USE OF TEXTURED SURFACES FOR CONDENSATION OF WATER VAPOUR AND MIST

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Producing purified water from air moisture is feasible even in arid areas where humidity is intermittent. This method relies on a condenser, usually cooler than the surroundings, where water condenses. Many studies use materials with diverse hydrophobicity, making it hard to pinpoint surface effects on condensation. Thus, comparing hydrophobic and hydrophilic surfaces with identical textures is crucial. The aim of this work is to determine the effect of gyrophobic metal surfaces on the processes of water collection from steam. Experiments in this work were conducted in a close chamber in the environment of water fog produced by the fog machine at the room temperature. It was shown that hydrophilic surfaces enhance water vapor condensation efficiency by up to 38% compared to hydrophobic ones. In this work, the femtosecond laser treatment was used to produce channel-shaped textures with a truncated trapezoidal cross-section, measuring 15 µm at the upper base, 45 µm at the lower base, and 22 µm in height. These textures were further extended by the development of aluminum oxide crystal inlays, ranging from 30-60 nm, due to metal oxidation from the laser's high-temperature interaction. Extended exposure to these textures in room environment naturally increases their water repellency. Contact angles can reach 148°, nearing the 154° efficiency achieved with stearic acid treatment. However, heating to 380 °C eliminates the hydrophobic layers, resulting in complete hydrophilisation. Textured hydrophilic surfaces prove most effective for condensate collection, outperforming hydrophobic surfaces by up to 28%. Additionally, microtexture orientation matters: a vertical orientation boosts condensate collection by 34% compared to horizontal orientation. The results may be useful in the development of water harvesting equipment for naturally dry regions, or place where extensive water purification is required.

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1. Introduction

Textured surfaces are increasingly being used to control wetting processes or the contact between a solid and a liquid. The history of the development of such materials is based on the features of surfaces that can be found in nature. For example, superhydrophobicity is a characteristic property of lotus leaves (Li, 2024), the body and limbs of some insect species (Wang, 2024), etc. The increased ability to self-clean is characteristic of the inner surface of the flytrap flower, which provides ultra-low rolling angles. This effect has been studied and used to create a number of SLIPS surfaces (Ma, 2020 and Villegas, 2019).

In addition to repelling liquids, texture also provides the opposite effect – complete adhesion. For example, superhydrophilic surfaces can be used to avoid fogging of glass, as water vapour does not form a lens of light-scattering droplets during condensation, but a continuous transparent water film. Developed affinity surfaces can also form a sufficiently strong mechanical contact, which allows geckos with a small body weight to literally "run on the walls" and has become the basis for the research and development of similar materials (Russell, 2019).

The decisive factors that ensure either repulsion or contact of such surfaces with liquid or other surfaces are their affinity.

A well-known way to produce condensed water is to use air moisture. This method works even for desert regions of the planet where the required air humidity is achieved only at certain times of the day. The essence of the method is the presence of a certain surface - a condenser, often with a temperature below the ambient temperature, on which a captured layer of water is formed. In some studies, purely hydrophilic or hydrophobic surfaces or combinations of these are used as condenser materials (LaPotin, 2019). In most studies, the materials being compared are heterogeneous and it is not possible to clearly establish the effect of the surface character on condensation processes. Therefore, in order to establish the effect of surface polarity on condensation processes, it is an urgent task to conduct such a study to compare condensation volumes using texturally identical surfaces with hydrophobic and hydrophilic properties.

The aim of this work is to determine the effect of gyrophobic metal surfaces on the processes of water collection from steam.

The tasks corresponding to the goal are to apply surface texture to samples by a method that allows obtaining highly regular repeatable patterns; to perform hydrophilic and hydrophobic treatment of identical surfaces; to determine the effect of surface treatment and orientation of anisotropic textures on water collection performance.

2. Materials and methods

In this work, we used femtosecond laser-textured aluminium 7500 surfaces of 12.6x12.6 cm in size and 1 mm thick. The textures on their surfaces were uniaxially oriented profiles, which in cross-section had the shape of a trapezoid with the geometric parameters shown in Fig. 1.

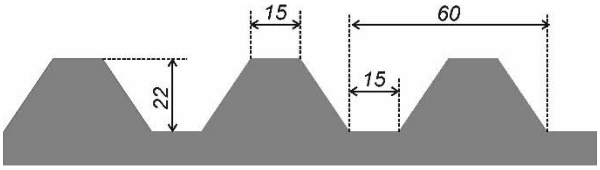

***Fig 1**. Anisotropic texture cross-section, sizes are noted in µm.*

It is known that after laser ablation, the surface textures on metal substrates are initially hydrophilic, but over time they become hydrophobic due to the gradual adsorption of organic contaminants from the air, which leads to increased water repellency. This effect is reversible, as the organic layer can be removed both by treatment at high temperatures (up to 400 °C) and by UV irradiation, as shown in (Myronyuk, 2023).

Along with spontaneous hydrophobisation, stearic acid was used as a surface modifier in this work. Samples of textured aluminium were placed in a muffle furnace at 380°C for 30 min, after which they were gradually cooled to room temperature. They were immersed in 100 ml of a 5 wt. % solution of stearic acid in isopropanol, removed from the solution and the residue was drained from the surface. After that, the samples were placed in an oven and dried at 120 °C, then washed with isopropanol again and dried again. These sampleas are referred as *t-St.*

To obtain samples that spontaneously hydrophobisized (hereinfurther noted as *SH*), the substrates were kept in a laboratory atmosphere for 2 months after texturing, which led to an increase in their hydrophobicity - reaching wetting angles above 150°. After the condensation tests, the samples were dried and placed in a 380 °C oven for 30 minutes, after which they were gradually cooled to room temperature. Such samples (hereinafter referred to as hydrophilic samples) exhibited high hydrophilicity and, accordingly, were completely wetted with water, without the possibility of contact angle determination. Such sampler are further noted as *Anneal*.

The determination of the condensation capacity of surfaces was carried out in a self-designed installation, which was a closed chamber with a volume of 18 litres, in which a sample was suspended, with a condensate receiver installed below it. The source of water mist was an ultrasonic mist generator Y09-010 (Sugold, China), which was used to maintain 100% humidity in the volume. Steam generation and condensation was carried out for 10-15 minutes, the time was measured to the nearest 1 second. The condensate was collected after running off the condensation plate into the collector vessel. Its weight was determined by the gravimetric method on an Axis 110S balance with an accuracy of 0.35 g per minute.

The geometry of the textured samples was determined by scanning electron microscopy using a MIRA3 TESCAN microscope in the secondary electron analysis mode. Since metal substrates were studied, no additional sputtering of the metal conductor layer was required.

Water contact angles were determined using the sessile drop thechnique with optical microscope Konus Accademy and goniometric set. Photos of the setting water droplet on the substrate were made in ScopePhoto application and contact angle value measured directly by the application tool.

3. Results and discussion

The femtosecond laser treatment of the aluminium surface produces a highly regular texture pattern in the form of grooves with a period of 60 µm. As can be seen from Fig. 2, the protrusions of the structure are encrusted with crystal-like formations, which may be the result of oxidation of a part of the material that was removed from the surface during processing. The bottom of the structure have a clearly distinguishable trace of the laser beam with periodically located pinholes corresponding to the places of maximum energy concentration. It can be said that the texture obtained at the previous stages of LIPSS, due to a significant tendency to form aluminium oxide crystals as a result of oxidation of fresh portions of metal in contact with air, remains indistinguishable.

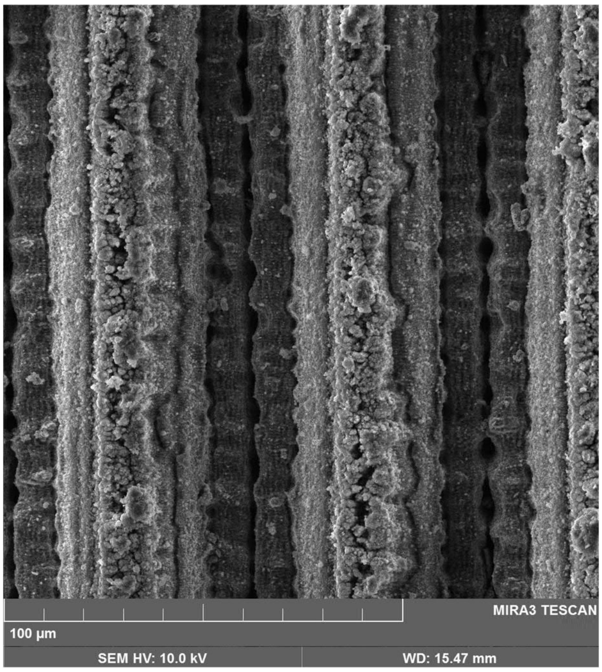

***Fig 2**. Surface texture of sample after laser ablation*

The resulting aluminium surfaces have a combination of micro- and nanoscale texture levels, which gives them an increased ability to repel water after hydrophobisation, as shown in (Barthwal, 2024), or, conversely, increased wettability with water in the case of fresh surfaces.

The type of hydrophobic agent determines the final values of the wetting angle, but for most functional modifiers, sufficiently high wetting angles are achievable, which do not increase significantly when switching, for example, from paraffin waxes to fluorinated paraffin waxes, which can be explained by the proximity of the contact angle of these materials and can be predicted using the classical Cassi equation. This is confirmed by the values of the contact angles of the samples treated with stearic acid, after spontaneous hydrophobisation and after annealing in a muffle furnace (Table 1).

Table 1. *Water wettability of surfaces*

Substrate treatment	Water contact angle of the textured surface, °	Contact angle of the respective flat surface, °
t-St	154 ± 3	70 ± 3
SH	148 ± 3	48 ± 3
Anneal	10 ± 3	25± 3

On flat surfaces that have been treated with stearic acid or kept in a laboratory atmosphere without treatment, the state of hydrophobicity is not achieved, as their wetting angle is below 90°. However, the textured ones achieved a state of superhydrophobicity, for example, when treated with stearic acid. This can be explained, in addition to the increased specific surface value, by the much higher orientation of the hydrophobic agent molecules on substrates with nanoroughness.

The ability of the samples to act as condensation surfaces was characterised by the amount of liquid collected in the receiver at the same performance of the mist generator per unit time (Table 2). The values shown in the table represent the condensation capacity excluding the capacity of the sample mounting system and the receiver itself, which is 10,04 g/min.

Table 2. *Water vapour condensation capacity (g/min)*

Texture	Treartment	Condensation, g/min
vertical	*t-St*	6.4
vertical	*SH*	6.5
vertical	*Anneal*	8.2
horizontal	*t-St*	3.9
horizontal	*SH*	4.1
horizontal	*Anneal*	5.4
none	*t-St*	3.2
none	*SH*	3.6
none	*Anneal*	3.9

All the samples studied show a pattern of increasing condensate flow with increasing surface hydrophilicity, which coincides with the results of (Pinheiro, 2019). Thus, the hydrophilic surface obtained after firing increases the efficiency of water collection by 28 % when the structure is vertically oriented and by 38 % when it is horizontally oriented. The stearic acid-treated and self-hydrophobised surfaces, which are relatively close in terms of contact angles, exhibit identical condensation performance within the measurement error.

Another significant factor is the presence of texture on the sample surface, which increases its activity compared to a flat surface. For anisotropic textures, such as the one used in this study, the orientation of the channels is an important factor: the vertical orientation increases liquid removal by 64 % compared to the horizontal orientation.

During the experiment, it was observed that at the beginning of condensate collection, surfaces with high hydrophobicity are wetted segmentally, and only after 10-15 minutes of exposure to the fog environment, a visually uniform wetting of the sample with water is achieved, which corresponds to the transition from the initial Cassie state to the stable Wenzel state.

The electric conductivity of the condensate, obtained in the experiment is 180 µS/cm, that is close to the values of the rain and dew water. The condensation plates are, therefore, the perspective and low energy consuming way for the development of water deficiency problem solutions.

4. Conclusions

It has been shown that hydrophilisation of surfaces for water vapour condensation increases the water collection efficiency up to 38 % of the performance of hydrophobic surfaces.

The texture obtained during the femtosecond laser treatment is in the form of channels, the cross-section of which has the shape of a truncated trapezoid with an upper base of 15 µm, a lower base of 45 µm and a height of 22 µm. It is shown that on the surface of this microtexture, an artefact structure is formed such as an inlay of aluminium oxide crystals with primary dimensions of 30-60 µm, which are formed as a result of metal oxidation during interaction with a high-temperature laser beam.

It has been demonstrated that after prolonged exposure of the textured surfaces, their hydrophobisation to sufficiently high levels of water repellency occurs spontaneously. The wetting angles reach 148°, which is close to the efficiency of chemical post-treatment with stearic acid - 154°, respectively. When fired at 380 °C, the hydrophobic layers of modifiers on the surfaces are destroyed, which leads to complete hydrophilisation of the textures.

It was shown that textured hydrophilised surfaces are the most effective for condensate collection. Compared to them, hydrophobisation reduces the process efficiency by up to 28%. The orientation of the microtexture is also an important factor. For the sample studied in this work, vertical orientation compared to horizontal orientation allowed to increase the condensate collection performance by 34 %.

In general, it has been shown that texturing and hydrophilisation of condensing surfaces is a promising way to increase the productivity of liquid water extraction from steam, which can be the basis for improving existing solutions and those that are being designed.

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ВИКОРИСТАННЯ ТЕКСТУРОВАНИХ ПОВЕРХОНЬ ДЛЯ КОНДЕНСАЦІЇ ВОДЯНОЇ ПАРИ ТА ТУМАНУ

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Виробництво очищеної води з вологи повітря можливе навіть у посушливих районах, де вологість нестійка. Цей метод ґрунтується на використанні конденсатора, зазвичай більш холодного, ніж навколишнє середовище, в якому конденсується вода. У багатьох дослідженнях використовуються різнорідні матеріали, що ускладнює визначення впливу поверхні на конденсацію. В той час як, порівняння гідрофобних і гідрофільних поверхонь з однаковою текстурою є надзвичайно важливим. Метою цієї роботи є визначення впливу гідрофобно-гідрофільних властивостей металевих поверхонь на процеси конденсації води з пари. Експерименти в цій роботі проводилися в закритій камері в середовищі водяного туману, що створюється туманоутворювачем при кімнатній температурі. Показано, що гідрофільність поверхні підвищує ефективність конденсації водяної пари на 38% порівняно з гідрофобними. У цій роботі фемтосекундна лазерна абляція була використана для отримання каналоподібних текстур з усіченим трапецієподібним поперечним перерізом, розміром 15 мкм у верхній основі, 45 мкм у нижній основі і 22 мкм у висоту. Субмікронний вимір текстур був артефактним – за рахунок утврення кристалів оксиду алюмінію розміром 30-60 нм, внаслідок окислення металу під дією високотемпературного лазерного випромінювання. Тривала витримка одержаних текстур в атмосфері збільшує їх водовідштовхувальну здатність. Кути змочування водою можуть досягати 148°, що наближається до ефективності 154°, досягнутої при обробці стеариновою кислотою. Однак нагрівання до 380 °C усуває гідрофобні шари, що призводить до повної гідрофілізації таких поверхонь. Текстуровані гідрофільні поверхні виявляються найбільш ефективними для збору конденсату, перевершуючи гідрофобні поверхні на 28%. Крім того, орієнтація мікротекстури має значення: вертикальна орієнтація збільшує збір конденсату на 34% порівняно з горизонтальною. Отримані результати можуть бути корисними при розробці обладнання для збору води в природних посушливих регіонах або там, де необхідне глибоке очищення води.

Ключові слова: *гідрофільність, гідрофобність, збирання пари, змочування, конденсація*