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SURFACE EMBOSSING TECHNIQUE FOR CONDENSATE MANAGEMENT IN AIR-COOLING HEAT EXCHANGERS

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ABSTRACT

Recent advances allow us to inexpensively impart micro-scale grooved surface features on heat exchanger construction material (surface embossing), which we exploit to reduce condensate retention. We report a study of wetting behavior and drainage performance on a series of embossed surfaces with different groove dimensions. Static contact angles, critical sliding angles, droplet aspect ratios, *etc.* are reported with detailed surface topographical information. Our results show that unless the spacing between grooves is very large (>100μm), the parallel-groove surface feature normally increases the apparent contact angle of a droplet placed onto the surface. A consistent reduction of critical sliding angle was observed on surfaces after embossing, and droplets exhibit an elongation behavior. These may be due to contact line discontinuities and contact-line pinning induced by groove structure on the surface. Smaller channel spacing, larger depth, and steeper sidewalls are observed to be favorable for drainage enhancement. Future work is discussed after a summary of the results.

INTRODUCTION

In a broad range of HVAC&R applications, water retention on the heat-exchanger surface is problematic. It can adversely affect the air-side heat transfer coefficient, increase core pressure drop, and provide a site for biological activity. Therefore, a good drainage performance of the heat exchanger is desired. People have been managing the wettability of aluminum fin surfaces by using coatings or plasma treatment. However, there is few research reported in the literature that investigated the feasibility of condensate management on heat exchangers by creating micro-scale textures on the fin surfaces. According to Wenzel [1] and Cassie [2], depending on the wetting conditions, micro-scale roughness on a surface can serve to make the surface more hydrophobic or more hydrophilic. Mechanical manipulation of the fin surface roughness might offer promise for condensate management, and it might be superior to using chemical coatings, especially when issues regarding robustness and longevity are concerned.

Not many papers have been published in the literature on wettability manipulation of aluminum substrates, and most of them have involved wet chemistry techniques or coatings [3-6]. Hong and Webb [7] tried to make fin surface more hydrophilic by imparting unidirectional micro roughness to bare aluminum fin stock through different levels of brushing. However, they did not achieve good wettability as expected and they thought it is possibly because the area increase was not insufficient, or that the required groove shape was not satisfied. On the other hand, another paper by Sommers and Jacobi [8] reports the exclusive use of surface topography to hydrophobize an aluminum surface. In this work, photolithographic techniques were used to create parallel grooves (30μm wide and tens of

NOMENCLATURE

r	[-]	Surface ratio in Wenzel's theory; Eqn. (1)
V_{drop}	[μL]	Droplet volume
α	[°]	Embossed grooves sidewall angle
α_{crit}	[°]	Critical sliding angle
β	[-]	Droplet aspect ratio $\beta=L/w$; see Figure 5(b)
Φ	[-]	Surface ratio in Cassie's theory; Eqn. (2)
θ	[°]	Contact angle on a horizontal surface
θ_C	[°]	Apparent contact angle; Cassie's wetting
θ_W	[°]	Apparent contact angle; Wenzel's wetting

microns in depth) on aluminum substrates. They found that a droplet placed on the etched aluminum surface exhibited an increased apparent contact angle. More than a 50% reduction in the volume needed for the onset of droplet sliding was observed. Although the etching technique is not feasible in general air-cooling applications, the work by Sommers and Jacobi strongly indicates the promise for drainage improvement by solely controlling surface roughness of the aluminum fins.

Micro-grooved aluminum fin stocks can be made in mass production by surface embossing techniques. Embossing is conducted by pressing a rubber engraved plate (or roll) with desired roughness design (shown in Figure 1) against the rolling fins, generating topographically modified surfaces. The scale of the design features is normally from tens to hundreds of microns and the shape of the grooves are usually triangular or trapezoidal. Depth of the embossed grooves on fin surfaces can be controlled by adjusting the magnitude of embossing pressure. However, the maximum depth discussed in this study is around 15μm, because exorbitant pressure may lead to deformation of the aluminum foil. Surface embossing of the aluminum fin stock is simple and commercially feasible for manufacture, and these micro-scale grooves are expected to provide directional wettability which can help water drain from the heat-exchanger surface. In this study, we report a series of embossed aluminum surfaces with different groove dimensions, and exploit how these topological features affect wetting behavior and drainage performance of the fin surfaces.

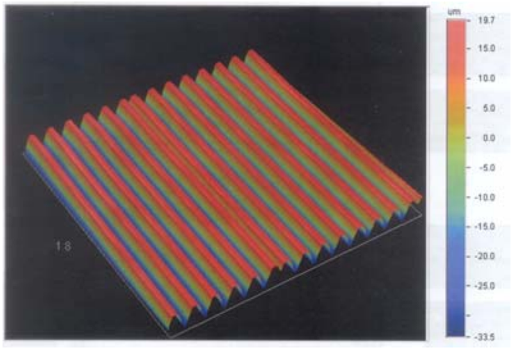


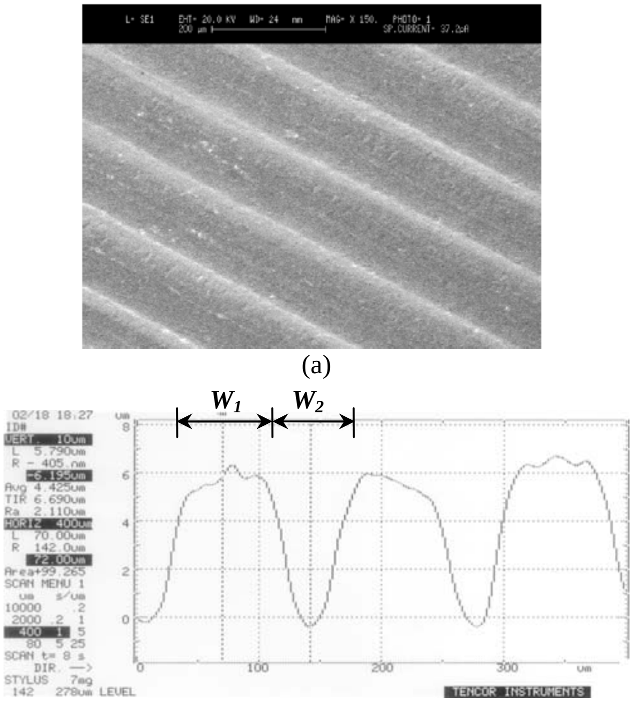
Figure 1 Embossing plate

EXPERIMENTAL METHODS

Prior to the experiments, surface samples were cleaned for 10 minutes with acetone in an ultrasonic bath, followed by a thorough rinse with distilled water in ultrasonic bath for 10 minutes. Information about wettability was obtained by photographing droplets placed onto these surfaces using a KAPPA DX 10-1394a high-resolution CCD camera (magnification up to 25×). Standard image analysis software was used to process the images and determine the contact angles. The critical inclination angle for droplet to start sliding on these surfaces was measured by capturing images of droplets at the point of incipient motion on an inclined surface. A tilt-table assembly with an extendable lever arm that permitted continuous inclination of the surface from horizontal was used in this measurement. A droplet was first placed on the test surface in the horizontal position using a micro-syringe, and the plate was then slowly tilted (in this setup the micro-grooves on the surface were aligned parallel to gravity) until imminent droplet motion was detected. Multiple independent measurements were recorded for each droplet volume which permitted the contact angle and critical sliding angle to be checked for consistency. The maximum uncertainty in the measured contact angle was approximately 4° and the uncertainty in the critical inclination angle was about 3° for droplets with small volume ($V_{drop} \le 40\mu L$), and only 1° for larger ones.

RESULTS AND DISCUSSION

Typical surface morphology of these embossed aluminum surfaces is revealed by a SEM picture shown in Figure 2(a). Quantitative measurements of the surface geometry were obtained with a Tencor Alpha-Step 200 Profilometer (image shown in Figure 2(b)). The cross section of aluminum foil after embossing is trapezoidal, but the shape is not as precisely controlled as created by an etching process in a cleanroom lab. Detailed information for channel spacing, depth, as well as the



(a)

(b)

Figure 2 Typical surface configuration of embossed aluminum surfaces: SEM (a) and Profilometer (b, note different scales are used in x- and y-directions) images.

Table 1 Topography and wettability measurements

Surface	Embossing plate	Spacing (w_1/w_2)[1] (μm)	Depth (μm)	Sidewall angle α (°)	Cassie Φ	Wenzel r	Contact angle[2] θ_{exp} (°)	Asp. Ratio[3] $\beta=L/w$
1	Orig. foil	-	-	-	-	-	60.1	1.00
2	Plate 1	41/70	3	7	0.37	1.00	68.6	1.07
3	Plate 1	46/62	4	11	0.43	1.01	69.4	1.14
4	Plate 2	67/68	6	12	0.50	1.01	72.7	1.23
5	Plate 2	60/77	8	15	0.44	1.02	76.8	1.33
6	Plate 3	60/99	10	14	0.38	1.02	81.2	1.15
7	Plate 3	67/86	9	17	0.44	1.02	83.6	1.24
8	Plate 4	128/192	14	12	0.40	1.01	59.2	1.24

[1] See Figure 2(b); [2] Always viewed parallel to micro-grooves; [3] See Figure 5.

channel sidewall angle, is provided in Table 1. These embossed surfaces normally have channel spacing from 50 ~ 200μm, and depth on the order of 10μm, depending on the embossing plate design and exerted pressure. It can be seen from Table 1 that the sidewall angles of these surfaces are very small (<20°), which indicates that these micro-grooves are very shallow, with their depth much smaller than the channel spacing.

Wenzel [1] and Cassie's [2] theories are widely accepted to explain the effects of surface roughness on its wettability. For fully wetted surfaces, the Wenzel model is adopted:

$$\cos\theta_W = r\cos\theta \tag{1}$$

For fully de-wetted surfaces (composite), the Cassie model is appropriate:

$$\cos\theta_C = \Phi(\cos\theta + 1) - 1 \tag{2}$$

Eqn. (1) describes the apparent contact angle θ_W when the water droplet completely fills the surface asperities. This particular wetting regime generally happens on an originally hydrophilic surface, or may result from condensing water vapor, dropping a droplet onto the surface from a certain height, *etc*. This wetting behavior normally results in a decrease in the apparent contact angle of the droplet, with r in Eqn. (1) to be the area ratio of the actual wetting area to the planar area (actual-to-projected surface area ratio, $r > 1$). Described in Eqn. (2) is the apparent contact angle θ_C when the droplet is suspended over the asperities, leaving air trapped beneath it. This form of wetting may occur on originally hydrophobic surfaces, and/or when the droplet is placed carefully onto a surface having sufficiently small/deep surface features. This wetting behavior normally results in an increase in the hydrophobicity of the surface, and Φ in Eqn. (2) is also an area fraction of the actual wetting area and the planar area ($\Phi < 1$).

Results for contact angle measurements of placed water droplets on horizontal embossed surfaces are listed in Table 1. It can be seen that micro-groove features on aluminum fin surfaces induce an increase in apparent contact angle for surfaces embossed by Plate 1, 2, 3, but a slightly decrease for Plate 4. Because the micro-grooves are very shallow, their effects on contact angles are not as prominent as for etched surfaces with steep walls. Surface ratios (r and Φ) for Wenzel and Cassie's models are calculated using geometrical details provided by the Profilometer measurements. Apparent contact angle predictions from Eqn. (1) and (2) (the θ value measured on "Surface 1" was used as the contact angle on a plain surface, θ~60.1°) are compared to the experimental measurements in Figure 3. Because the channels are all shallow, the values of r in Eqn. (1) are very close to 1. Therefore, Wenzel's prediction in Figure 3 (r ~ 1.02) is very close to the contact angle observed on original aluminum surfaces.

As shown in Figure 3, measured contact angles on these embossed aluminum surfaces are mostly between the values predicted from the Wenzel and Cassie models, and nearer to Wenzel's wetting regime. Because aluminum surface is intrinsically hydrophilic, and surface features have large spacing and small depth, it is easy for water to enter the grooves and wet the channel bottom. Cassie's "composite surface" wetting is very difficult to be achieved on these surfaces.

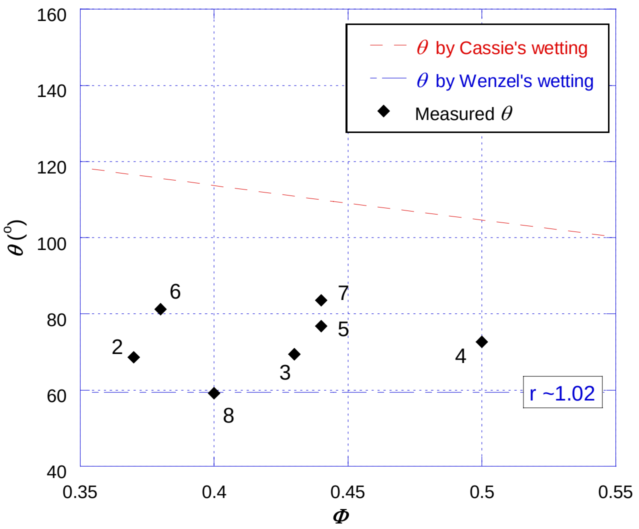


Figure 3 Contact angles under Cassie's and Wenzel's wetting conditions *vs.* experimental data

The fin surface embossed with Plate 4 exhibits contact angles very close to the values on an original aluminum foil.

This is because its roughness length scale is too large (>0.1mm) to cause any "hydrophobizing" effect in apparent contact angles. The large channel spacing ensures water to enter the channels and acquire Wenzel's wetting mode. Apparent contact angles on surfaces embossed with plate 1, 2, 3 increase with the depth of the grooves, as they have similar spacing distances. This is probably because deeper grooves reduce the chance for water to completely wet the surface asperities.

Sometimes, larger contact angles of droplets on a surface do not ensure that water is easier to be shed from the surface. The critical sliding angle (or critical inclination angle), is a useful criterion for evaluating the water drainage performance of surfaces. It is the critical angle of an inclined surface on which a water droplet of specified mass/volume will start sliding. Generally, it is more convenient and straightforward to evaluate the drainage performance of two different surfaces by comparing their critical sliding angles than analyzing two groups of advancing and receding angle values. For both of the original aluminum foil and some surface samples after embossing with different plate designs, critical sliding angle data were collected and presented in Figure 4. For these data, the droplet volume of the placed droplets was determined from the micro-syringe.

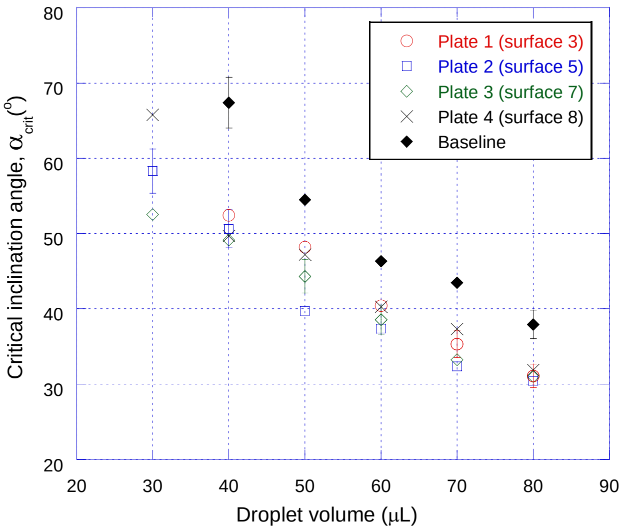
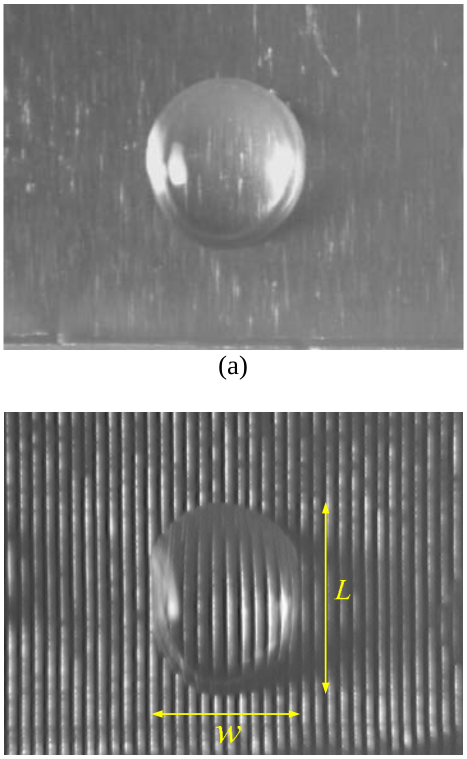


Figure 4 A reduction in the critical inclination angle was observed on embossed aluminum surfaces

As shown in Figure 4, a consistent reduction of critical sliding angle was observed on the embossed surfaces, which indicates that the parallel-grooved features on aluminum surfaces could assist in water removal. The volume reduction ranged from about 10% to about 30% - it is significant. This reduced droplet size is attributed to reduced retentive forces, which is probably due to the base contour shape of the droplets. As we will discuss later, the base contour shape of a droplet on an embossed surface is parallel sided (see Figure 5(b)). As a result, on the two sides of the droplet surface tension forces are orthogonal to the direction of gravity and do not contribute to the overall retention of the droplet. Moreover, the micro-grooved features on the surface also introduce certain degree of contact line discontinuities at both the advancing and receding fronts, which also serve to reduce the surface tension force of the droplet, helping to reduce its retention.

The parallel sided base contour shape of water droplets is caused by the pinning of contact line due to groove structure. The embossed micro-grooves introduce a periodic step-wise motion of the contact line as it moves perpendicular to the grooves. This sometimes causes the contact line to be pinned at the sidewall of a groove. Because droplet spreading is continuous in one direction but step-wise in the other it leads to a preferential spreading parallel to the grooves. This makes the droplet shape elongated in the direction parallel to the micro-grooves (Figure 5(b)). Droplet elongation behavior was observed on all grooved surface samples, and measurements of droplet aspect ratio ($\beta = L/w$) for 10μL volume droplets on vertical surfaces are listed in Table 1. It can be seen that surfaces exhibiting larger aspect ratios for droplets normally have larger channel sidewall angles, which indicates a larger sidewall angle will assist the contact line pinning. This is probably because it is easier for a steeper channel wall to hold the motion of a contact line. However, because our specimens



(a)

(b)

Figure 5 Droplet shapes on original aluminum foil (a) and embossed surface (b, surface 8), V_{drop}~ 10μL.

have small sidewall angles it is sometimes observed that pinning of the contact line fails, and usually only fails on one side (see Figure 6).

It has been well accepted that a surface with very small contact angle can achieve good drainage because of its way of shedding water as a continuous film. However, for aluminum surfaces studied in this paper, condensate is retained as droplets. Smaller critical sliding angles observed after embossing proved that this technique can improve drainage (even though static contact angles become larger) because the droplet sizes retained on fin surface are reduced. For dropwise retention, it is commonly held that Cassie's "composite wetting" with air trapped underneath the surface structures is preferred for better water drainage performance. Therefore, as a guideline for the surface feature design of an embossing plate, it is recommended that within the capabilities of current technology, smaller and deeper surface features are preferred. This will help reduce the chance for water droplets to completely wet the surface structures and increase contact line discontinuities. The groove sidewall angle should also be made as large as possible, because it can help contact line pinning effects. Therefore, it is better to make the channel cross-section more rectangular, instead of trapezoidal or triangular.

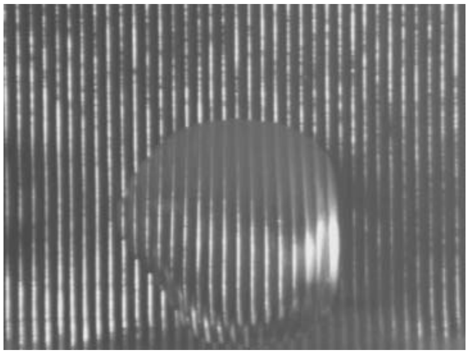


Figure 6 Contact line pinning failure

SUMMARY

In this study, a surface embossing technique that can inexpensively impart micro-grooved topographical features on aluminum fin stock to enhance water drainage is introduced. Wetting behavior and drainage performance on a series of micro-embossed surfaces with different groove dimensions is reported. It was found that the parallel groove surface features serve to increase the apparent contact angle of water droplets placed onto the surface, unless the groove spacing is very large (>100μm). A consistent reduction of critical sliding angle was observed on these embossed surfaces, and droplets exhibit an elongation behavior. These are possibly due to the contact line discontinuities and contact line pinning induced by groove structure on the surface. These preliminary results show the promise of water drainage enhancement by economically changing fin surface morphology during mass production. Smaller channel spacing, larger depth, and steeper channel sidewalls were observed to be favorable for drainage enhancement, and recommended as guidelines for surface feature design of embossing plate.

Future work will include the study of droplet condensation on embossed surface samples, because the condensation process and evolution of droplets can influence droplet geometry. We are currently constructing two heat exchangers with the direction of the same types of grooves along and transverse to the rolling direction, to study their performance in a wind tunnel as compared to an unmodified surface.

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