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Influence of initial distance between needle tip and substrate on contact dispensing of high-viscosity adhesive

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A R T I C L E I N F O

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A B S T R A C T

In contact dispensing process including the extruding, stretching, and liquid-bridge breakup, the initial distance d_{n-s}^{ini} between the needle tip and the substrate has great influence on the dispensed adhesive volume. Herein, the effect of d_{n-s}^{ini} on the dispensing process in nano-liter level is studied for high-viscosity adhesive. Complete contact dispensing process is simulated using computational fluid dynamic technique. Moreover, the experimental platform including heating device, dispenser, and imaging unit etc. is built up to investigate the dispensing process. According to the results, with the increase of d_{n-s}^{ini}, the variation of extruded adhesive volume can be divided into three regimes that are respectively dominated by different factors. As d_{n-s}^{ini} is in the range of 45–75 μm, due to the spatial flow resistance decreasing, the extruded volume sharply increases. Then, when d_{n-s}^{ini} is in the range of 75–115 μm, owing to the contact area $s_{a\text{-}s}$ between the extruded adhesive and the substrate continuing to decrease, the increase of extruded volume becomes slow. Once d_{n-s}^{ini} reaches 115 μm, comparing to the decrease of $s_{a\text{-}s}$, the contribution of spatial flow resistance can be neglected, thus the extruded volume will decrease until $s_{a\text{-}s}$ approaches to zero. Additionally, the following transfer process based on the liquid-bridge breakup is studied too. The variation of absolute transferred volume is consistent with that of the extruded volume. However, since $s_{a\text{-}s}$ continuously decreases with the increasing of d_{n-s}^{ini}, the transfer ratio gradually decreases. The presented results can improve the precise contact dispensing process and other related techniques.

1. Introduction

Contact dispensing with nano-liter level has been widely used in a variety of fields [1–4]. Especially, due to its unique advantages including low temperature and pressure, weak interior stress, high flexibility [5], viscous adhesive in nano-liter level are commonly utilized to accurately assembly microparts to form micro-electro-mechanical systems (MEMS). However, in microscale, short filling and overfilling of joints can lead to the reduction of adhesive strength and the contamination [6–9], which was predicted and in-depth analyzed by R. D. Adams et al. [10,11]. Thus, the precise volume-controlling in adhesive dosing process becomes extremely important. The dispensing methods of liquid adhesive can be coarsely divided into contact dispensing and no-contact dispensing [12,13]. Currently, limited by the viscosity, for high-viscosity adhesives (> 1 Pa·s), the contact dispensing is still the most efficient approach since the adhesive force between the substrate and the adhesive can help the adhesive breaking away from the injection needle [14].

Generally, the contact dispensing process of liquid adhesive involves three typical steps: extruding, stretching, and liquid-bridge breakup, as shown in Fig. 1a–c. In extruding process, the liquid adhesive is extruded from the needle to the substrate by external gas pressure at an initial distance between the needle tip and the substrate (d_{n-s}^{ini}, '*d*' represents distance, '*ini*' represents initial, and '*n-s*' represents needle tip and substrate respectively). Then the pressure is cut off after a period t_0. And the adhesive from the needle is defined as the extruded volume. In stretching process, the needle is lifted up at a speed v_0 after a short dwell period t_1. The extruded adhesive is stretched and produces a necking liquid-bridge. At last, the liquid-bridge breaks in the critical point. A small part of adhesive stays on the needle, and the other called the transferred volume sticks to the substrate. In the term of the contact dispensing of high-viscosity adhesive in nano-liter level, the initial distance d_{n-s}^{ini} is reduced into the micrometer scale. Following the d_{n-s}^{ini} decrease, the spatial flow resistance remarkably increases and the surface effect enhances too that affect consequentially the dispensing process. Therefore, it is important to understand its rheology behavior for precise control of the amount of dispensed adhesive.

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Nomenclature

d_{n-s}^{ini}	initial distance for extruding between needle tip and substrate
$s_{a\text{-}s}$	contact area between extruded adhesive and substrate
r_{min}	minimum radius of liquid-bridge
R	inner radius of needle
∇	Hamiltonian differential operator
$\vec{v}$	velocity vector of adhesive
μ	dynamic viscosity in the whole flow domain
μ_1	dynamic viscosity of adhesive
ρ	density in the whole flow domain
κ	curvature of interface between air and adhesive
l'	one twentieth of pinhead length
Q_v	flow of liquid adhesive through needle
r_i	meniscus radius of liquid-bridge
h	total pixel height of extruded and transferred volume
F_a^{ini}	adhesive force of initial stretching stage
t_0	extrusion time
t_1	short dwell period
p	internal pressure
$\vec{F_S}$	surface tension vector
θ	wetting angle
v_0	needle lifting speed
σ	surface tension coefficient
ρ_1	liquid adhesive density
d	inner diameter of the needle
α_1	volume fraction of adhesive
l	length of needle
p_0	inlet pressure
p'_0	equivalent inlet pressure
x	horizontal unit pixel
F_a	adhesive force

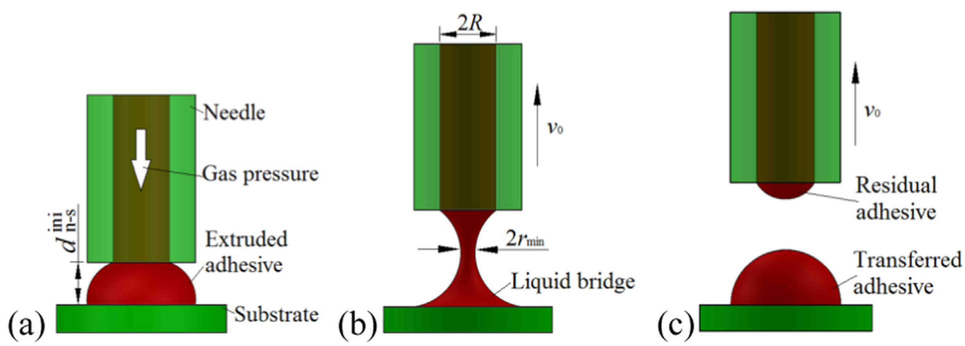

Fig. 1. Contact dispensing process of adhesive: (a) extruding (b) stretching (c) liquid-bridge breakup.

In decades, most research interests were focused on the critical point of liquid-bridge breakup. It was found that the liquid-bridge breakup process is dominated by different factors for various conditions. For most low-viscosity fluids (< 1 Pa·s), viscous force is weak with the liquid-bridge stretching [15]. And the stretching-then-breakup is dominated by inertial force and surface tension, belonging to the inertial regime. The break point is usually expressed by $r_{min}{\sim}R\tau^{2/3}$ in the regime, where τ is dimensionless time ($\tau = t_b\text{-}t/t_c$, t_b is the breakup time, $t_c \equiv \sqrt{\rho R^3/\sigma}$) [16], R and r_{min} are respectively the inner radius of needle and the minimum radius of liquid-bridge, as shown in Fig. 1b. As the thinning liquid-bridge shrinks rapidly, the liquid-bridge breaks and meanwhile τ approaches zero. Thus, Reynolds number $Re(t)$ also approaches zero since $Re(t){\sim}\tau^{1/3}Oh^{-1}$ (Ohnesorge number Oh «1 for low-viscosity fluids). However, since the Reynolds number can't be infinitesimal in practice, the inertial regime can only apply to the initial stretching dynamics of low-viscosity fluids [17]. For high-viscosity fluids ($Oh >\ > 1$), the viscous force plays a leading role. The breakup process is dominated by viscous force and surface tension, belonging to the viscous regime [18,19]. Since Reynolds number $Re(t){\sim}\tau^{2\beta-1}/Oh^2$ ($\beta \approx 0.175$) can't be infinite, the viscous regime is only applicable to initial stretching dynamics of high-viscosity fluids [20]. As r_{min} tends to zero, the viscous-inertial regime occurs in the near breakup state, where there is a balance between viscous force, inertial force, and surface tension [21–24]. In addition, the impact of adhesive force that is contributed by meniscus force and viscous force has been investigated too [25,26]. According to their reports, with the initial distance between two substrates decreasing from 6 nm to 2 nm, the meniscus force and the viscous force increased respectively by about 2 times and 5 times. With a contact area between the adhesive and the substrate ($s_{a\text{-}s}$) increasing, the adhesive force presented a monotonic increasing function. Therefore, the role of adhesive force is more obvious when the initial distance decreases and $s_{a\text{-}s}$ increases.

Besides, in order to precisely estimate the final transferred volume, the transfer mechanism *via* the liquid-bridge breakup had attracted much attention too. And the ratio of transferred volume to extruded volume, namely transfer ratio, was often utilized to define the transfer

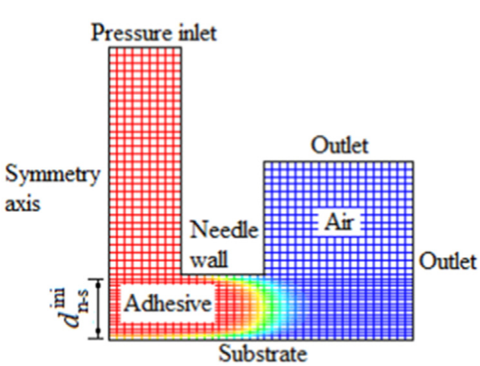

Fig. 2. Schematic diagram of the extruding simulation.

Table 1
Parameters for simulation.

Parameters	Value
Adhesive density ρ_1	960 kg/m^3
Surface tension coefficient σ	23.78 mN/m
Extrusion time t_0	30 ms
initial distance d_{n-s}^{ini}	45–145 µm
Wetting angle θ	39.88°
Needle wall	0.11 mm