

Spreading of a distilled water droplet over polished and laser-treated aluminum surfaces

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HIGHLIGHTS

- A hypothesis about physical mechanism of wetting and dewetting is formulated.
- A porous microstructure is obtained by laser treatment of the aluminum surface.
- The molecular-kinetic theory is applied to the spreading on laser-treated surface.
- The contact angle hysteresis on such surface decreases due to a “lubricant” layer.

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ABSTRACT

Spreading of a distilled water droplet over polished and laser-treated aluminum surfaces is studied experimentally. We present an attempt to apply the molecular-kinetic theory to the experimental dependences of the dynamic contact angle on the contact line speed. Advancing and receding contact angles at different liquid flow rates are obtained experimentally, and their values are used to calculate the contact angle hysteresis on each substrate. The bottom-up approach is used to form a droplet on the surface when liquid is supplied through an opening in the substrate. This makes it possible to control wetting and dewetting by increasing and decreasing the droplet volume. The main geometrical parameters are obtained using the shadow method by Axisymmetric Drop Shape Analysis-Profile. Experimental data on the dynamic contact angle on a laser-treated surface are found to be a better fit to the theoretical equation in comparison with the results on a smooth polished surface. We have formulated a hypothesis that the theoretical and experimental values of the dynamic contact angle are in good agreement due to the physics of the process (smaller hysteresis on the laser-treated surface).

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1. Introduction

Droplet spreading and evaporation are the key phenomena of spray cooling, crop spraying, spin soldering, spray coating, and DNA synthesis [1–5]. The technologies of droplet cooling are known to be more effective than film or rivulet cooling [6–8]. It is caused by the greater evaporation surface area of droplets compared with the film of the same mass and wetted surface. And the greater surface area of droplets is connected with the curvature of the interface. Prior research has shown that the heat transfer conditions during cooling of the surface by single droplets are affected by the properties of the environment, surface vibration [9,10], as well as the location of droplets on the surface [11]. The close distance between the droplets provides rapid heat dissipation, but there is a possibility of their coalescence in the liquid film. Long

distance (much bigger than the diameter of the droplets) leads to the overheating of the local areas of the cooling surface and the occurrence of thermal stresses. It is possible to adjust the location of droplets by changing the roughness, structure and chemical composition of the surface [12,13].

Nowadays, the search of ways to create surfaces with controlled wettability is in progress. The following methods can only be used with chemical layer coating in order to control wetting properties: chemical deposition of structures from the gas phase [14], sublimation [15], templating methods [16], lithography [13], and laser radiation [17]. The bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity [18] are also known as surfaces with controlled wettability. From the above-mentioned approaches, laser radiation provides a wide range of textures on different materials. However, the mechanism of spreading on these surfaces is not studied well enough to predict wetting and spreading.

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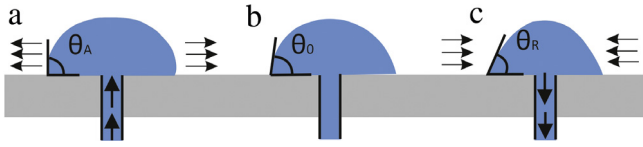


Fig. 1. DCA measurement: (a) advancing contact angle; (b) equilibrium contact angle; (c) receding contact angle.

The interaction of a droplet with a solid substrate is characterized by a contact angle (the angle formed by the tangent to the surface of the liquid and wetted surface of a solid whose angular point is located on the liquid/gas/solid interface line), which according to Young’s equation depends only on the surface tension at the interface. The angle is a unique characteristic of the liquid/gas/solid system [19]:

$$\cos \theta_Y = (\gamma_{SG} - \gamma_{SL}) / \gamma_{LG}$$

where θ_Y is a single-valued equilibrium contact angle, γ_{SG} , γ_{SL} , γ_{LG} are the solid/gas, solid/liquid and liquid/gas interfacial tensions, respectively. Further, liquid/gas interfacial tension will be denoted as γ .

Nevertheless, the liquid/gas/solid system can have several contact angles [20]. This is due to the fact that Young’s equation is correct only with the following assumptions: the surface has to be smooth and homogeneous, physically and chemically inert to the liquid [21]. Real surfaces have roughness, and their local areas can be chemically heterogeneous. Moreover, even on thoroughly cleaned and relatively smooth surfaces, several contact angles were recorded [8]. This effect is called contact angle hysteresis (H).

To quantify the hysteresis, it is necessary to know the dynamic contact angles (θ_D are the angles formed between the moving liquid interface and the solid surface). The values of these angles are in the range between the advancing and receding dynamic contact angles (DCA) [22]. The advancing contact angle is determined during the advancing movement of the three-phase contact line (CL) when the contact area between the liquid and solid increases. The receding contact angle corresponds to the decreasing contact area [22].

DCA can be measured by sequentially increasing and decreasing the volume of the droplet sitting on the surface [20–22] (Fig. 1).

During the advancing CL motion of a droplet, the speed of its displacement $U > 0$ (Fig. 2) and during the receding one, $U < 0$. When CL speed is equal to zero $U = 0$, there are two angles [22] called static advancing θ_{0A} and static receding θ_{0R} DCA (with a constant wetted area). The difference between these values is the contact angle hysteresis [20]:

$$H = \theta_A - \theta_R. \tag{1}$$

According to the experimental results [23], the contact angle hysteresis can even be equal to 50° . So, it is necessary to take into account its value, determine its causes and the impact on the process under consideration in the description of the contact line movement mechanism.

There are several factors leading to the contact angle hysteresis: the surface roughness [23], its chemical heterogeneity [24], and chemical interaction between liquid and solid [25]. The surface roughness is found to influence the hydrophobic as well as hydrophilic properties of the surfaces [26].

The influence of roughness was studied on the substrates with different types of microstructures: chaotically arranged cavities and asperities [21,23], specially structured substrates [27], and micro- and nano-coated ones [28,29]. It was found [12,13] that it

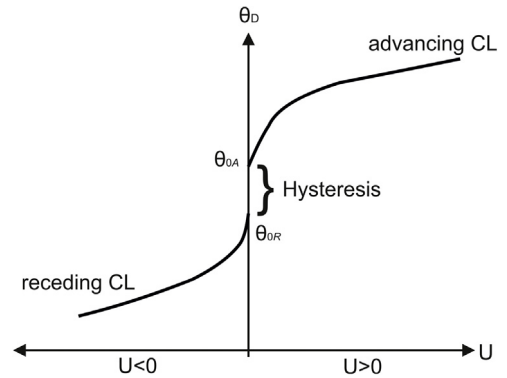


Fig. 2. Determination of the contact angle hysteresis.

is possible to control wetting and spreading by changing the shape and size of the microstructures.

There are several theories to interpret the spreading process, which presents the functional dependences of DCA on the CL speed [30–33]. They can be classified according to the different energy dissipation mechanisms near the contact line: molecular-kinetic (MKT) [30,31] and hydrodynamic (HDT) [32,33].

MKT is based on Eyring’s statistical treatment of the transport process [30,31]. According to this theory, the dependence of the dynamic contact angle on the contact line speed results from molecular adsorption and desorption on the three-phase contact line [30,31]. The following equation for the contact line speed of droplet spreading on a solid is known [30]:

$$U = 2\kappa^0 \lambda \sinh \left\{ \frac{\lambda^2 \gamma}{2k_B T} (\cos \theta_S - \cos \theta_D) \right\}. \tag{2}$$

The dynamic contact angle from Eq. (2):

$$\theta_D = \arccos[\cos \theta_S - (2k_B T / \gamma \lambda^2) \text{arc sinh}(U / 2\kappa^0 \lambda)] \tag{3}$$

where θ_S is a static contact angle (for a constant wetted area), k_B is the Boltzmann constant, T is the temperature, κ^0 is the equilibrium frequency of the random molecular displacements occurring within the three-phase zone, and λ is the average distance of each displacement.

If the argument of the sinh function is small, Eq. (1) is written as:

$$U = \gamma (\cos \theta_S - \cos \theta_D) / \xi$$

where $\xi = (k_B T) / (\kappa^0 \lambda^3)$ is the coefficient of three-phase line friction, Pa sec. It should be noted that experimental values of the friction coefficient are always larger than the viscosity of spreading liquid [31].

Currently, there are no equations for theoretical determination of ξ , κ^0 , λ . These coefficients are determined by approximating the experimental results by Eq. (3) [34]. Obtained for some materials and liquids, ξ , κ^0 , λ are listed in Table 1 [35–41].

From Table 1, we can see that the parameter κ^0 varies in quite a wide range, even when comparing the experimental data obtained for one type of liquid (in this case water). We could not find any explanation of this fact in the published literature.

From the hydrodynamic theory [32,33] it is known that the bulk viscous friction prevents the contact line motion. The shear flow in the vicinity of the contact line deforms the liquid/gas interface. Therefore, the dynamic contact angle deviates from the equilibrium value θ_0 and can be defined as [32]:

$$\theta_D^3 = \theta_0^3 \pm (9\mu U / \gamma) \ln(L / L_m) \tag{4}$$

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