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ABSTRACT

Many scholars have conducted in-depth analysis on relevant factors that affect the accuracy of jet dispensing. However, research on the influence of needle impact velocity on jetting performance is limited. Thus, a piezoelectric needle-collision dispenser for micro-droplet jetting is designed in this study, and the influence of the needle impact velocity on jetting effect is deeply analyzed. Initially, the principle of droplet formation and injection is analyzed by Fluent simulation. Thereafter, the mathematical model of the droplet velocity in the nozzle orifice is derived, and the influence of the needle impact velocity on the jetting performance is simulated and analyzed. Results show that the needle impact velocity has an influence on the jetting effect. A prototype of the jetting dispenser is subsequently fabricated, and the needle impact velocity is tested with laser micrometer. The relationship between the needle impact velocity and droplet weight and its corresponding ejected effect are obtained through experimental research. Finally, a UV glue with viscosity of 5,000 cps can be ejected with a minimum average diameter of 272.1 μm by using a needle with a radius of 0.5 mm, a nozzle with a diameter of 50 μm, a taper angle of 90°, a supply pressure of 0.2 Mpa, and a needle impact velocity of 0.13 m/s. The variation of the droplet diameter is within ±2.5%.

I. INTRODUCTION

Electronic packaging plays a key role in electronics manufacturing, and dispensing is a key part of electronic packaging technology.[1–4] Dispensing is a technology that distributes viscous fluids to a specified location to achieve bonding, fixing, encapsulation, and soldering of electronic components.[5,6] It penetrates nearly all processes in electronics manufacturing, including speaker manufacturing, cell phone assembly, connector assembly, surface–mount technology, liquid crystal display, light-emitting diode, and contraction camera module.[7–9] The dispensing technology used in the industry has evolved from contact-type pneumatic dispensing to non-contact jet dispensing, which is divided into gas-driven and piezoelectric dispensing. However, the piezoelectric jet dispensing technology is favored in the electronics packaging field because of its high efficiency, fast response, and high precision.[10,11]

The requirements for dispensing precision and ejected droplet dimension are raised. Therefore, the research on piezoelectric jet dispensing technology is extended.[12,13] In the past three years, scholars have conducted extensive research on the impact of needle- and nozzle-related parameters on jetting effect. Central South University developed a bi-piezoelectric dispensing mechanism that investigates the influence of flow channel and nozzle structure on the droplet injection through simulation and experiments.[14,15] Shandong University studied the effect of nozzle diameter on droplet injection and the relationship between supply pressure and glue viscosity to obtain a stable ejection state.[16] Jilin University also investigated the effect of nozzle and needle structure on jetting effect. They replaced the needle impact velocity with the amount of spring deformation and needle displacement and investigated their influence on jetting effect because the needle impact velocity cannot be possibly measured.[17,18] In addition, many other

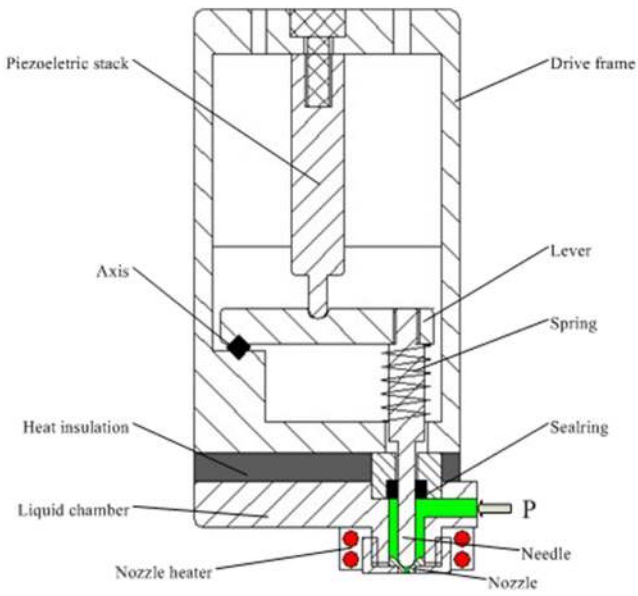

FIG. 1. Structure of piezoelectric needle-collision jetting dispenser.

experts have studied jetting dispensers and made considerable achievements.[19–21]

Nearly all piezoelectric jetting dispensers are operated by needle striking; however, the influence of needle impact velocity on the jetting effect has not been studied. A device for micro-droplet jetting is designed by analyzing the needle impact velocity. The advantages of the high precision and fast response of the piezoelectric stack are applied to micro-droplet jetting. Initially, the principle of the droplet injection is obtained through Fluent simulation. Thereafter, the mathematical model of the droplet velocity in the nozzle orifice is derived, and the influence of the needle impact velocity on jetting performance is verified by Fluent. Subsequently, the prototype of the jetting dispenser is fabricated, and the needle impact velocity is tested by laser micrometer. Finally, the experimental result corroborates that the needle impact velocity is closely related to the injection performance of the jetting dispenser. A UV glue with viscosity of 5,000 cps can be ejected with a minimum average diameter of 272.1 μm by selecting the optimum needle and nozzle and adjusting the appropriate needle impact velocity. The variation of the droplet diameter is within ±2.5%.

II. PRINCIPLE OF INJECTION AND ANALYSIS OF NEEDLE IMPACT VELOCITY

A. Structure of jetting dispenser

Fig. 1 depicts the structure of the piezoelectric needle-collision jetting dispenser, which comprises piezoelectric stack, lever, drive frame, heat insulation, nozzle heater, spring, nozzle, and needle. The piezoelectric stack is sintered from many ceramic sheets and it is the power source of the jetting dispenser. The piezoelectric stack can vibrate in high frequency while an electric field is being applied to it. The jetting dispenser mainly uses a lever to amplify the displacement of the piezoelectric stack, and the needle moves up and down under the combined effects of the lever and the force of the spring. The high-viscosity glue can be heated to reduce the viscosity using the nozzle heater, and heat insulation can be used to protect the piezoelectric stack from the heat induced by the nozzle heater to form a perfect injection.

B. Principle of droplet injection

Fig. 2 shows that the injection principle of the jetting dispenser can be divided into four steps as follows.

1. In the normal state, the piezoelectric stack is powered on and in an extended state, and the needle and the nozzle are in a close-fit state, which can effectively prevent the glue from flowing out through the nozzle orifice (Fig. 2(a)).

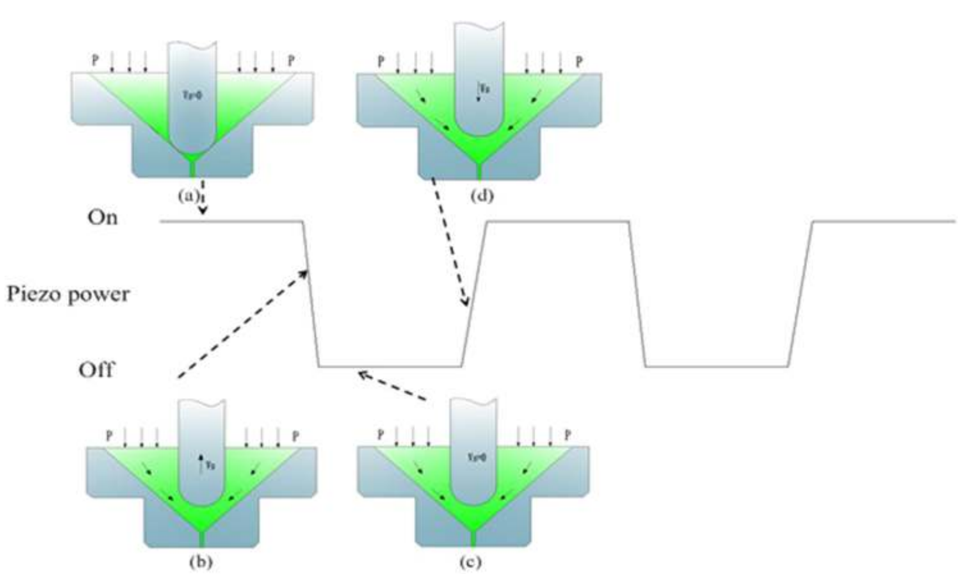

FIG. 2. Jetting principle. (a) Normal state; (b) Needle upward movement; (c) Highest state; (d) Needle downward movement.

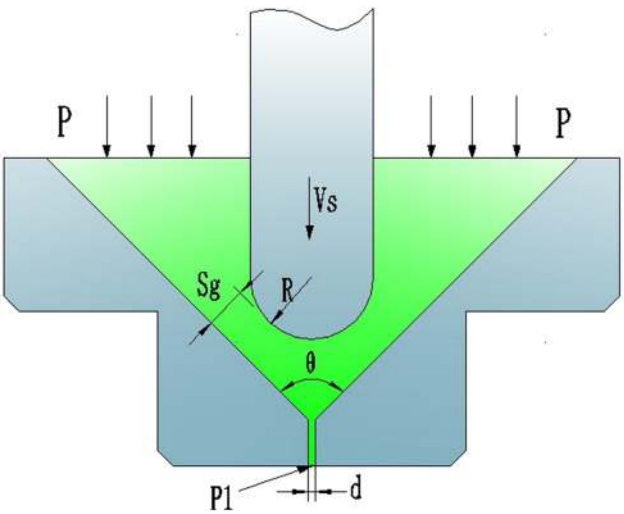

FIG. 3. Geometric model of needle and nozzle.

2. When the driving signal generated by the piezoelectric power is on the falling edge, the piezoelectric stack gradually recovers, and the needle raises up and separates from the nozzle under the restoring force of the spring (Fig. 2(b)).
3. The piezoelectric stack is powered off when the driving signal is at a low level. The glue to be sprayed is continuously transported to the gap between the nozzle and the needle under supply pressure (Fig. 2(c)).
4. The needle immediately moves down while an electric field is applied to the piezoelectric stack, and the injection is realized when the needle hits the nozzle (Fig. 2(d)).

To illustrate the principle of the droplet injection in depth (Fig. 2(d)), Fluent 6.3 (Ansys, Inc., USA) is used to simulate and analyze the process of the needle that hits the nozzle. Fig. 3 presents a geometric model of the nozzle and needle; this model is introduced to Fluent for simulation analysis. An adhesive with viscosity of 5,000 cps and density of 1,200 kg/m^3 is selected as the simulation object, and the boundary conditions are set (Table I). The flow is assumed to be in the laminar regime in the following simulation because of the high viscosity of the fluid.

Fig. 4 illustrates the pressure cloud between the needle and the nozzle at four different times during the impact of the needle on the nozzle. On the basis of the simulation, an instantaneous pressure is formed in the gap between the needle and the nozzle when they hit at a velocity of 0.2 m/s. The pressure gradually increases accordingly as the needle gradually approaches the nozzle. When they finally collide, the internal pressure reaches a peak value, and the glue in the confined space obtains kinetic energy under the action of high pressure. The glue droplet with a certain velocity is then ejected from the nozzle orifice.

TABLE I. Injection principle simulation parameters.

Properties	Value
Inlet pressure	2×10^5 Pa
Outlet pressure	1.01×10^5 Pa
Surface tension coefficient	20 mN/m
Yield stress	150 Pa
Needle impact velocity	0.2 m/s

C. Theoretical analysis of droplet injection

The inertial force obtained by the ejected droplet must overcome the surface tension and viscous drag to form the droplet ejection. The droplet velocity must exceed a critical value for the adhesive to achieve injection.[17] In this section, the factors that influence the formation of injection are analyzed, and the relationship between them is finally obtained.

When the needle impacts the nozzle, a portion of the glue between the needle and the nozzle is jetted from the nozzle orifice, and the remaining liquid flows back to the liquid chamber (Fig. 3). This phenomenon is determined by the law of conservation of mass, which is expressed as follows:

$$Q = Q_g + Q_{\mathrm{h}}, \tag{1}$$

where Q is the reduced flow between the nozzle and the needle when the latter strikes downward, Q_g is the returning adhesive, and Q_h is the flow rate in the nozzle orifice.

When an electric field is applied to the piezoelectric stack, the needle strikes downward at velocity v_s, and the reduced flow between the nozzle and the needle can be expressed follows:

$$Q = \pi V_s R^2 \cos^2\frac{\theta}{2}, \tag{2}$$

where Q is the nozzle taper angle, and R is the needle radius.

As the needle nearly impacts the nozzle, the gap between the nozzle and the needle becomes close to zero, that is, $Q_g\underset{S_g\to 0}{=}0$; therefore,

$$Q = Q_h = \frac{\pi d^2}{4} V, \tag{3}$$

where S_g is the gap between the nozzle and the needle, V is the flow velocity in the nozzle orifice, and d is the nozzle diameter.

Therefore, when the needle hits the nozzle, the droplet velocity in the nozzle orifice can be determined by Formulas (2) and (3).

$$V_P = \frac{4V_s R^2 \cos^2\frac{\theta}{2}}{d^2} \tag{4}$$

Formula (4) indicates that the droplet velocity, which can determine the injection, is related to the needle impact velocity, needle radius, nozzle diameter, and taper angle. Here, we focus on the needle impact velocity on the jetting effect because the study on the needle impact velocity is limited in the field of jet dispensing.

D. Analysis of needle impact velocity

In this section, Fluent is used to simulate the influence of the needle impact velocity on droplet injection. The geometry in Fig. 3 is reintroduced to Fluent as a simulation model. The boundary conditions are set (Table I and Table II). In addition, point P1 is set at the nozzle orifice outlet to monitor the droplet velocity.

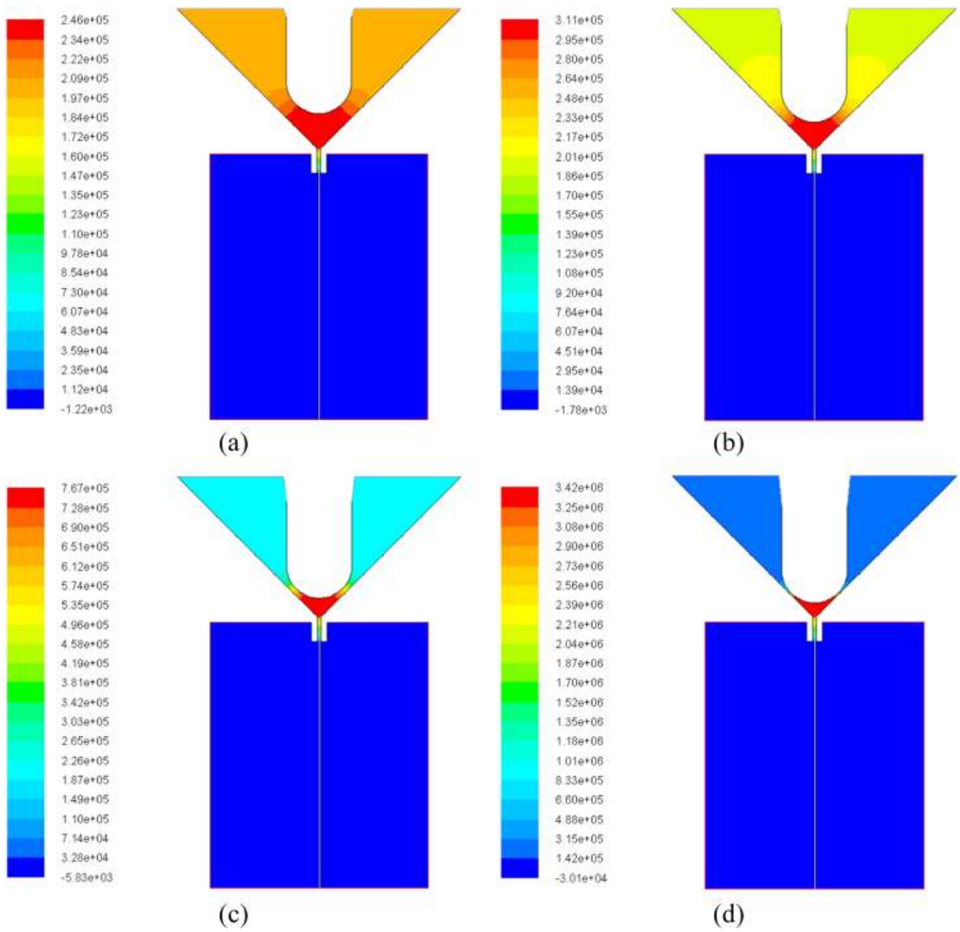

FIG. 4. Pressure cloud at different times during the impact. (a) $t_1 = 5 \times 10^{-4}$ s; (b) $t_2 = 1 \times 10^{-3}$ s; (c) $t_3 = 1.5 \times 10^{-3}$ s; (d) $t_4 = 2 \times 10^{-3}$ s.

When the needle hits the nozzle at different velocities, various velocity clouds are formed correspondingly (Fig. 5). On the basis of the simulation, the droplet velocity V_P at point P1 increases accordingly with the needle velocity V_S; thus, droplet injection is easy to form.

The droplet velocity at different needle impact velocities is plotted as a line graph for intuitive analysis, and the droplet ejection effect at various needle impact velocities is simulated (Fig. 6).

As shown in Fig. 6, under the parameters we set, the ejection droplet velocity is linear with the needle impact velocities. However, if the needle impact velocity is less than 0.15 m/s, ejection cannot be formed because the inertial force of the droplet at P1 cannot overcome its own viscous resistance when the needle impact velocity is inadequately fast. When the needle impact velocity is larger than 0.4 m/s, the droplet velocity at P1 becomes extremely large, and the ejected droplet sputters with satellite drops because of the excessive inertia force. A perfect injection droplet can be formed only when the needle impact velocity is between 0.15 m/s and 0.4m/s.

TABLE II. Needle impact velocity simulation parameters.

Properties	Value
Needle radius	0.5 mm
Liquid viscosity	5000 cps
Nozzle diameter	0.05 mm
Nozzle taper angle	90°

III. EXPERIMENT AND DISCUSSION

A. Test of needle impact velocity

An experiment bench is designed for measuring the needle impact velocity to verify the aforementioned conclusion. The experiment bench is composed of a driving power, a piezoelectric jetting dispenser, a laser micrometer (Keyence, LK-H020, Japan), and a PC (Fig. 7). The piezoelectric stack vibrates under the driving signal generated by the driving power and drives the needle to move through the lever amplification mechanism. The laser micrometer can precisely capture the track of the needle movement and transmit it back to the PC to generate the motion characteristic curve.

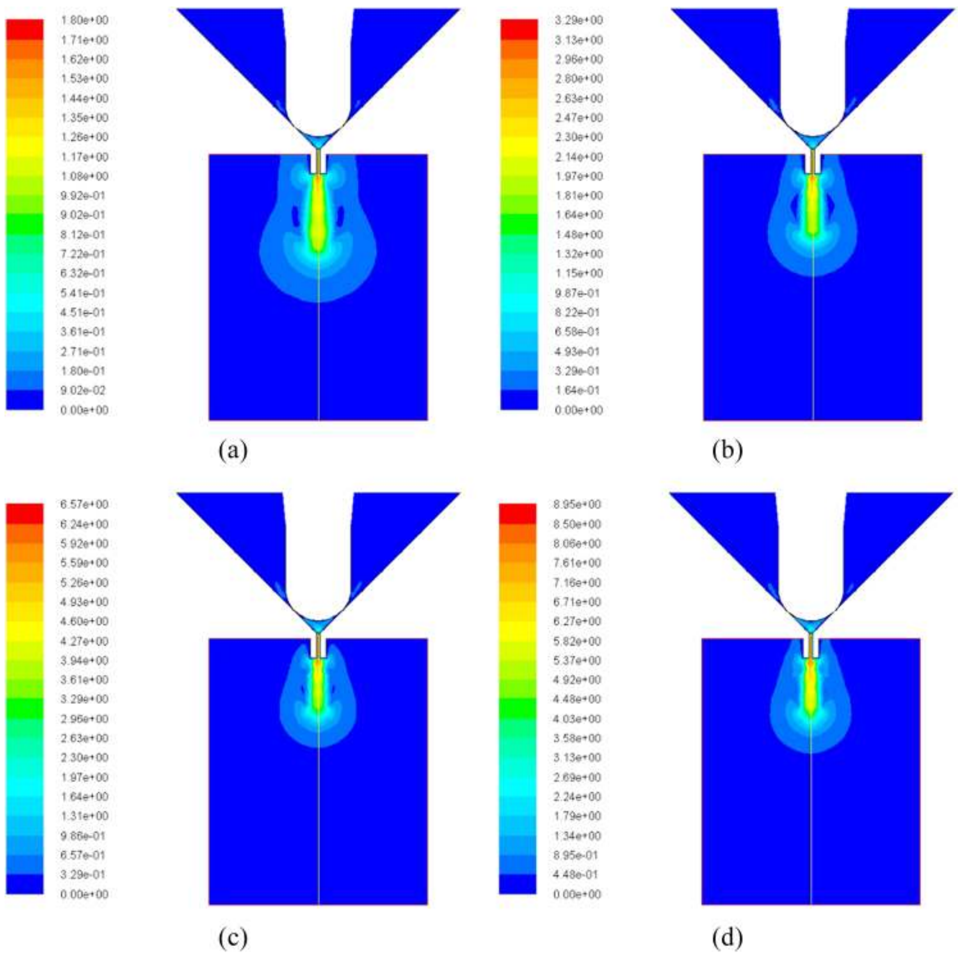

FIG. 5. Flow velocity cloud at different needle impact velocities. (a) V_S = 0.08 m/s, V_P = 1.8 m/s; (b) V_S = 0.15 m/s, V_P = 3.38 m/s; (c) V_S = 0.3 m/s, V_P = 6.75 m/s; (d) V_S = 0.4 m/s, V_P = 9 m/s.

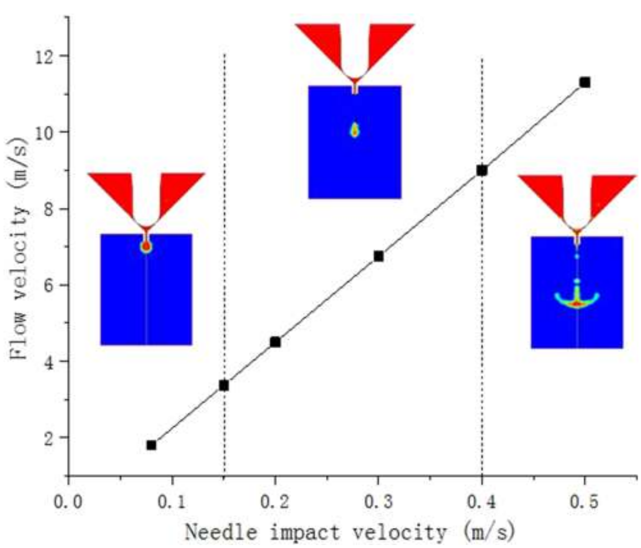

FIG. 6. Droplet ejection effect in different needle impact velocities.

Fig. 8 shows the motion characteristic curve of the needle, from which the rising and falling edges change nearly linearly with time. The rising and falling edges of the curve represent the downward and upward movement of the needle, respectively. The abscissa represents the signal points collected by the laser micrometer (which can be converted to time), and the ordinate represents the relative displacement of the needle. Cursor A is at a low level, whereas cursor B is at a high level. The difference between the ordinates of cursors A and B is the absolute needle displacement.

The needle impact velocity can be calculated through absolute displacement divided by the rising edge time.

The absolute needle displacement at different driving voltages is measured, and the corresponding data are obtained and plotted, as shown in Fig. 9. The figure shows that the absolute needle displacement is positively correlated with the driving voltage.

The previous experiments reveal that the needle impact velocity is related to the driving voltage and the rising edge time. Therefore, these parameters are combined to measure the needle impact velocity in the following experiment (adjusted at intervals of 0.05 m/s). As shown in Fig. 10, the target needle impact

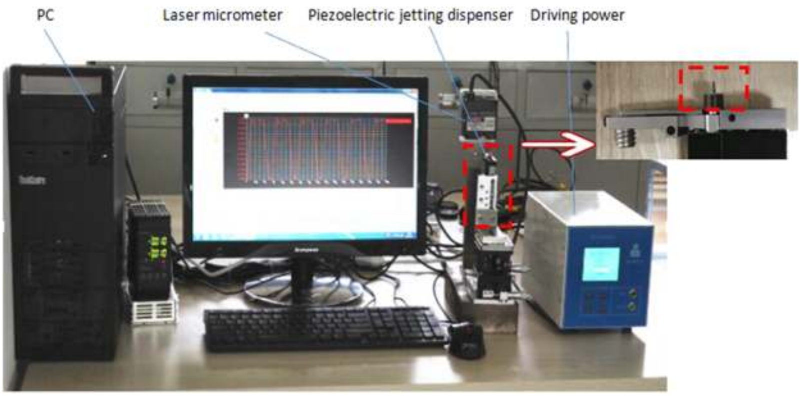

FIG. 7. Experiment bench for needle impact velocity.

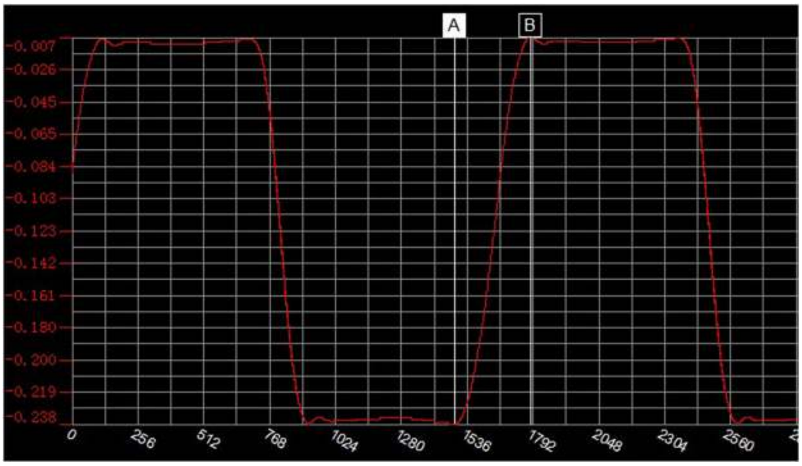

FIG. 8. Motion characteristic curve of the needle.

velocities from 0.05 m/s to 0.55 m/s are obtained by adjusting the two parameters.

In the following experiment, the needle impact velocity will be conducted as a variable to verify its influence on the jetting effect.

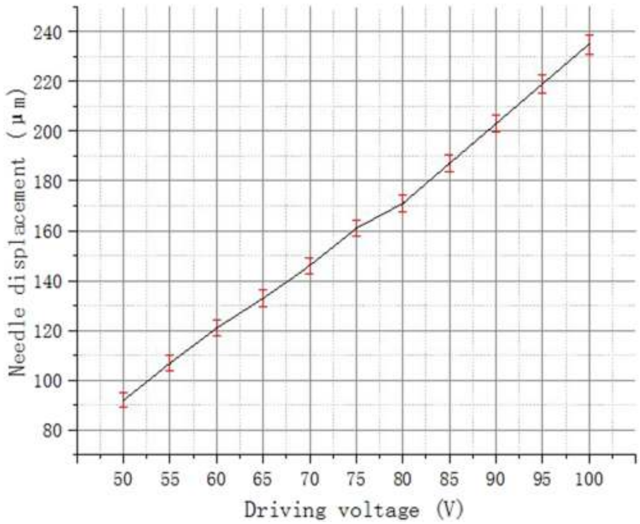

FIG. 9. Relationship between driving voltage and needle displacement.

B. Experiment on the influence of needle impact velocity on jetting performance

Needle impact velocity influences injection effect, as discussed in Sections II C and II D. The experiment is performed in this section for verification.

UV glue (Model 3321, Loctite, USA), which is colorless and has 5,000 cps viscosity, is the experimental medium used in this test. The experiment bench includes a piezoelectric jetting dispenser, a motion platform, a piezoelectric driving power, an image measuring instrument (Wanhao, VMS-1510F, China; precision: 2 μm), a high-precision electronic scale (Sartorius, BT125D, Germany; range: 120 g, resolution: 0.01 mg), and a pressure valve (SMC, IR1020-01, Japan, range: 0.005–0.8 Mpa; Fig. 11).

The motion platform drives the piezoelectric jetting dispenser according to the specific order. When the designated location is reached, the motion platform sends an operating signal to the driving power. Thereafter, the driving power sends a pulse signal and drives the piezoelectric stack to vibrate. Meanwhile, the droplets are ejected from the operating jetting dispenser onto the substrate.

In this experiment, the supply pressure is set to 0.2 MPa in the entire process. The selected nozzle has a diameter of 50 μm and a taper angle of 90°, and the selected needle has a radius of 0.5 mm. Different needle velocities measured in Section III A are set for injection experiments. The droplet weight is measured five times in each velocity, and the standard deviation is calculated in

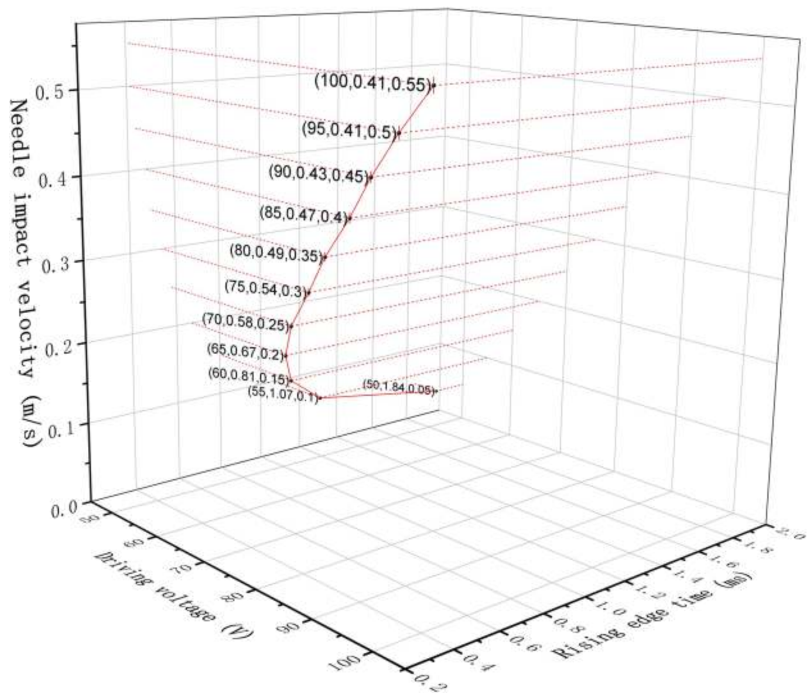

FIG. 10. Combination parameters for the target needle impact velocities.

each set of data (the droplet weight in this study is based on the injection of 1,000 droplets, the total weight is measured by the precision electronic scale, and the weight of a single droplet is averaged by calculation). The relationship curve between the needle impact velocity and droplet weight is plotted in Fig. 10, as well as the injection effect graphs at different needle impact velocities.

When the needle impact velocity is $V_S < 0.15$ m/s, the droplets cannot be detached from the nozzle to achieve jetting but adheres to the nozzle orifice (Fig. 12). When the needle impact velocity is $V_S > 0.15$ m/s, the weight of the droplet is positively correlated with the needle impact velocity. However, if $V_S > 0.4$ m/s, then the droplet sputters with satellite drops. The perfect droplet ejected effect is obtained only when 0.15 m/s $< V_S < 0.4$ m/s in such condition.

In summary, the experimental conclusion is consistent with those obtained from the previous simulated analyses.

C. Minimum droplet and consistency analysis

The minimum droplet and consistency determine the jetting resolution and precision of the piezoelectric jetting dispenser. Therefore, the minimum droplet and consistency that the device can achieve are investigated. The optimum size of the needle and

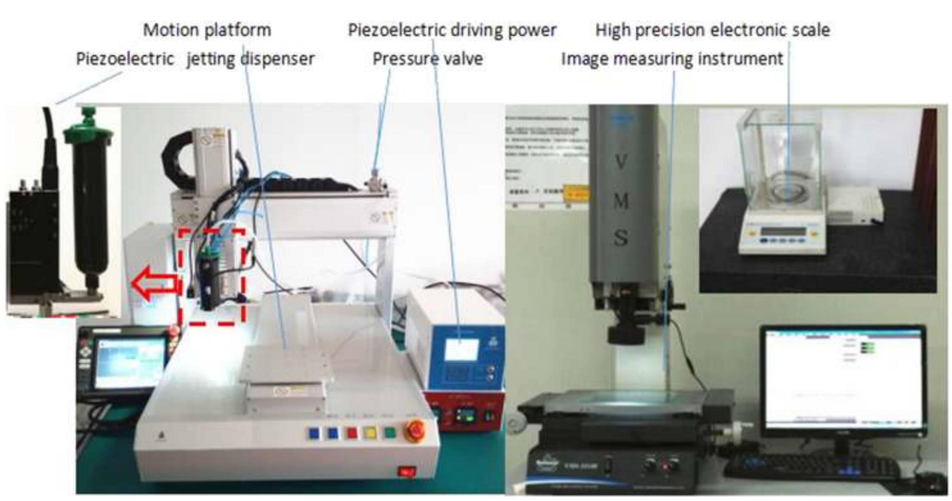

FIG. 11. Jetting experiment bench.

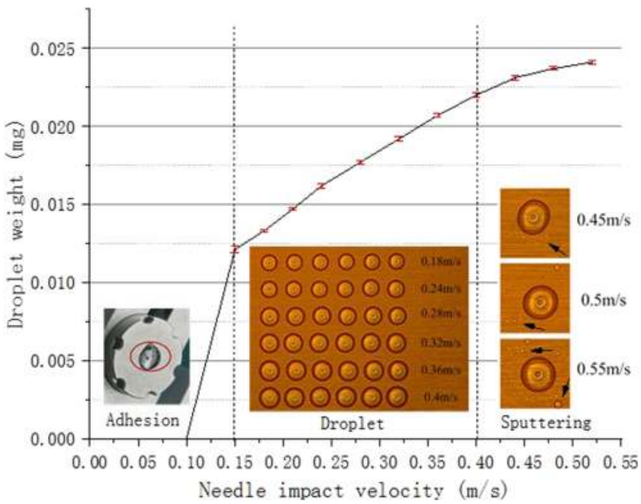

FIG. 12. Relationship between needle impact velocity and injection effect.

nozzle should be selected for the minimum droplet on the basis of the previous analysis.

In the following experiment, we select the needle with a minimum radius of 0.5 mm, the nozzle with a minimum diameter of 0.05 mm, and a maximum taper angle of 90°. The needle impact velocity is adjusted for the dispensing experiment in these configurations. Finally, we obtain a minimum needle impact velocity of 0.13 m/s (the driving voltage and the rising edge time are adjusted to 60 V and 0.93 ms, respectively), which is only adequate for stable injection. A total of 100 droplets are continuously ejected, and the diameter of each droplet is measured and recorded (the droplet diameter that is cooled and solidified on the substrate is measured by the image measuring instrument).

The average diameter of the 100 droplets is 272.1 μm, and the dispensing accuracy is ±2.5%. Fig. 13 shows the droplet diameter distribution and the magnification view of the minimum droplets.

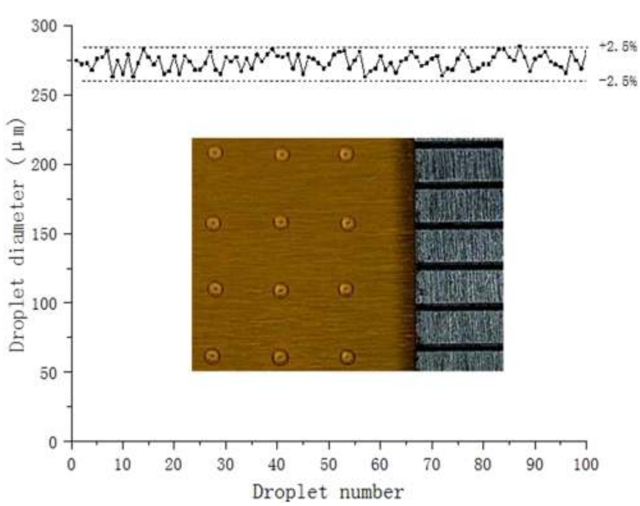

FIG. 13. Droplet diameter distribution.

IV. CONCLUSIONS

A piezoelectric needle-collision jetting dispenser for micro-droplet jetting was proposed in this study. The influence of the needle impact velocity on the performance of micro-droplet jetting was verified with theoretical and simulation analyses and experimental study. This work draws the following conclusions:

1. The droplet injection effect is related to needle impact velocity. Under specific experimental parameters (needle radius of 0.5 mm, nozzle diameter of 0.05mm, nozzle taper angle of 90°, liquid viscosity of 5000 cps, and inlet pressure of 0.2 MPa), when the needle impact velocity is less than 0.15 m/s, the injection can not be formed. By contrast, when the needle impact velocity exceeds 0.4 m/s, the ejected droplet sputtered with satellite drops. A perfect injection droplet will be formed only when the needle impact velocity is between 0.15 and 0.4 m/s.
2. The needle impact velocity is positively correlated with the weight or volume of the sprayed droplets.
3. Experimental analysis indicates that a UV glue with viscosity of 5,000 cps can be ejected with a minimum average diameter of 272.1 μm by using a needle with a radius of 0.5 mm, a nozzle with a diameter of 50 μm, a taper angle of 90°, a supply pressure of 0.2 Mpa, and a needle impact velocity of 0.13 m/s. The variation of the droplet diameter is within ±2.5%.

Needle impact velocity was investigated in this study. Future work will focus on the jetting effect of the needle structure, such as flat-head and concave needles, to examine further the needle-collision dispenser.

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REFERENCES

[1] D. M. Jacobson, “Lightweight electronic packaging technology based on spray formed Si-Al,” Powder Metallurgy **43**(3), 200 (2000).
[2] K. Y. Ahn, L. Forbes, and E. H. Cloud, U.S. Patent 6,570,248 (27 May 2003).
[3] F. Medina, R. Wicker, and J. A. Palme, U.S. Patent 8,252,223 (28 August 2012).
[4] D. Sun, J. Gao, and J. Du, “Advances in fluid dispensing technology for micro-electronics packaging,” China Mechanical Engineering **22**(20), 2513–2519 (2011).
[5] T. Enderle, C. Fattinger, and G. Flury, U.S. Patent 6,415,995 (9 July 2002).
[6] Y. F. Yao, “Research on automated micro-liquid dispensing technology,” Journal of Mechanical Engineering **49**(14), 140–153 (2013).
[7] F. Medina, R. Wicker, and J. A. Palmer, U.S. Patent 8,252,223 (28 August 2012).
[8] J. Fan, J. L. Knighten, and N. W. Smith, “Evaluation of SMT decoupling design in a functioning high-speed PCB,” 2001 IEEE International Symposium on. IEEE 2, 1097–1101 (2001).
[9] Y. Chu, C. Chen, and C. Tsou, “A silicon-based LED packaging substrate with an island structure for phosphor encapsulation shaping,” Packaging and Manufacturing Technology **5**(2), 155–162 (2015).
[10] H. L. Tsai, W. S. Hwang, and J. K. Wang, “Fabrication of microdots using piezoelectric dispensing technique for viscous fluids,” Materials **8**(10), 7006–7016 (2015).

[11] X. Y. Shu, H. H. Zhang, and H. Y. Liu, "Experimental study on high viscosity fluid micro-droplet jetting system," Science in China Series E: Technological Sciences **53**(1), 182–187 (2010).
[12] H. Liu and H. Gao, "Research on jetting process of micro-droplet jetting technique based on converse piezoelectric effect," 2010 International Conference on. IEEE 2, 224–227 (2010).
[13] L. Wang, X. Du, and Y. Li, "Simulation and experiment study on adhesive ejection behavior in jetting dispenser," Journal of Adhesion Science and Technology **28**(1), 53–64 (2014).
[14] C. Zhou, G. Deng, J. Li, and J. Duan, "Flow channel influence of a collision-based piezoelectric jetting dispenser on jet performance," Sensors **18**, 1270 (2018).
[15] G. Deng, "A simplified analysis method for the piezo jet dispenser with a diamond amplifier," Sensors **18**(7), 2115 (2018).
[16] S. Lu, G. Cao, and H. Zheng, "Simulation and experiment on droplet formation and separation for needle-type micro-liquid jetting dispenser," Micromachines **9**(7), 330 (2018).
[17] S. Lu, H. Jiang, and M. Li, "Nozzle and needle during high viscosity adhesive jetting based on piezoelectric jet dispensing," Smart Materials and Structures **24**(10), 105023 (2015).
[18] S. Lu, B. Chai, and Y. Liu, "The experimental study on the influence factors in adhesive dispensing dot diameter of impact jetting valve," Packaging and Manufacturing Technology **6**(2), 326–330 (2016).
[19] C. Zhou, J. Duan, and G. Deng, "A novel high-speed jet dispenser driven by double piezoelectric stacks," IEEE Transactions on Industrial Electronics **64**(1), 412–419 (2017).
[20] C. Zhou, J. Li, and J. Duan, "Control and jetting characteristics of an innovative jet valve with zoom mechanism and opening electromagnetic drive," Mechatronics **21**(2), 1185–1188 (2016).
[21] C. Zhou, J. Duan, and G. Deng, "Giant magnetostrictive material based jetting dispenser," Optik-International Journal for Light and Electron Optics **126**(24), 5859–5860 (2015).