Thermally Sprayed Coating-Based Heating Systems for Boundary Layer Transition Detection – An Experimental Approach

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Abstract

Boundary layers on surfaces will change from laminar to turbulent flow after a critical length. Due to the differing heat transfer coefficients of laminar and turbulent flow the point of transition can be detected by heating the surface and measuring the surface temperature by thermographic imaging. Locating the transition point is crucial for the aerodynamic optimization of components in many industries such as aerospace. In this study, fiber reinforced polymer composites (FRPCs) were chosen as the substrates for the experiments. Experiments with the flame spray (FS)-process and NiCrAlY-coatings on CFRP surfaces were conducted. Multilayered coatings consisting of an aluminum bond coat, a layer of alumina as electrical insulation, and a heating layer of titania were fabricated by using atmospheric plasma spraying (APS). Free-flight tests were conducted with a functionalized winglet in order to test the ability of thermally-sprayed coating heating elements to detect the location of transition of the flow regime. The results showed that these heating elements can be used to heat a surface uniformly, with sufficient surface radiation losses for thermographic imaging. It was observed that a sudden change in surface temperature occurs at the point of transition, separation and reattachment. The results suggested that thermography of thermally sprayed heating layers on complex geometries such as winglets may be used in the design process to examine their aerodynamic properties during free flight conditions.

Introduction

In order to meet the growing economic and ecological requirements for aircraft it is necessary to improve their aerodynamic performance [1]. Both for the overall aircraft design and for the detailed examination of its individual components, a significant amount of development time has been used and increasingly complex methods such as computational fluid dynamics (CFD) are being facilitated for aerodynamical design of aircraft. Although these simulations have become more important with the growing processing power of computers they cannot yet completely replace experimental studies such as wind-tunnel testing and free-flight investigations [2].
An example of the use of experimental methods is the boundary layer flow visualization with the help of infrared-thermography. Especially for complex geometries, such as winglets, experimental methods are used to detect possible aerodynamic problems that can diminish the positive attributes of a winglet [3]. In order to detect especially separation bubbles, painting tests are commonly used for boundary layer flow visualization [4]. Here, a solution of a paint powder with a binding agent and a volatile carrier liquid is applied to the winglet. During flight, the liquid evaporates and by means of the paint pattern conclusions can be drawn about the existing flow conditions. The disadvantage is that only one flight condition can be tested per flight which makes an in-depth investigation costly and time-consuming.
Thermographic investigations are currently a common method of examining these flow states on bodies in fluid flow conditions [5]. For this purpose, wing profiles are usually heated in order to achieve the desired temperature difference between outer skin and ambient air [6]. However, if this method is applied to components with more complex geometries such as the wing-fuselage intersection or winglets, heating with simple heating foils is no longer possible as these geometries are unwindable. Therefore, another possibility to heat a surface has to be implemented, for instance heating with thermally sprayed resistive heating layer systems.
Since fibre-reinforced polymers (FRP) are state of the art in small aircraft construction as well as increasingly used for commercial aircraft [7], the goal was set to apply thermally sprayed heating layers on FRP substrates in order to conduct thermographic tests to evaluate the aerodynamic behavior of the surrounding airflow.

Aerodynamic principles of transition detection

In fluid mechanics, the boundary layer describes the layer of fluid in the direct vicinity of a surface. Its laminar-turbulent transition describes the point at which the boundary-layer flow condition changes from laminar to turbulent. Turbulent flow produces increased aerodynamic drag relative to laminar flow. For example on aircraft wings, it is of particular interest to maintain laminar flow as long as possible and to detect the point of transition.
One principle of transition detection is based on thermographic imaging and the proportionality of wall friction coefficient $\boldsymbol{c_f}$ and heat transfer coefficient α as seen in Equation (1), where $\boldsymbol{U_\infty}$ stands for the free-stream velocity, λ for the thermal

conductivity of the body and ν for the kinematic viscosity of the fluid.

$$\alpha = \frac{1}{2} c_f U_\infty \frac{\lambda}{\nu} \quad \text{(eq. 1)}$$

The friction coefficient varies depending on the surrounding flow properties. Under forced convection conditions and depending on the flow state of the surrounding air flow, with a wall temperature higher than the ambient air, a surface temperature depending on the boundary layer conditions is established which can be measured with a thermographic camera. On the basis of the temperature gradient on the surface, changes in the boundary layer such as laminar-turbulent transition and possible separation bubbles can be detected.
The expected temperature changes are shown schematically in Figure 1. In the laminar separation region, there is a significantly reduced vertical heat exchange and therefore the surface heats up more. In the area of turbulent flow the heat exchange is highest and thus the surface is cooled down most strongly there.

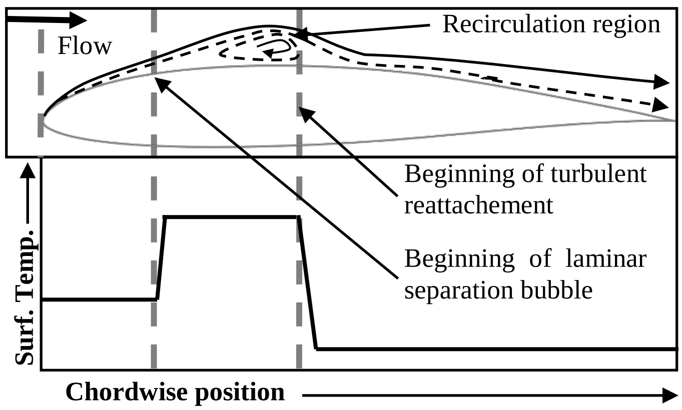

Figure 1. Surface temperatures depending on the flow state and chordwise position

Experimental methods

Two layered coating systems and deposition processes were considered:

- A metallic heating coating consisting of NiCrAlY, applied by the flame-spray process (FS). The deposition of NiCrAlY heating layers on glass fibre substrates have already been shown elsewhere [8]
- A multi-layer system with a heating coating consisting of titanium suboxide (TiO_x), applied by the atmospheric plasma spray process (APS) as shown in [9] for metallic substrates

The commercial powders used in the coating process and their parameters are shown in Table 1.

Table 1. Properties of the powders used

Powder Name	Particle Size, µm (+d90-d10)	Composition
Metco 54NS-1	-75+45	Al, 99 %
Metco 101NS	-45+11	Al_2O_3, 94 %; TiO_2, 3 %
Ceram TiO_x	-36+10	TiO_x, 99 %; x~1,6-1,9
ECKA Granules Copper AN	-46+22	Cu, 99 %
Metco Amdry 964	-106+37	Ni: 57 %; Cr: 31 %; Al: 11,5 %; Y: 0,5 %

Deposition of a single layer of NiCrAlY heating coating is less expensive and faster compared to a multi-layer-system sprayed by APS which makes it more interesting for industrial applications. Therefore, at first the goal was to apply a functioning heating layer of NiCrAlY on CFRP substrates that are as close as possible to industrial applications. CFRP plates with the dimensions 100x40 mm2 and a thickness of 2 mm were used as substrates for both layer systems.

Sample preparation

The samples were manufactured with the hand-layup process and made of satin weave carbon-fibre fabric with an areal weight of 200 g/m^3 and the LR285 resin system by Hexion (LR285/LH286, Hexion, Columbus, NY, USA) which is common for the manufacturing of general aviation aircraft. In general, samples with two different dimensions were used. Small samples with a size of approx. 30x100 mm^2 were used as test carriers for the basic layer structure in order to be able to obtain analyzable results quickly and without much material expenditure. In addition, samples with significantly larger dimensions (approx. 600x300 mm^2) were prepared which are suitable for aerodynamic investigations.
Both samples had a thickness of about 2 mm to ensure sufficient stiffness to withstand the forces occurring during the spray process, but at the same time the aim was to keep the thickness as low as possible to remain as close as possible to the carbon fibre components used in industry.

Surface Treatment

Besides the parameters that directly influence the thermal spray process the preparation of the surface is vital for the quality of the applied coating [10]. The most common way is to use the surface preparation established for metallic substrates, grit blasting, also for FRP substrates. However, the disadvantage of sandblasting for FRP components is that the structural integrity of the component is reduced [11] and damage to the fibres is difficult to detect.
Therefore, within the scope of this work, a number of experiments regarding a new surface preparation method specifically for CFRPs have been conducted. Peel ply technique is widely used in the production of FRP components to roughen the surface for bonding and to protect it from external influences such as grease or contamination. The substrates used were prepared using this peel ply and the possibility of coating them was further investigated. Previous investigations have

already shown an improvement in coatability compared to grit blasting, which is why this surface preparation has now been submitted to the German patent and trademark office (DPMA) as a patent [12].
The surface morphology of a CFRP sample after surface preparation with peel-ply is shown in Figure 2. The fabric is applied during the manufacturing process and is removed right before the beginning of the thermal spray process leaving a fine resin coat with a uniform, net-shaped mark of its fibres. Therefore, it is roughening and cleaning the surface and no further surface preparations were necessary prior to the application of the coatings.

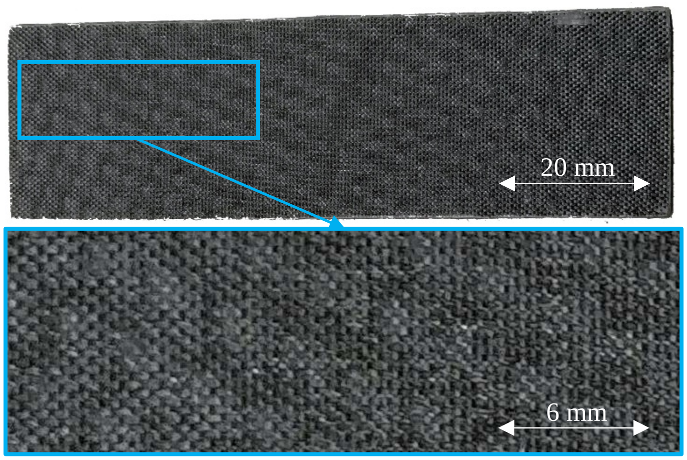

Figure 2. CFRP substrate after peel ply surface treatment

Flame spray coating with NiCrALY heating layer
The experiments with the FS-process were conducted at the University of Alberta. For the FS-process, a 6P-II torch (Oerlikon Metco, Westbury, NY, USA) and NiCrAlY-powder (Amdry 964, Oerlikon Metco, Westbury, NY, USA) were used to deposit the desired coating. The torch was mounted on a robot (HP-20, Motoman, Yaskawa Electric Corp., Waukegan, IL, USA) to ensure repeatability and process reliability; the maximum robot speed was technically limited to 250 mm/s. The NiCrAlY coating system was already applied on glass fibre substrates that had been prepared with a layer of garnet-sand on their surface [8]. The goal within the scope of this work was to apply the same methodology to carbon fibre samples that had been prepared by a peel ply. In order to achieve a coating, the parameters were varied, such as the spray distance (140-240 mm), the flow rate of acetylene (15-19 NLPM) and oxygen (25-30 NLPM) as well as cooling air pressure (0-2 bar).

Atmospheric plasma sprayed multilayer system
The multilayer heating system could already be identified as a functioning heating system on metallic substrates [9]. Within the scope of this work, this layer system should be transferred to CFRP components. The coating of the CFRP substrates by APS was conducted with a robot-mounted F6-torch (GTV GmbH, Luckenbach, Germany) at the Fraunhofer Institute for Material and Beam Technology (IWS). For the APS-process, a multi-layer coating system was selected. Figure 3 shows schematically the structure of the layers.

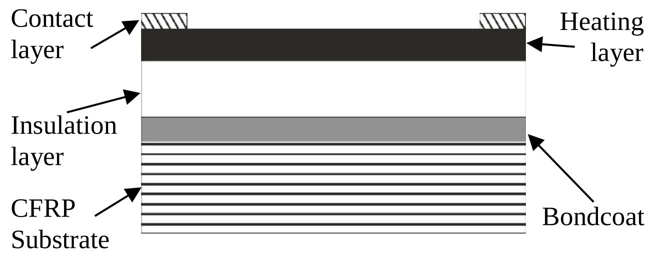

Figure 3. Layer structure of the multilayer heating coating

The substrate was first coated with an aluminum bond-coat to achieve a good bonding and to protect the surface of the substrate. To prevent short-circuiting, an electrical insulation layer consisting of Al_2O_3-3%TiO_2 was added between the bond-coat and the TiO_x heating layer. For a better contact and the possibility to solder cables, copper strips were applied to the heating layer.

Modification of the cooling system
The mentioned heating system has first been tried to apply onto small CFRP samples. After a parameter variation it could be proven that CFRP samples prepared with peel ply can be coated with the APS process and the mentioned layer structure. Despite the possibility to coat relatively small CFRP substrates, this cannot be transferred to large components without further modification, as the temperature input and cooling have a high influence on the layer structure and heat damage to the component.
The cooling system used in thermal spraying is usually a combination of stationary cooling nozzles mounted on the sample holder and additional nozzles mounted on the torch itself. In order to carry out thermographic investigations, however, the plates must be large enough for the transition to occur within its boundaries. In order to cool the whole plate uniformly, it is considered to be better to implement a cooling system mounted on the robot, instead of stationary cooling nozzles that only cool one part of the plate at one time.
Therefore, three venturi nozzles were mounted on top of the F6-torch and three air-jets were mounted below (see Figure 4) additional to the default cooling nozzles that are mounted next to the nozzle of the spray torch.

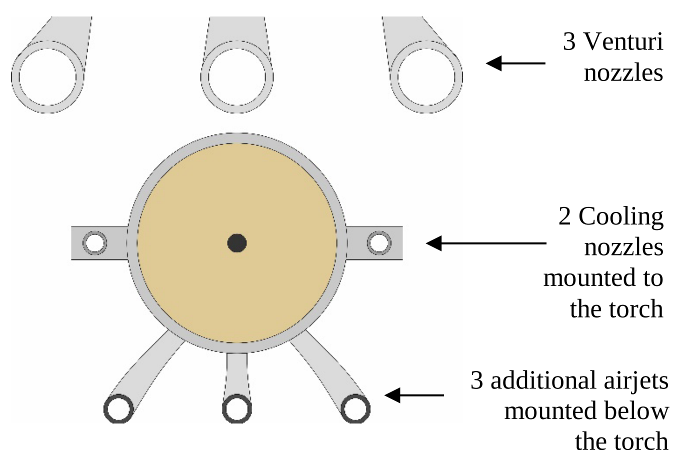

Figure 4. Modified cooling system on the F6 torch (front view)

Planning of the heating tests

In order for the surface of the samples to be heated sufficiently by the heating layer, it was necessary that the electrical resistance was matched to the power supply. With preliminary tests on steel substrates, the resistivity (ρ) of a thermally sprayed TiO_x-coating was determined to be around $\mathbf{2.5 \cdot 10^{-4}\,\Omega \cdot m}$, according to Eq. 2, whereas R is the desired electrical coating resistance, l is the distance between the two contacts, T and W are the layer's thickness and width, respectively, shown below.

$$\boldsymbol{\rho = R \cdot \frac{T \cdot w}{l}} \qquad \text{(eq. 2)}$$

With this value, a needed coating thickness of around 10-15 µm was calculated to achieve a total resistance for the heating layer of around 40-60 Ω for a plate with the dimensions of 600x300 mm^2, what has been determined to be a suitable resistance value with the available power supply. The thermographic images were recorded with an infrared camera (Pi 640, Optris, Berlin, Germany).

Results and Discussion

NiCrAlY heating layer

Figure 5. CFRP sample with applied NiCrAlY coating

Given that the robot speed was limited to 250 mm/s in the flame sprayed coatings, heat transfer to the substrate was so high that the epoxy resin of the samples evaporated and burned for the first samples. Although individual spray particles adhered to the fibres exposed as a result, this cannot be considered a satisfactory coating. Therefore, additional cooling with a vortex generator was implemented and the spray parameters were varied to achieve a colder flame and lower surface temperatures on the sample. For instance, the stand-off distance was increased and the stoichiometry of the combustion gases as well as the gas flow for these gases were changed to achieve lower flame temperatures. However, discoloration of the substrate and distortion of the sample were still observed. Thus, it can be assumed that the integrity of the sample was significantly reduced by the spray process. After the parameter variation mentioned above, a light coating of NiCrAlY particles could be applied to the surface, but even after several passes it was not possible to create a closed layer (see Fig. 5). The partial coating can be seen in a 3D-image shown in Figure 6. The elevations, colored in red, mark the areas where the spray particles were able to stick to the surface. The uncoated parts of the sample are colored in blue/green. The measurement was performed with a digital microscope (VHX-5000, Keyence, Neu-Isenburg, Germany).

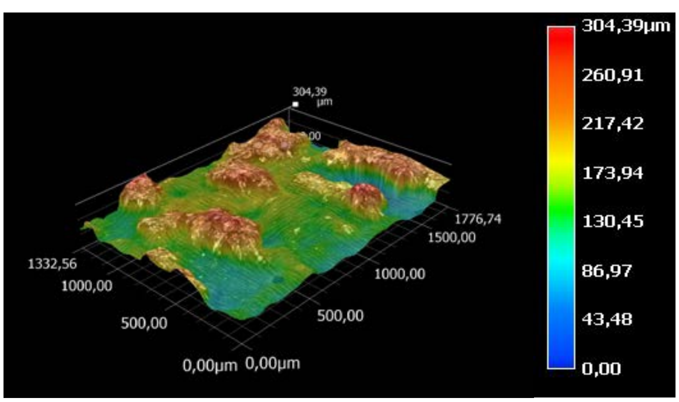

Figure 6: 3D-Microscope image of the CFRP sample with NiCrAlY-coating

Although it was already demonstrated in the past that the FS process can be used to coat FRP substrates prepared with an epoxy resin-garnet sand mixture on the upper side [8], no satisfactory coating application without additional surface modification for CFRP-samples could be demonstrated within the scope of this work.

Multilayer heating system

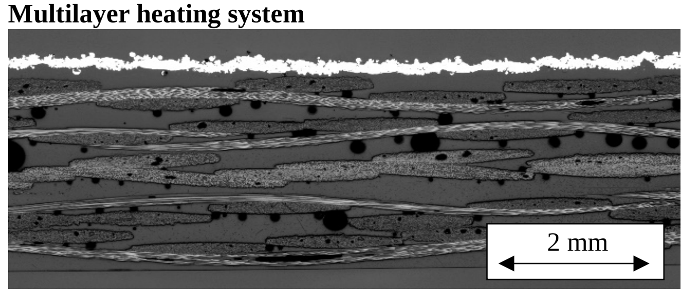

Figure 7. Cross-sectional image of a CFRP sample with peel ply surface treatment and applied Al-bondcoat

It could be shown that the peel ply treatment in general can be a sufficient surface treatment for the APS process and rather small samples, as it can be seen in Figure 7.

The desired electric insulation as well as the electric conductivity of the heating layer as calculated in section 3.4.2 could easily be measured right after the application of each layer to check if the desired properties are already achieved. The insulation capability was measured with an insulation measurement device (Mi 3321 MultiServicerXA, Metrel, Eckental, Germany) with a test voltage of 125 V. The insulation capability was considered sufficient when the measurement

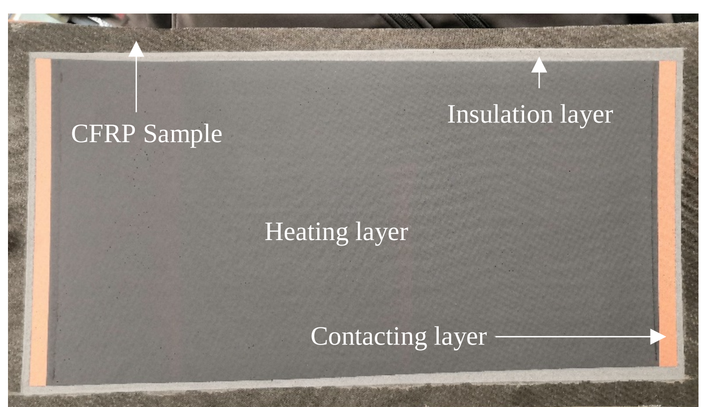

Figure 8: CFRP-plate coated with a multilayer heating system

device did not detect any conductivity anymore. For the insulation layer, a total of seven passes (110 µm layer thickness) were needed for a sufficient insulation to the aluminum bond coat and two layers of the heating coating were deposited to achieve the desired electrical coating resistance. The CFRP plate with the multi-layer-coating is shown in Figure 8.

The contacting strips were also applied by APS and a Cu-powder in order to reduce the contact resistance and to facilitate the soldering of cables. After applying the copper layer, however, it was found that the resistance of the layer system of the large plate was significantly reduced. In order to detect the reason for this, cross-sectional images of a comparable layer system on steel substrates were taken in which a reduction of the resistance also occurred. The cross-sectional images showed no visible coating damage that could lead to a drop in resistance due to a short circuit between the heating layer and bond coat. Therefore, further investigations are to be performed in the future both to improve the ability to contact the heating layer as well as to improve the overall coating resistance.

Free-flight tests

To prove the functionality of the multilayer heating system, tests in free-flight conditions were conducted. A winglet was coated with the heating system mentioned above and investigated during flight using a thermographic camera.

Winglets reduce the induced drag especially in slow flight and are widely used in general and commercial aviation today. As a rule, numerical methods are used to design winglets, but this does not allow a final statement to be made as to whether these winglets function at the respective operating point. For instance, laminar separation bubbles or early transition can significantly reduce the advantages of winglets.

To prove the feasibility of this method, a thermally sprayed heating coating was applied on a winglet shell and attached to the wing of a glider. At approximately half distance between winglet and fuselage the thermography camera was mounted to take pictures of the winglet during the flight (see Figure 9a).

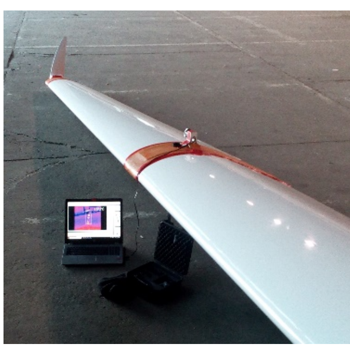

Figure 9a. Heated winglet and thermographic camera

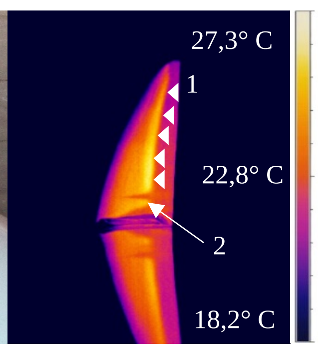

Figure 9b. Thermographic image of the winglet in-flight with visible laminar separation bubble and turbulent reattachment (1) as well as turbulent wedge (2)

In Figure 9b, a thermographic image of a winglet in free-flight can be seen. The laminar separation bubble and the following turbulent reattachment are clearly visible (1). In addition, a turbulence wedge (2) can be seen which forms on the winglet in the wake of a contamination. For verification purposes, a paint test was also carried out in this flight condition in which the position of the transition coincides with that detected by the thermographic camera.

These results prove that thermally sprayed heating layers are basically suitable for aerodynamic investigations in free flight, even if some detailed adaptations are still necessary. For example, the contact resistance at the soldering spot was increased, resulting in hotspots in the thermographic image.

Conclusion and Outlook

Two processes were tested to apply thermal sprayed heating layers on CFRP substrates. The FS process with NiCrAlY heating layers did not show satisfactory results in coating deposition because the samples sustained significant heat damage. Maybe these damages can be reduced in the future with an improved cooling system.

However, with the APS process and a multilayer system of Al, Al_2O_3-TiO_2, TiO_x and Cu, CFRP substrates of different sizes could be coated and it could be shown that a heating of the CFRP surface could be achieved. It was observed that the heating layer as such provides desirable resistance values and layer properties, but that the contacting still needs to be optimized.

The possibility of heating CFRP surfaces with thermally sprayed resistive heating systems enables further areas of application in addition to the aerodynamic investigations mentioned above. With the increasing electrification of aviation and automotive industry, for example, energy-saving and lightweight solutions for cabin heating are increasingly required, for which thermally sprayed heating plates could be used. Also the de-icing of the leading edge of aircraft and wind turbine blades could potentially be realized by thermally sprayed heating layers.

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