficient pressure value for testing in wind tunnel such as a ludwieg tube or shock tube. These tests confirm that PVC adhesive film can be used successfully in a vacuum.

VI. Summary and Conclusions

The static calibration, time response testing, and vacuum testing were all completed to determine if TSP could be applied to PVC tape to make the paint application process more efficient. Five variations of paint were tested during these experiments: a control group of traditional base coat with TSP top coat applied, base coat and TSP top coat applied to a PVC adhesive film, and the remaining three groups consisted of top coat applied to a PVC adhesive film that had been sanded with its respective 400 grit, 1000 grit, and Scotch Brite sanding. The static calibration yielded very similar qualitative and quantitative results as the control group through a series of hot plate measurements. The dynamic calibration of TSP applied to PVC adhesive was also confirmed to be capable of obtaining a temporal response by comparison to the control group. When placing the adhesive film into a vacuum, it was noted that cleaning the model with methanol before its placement into a vacuum was necessary for consistent adhesion to the model. In that case, there were no visible occurrences of bubbling or peeling. To further this research, new materials could be analyzed for the adhesive film, the sanding process could be improved, and these films could be applied in wind tunnels. It was shown through these experiments that adhesive film applied to the base coat is comparable to traditional TSP application.

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