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POLYMER RIBLET SURFACE COATINGS FOR GREEN AVIATION

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ABSTRACT

Riblet coating, or the so-call sharkskin with periodic micro-ridges aligned with the direction of air flow, has shown potential in reducing up to 10% drag under turbulent flow conditions. This may translate into multi-million tons of kerosene saving per year for the global fleet of long-haul aircraft. As such, riblet technologies have been intensively developed in the past decades; Lufhansa Technik has recently successfully demonstrate the reduction of fuel burn by riblet implementation on Boeing 747 and Boeing 777 cargo planes. Nevertheless, riblet technology is not yet mature; there remain critical challenges with, for example, the 2D and 3D riblet designs, material durability, manufacturing and on-aircraft application, and maintenance of the riblet coating.

Given the sensitivity of laminar flow to the surface microstructure, riblet coatings that are resistant to erosion damages caused by the high-speed impact of liquid droplet and solid particles are needed. National Research Council Canada (NRC) developed novel hydrophobic, erosion-resistant polyurethane coatings and thin films for passive drag reduction. In comparison with commercial erosion protective tapes, the NRC coating materials showed drastically improved erosion resistance against both sand particles and rain droplets, much enhanced hydrolytic stability, as well as high mechanical strength and resilience. These polyurethanes can be readily solution-sprayed or melt-cast on a micro-structured mold to replicate precisely a ribletdesign to the coating film. The experiment results of the riblet thin film showed no decrease in mechanical properties as compared to a smooth thin film of the same material. Adhesive transfer film can be easily applied to the resulting riblet film for its application on aircraft. This paper discusses the work at NRC to develop riblet technologies to enhance aerodynamic performance for aerospace applications.

1 INTRODUCTION

In the global effort of achieving net zero carbon emission by 2050, many aerospace companies have pledged to invest in green aviation. While great efforts are being made in the development of low-emission engines and fuel-efficient unconventional aerospace configuration, amongst other enabling technologies, near-term solutions such as riblets for drag reduction in wall-bounded flows can provide an effective measure to reduce fuel consumption in the meantime.[1-3] The key advantages of riblet technologies are the demonstrated fuel consumption reduction, increased capability (e.g., payload and range), cost savings, and fast deployment on legacy and new fleet.

The development of riblet coating materials viable for aerospace applications requires optimal design of the micro-riblet structures based on the flow characteristics of the aircraft for the maximum drag reduction, as well as cost effective manufacturing of high-quality, robust riblet materials that can be readily applied, inspected and maintained. Numerous studies have been conducted to address the above challenges and much success has been achieved.[4] However, there is still a lack of knowledge about how surface contaminations and riblet damages will impact the aircraft operations and there are few dedicated studies to develop highly durable riblet materials for practical applications.[5,6]

The objective of this study is to obtain novel coating materials that are highly durable under flight conditions against, for example, high-speed impact of rain droplets and dust particles and weathering, and at the same time readily processable to produce high quality riblet thin films or tapes through scalable processes.

2 EXPERIMENTALS

2.1 Materials

The following chemicals were acquired and used without further treatment: AndurElite® PT93AP, an aliphatic polyisocyanate based on 1,4-bis(isocyanatomethyl cyclohexane) (1,4-H6XDI), commercially available from Anderson Development Company (Adrian, Michigan); 1,4-butanediol (BD, 99%, Sigma-Aldrich); poly(oxatetramethylene) glycol with a molecular weight of about 2000 g/mol (PTMEG-2000, Sigma-Aldrich) and dibutyltin dilaurate (DBTDL, 95%, Sigma-Aldrich). 2-Hydroxyethyl disulfide (HEDS, technical grade, Sigma-Aldrich) was dried over molecular sieves (4 Å) prior to use. Organic solvents such as n-butyl acetate (BA, >99.5%) and 4-methyl-2-pentanone (MIBK, >98.5%) were purchased from Sigma-Aldrich and dried over molecular sieves (4 Å).

2.2 Instruments and test methods

Tensile properties of thin films were measured on Instron model 5565 tensile tester equipped with pneumatic grips according to standard ASTM D412. Dumbbell-shaped film coupons were die-cut using a DIN-53504-S3A type cutting die (ODC tooling & molds). All samples were conditioned at 23±2 °C and 50±5%RH for at least 24 hours before testing. Due to the fact that slippage at the grip areas occurred during testing, benchmarks of 10±1 mm distance (LO) in the middle of the dumbbell-shaped samples were drawn and followed during testing to obtain true elongation at break. The rate of grip separation was 500 mm/min. After rupture, the distance (LF) between the benchmarks was measured within ca. 1 min for the calculation of tensile set.

Solid particle erosion tests were performed according to ASTM Standard G76-04 using angular alumina particles of ca. 50 µm (AccuBrade 50, part No.: AP106, S.S. White Technologies) as the erodent. During testing, the alumina particles were fed into a compressed air carrier stream from a pressurized vibrator-controlled hopper, which was allowed to pass through a silicon carbide nozzle with an inner diameter of 1.14 mm and directed towards the test sample at a preset impingement angle of 30° or 90° with respect to the test sample surface. The impingement speed of the ejected alumina particles was 150 m/s, which was controlled through adjusting the pressure of compressed air. The particle flux was regulated at 3-5 g/min by changing the vibrating amplitude of the hopper. The stand-off distance was maintained constant at 50±1 mm. After each 3-4 min of testing, the test sample was removed from the erosion rig and measured for its weight using an analytical balance with an accuracy of ± 0.01 mg. At the same time the weight of the consumed erodent was measured. Then the sample was returned to the test rig and erosion testing was resumed.

Water droplet erosion (WDE) resistance of coated samples was evaluated according to ASTM Standard G73 using a testing rig that is equipped with a working chamber, a vacuum system, a compressed air driven turbine and a water droplet generating system. During testing, two test coupons having mass differences of less than 0.1 g were mounted on the opposite ends of a rotating disc, with one as the comparative control and the other as the test sample. The disc was rotated at a specific speed while water droplets were formed in the test chamber on a path of the test coupons. A 30-50 mbar vacuum is maintained during the test to avoid temperature rise caused by friction between the rotating disc and air. In this study, the disc was rotated at a rate of 7000 rpm, corresponding to a water droplet impingement velocity of 175 m/s. The impingement angle was 90°. The average size of water droplets produced using a 400 µm shower head was about 463 µm. The test coupon underwent about 42,000 individual water droplet impingements during each minute of testing.

2.3 Material and test sample preparation

Polyurethane thin films by solution casting. Stock solutions of PT93AP (70 wt%), BD (10 wt%), HEDS (10 wt%), PTMEG-2000 (50%), and DBTDL (0.2 wt%) were first prepared in a solvent mixture of MIBK/BA (3/1, v/v). A typical coating thin film is prepared as follows: To a mixture of stock solutions of 1.20 g of BD (10%), 2.00 g of HEDS (10 wt%), 4.00 g of PTMEG-2000 (50%), 0.82 g of DBTDL (0.2 wt%), and 2.32 g of MIBK/BA (3/1, v/v) solvent mixture, was added 6.06 g of PT93AP (70 wt%). The mixture was thoroughly mixed and degassed under ultrasonication to provide a clear viscous solution. For solid particle erosion test, about 1.5 g of the coating solution was deposited on a fiberglass (FR-4) plate of 5 cm x 5 cm x 0.6 cm, followed by drying at 60^{o}C for 30 min in a convection oven and then thermal curing at 100^{o}C overnight. For rain erosion test, about 0.1 g of the coating solution was dispensed on the surface of an epoxy primed aluminum alloy (AA2024) specimen of 8.2 mm x 23.2 mm x 3.0 mm, followed by drying at 60 ^{o}C and curing at 100^{o}C. For mechanical testing, free standing thin films were prepared by pouring about 14 g of the coating solution into an AA2024 cavity mold (12 cm x 12 cm x 6 mm, pretreated with a silicone-based release agent) followed by drying and curing processes as described above.

Preparation of riblet thin films. A generic solution casting procedure is as follows: a pre-machined polyvinylenedifluoride (PVDF) triangular riblet mold (15 cm x 15 cm) that has a peak height of 50 µm and an included angle of 90° was cleaned with acetone and blown-dried using a gentle stream of nitrogen to remove oil contamination and dust. The mold was placed on a leveled stage and the coating solution prepared above was doctor-blade coated with a wet film thickness of about 0.4 mm. After drying at 60^{o}C for 30 min and curing at 100^{o}C overnight, the coating film with the replicated riblet structures was peeled off.

3 RESULTS AND DISCUSSION

3.1 Material synthesis

To be used on an aircraft for drag reduction, the riblet skin material must show high resistance against erosion from high-speed rain droplets and dust particles, as well as UV irradiation, hydrolysis and aircraft fluids. It is known that aliphatic polyurethanes free of ester linkages are preferred polymer materials to offer light fastness and hydrolytic stability. However, for the rain and solid particle erosion resistance, there is no established structure-property relationship to guide new material development, except for the observation that a high resilience tends to lead to a high erosion resistance. In our study, a 1,4-H6XDI-based polyisocyanate precursor was used to produce aliphatic polyurethanes. It was expected that the relatively rigid and symmetric structure of 1,4-H6XDI would facilitate the formation of strong hydrogen bonds and therefore providing high mechanical strength. In the isocyanate-reactive component, a combination of small molecular diols (i.e., BD and HEDS) and a polymer diol (i.e., PTMEG-2000) was used to provide balanced soft and hard segments and therefore a high resilience of the resulting polyurethane. Table 1 summarizes the compositions of polyurethanes produced in this study. These polyurethanes can be classified into three series:

1) PU-1 to PU-4 are polyurethanes prepared from PT93AP, BD and varying amounts of PTMEG-2000. No HEDS was used in the synthesis.
2) PU-5 to PU-7 and PU-8 to PU-10 are polyurethanes prepared using constant amounts of PTMEG-2000, respectively, but having different HEDS/BD molar ratios; and
3) PU-11 to PU-15 are polyurethanes prepared with varying amounts of PTMEG-2000 but at a relatively constant HEDS/BD molar ratio.

Table 1. Preparation of polyurethanes.

I.D.	composition(wt% vs total solid)				BD/HEDS (wt/wt)	HS (wt%)	Tensile strength (MPa)	Elongation at Break (%)	Tensile set (%)
	polyisocyanate	BD	HDES	PTMEG-2000					
PU-1	92.4	7.6	0.0	0.0	–	0.3	33.2	625	75
PU-2	76.5	5.4	0.0	18.1	–	0.2	34.0	650	40
PU-3	65.3	3.9	0.0	30.8	–	0.2	40.6	750	30
PU-4	57.0	2.7	0.0	40.3	–	0.2	39.5	750	20
PU-5	76.1	4.5	0.6	18.0	7.4	0.2	40.3	700	30
PU-6	75.7	3.6	1.2	17.9	3.0	0.3	41.0	700	20
PU-7	75.3	2.7	1.8	17.8	1.5	0.3	40.5	700	10
PU-8	65.0	3.1	0.6	30.7	5.5	0.2	45.8	750	10
PU-9	64.7	2.6	1.0	30.5	2.6	0.2	42.8	700	10
PU-10	64.6	1.8	1.4	30.5	1.3	0.2	45.7	700	0
PU-11	90.2	3.6	2.4	0.0	1.5	0.3	36.6	650	20
PU-12	86.0	3.3	2.2	5.1	1.5	0.3	43.1	650	10
PU-13	82.0	3.1	2.1	9.7	1.5	0.3	37.6	675	25
PU-14	69.5	2.1	1.7	24.6	1.3	0.2	43.9	700	5
PU-15	56.5	1.3	1.1	40.0	1.2	0.2	35.1	650	10

**HS = hard segment content*

3.2 Mechanical properties

After curing, all the polyurethanes were obtained as tough and flexible thin film with a shore A hardness in the range of 70-90, depending on the compositions. As shown in Table 1, the tensile measurements found high ultimate strength in the range of 33-45 MPa and high elongation at break in the range of 625-700%. The tensile set, however, varied significantly from 0% to 75%, indicating different resilience of these polyurethanes. Some key observations include 1) for PU-1 to PU-4, where no HEDS was used, higher tensile sets were obtained. The presence of PTMEG-2000 can reduce the tensile set to a certain level but not less than 20%; 2) at constant PTMEG-2000 contents (PU-5 to PU-7 and PU-8 to PU-10), the tensile set decreases with the BD/HEDS weight ratio. The lowest tensile set was obtained at a BD/HEDS weight ratio of < 3.0. 3) at a constant BD/HEDS weight ratio of about 1.5 (PU-11 to PU-15), increasing the PTMEG-2000 content appears beneficial in achieving a low tensile set.

3.3 Erosion resistance

The solid particle erosion resistance of these polyurethanes was measured on the coated FR-4 specimens. The coating thicknesses were about 0.3 mm. Figure 1 (left) compares the erosion rates of the polyurethanes with two commercial erosion resistant products (i.e., C1 and C2). As it shows that all the polyurethane coatings produced in this study showed drastically lower erosion rates than commercial references at 30° impingement angle. Among the polyurethanes, those that exhibited higher tensile sets (e.g., PU-1, PU-2 and PU-11) showed higher erosion rates, confirming the previous observation that a high resilience correlates to a high erosion resistance. At 90° impingement angle, all materials showed low erosion rates of 9-30 µg/g of sand. Figure 1 (right) compares the water droplet erosion resistance of PU-10 with the commercial references. Both commercial products failed at 2.5 min of testing, while PU-10 showed only minor material removal at 10 min of testing.

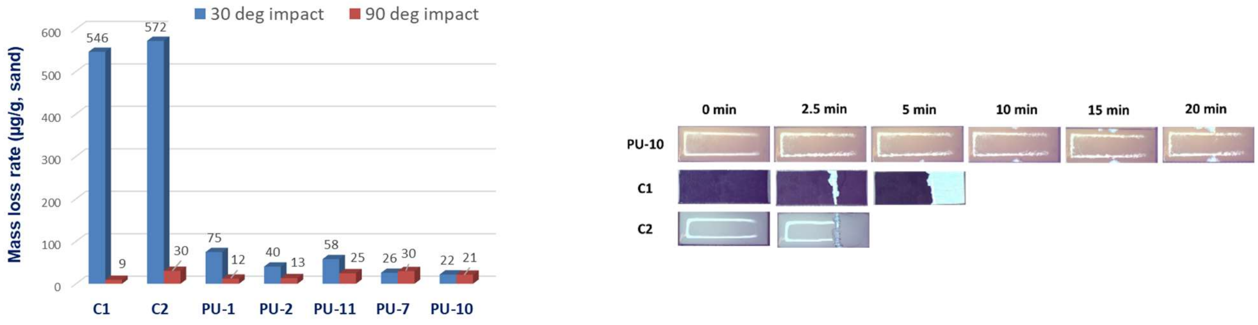

Figure 1. Comparison of erosion resistance of polyurethanes of this study with commercial erosion resistant materials C1 and C2: solid particle erosion (left) and water droplet erosion (right)

3.4 Other resistance properties

The hydrolytic stability of polyurethanes PU-7 and PU-10 were evaluated by conditioning their dogbone samples at 85°C and 100% relative humidity (RH), followed tensile testing. As displayed in Figure 2, PU-7 and PU-10 showed minimal degradation of mechanical strength after >300 hrs of exposure, whereas the commercial references showed a significant drop in strength after only 24 hrs of conditioning. The fluids immersion tests (immersion of dogbone samples in lubricating oil Royco 500, jet A1 fuel and hydraulic oil Mobil DTE-25 for 4 hrs and immersion in deicing fluid ethylene glycol for 18 hrs) also showed high resistance to various aircraft fluids, as evidenced by the minimum change in the stress-strain curves of the immersed test samples.

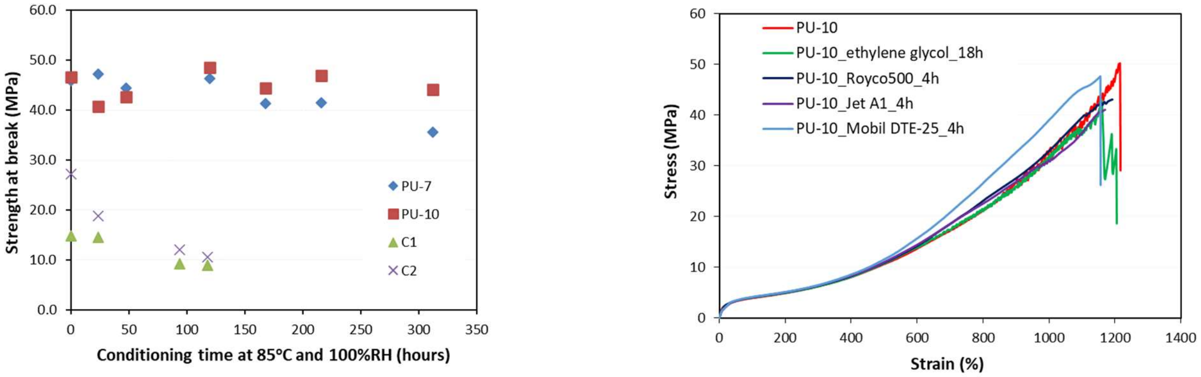

Figure 2. Tensile strength of polyurethanes (PU-7 and PU-10) that were subjected to hydrolytic stability test (left) and fluids immersion test (right)

3.5 Fabrication and properties of riblet thin films

Riblet thin films of the polyurethanes can be prepared by melt casting, solution casting or spraying onto a riblet mold. A roll-to-roll manufacturing of the riblet film through sheet casting is being developed. Solution casting, however, can be easily performed to produce riblet films batch to batch. Figure 3 shows the PU-10 film prepared from a PVDF riblet mold. Very well defined micro-riblet structures were replicated from the mold to the polyurethane thin film. Tensile tests of the riblet film along and normal to the riblet directions showed the same stress-strain behavior (Figure 3, right). Although lower ultimate strength and elongation at break were found normal to the riblets, the riblet film was highly stretchable and elastic in both directions.

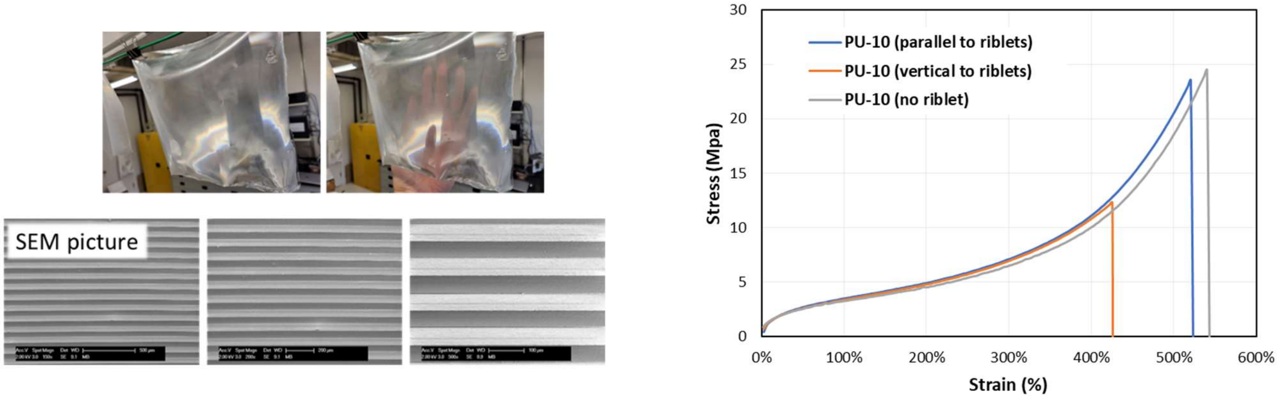

Figure 3 Pictures of PU-10 riblet film prepared by solution casting on a PVDF mold (left) and tensile stress-strain curves of PU-10 tested along or normal to the riblet directions (right)

4 CONCLUSIONS

New elastomeric polyurethanes were developed that demonstrate superior erosion resistance against high-speed impact of solid particles and water droplet, along with excellent stability against hydrolysis and aircraft fluids immersion. These polyurethanes can be processed easily into high-quality riblet thin films by solution or melt casting, showing good potential for aircraft drag reduction applications.

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