Curing Functional Properties into UV Coatings: Direct Contactless Microfabrication of Drag Reducing, Anti-bacterial, Anti-fouling and Optical Microstructures

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Abstract

Properties of a final cured surface are traditionally achieved through formulating the UV curable coating. Different functional properties may also be produced through physical means – resulting from microscopic patterns on a surface like those found on the skin of plants and animals in nature. MicroTau's Direct Contactless Microfabrication (DCM) technology is a process of curing these functional microstructures into UV curable coatings to produce properties such as drag-reducing, optical, anti-bacterial and anti-fouling effects. This paper provides an overview of new functional properties cured into UV coatings with the DCM technology.
Keywords: Biomimicry, Microstructures, DCM, Riblets, Drag-Reduction

1 Introduction

The material properties of UV curable coatings are traditionally achieved during the process of formulating through a selection of oligomers, reactive diluents, additives, photoinitiators and pigments/fillers. Once cured the final surface properties are set as a consequence of the coating formulation's chemistry. The present paper describes a process of achieving novel surface properties through physical rather than chemical means - resulting from microscopic patterns cured into the coated surface that impart properties in addition to those that result from the coating formulation chemistry. MicroTau's Direct Contactless Microfabrication (DCM) technology is a process of curing these functional microscopic patterns into UV curable coatings.

In nature, plants and animals have developed microstructured skins that impart specific properties to give them advantages adapted to their environment. The exact nature of the microstructure determines the physical properties – low-drag shark skin, self-cleaning lotus leaves, anti-reflective moth eyes and anti-bacterial pitcher plants are all the result of microscopic patterns on the surface of the plant or animal. Decades of scientific research has demonstrated that replicating these microscopic patterns replicates these functional properties [1]. Despite the significant commercial potential of these functional microstructured surfaces across a range of industries, their value has yet to be realised due to a lack of a viable method of production at scale [2].

MicroTau's proprietary DCM technology prints microstructures out of UV curable coatings used across numerous industries in a manner that is economical, fast and scalable. By imparting properties through the physical means of micropatterning the surface, DCM can leverage existing UV curable coatings and provide functional properties in addition to the coating properties. The present paper will provide an overview of the DCM technology and the functional properties it has produced.

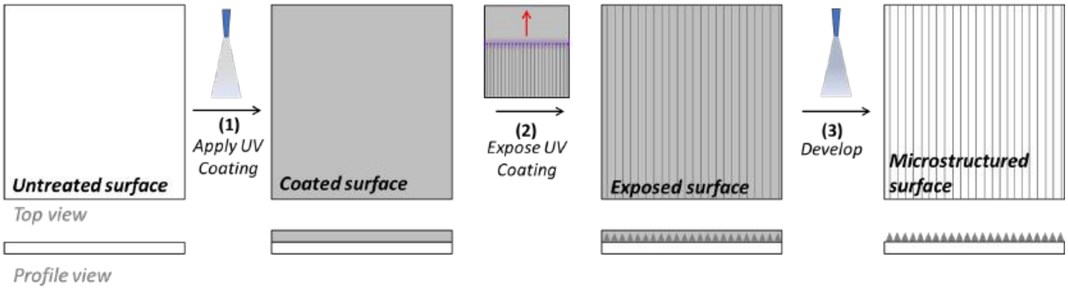

Figure 1. *The three step DCM process with top and profile views.*

This includes shark skin-inspired surfaces with 7% skin friction drag reduction developed with the US Air Force Research Laboratory as well as optical, matting and wetting properties. Also covered are further properties under development including adaptive visual camouflage microstructures with the Australian Defence Science and Technology Group (DST); marine anti-fouling properties being developed with the University of Sydney and anti-bacterial properties being developed with the University of Technology Sydney. Finally a summary of advances being made with the DCM technology will be provided including robotics integration for scaled aircraft application and qualification with aerospace, marine drag reduction, manufacturing integration and rapid prototyping capabilities.

2 Direct Contactless Microfabrication

The MicroTau Direct Contactless Microfabrication (DCM) has been described in preceding papers [3, 4, 5] and will be described only briefly here. DCM consists of three key steps: (1) application of a UV curable coating; (2) exposure in the desired pattern; and (3) developing (i.e. removing unexposed material) as shown in Figure 1.

The DCM process is agnostic to the method of coating application. The UV curable coating is applied to the desired surface to the thickness of the desired microstructure height. During exposure an optical system is kept at a predetermined distance from, and parallel to, the coated surface. The system projects a 1- or 2-dimensional intensity profile pattern that is moved relative to the surface to draw out the desired microstructure designs in a continuous exposure. Finally the unexposed UV curable coating is removed using either a chemical method (utilising a solvent the uncured UV coating is soluble in), a physical method, or some combination of the two.

There are a number of benefits of the DCM process over alternative methods of microfabrication that make it a well suited solution to both manufacturing functional microstructures at scale and rapid prototyping of different microstructure designs.

As DCM is a contactless process there are no constraints placed on the UV curable coating from which the microstructures are fabricated. This is in contrast to alternative methods like nanoimprint lithography that involve a mask or stamp template coming in physical contact with the UV curable material. This puts formulating requirements on the UV curable material to ensure it fills the template and that it does not adhere to the template. These issues can cause defects and damage the template with replacement costs of up to six-figures. Being contactless has enabled MicroTau to use pre-existing UV curable coatings from industries including aerospace, automotive, wood and 3D printing. DCM has demonstrated successful microfabrication with exposure distances ranging from 1 mm-1000 mm and depths of focus up to 10 mm. This also enables *in situ* fabrication of microstructures directly onto desired surfaces such as on to the skin of an aircraft or to integrate into existing manufacturing processes.

The DCM process is a scalable process and has been designed with scale manufacturing in mind. Low cost solid state light sources are used and are parallelizable such that a larger print area can be swept out during the continuous exposure process. To date feature sizes down to the order of single micron resolution have been achieved and linear print speeds of over 1 metre per minute which represents the limitation of our current linear actuator system, therefore we are confident higher cure speeds are achievable.

The rapid prototyping capability of DCM for microstructure pattern designs is a unique one. The process allows for manipulation of 3D topologies on the micro-scale in a single exposure step. In contrast to conventional 3D printing which stacks a series of 2D cross-sections to build a 3D topology, DCM manipulates the heights and profiles of the microstructures with a single exposure by adjusting optical irradiance profiles and other printing parameters. What results is a rapid method of exploring large design parameter spaces for microstructures which enable the demonstration and development of different functional properties discussed below. These parameters can be adjusted as the irradiance profile traverses across the surface allowing for unique microstructure designs for example those shown in Figures 3 and 5.

3 Shark Skin Drag Reduction

The skin of the Mako shark has been found to reduce drag under turbulent flow conditions. Rather than being perfectly smooth shark skin exhibits periodic microscopic ridges aligned with the direction of flow were found to be responsible for the reduction of drag [6]. These microscopic ridges are known as riblets, and have a typical spacing of between 50 and 150 um that is related to the flow conditions over the surface. These ridges have a range of cross-sectional geometries, key ones of which are shown in Figure 2, have different degrees of drag reduction as well as different mechanical properties. These microstructures have been studied for over three decades and have reliably demonstrated turbulent flow viscous drag reduction of up to 5% for sawtooth type riblets and up to 10% for blade type riblets (see Figure 2).

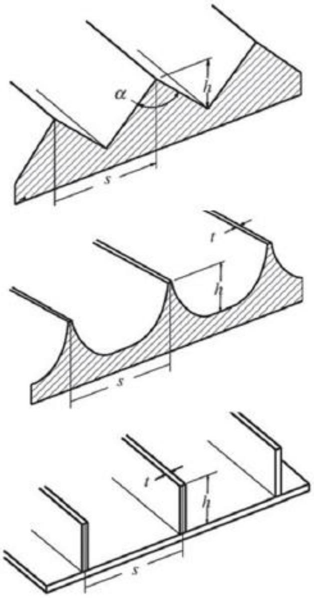

Figure 2. *A range of riblet cross-sections geometries: Sawtooth (top), scalloped (centre) and blade riblet (bottom) [6].*

MicroTau has been working with the U.S. Air Force Research Laboratory (AFRL) as part of their Engineered Surfaces, Materials and Coatings (ESMC) program for drag reduction since 2016. 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. Riblet panels produced using MicroTau's DCM technology have reliably exhibited 7% skin friction drag reduction in wind tunnel testing conducted by project partner Lockheed Martin [3, 4, 5, 7]. Applied to commercial aircraft this equates to a net fuel saving of 2% or greater, representing potential $5.5 billion in fuel savings across commercial aviation[1] and a reduction of

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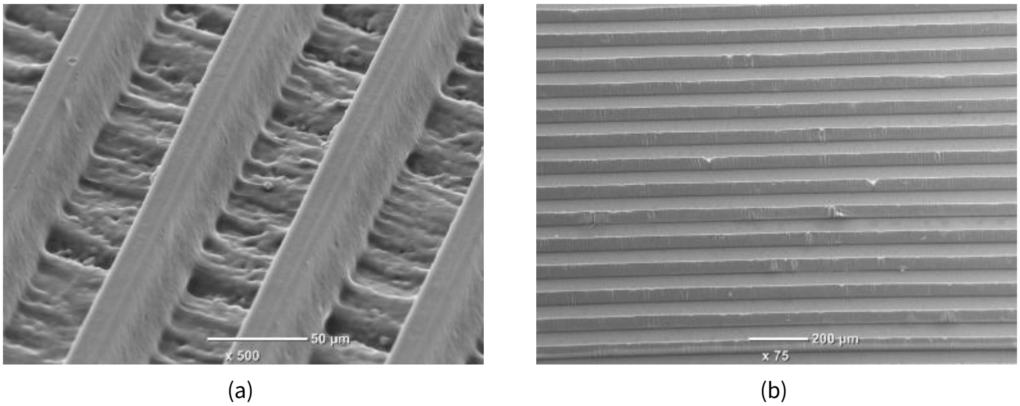
[1] International Energy Agency https://www.iea.org/statistics/oil/; 2017 Aviation Fuel demand from chart "World Demand From Product Groups" = 310 million tonnes; Price = US$618.54 per tonne, Average price 2019 = US$79.7/bbl 1 tonne = 7.765 bbls



(a) (b)

Figure 3. *Scanning Electron microscopy of various 2D riblet designs.*

CO_2 emissions by 20 million tonnes [2].

MicroTau's DCM process has demonstrated a unique ability to fabricate a range of riblet profiles. This comes from the adaptability of the DCM process in that it can manipulate microstructure topologies in a single step by adjusting optical and print parameters. Figure 4 shows a range of riblet profiles produced with the MicroTau DCM process. The top four are of the sawtooth-like design, with adjustments made in peak angles, spacing between the base of the riblets (touching or with a flat region in between) and different spacings and heights. The fifth from the top shows a scalloped-type riblet profile. The next four below that show blade riblet profiles of different heights, thicknesses and spacing. The final of those (fourth from the bottom) provides designs suitable for transonic flight conditions – with spacing of s = ~76 um height h = ~38 um and thickness of ~3-4 um.

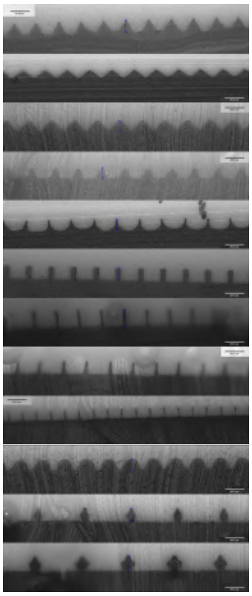


Figure 4. *Optical microscopy of molds of different riblet profiles made with the DCM process including (from top to bottom) different sawtooth, scalloped and blade riblet profiles as well as rounded and diamond re-entrant profiles.*

The versatility of the DCM process and its ability to manipulate microstructure designs live during the fabrication process resulted in working with ESMC project partner Lockheed Martin to fabricate novel riblet designs.

Lockheed Martin conducted Computational Fluid Dynamics (CFD) simulations producing more complex riblet designs with a periodic variation in height along the direction of fluid flow, termed three-dimensional (3D) riblets. These simulations indicated such 3D riblet microstructures that have the potential to reduce skin friction drag by over 10% [3, 4, 5, 7]. MicroTau has successfully fabricated various 3D riblet designs with the DCM process as shown in Figures 4, 5 and 6 below. To date wind tunnel testing of 3D riblets have not yet demonstrated drag reduction greater than for 2D riblets however further testing is ongoing with Lockheed Martin in 2020.

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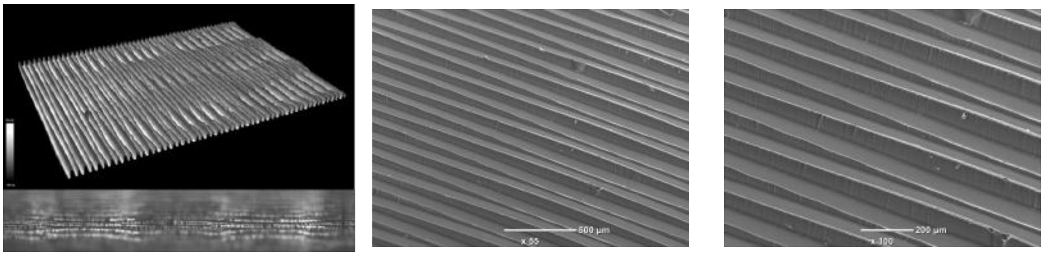
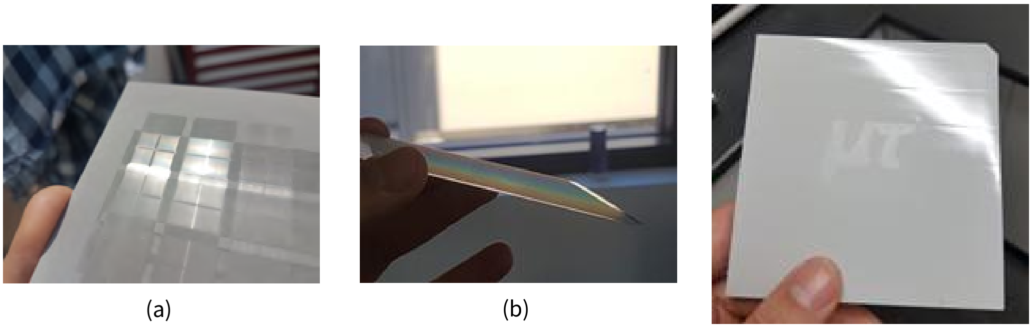
[2] CO_2 Emmissions: 1 kg of jet fuel translates into 3.15 kg of CO_2 [8]. 2% of 310 million tonnes = 6.2 million tonnes fuel = 19.5 million tonnes



(a) (b) (c)

Figure 5. *Various Images of 3D riblets. Figure 5a shows the optical microscope images of 3D printed riblets, in addition to a side on image of a 3D riblet (bottom). Figures 5b, 5c are SEM images of 3D riblets fabricated with the DCM process.*

4 Optical, Tactile and Wetting Properties



(a) (b)

(c)

Figure 6. *Optical properties observed from DCM fabricated surfaces in a high-gloss aerospace coating: diffractive properties (6a, 6b) and controllable matte properties seen in the MicroTau logo (6c).*

In the process of further developing the DCM technology and undertaking the above work for drag-reducing riblet microstructures, we also observed other functional properties we were able to produce. This includes different optical properties such as diffractive and matting effects that we could control by manipulating the microstructures imparted into the same high gloss aerospace coating as all previous samples were printed from (see Figure 6). This matting effect was replicated out of a glossy wood UV curable coating on a wood substrate (Figure 7). Further optical properties including light-guiding effects of microstructures have lead MicroTau to contract with Australian Defence Science & Technology Group (DST) to explore visual adaptive camouflage surfaces for Unmanned Air Vehicles (UAVs) [3].

DCM-produced microstructures have also demonstrated wetting and de-wetting effects whereby the direction of flow of water can be manipulated as well as imparting hydrophobic properties to a surface. Similarly microstructures that change how condensation sits on a surface have been observed, see Figures 8a and 8b below.

5 Properties Under Development

Two further functional properties are under development with project partners to demonstrate with the DCM capability.

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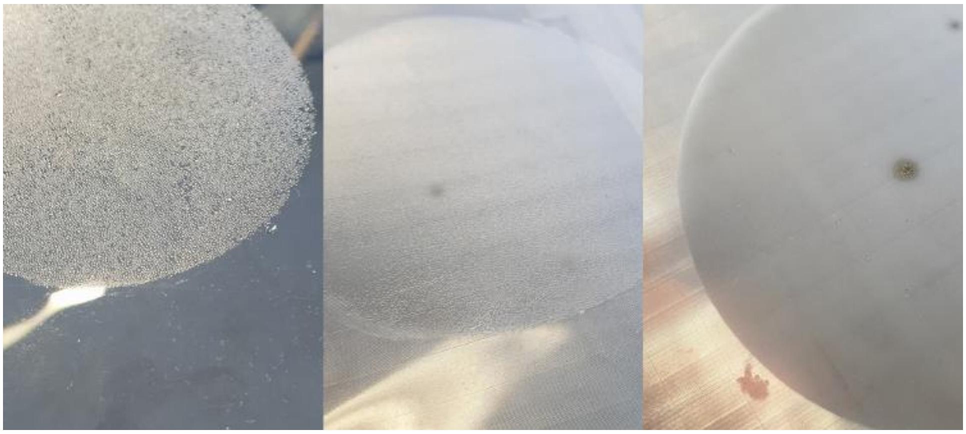
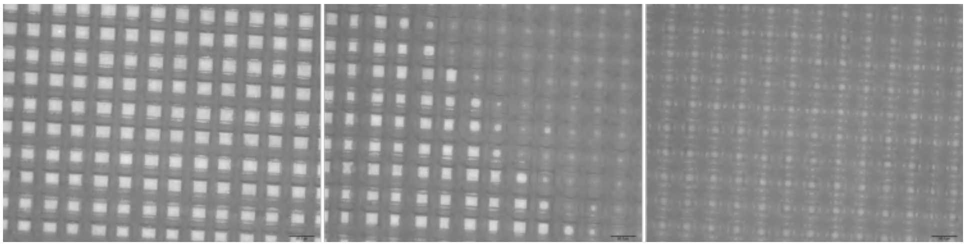
[3] https://www.youtube.com/watch?v=6RXFmDajwsk

Figure 7. *Matte properties imparted in a glossy wood UV curable coating with the DCM process.*



(a) *Condensation forming, from left-to-right, on an untreated surface; a crosshatch microstructured surface; and a finer crosshatch microstructured surface.*



(b) *Optical microscopy of the crosshatch microstructured surface , from left-to-right, when dry; the transition from dry-to-trapping condensation; and trapping condensation.*

Figure 8. *Crosshatch microstructures, and the retention of water on a surface.*

5.1 Marine Anti-fouling

The first project is with A/Prof Chiara Neto from the University of Sydney. Neto has published work in the area of anti-fouling microstructures and has expertise in relevant testing protocols for determining their potential to reduce marine fouling. Despite promising results from her research, a practical, scalable method of fabricating said antifouling microstructures for the marine application is thus far absent from real world implementation [9]. The MicroTau DCM technology represents an advanced manufacturing solution for this problem. This project is ongoing and uses the DCM process fabricate and test the anti-fouling performance of micropatterned surface coatings and test for their ability prevent the accumulation of microorganisms, plants, algae, or animals on immersed surfaces, such as ship hulls.

5.2 Anti-bacterial

The second project is with Professor Cynthia Whitchurch of the ithree institute at the University of Technology Sydney. Bacteria have a difficult time attaching to the microstructured surface, and biofilm growth is inhibited by the ridges that form the shape. Whitchurch's recent research has found microstructure designs that most inhibit the growth of bacterial biofilm [10]. The implementation of these microstructures for medical applications including urinary catheters to reduce risk of infections has been prevented by a lack of a practical manufacturing method. This project is ongoing and aims to fabricate these microstructured surfaces with the DCM process, to replicate Whitchurch's results and explore further designs for antibacterial performance.

6 DCM Advances Going Forward

The goal of our technology is to provide a solution for custom microstructure designs that can be applied to a large number of different substrates, depending on the end user's requirements. To this end, MicroTau is building a pilot manufacturing facility for custom microstructure development and production and has been awarded an Accelerating Commercialisation grant from the Australian Federal Government supporting this and the commercialisation of the DCM technology[4]. We will be investing in providing a rapid prototyping service for customers to demonstrate or customise functional microstructure surfaces and scale manufacturing solutions for end users.

Figure 9. *Example of 3D riblet film produced with the DCM film-printing process. MicroTau is building a pilot film printing capability to fulfil custom microstructure films orders.*

We will continue to explore how to integrate the DCM process into existing UV manufacturing processes and products. In principle this should be applicable wherever UV coatings are used and has been demonstrated on aluminium, primers, topcoats, plastic film, wood, paper and even flexible textiles such a lycra (see Figure 10).

For aircraft integration a first prototype of a portable DCM printer has been made and demonstrated riblet printing capability with a moving optical system. In 2020 we will be undertaking a project to integrate this capability with robotic arm system currently deployed with the US Air Force for laser

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[4] https://www.business.gov.au/News/Eight-businesses-share-$3-1-m-to-support-their-innovative-ideas

Figure 10. *Riblets fabricated on a textile substrate. Frames from a video demonstrating ability to be stretched and return to original form.*

paint removal. This project is to design a DCM end effector to integrate with the aircraft-capable robotic arm system to scale the process for direct aircraft application. In 2020 MicroTau will also be working with an aerospace coatings manufacturer to develop a military aerospace qualified UV curable coating that is compatible with the DCM technology. The goals are to fabricate riblets from this coating to undertake drag reduction and durability testing.

Further drag reduction applications will be undertaken in 2020 for marine applications, fabricating riblets out of antifouling UV curable materials with testing on boats and pipelines.

7 Conclusion

The DCM technology has demonstrated the ability to impart functional properties onto UV curable coatings through physical means of micro-patterning their surface. Demonstrated properties include 7% skin friction drag reduction, optical, tactile and wetting effects. Further properties are under development including marine anti-fouling and anti-bacterial properties.

This technology offers a unique capability to both rapidly prototype functional microstructures and provide solutions for their manufacturing at scale. MicroTau is building a pilot manufacturing capability to provide prototyping services to project partners to fabricate custom novel or optimised microstructure designs. Scaled solutions for aerospace and marine drag reduction applications will continue to be developed with our project partners.

8 Acknowledgements

This work is supported in part by the Operational Energy Capability Improvement Fund (OECIF) from the Office of the Assistant Secretary of Defense for Operational Energy Plans and Programs, ASD (OEPP). The MicroTau Pty Ltd author would like to acknowledge the Ohio Aerospace Institute, through which they were funded. The authors would also like to thank Dr. Renzo Fenati, Ms. Rebecca Hartstein, Mr. David O’Connor, Mr. John Whitelock, and Ms. Emily Wotherspoon for their assistance in preparing, fabricating and inspecting the riblet microstructures and general design and technical support.

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