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Short communication

Self-driven flow in surface grooves fabricated by femtosecond laser

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The self-driven flow in microfluidic devices has attracted much attention due to its efficient, fast and convenient properties. We investigated the effect of femtosecond laser pulse overlap on the liquid flow characters in surface grooves both in experimental evidence and theoretical analysis. With the increase of the femtosecond laser pulse overlap, the speed of water flowing in grooves is increased. Both the surface granular protrusions microstructures and the surface chemical composition can influence the liquid dynamics in grooves. Femtosecond laser may have potential applications in self-driven microfluidic devices.

1. Introduction

Microfluidic devices have attracted much attention because they have many applications in medical analysis, environmental monitoring, biochemical analysis, and microchemistry [1,2]. Accurate control of the flow of liquids in microfluidics is key to their proper functioning [3]. Actuated microfluidics [4–6] and passive microfluidics [7,8] are two modes which can drive fluid to flow in microfluidic devices. Capillary-driven flow is one of the simplest approaches to driving flow in microfluidics. With the miniaturization of the microfluidic devices, self-driven microfluidic devices have many advantages due to its portability, low volume and small power consumption. Capillary-driven microfluidics have been used in chemical/biochemical analysis and clinical diagnostics [9,10]. Water kinetics in self-driven microgrooves is determined by the geometry features of the grooves, the liquid properties and the contact angle. It's known that the contact angle of a rough surface is determined by its chemistry and morphology. In recent years, laser surface structuring has been used to alter solid surface wetting properties in air [11,12]. The microgrooves with different widths and surface energy induced by nanosecond laser in air were studied [13]. We want to tackle the effects of the surface morphology and the surface chemical composition on liquid dynamics in surface grooves. Here, we used femtosecond laser to produce self-driven surface grooves on aluminum surfaces in air and studied water flow characters in them. We conducted this study to determine whether different femtosecond laser pulse overlaps can influence the dynamics of the liquid in surface grooves. We investigated the change of the microstructures and chemical composition of the aluminum surfaces grooves after femtosecond laser irradiation. Moreover, we analyzed the influence of surface microstructures and the surface chemical composition on the liquid dynamics in surface grooves. It is meaningful for microfluidic devices to fabricate self-driven surface grooves on samples by using femtosecond laser.

2. Experimental section

Schematic illustration of the experimental system is shown in Fig. 1. We used an amplified Ti: sapphire laser system to process aluminum surface and studied the liquid dynamics on the treated surface grooves. The system generates the pulse duration of 120 fs at a maximum repetition rate of 1 kHz. The laser beam has the central wavelength of 800 nm. The combination of a $\lambda/2$ wave plate and a Glan–Taylor polarizer is used to vary the pulse energy. Lens A and Lens B make up the shrink-beam system. In the fabrication, the laser beam position was controlled by the Galvo Scanning System (Scanlab hurrySCANII) commanded by a computer. High-purity (99.99%) aluminum slides (GRINM) with a dimension of $30 \times 10 \times 0.3$ mm^3 were used in our experiments. Before the femtosecond laser irradiation, the aluminum samples were degreased in acetone and ethanol. And then the samples were washed in deionized water and air dried. The laser beam with an average fluence of 318.3 J/cm^2 was horizontally polarized and focused normally on the samples which were mounted horizontally on a stage. The diameter of the focal spot was about 20 μm which was focused by a focusing lens with 50 mm focal length. The laser scanning velocities were set as 1 mm/s, 5 mm/s, 9 mm/s and the corresponding pulse overlaps were 0.95, 0.75, and 0.55. By scanning the laser beam over the sample, a 20-mm-long microgroove along the x-direction was produced. After a y-direction shift of the laser position by 20 μm we produced the next microgroove and the process was repeated to create an irradiated area of 20×2 mm^2. All the samples were fabricated in air of atmospheric pressure.

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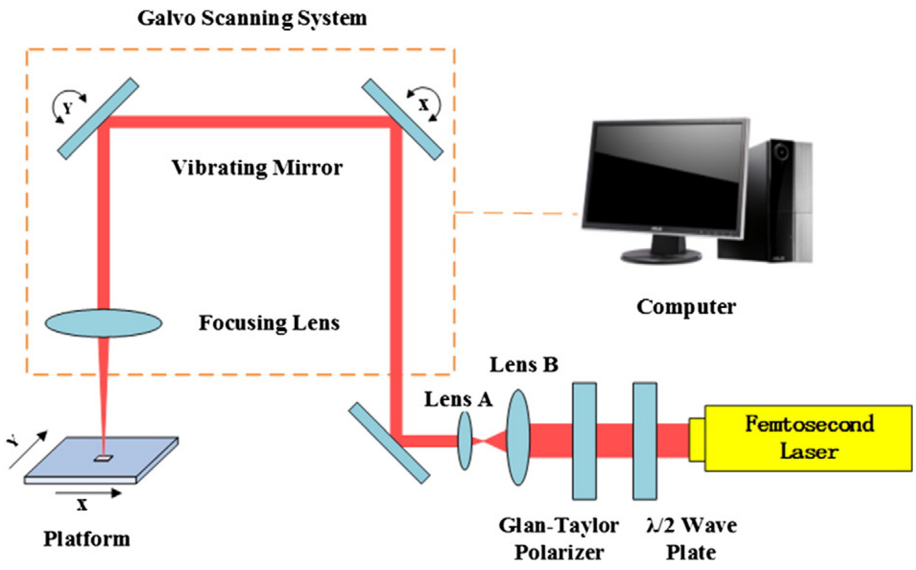

Fig. 1. Schematic illustration of the femtosecond laser experimental system.

3. Results and discussions

We studied the manufactured aluminum surface grooves wetting properties by examining the spreading dynamics of liquid on the produced samples. Deionized water was used in our study, and we captured the close-up video of the capillary rise of liquids over the aluminum surface grooves by using a 30 fps Sony digital camera. Fig. 2 shows that the water spreads highly anisotropically on the treated area and flows preferentially along the modified area fabricated at 75% pulse overlap. It can be observed that the water spreading speed decreases with time and the water can rise several centimeters on the textured sample. The results we obtained demonstrate that the produced aluminum surface grooves become superhydrophilic. We believe that self-driven flow phenomenon is due to the supercapillary effect [12].

Treatments of the kinetics of capillary flow have been studied for over 90 years. In 1921, Washburn showed that the length of liquid column z, entering the horizontal cylindrical capillary followed relatively simple kinetics $z(t) = [\gamma r \cos\theta/(2\mu)]^{1/2}t^{1/2}$ [14]. z is the distance traveled by the liquid, θ is the contact angle, r is the capillary radius, γ and μ are the surface tension and viscosity of liquid. The equation shows that capillary-driven liquid advances with a $t^{1/2}$ dependence. The flow of liquid on a surface with open V-shaped grooves has been reported by Rey and Yost et al. in 1996. They reported that for horizontally placed capillary flow, experiment and a model agree on kinetics of the form $z(t) = [K(\alpha,\theta)h_0\gamma/\mu]^{1/2}t^{1/2}$ [15–17]. h_0 is the groove height, and $K(\alpha,\theta)$ is a geometric term containing the groove angle α and the contact angle θ, γ and μ are the liquid surface tension and viscosity. The dynamics of liquid on the structured surface is purely capillarity driven and depends on the contact angle, the surface tension and viscosity of the liquid, and the geometry of the groove [9,18]. For the purpose of simplicity of the penetration, the surface roughness is assumed to be composed of an array of well-defined pillars [19], channels [20] or a network of grooves [21]. The analytical model established in their studies recovered the Washburn-type kinetics for the early stage of the spreading process. Hemiwicking is a term employed by Quéré to categorize nearly all dynamic wetting across textured surfaces [22]. As he emphasized, a well-controlled micro/nanostructures on a solid may induce roughness effects on wetting. They summarized the dynamic law of the capillarity on textured surfaces as $z(t) = (\mathrm{D}t)^{1/2}$. D is the coefficient which can characterize the dynamics.

In order to determine whether the laser pulse overlap can influence the groove penetration coefficient, we used different pulse overlaps to fabricate surface grooves. To determine the diffusion dynamics of the femtosecond laser-structured surface grooves, we plotted the uphill travel distance z as a function of $t^{1/2}$ for the vertically standing sample fabricated at different laser pulse overlaps, as shown in Fig. 3. The penetration distance is directly proportional to the square root of the associated time. The slope of the line at high pulse overlap is higher than that at low pulse overlap. The slopes of the fitting lines are 5.3, 4.2 and 3.6. And the corresponding dynamic coefficients are 28.09 mm^2/s, 17.64 mm^2/s and 12.96 mm^2/s. The theoretical model fits the experimental data well. We can change the sample dynamic coefficient by varying femtosecond laser pulse overlap. Therefore, we can control the dynamic properties of the liquid in aluminum surface grooves.

The driving force for capillarity is surface tension, so it is also known as surface tension effects. The occurrence of capillarity requires a good wetting condition between liquid and solid [23]. Wetting of a solid surface is studied for many years [20,22,24]. It's known that the wettability

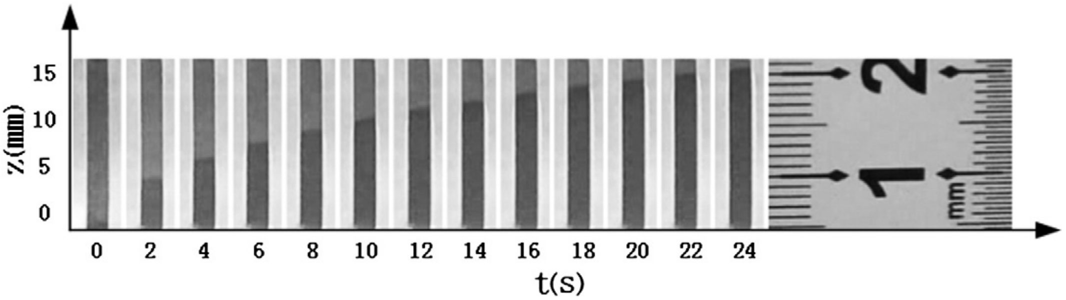

Fig. 2. Image sequence of capillary rise fronts of water wicking over an aluminum surface groove.

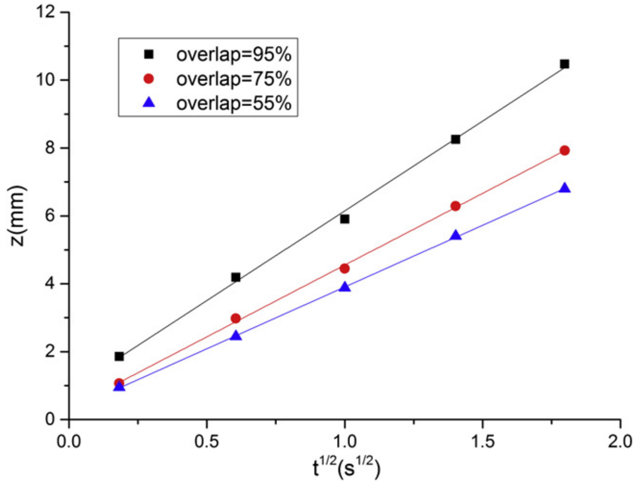

Fig. 3. Dynamics of the water flow on vertically standing aluminum samples created by femtosecond laser at different pulse overlaps.

of a rough surface is determined by its chemistry and morphology. The classical Wenzel model [25] and Cassie–Baxter model [26] can be used to explain wetting of a rough surface. According to Wenzel's theory, surface roughness plays an important role in enhancing surface wettability: a hydrophilic solid becomes more hydrophilic and a hydrophobic solid becomes more hydrophobic. A chemically heterogeneous surface can be analyzed by the Cassie–Baxter model. We can deduce from the Cassie–Baxter model that surface chemical composition can also influence surface wettability.

A Field Emission Scanning Electron Microscopy (FESEM, JSM-6700F) was used to examine the surface grooves microstructures after laser irradiation. Fig. 4(a) shows the SEM images of an aluminum surface without femtosecond laser irradiation. SEM images of the microstructured surface grooves created on aluminum surfaces under different femtosecond laser pulse overlap irradiation conditions are shown in Fig. 4(b)–(d), where we can see the microstructures of the samples. The groove microstructures change from small block-like structures to microscale granular protrusions as the laser pulse overlap increases. Through SEM images, we can easily find that the microstructures of the grooves are obviously changed. It is clear from the pictures that higher laser pulse overlap induces more rough surface structures. We believe that higher pulse overlap makes more surface materials vaporize, therefore both the quantity and the size of granular protrusions increase. With the increase of the laser pulse overlap, the unevenness of the grooves is increased.

To investigate the influence of the surface microstructures and the surface chemical composition on liquid dynamics, a magnetron sputtering equipment (SP-2, IMECAS) was used to sputter aluminum onto the laser-treated aluminum samples. The thickness of the sputtered thin films was about 100 nm and the liquid kinetics in these surface grooves was analyzed after the sputtering process. In this condition, we believe that the laser-treated samples surface chemical compositions are the same and the change of surface morphology can be ignored following coating with aluminum by magnetron sputtering. The sputter coated films were only 100 nm, which affect the surface morphology little. Fig. 5 shows the SEM images of the laser-treated aluminum surfaces coated with aluminum. From the SEM images, we can easily find that the Al-coated aluminum surface microstructures are different. In the meantime, Fig. 6 shows the water dynamics on the laser treated aluminum surface sputtered with aluminum. The slopes of the Al-coated aluminum surface grooves are 3.4, 3.0 and 2.5. And the corresponding dynamic coefficients are 11.56 mm^2/s, 9.00 mm^2/s and 6.25 mm^2/s. The dynamic coefficient increases with the femtosecond

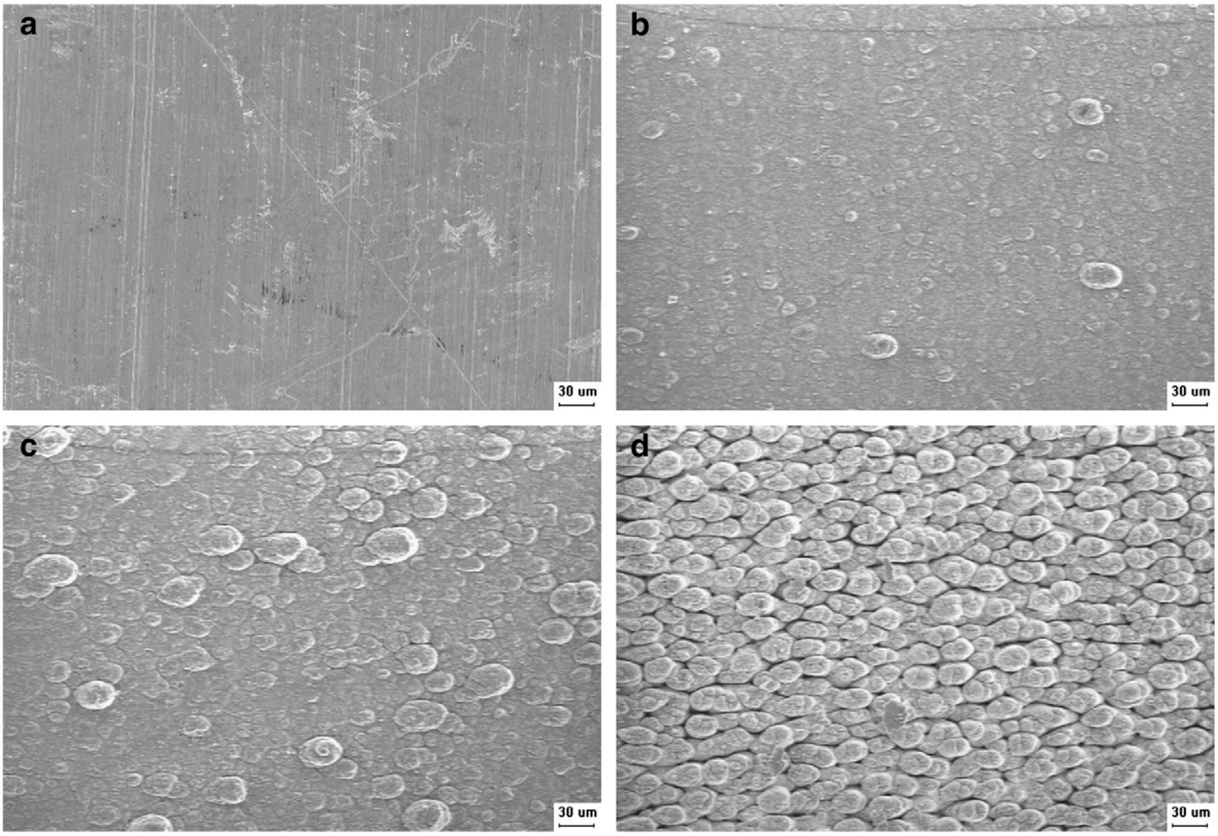

Fig. 4. SEM images of the structured aluminum surfaces irradiated at different femtosecond laser pulse overlaps: (a) untreated surface; (b) pulse overlap = 55%; (c) pulse overlap = 75%; (d) pulse overlap = 95%.

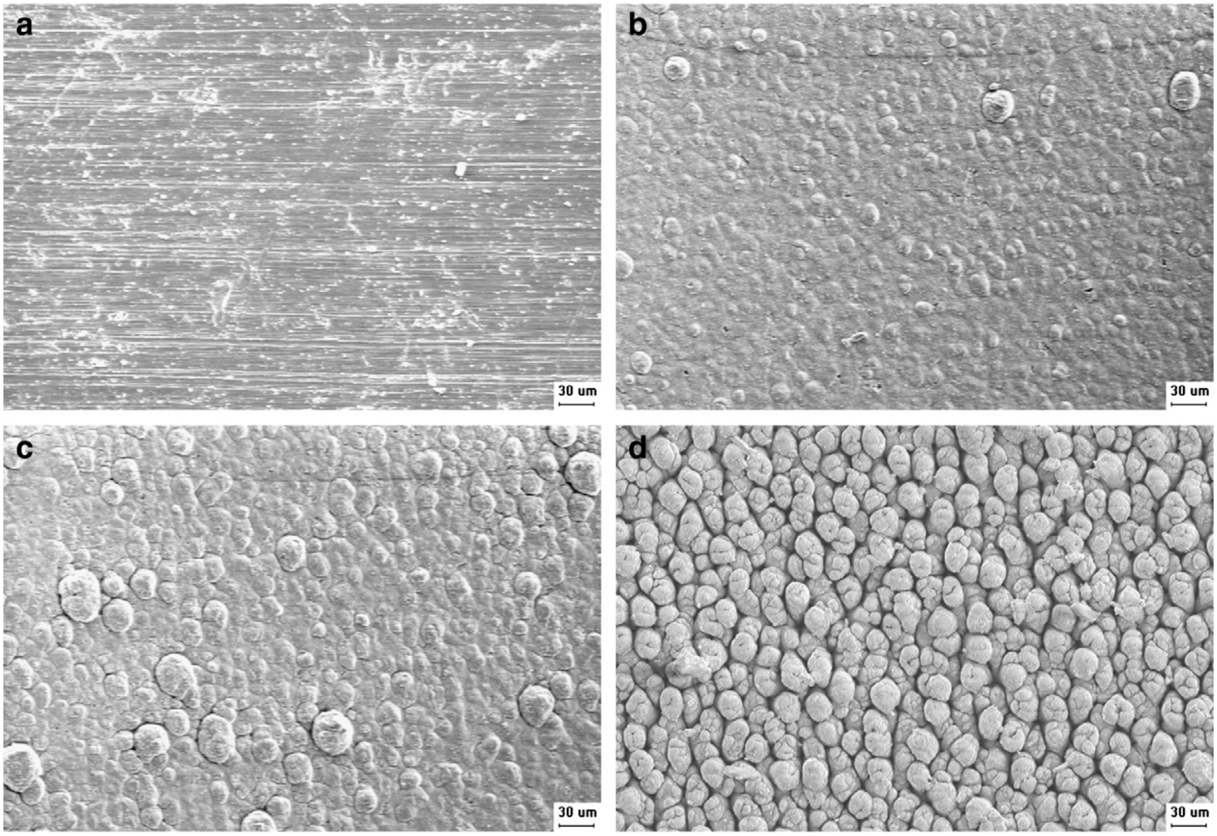

Fig. 5. SEM images of the laser-treated samples following coating with Al by magnetron sputtering: (a) untreated surface; (b) pulse overlap = 55%; (c) pulse overlap = 75%; (d) pulse overlap = 95%.

laser pulse overlap. With the increase of the quantity and the size of the surface granular protrusions microstructures, the speed of the water flowing in the surface grooves is increased too. So the surface microstructures can influence the dynamics of the liquid in the grooves.

From Figs. 3 and 6, we can easily find that the dynamic coefficient of the uncoated aluminum surface grooves was significantly higher than the Al-coated aluminum surface grooves. If the surface chemical composition is not changed after femtosecond laser irradiation, the water dynamics in the Al-coated aluminum surface will change little. However, the dynamic coefficient of the uncoated aluminum surface grooves was significantly higher than the Al-coated aluminum surface grooves.

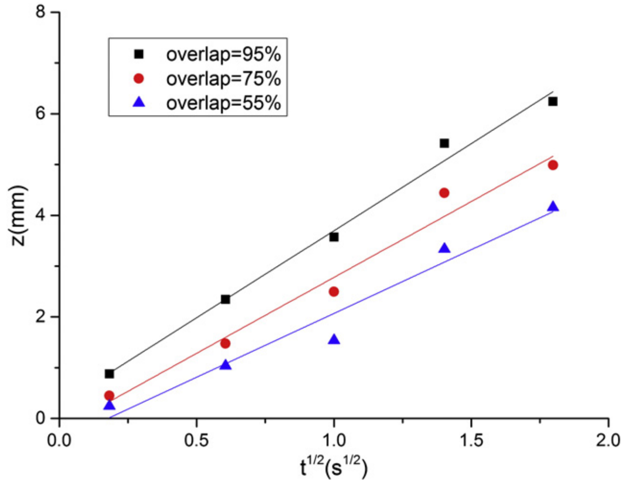

Fig. 6. Dynamics of the water flow on vertically standing Al-coated aluminum surface created by femtosecond laser at different pulse overlaps.

Therefore, we believe that the sputtered metal covered the laser irradiated aluminum surface groove chemical composition and made surface grooves less hydrophilic. We can conclude that the laser irradiated aluminum surface groove chemical composition can turn the surface grooves more hydrophilic. In fact, the change of aluminum surface chemical composition after femtosecond laser irradiation has been confirmed in [27,28]. Both the laser induced surface grooves microstructures and chemical composition can influence water dynamics in surface grooves.

SEM images imply that the femtosecond laser can change the microstructures of the aluminum surface grooves. In [27], the XRD experiment results indicate that with the increase of the laser pulse overlap, the sample surface content of Al_2O_3 is increased while that of $Al(OH)_3$ is decreased. The contact angle of water droplet on the laser-treated surface was very small which means we made the aluminum surfaces superhydrophilic. Contact angles were measured using the sessile drop method on flat surfaces. One microliter deionized water was pipetted onto the surface and a CCD imaging system was used to capture pictures. The contact angle of the untreated aluminum surface was about 67.2° which means that the sample was originally hydrophilic. According to Wenzel's theory, the surface roughness will enhance the hydrophilicity of the aluminum surface. The aluminum hydroxide and aluminum oxide are both well-known hydrophilic chemical due to their hydroxyl group [28]. When the laser pulse overlap increases, the aluminum surface grooves will be more hydrophilic. We believe that both the morphology and the chemical composition enhance the wettability of the aluminum surface grooves after femtosecond laser irradiation. From the experiment, we find that when the laser scanning velocity decreases i.e. the pulse overlap increases, the dynamic coefficient will increase. Through femtosecond irradiation, the surface morphology is changed, so is the surface chemical composition [28], which results in the change of the surface wettability. The two factors determine the diffusion constant together and finally affect the dynamic of the capillary.

4. Conclusions

In summary, the hydrophilic aluminum surface grooves are created by using high-intensity femtosecond laser pulse. The irradiated area is covered with extensive surface granular protrusion microstructures. With the increase of the femtosecond laser pulse overlap, the speed of water flowing in the aluminum surface groove is increased too. The sample dynamic coefficient increases with the laser pulse overlap. Magnetron sputtering can change laser-treated sample dynamic coefficient. Our experiments of the fluid dynamics demonstrate that the self-driven motion of water is due to the supercapillary effect from the created surface. The structured surface grooves can offer certain drag force for fluid flow in them. The drag force can be used as an input of power for driving liquid flow in microfluidic devices, which can minimize the size of the microfluidic devices. The wicking dynamics follows the classical Washburn equation and we analyzed the relationship between the dynamic of the liquid on the aluminum surface and the surface wetting properties. The solid surface wettability can be controlled by femtosecond laser pulse overlap which can change the morphology and the chemical composition of the surface i.e. the dynamic of the liquid can be controlled by changing the femtosecond laser pulse overlap. We can calculate the sample dynamic coefficient, allowing us to control the liquid dynamics more precisely by the design of the textured surface grooves using femtosecond laser irradiation. The superwicking effect utilized femtosecond laser manufacture technique may find a wide range of applications in microfluidics, biomedicine and chemical sensors. This work provides fundamental theory and reference for capillary-driven microfluidic devices by using femtosecond laser surface structuring technique. We are now conducting experiments on bioanalytical research by using femtosecond laser inducing capillary driven effect on glass surface. Experiments similar to those reported here should be conducted using a wider variety of materials.

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