Direct Contactless Microfabrication for Application of Drag Reducing Riblets onto Aerospace Vehicles Utilizing UV Curable Allophanate Structures

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This paper reports on the successful proof of concept demonstration of the MicroTau Direct Contactless Microfabrication (DCM) technology for the application of drag-reducing riblet microstructures. The DCM technology is designed to be a fast, low-cost, scalable and durable method of directly applying riblets onto an external aircraft surface. Panels produced using the DCM method reliably exhibited a 6-7% viscous drag reduction in wind tunnel testing. We also successfully fabricated novel 3D riblet microstructure designs, confirming the 'single exposure 3D printing' capability of the DCM technology. Ongoing is the development of the coating system from which the riblets are fabricated to meet U.S. Air Force (USAF) operational and durability requirements as well as optimization of the optical system for compatibility with a hangar environment. This will be followed by an investigation into automatic applicators to translate the system across the aircraft's surface.

I. Introduction

MICROTAU'S 2017 AIAA SciTech paper titled *Microfabrication of Riblets for Drag Reduction*[1] reported on the successful proof of concept demonstration of a novel method of Direct Contactless Microfabrication (DCM) for application of drag-reducing riblet microstructures. Riblet panels produced using this prototype reliably exhibited a 6-7% viscous drag reduction in wind tunnel testing. This research was carried out as part of Phase I of the U.S. Air Force Research Laboratory's (AFRL) Engineered Surfaces, Materials and Coatings (ESMC) program for drag reduction.[2] The ESMC program goal is the practical application of drag reduction technology to U.S. Air Force (USAF) legacy transport aircraft fleet in order to reduce their $8B+ annual spend on aircraft fuel.

The present paper provides an overview of the Phase I and partially completed Phase II efforts of the ESMC program. The Phase I effort goal was proof of concept and produced a successful prototype DCM device capable of fabricating riblet microstructures and panels that reliably demonstrated for drag reduction in wind tunnel testing. The Phase II effort is to mature the DCM technology from a laboratory environment to ready it for application to a C-130 aircraft. The first objective of Phase II is to adapt the prototype DCM technology for the fabrication '3D riblets.' Theoretical calculations by Lockheed Martin suggest these 3D riblet microstructures have the potential to reduce viscous drag by up to 15%,[3] however this has yet to be demonstrated experimentally. The scope of this research also covers development of the ultraviolet (UV) curable coating system from which the riblets are fabricated to meet USAF operational and durability requirements; development and optimization of the optical components for compatibility with a hangar environment; and an investigation into automatic applicators to translate the DCM system across the aircraft surface.

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II. Technical Background

Riblet microstructures hold great promise to reduce aircraft skin friction but have yet to be successfully implemented on aircraft due to problems with cost, maintenance, durability and application.[4] Riblets are small surface protrusions aligned with the direction of flow and spacing in the order of 50-150μm.[5] These microstructures have been studied for over four decades and have reliably demonstrated turbulent flow viscous drag reduction of 5-10%.[6] Appliqué riblet films developed by 3M demonstrated an almost 2% net drag reduction however failed to prove economically viable due to manual application adding unacceptable time and cost to the maintenance process,[4] inability to cover more that 70% of the aircraft without adversely impacting flight characteristics,[7] materials adding excess weight to the aircraft counteracting the drag benefit,[8] and surface degradation reducing the performance of the riblets over time.

The MicroTau DCM method allows for greater coverage, lower cost of application from a durable material, as well as riblet geometry optimization for drag reduction. The DCM method derives from mature and commercially successful computer chip photolithography technology able to fabricate feature sizes orders of magnitude smaller than drag-reducing microstructures. Previous attempts to transition this technology to aircraft surfaces have failed to see implementation to date due to photomask contact imposing strict requirements on the UV curable material used.[9] By using a robust contactless optical system the DCM method overcomes this problem and as a continuous process is well suited to exposing large areas quickly. Without strict requirements on the UV curable material an extensive range of coatings may be selected from, allowing the use of UV-A curable military aircraft topcoats[10] developed with AFRL for Department of Defense (DoD) applications.[11]

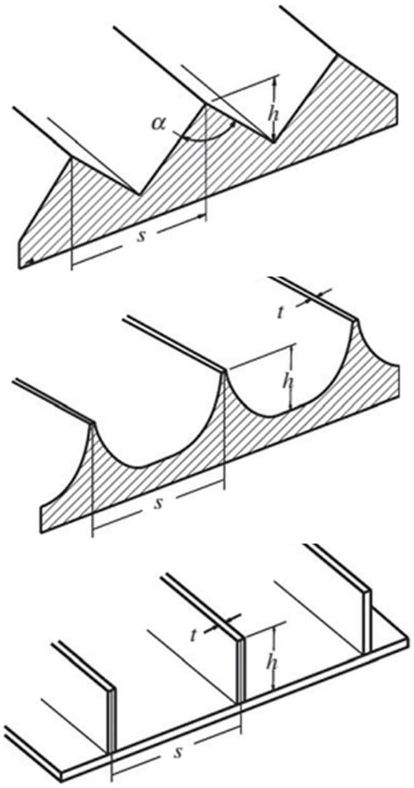

Figure 1. From left to right: sawtooth; scalloped and blade riblet geometries.[6]

III. Development of UV Curable Coatings with Low UV energy Light Sources

Many researchers have tried to develop UV curable coatings that can cure in ambient atmospheric conditions. Work done in the early 1950's developed chemistries that overrode oxygen inhibition through the use of TMPDAE.[12] However; high performance coatings that will meet the rigours of aerospace performance need to be based on aliphatic backbones to meet this strigent performance requirement.

Up until the early 2000's most aliphatic polymer building blocks used in making oligomers resulted in very high viscosities. These high viscosities in turn required large amounts of acrylate monomer to reduce the formulations to its use viscosity. These high levels of acrylate monomers resulted in surface inhibition by oxygen resulting in poor coatings performance. In RADTECH Europe 2005[13] and RADTECH NA 2010[14] papers a new class of aliphatic urethane oligomers was revelaed based on an Allophanate structure. This Allophanate urethane oligomer development resulted in two distinct adavntages over conventional isocyanurate urethane chemistry: (1) the Allophanate structure allowed the tuneability of the hydrogen bonding within the structure to be low enough to give low viscosity yet maintaining enough hydrogen

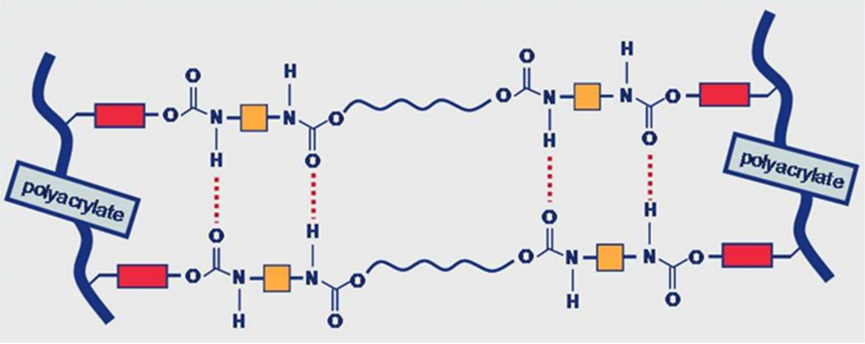

Figure 2. Allophanate Chemistry; H-bonding plays an important role in the UV cured coating.

bonding to act like a pure urethane oligomer; (2) due to this low hydrogen bonding the amount of acrylate monomer needed for adjusments to use viscosity was lower since the hydrogen bonding was lower; and (3) high functionality was maintained which offered similar coating performance of the older style aliphatic urethane oligomers.

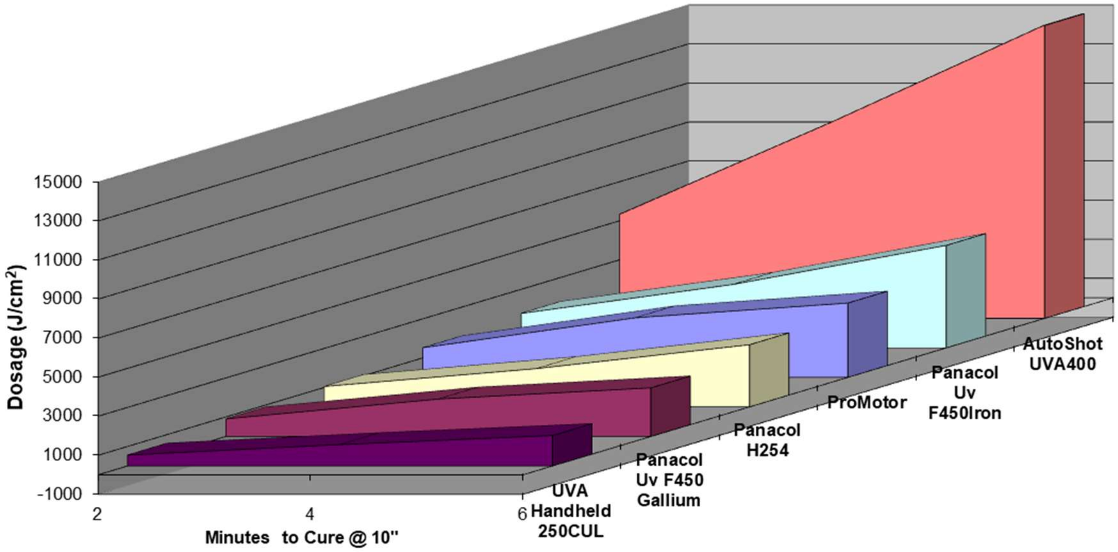

Figure 3. Evaluation of UV A Automotive light sources for curing primers and clear coats

Low energy UV cure light units are an additional source of issues for curing coatings that need high performance properties. Researchers in 2004 presented a paper on all of the UVA light sources at the time.[15] The result of this study confirmed that the amount of energy hitting the surface needs to be measured and understood. The energy density to develop the proper kinetics must be at a proper level to cross link via free radical chemistry to override the issues with oxygen inhibition. In the DCM manufacturing of riblet microstructures we are using a low energy laser that has its own special issues since its performance has enough power to cross link the system but not enough power to override the oxygen inhibition at the air interface.

Another critical part of the coatings performance equation was the use of certain photoinitiators to override the oxygen inhibition issues due to low energy light sources as shown in Figure 4. Researchers were able to use a unique technique to develop a road map of the proper photoinitiator to use in combination with the right oligomers to override the oxygen inhibition issues.[16] This rapid evaluation tool allowed the proper selection of the oligomer in combination with the photoinitiator. These combinations were further evaluated

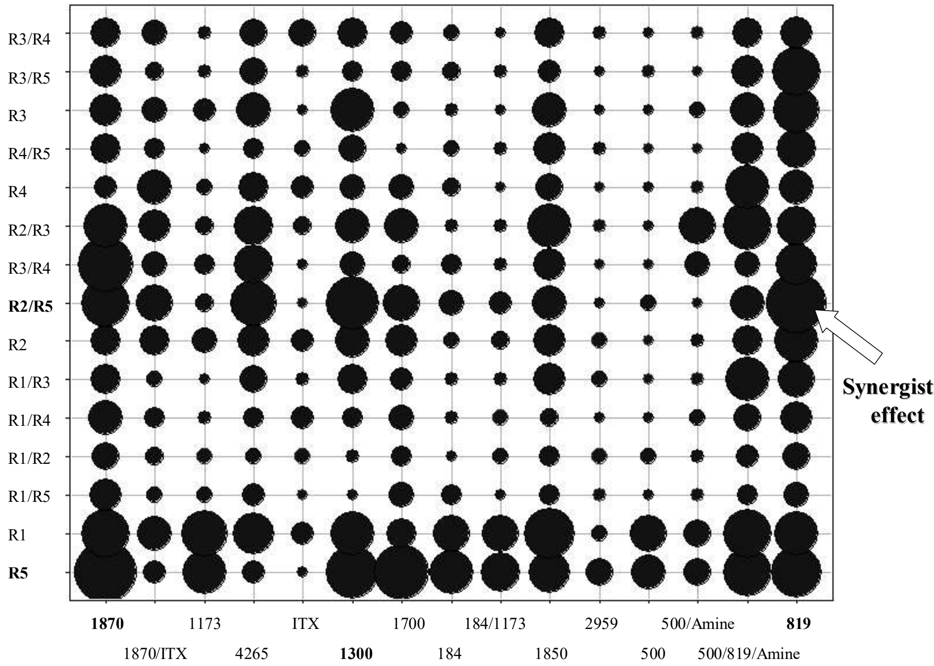

Figure 4: Average predicted surface cure (larger the circle the better the cure) for all oligomer-photoinitiator combinations after curing with a UV-A light source.

and applied to the current riblet microstructures to obtain maxium cure performance while still maintaining the proper riblet structure.

Work is now being implemented in this phase of formulating to understand the interplay of oligomer, monomer, photoinitiator and UV light source. In addition; this phase will call on formulation skill developed in the past on understanding the proper photoinitiator selection and and UV light source for a highly pigmented system[17] to meet revelant Military Specifications.

IV. Direct Contactless Microfabrication

The MicroTau DCM method consists of three key steps: (1) application of the UV curable coating; (2) exposure in the desired pattern; and (3) developing (i.e. removing unexposed coating).

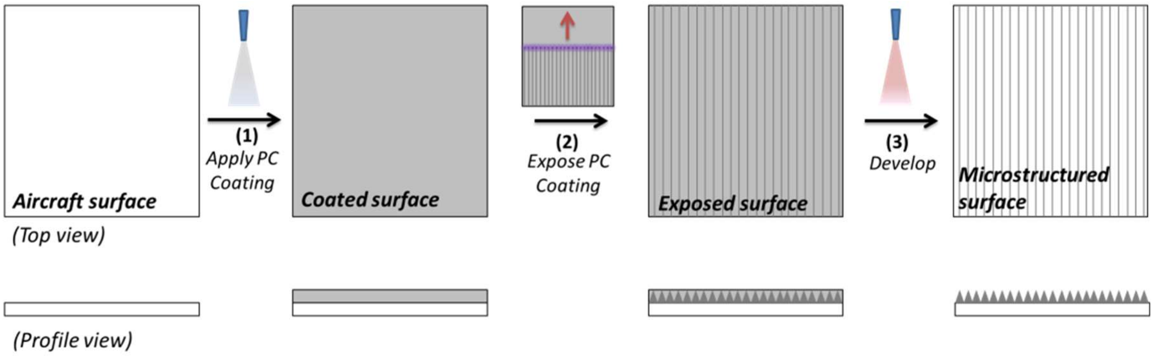

Figure 5. Three step DCM process with top- and profile-views

A. Apply UV Curable Coating

The UV curable coating is applied to the external aircraft surface to the thickness of desired riblet height or greater (50-150μm). The present DCM laboratory set up uses a drawdown method of coating application for experimental purposes, however we will be exploring using existing aircraft coating methods and equipment such as spray painting by the end of the current Phase II project.

B. Expose UV Curable Coating

An optical system is kept at a predetermined distance from, and parallel to, the coated aircraft surface during exposure. The system projects a 1- or 2-dimensional intensity profile pattern that is traversed across the surface to draw out the desired riblets shapes in a continuous exposure.

C. Develop

The unexposed UV curable coating is then removed using an appropriate developing method. The developing method is dependent on the coating used, e.g. mineral alcohol for unexposed UV curable coatings.[18] This may be assisted with some physical removal processes.

V. Phase I Proof of Concept

A laboratory prototype demonstrated this process in the Phase I effort. A bottom-up curing effect was observed enabling 3D manipulation of microstructure profiles in a single exposure.[1] Combined with a continuous exposure method, riblet microstructure heights and profiles can be manipulated as they are applied to the external aircraft surface. The optical system demonstrated fabrication at distances of 100-600mm from the coated surface with an exposure speed capability of ~1 metre squared per minute, suggesting the method is scalable to aircraft surfaces for fast application to large areas. Feature sizes down to the order of ~1μm were achieved (Figure 6). Fabrication of riblet microstructures was successfully demonstrated and wind tunnel samples exhibited a 6-7% viscous drag reduction. Subsequent wind tunnel testing has shown reliability across multiple DCM fabricated riblet panels (Figure 7).

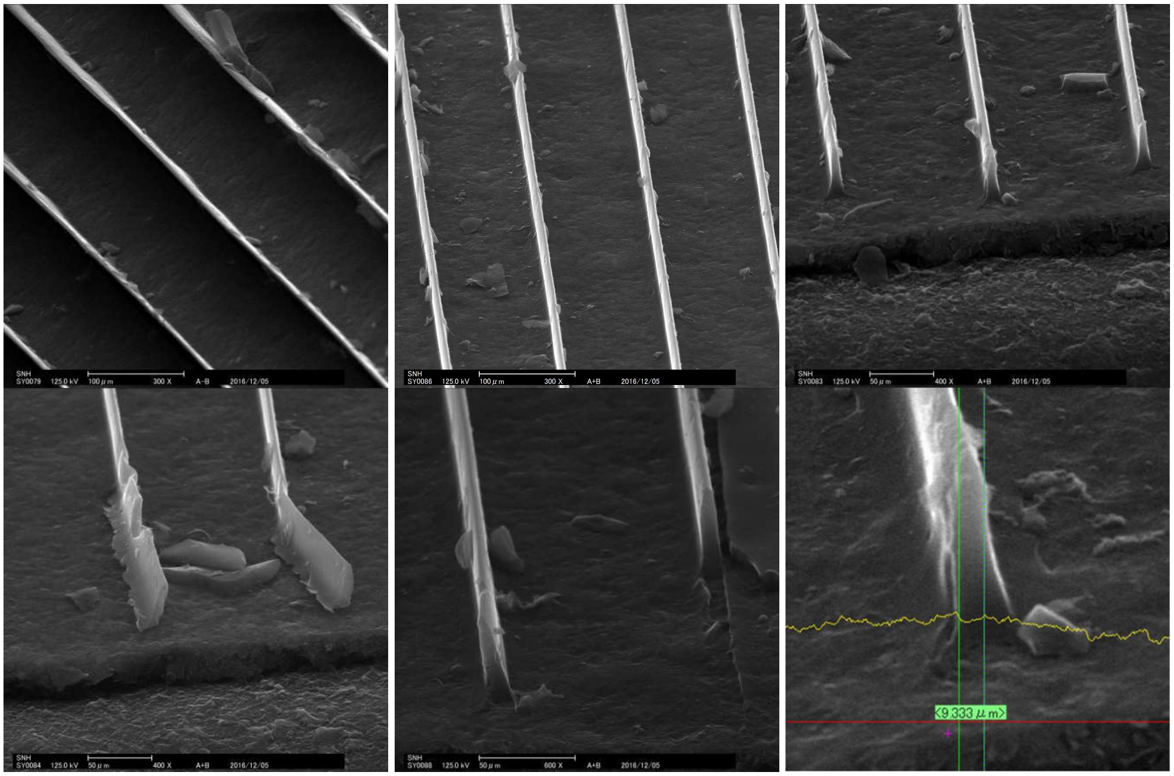

Figure 6. SEM images of riblets fabricated reveal far sharper, smoother and narrower microstructures than anticipated. Scale bars in first 5 images are 100µm. The last image is a magnified riblet profile showing a 9µm width.

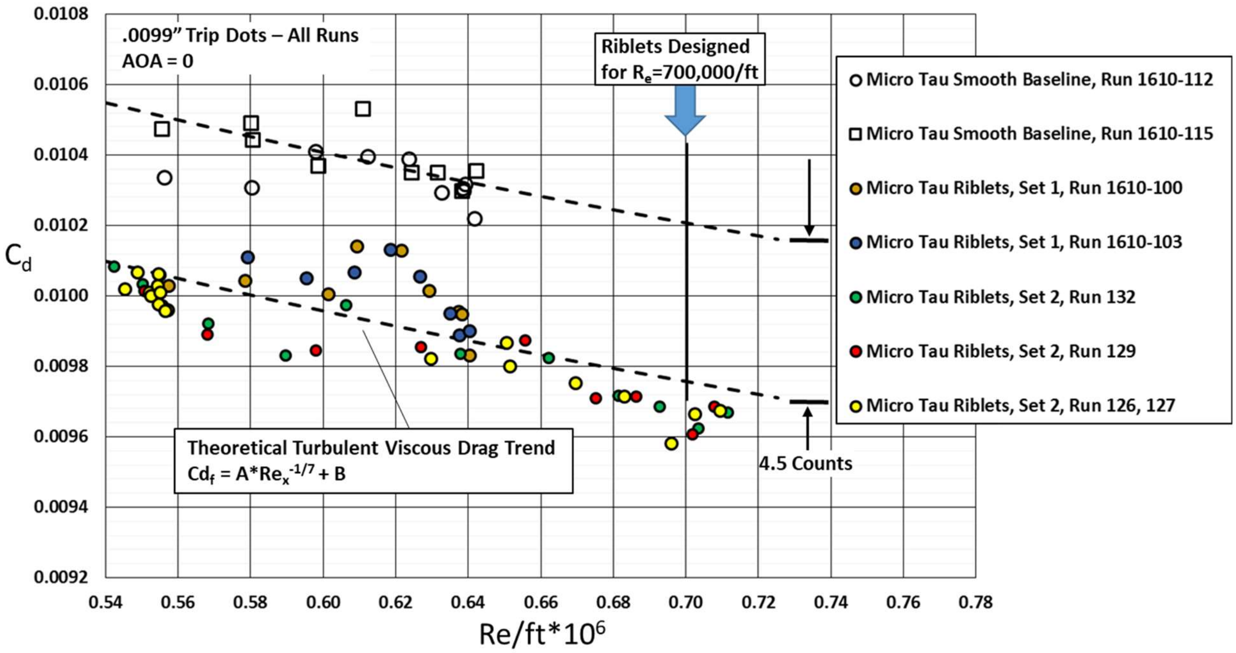

Figure 7. Wind tunnel drag coeffieicnt (C_d) reduction results of DCM fabricated riblet panels

VI. Fabricate 3D Riblets for Wind Tunnel Testing

The first effort of the Phase II project was to confirm the 3D manipulation capability of the DCM technology and utilize it to fabricate novel 3D riblet designs for wind tunnel testing. These new 3D microstructure designs require the heights of the riblets to vary in the streamwise direction.[3] This is possible to fabricate using the DCM process as a result of the bottom-up curing mechanism enabling 'single exposure 3D printing.'[1]

A. 3D Riblet Microstructures

As previously indicated,[1] the MicroTau DCM technology is capable of manipulating microstructure 3D topologies in a single exposure, theoretically enabling the fabrication of any number of geometries. One avenue we wished to explore was to fabricate 3D riblet geometries. 3D riblets have a variable streamwise height and according to computational fluid dynamics conducted by McClure et al.[3] showed promise to increase the drag reduction delta of traditional 2D riblets.

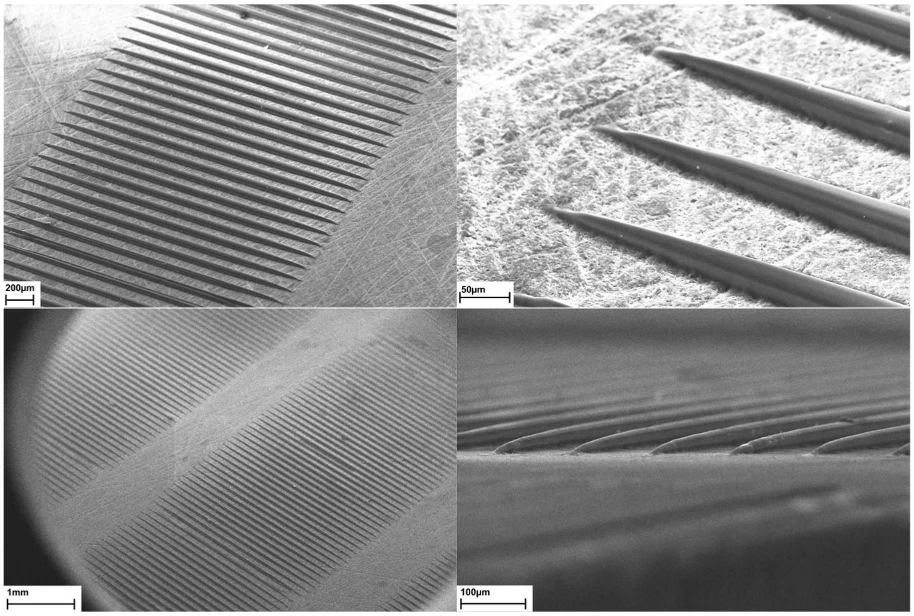

Figure 8. Scanning electron microscopy images of DCM fabricated 3D riblet samples for wind tunnel testing.

With further development of the DCM fabrication system and parameter adjustments we were able to fabricate the 3D riblet designs provided by the Lockheed Martin team (Figure 8) also working under the ESMC program. These 3D riblet geometries were fabricated through the DCM continuous exposure process combined with active optics to manipulate the riblet geometry whilst printing, demonstrating the capability hypothesized in Phase I.[1]

B. Wind Tunnel Panels

A selection of 3D riblets designs were printed on 600mm x 600mm wind tunnel panels to be adhered to a NACA 0012 airfoil wind tunnel model installed at the Lockheed Martin Aerodynamic Development Facility.

C. Wind Tunnel Results

At the time of writing, the subset of 3D riblet panels delivered to Lockheed Martin that have been tested have not demonstrated the expected 15% viscous drag savings. However, results show a substantial improvement on prior 3D riblet research[3] and data trends indicate promise of achieving the improved drag reduction figures. To date only a small fraction of the 3D riblet design space has been explored and we will continue to do so during Phase II.

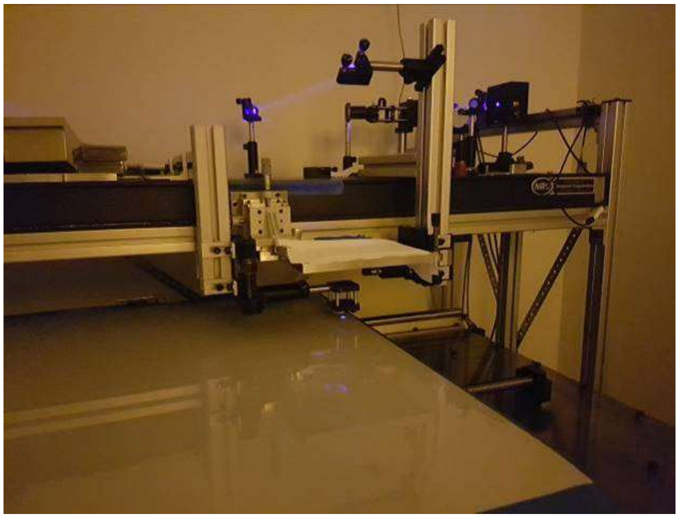

Figure 9. Printing 3D riblet wind tunnel panels with the DCM process

VII. Ongoing Phase II Work

At the time of writing we are approximately halfway through Phase II project. This section describes the three areas of development that are still ongoing: developing the coating system from which the riblets are fabricated to meet US Air Force (USAF) operational and durability requirements; optimizing the optical system for compatibility in a hangar environment; and an investigation into automatic applicators to translate the optical system across the aircraft's surface for scaled implementation of the DCM technology.

A. Coating System Development

The first goal of the coating system is to ensure it is compatible with USAF Programmed Depot Maintenance (PDM) processes for coating an aircraft. We will be testing our UV curable coating formulations with existing aircraft spray coating methods and equipment to ensure it can be applied with minimal impact on existing PDM processes. Another critical step is to ensure that the third "developing" step of the DCM process (i.e. removing uncured coating) uses materials and equipment compatible with PDM. Strong solvents such as those used in the Phase I effort[1] are not be appropriate for USAF PDM use, however we have already had success using a combination of milder solvents and a physical removal process. We will continue on this work with the goal of minimizing or perhaps even eliminating the use of solvents in the developing step altogether.

The second goal is to ensure that we meet USAF durability requirements. We have a number of candidate coating formulations based on a UV curable military aircraft topcoat developed by AFRL to meet the MIL-PRF-85285 specification[10] but with new oligomer chemistries for improved durability and UV stability and modified for compatibility with the DCM technology. We will undertake testing at the University of Dayton Research Institute (UDRI) Coating Corrosion and Erosion Laboratory (CCEL) at Wright-Patterson Air Force Base (WPAFB) both on the performance of the total coating stack and the resilience of the riblet microstructures themselves.

B. Optical System Optimization

Optimization of optical components for compatibility with a hangar environment is ongoing. Critical capabilities such as focal range and stand-off distances will be determined with the goal to be compatible with numerous automatic applicator systems and thus ensure implementation in the USAF PDM processes is as simple as practicable. Already we have demonstrated improvements to the optical system including compatibility with active optics to both direct and manipulate the curing intensity profile. This may allow a simpler, more cost-effective process to implement whereby the intensity profile can be translated across the aircraft surface using optical methods rather than translating the entire optical system.

C. Automatic Applicator Investigation

An investigation into automatic applicators to translate the optical system across the aircraft's surface shall benchmark the performance of possible systems. This has yet to be undertaken, however with the above optical and coating efforts we will narrow down which available automatic applicators have adequate performance to fabricate riblets using the DCM method. The most promising system shall be trialed with the MicroTau DCM method to fabricate riblets and metrology undertaken to determine fidelity of the riblet microstructures produced.

VIII. Conclusion

At the midpoint of the Phase II program, we have encouraging results that suggest the possibility of achieving the ESMC goal for practical drag reduction on USAF legacy transport aircraft. Specifically, we have demonstrated the Direct Contactless Microfabrication (DCM) process that is capable of rapidly producing properly dimensioned riblet microstructures, in situ, out of a UV curable military aircraft topcoat being developed to meet the MIL-PRF-85285 specification presently used by USAF transport aircraft. This procedure adds negligible weight to the aircraft (less than 100lbs), since microscopic riblets are printed directly onto the aircraft's skin, it is inexpensive to fabricate, and the process shows promise of being easy to integrate into the normal cycle of depot maintenance. At the time of writing this paper we have successfully demonstrated the ability to fabricate numerous microstructure topologies including advanced 3D riblet geometries that may significantly improve the viscous drag reduction properties of standard riblets. Initial 3D riblet wind tunnel results improved on McClure et al.'s[3] prior work however have not yet achieved the drag reduction results hoped for but we will continue with further designs and wind tunnel samples during 2018. Development of the DCM coating system and optimization of the optical system is ongoing, however initial results are promising and we are on track to a planned automatic applicator demonstration during the Phase II effort. The DCM application of drag-reducing riblet microstructures is projected to reach at least Technical Readiness Level 5 (TRL 5) the conclusion of this Phase II project in 2018.

Acknowledgments

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