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Optimized Performance of Piezo-Driven Jet Actuator for Thixotropic Epoxies in Electronics Assembly

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***Abstract*—The electronic assembly industry's growing need for advanced packaging and miniaturization calls for a more automated, regulated process with higher units per hour and tighter tolerance levels. This article deals with an advanced low-volume fluid dispensing process on various substrates using new jet dispensing technology on a faster and more accurate platform. Jetting has been widely used to jet out material in small quantities for various purposes. By striking a piston over a seat, jetting technology helps dispense fluid droplets from the nozzle tip and propagate them toward the substrate in a precise volume A new jet dispensing valve with a piezoelectric base improves performance and stability over time by depositing thixotropic adhesive materials within tighter tolerances in smaller volumes. One noticeably clear advantage is the ability to control the droplet size as a function of piston lift with good volume control. The ability to deposit small masses consistently and precisely, with droplet placement accuracy is determined by the relationship between the commanded and actual positions in two-dimensional spaces, which is what defines performance. The new feed-forward control piezo-driven jet valve hardware, which demonstrates faster performance with necessary valve stability equivalent to the assembly production environment, resolves two major challenging factors: dispense accuracy and throughput. This article addresses dispensing requirements like droplet dispense quality, droplet placement accuracy, droplet circularity, and line dispense quality.**

***Keywords*—dispensing, jetting, piezo-driven, UPH**

Introduction

Demands for more compact devices lead to smaller printed circuit boards (PCB) with higher density possessing a mix of surface mount components. Shorter product life cycles and an increase in units per hour (UPH) during assembly production offer some challenges to the process engineer [1]. The process engineer must be familiar with the latest innovations in dispensing, understand their strongest and weakest elements to determine the benefit of implementing any modern technology into the production environment.

More recently, researchers have proposed the use of dispensing for independent operation of fluids application, such as epoxies, onto the PCB for securing components. Needle contact applications like time-pressure, and rotary auger screw dispensing fall under the same application to dispense the fluid through the needle contact to the PCB.

The time-pressure dispensing mechanism as shown in Fig. 1a drives the fluid out of the needle through the application of pressure onto the syringe. The fluid will stop dispensing from the needle as the applied pressure is switched off from the actuator. In rotary auger-screw dispensing, shown in Fig. 1b, the fluid is moved along the cartridge by the rotary motion of the helical auger screw controlled by the driven motor through the application of pressure onto the syringe and finally driving it out of the needle. It is generally used for high-viscosity applications due to the steady movement of the fluid through the cartridge and developed high pressure at the bottom of the cartridge due to a shearing force because of the rotary motion of the auger. Jetting works mostly on the principle of positive-piston displacement fluid dispensing (Fig. 1c) which involves a mechanism of pushing the fluid along the cylinder chamber through the reciprocating motion of the piston which forces the material out of the needle. Herein, the piston and cylinder are the two essential components in this driving mechanism.

Time-pressure has no shut-off mechanism to avoid low and medium-viscosity fluids to drool and string off from the nozzle tip. Also, it has varying reply times due to changing air volume between the cartridge plunger and the air feed mechanism which leads to inconsistent dot volumes. Time-pressure dispensing is mostly applicable to high-viscosity fluids used for gasketing and RTV silicone handheld applications. Time-pressure dispensing has another inherent disadvantage: slow dispensing speed due to repetitive *Z*-axis motion—move down to place the fluid, then move up to break away. As it retracts, the dispense head sometimes leaves behind strings or tails that can contaminate the work surface or create unwanted interconnections. Programming special maneuvers to reduce stringing/tailing is only moderately effective and adds even more time. Jetting is mostly applicable to all fluid types ranging from low to semihigh viscosity fluids which can be jetted at a much faster speed. Jet dispensing is common in Surface Mount Technology applications such as silver epoxy for die bonding, adhesive dispensing for component assembly and encapsulant underfill for flip chips. For example, time-pressure dispensing with a 22-gage needle, i.e., hole inner diameter of 430 μm will take around 5-6 s while jetting would take 1 s to dispense a 25-mm-long epoxy line.

Figure 2 displays that jet dispensing had a revolutionary effect over needle dispensing like rotary auger or time-pressure which requires motion of the dispense valve in the *z*-axis to dispense good quality droplets. Vertical *z*-axis motion was required to overcome fluid cohesion which was eliminated when jetting was introduced with no *z*-axis motion required. Jetting is performed "on the fly," meaning that as the dispense

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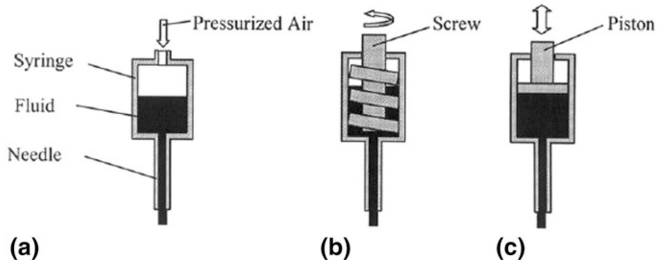

Fig. 1. Schematic Diagrams of the Fluid Dispensing Systems: (a) time-pressure, (b) rotary auger-screw, (c) positive-displacement [5].

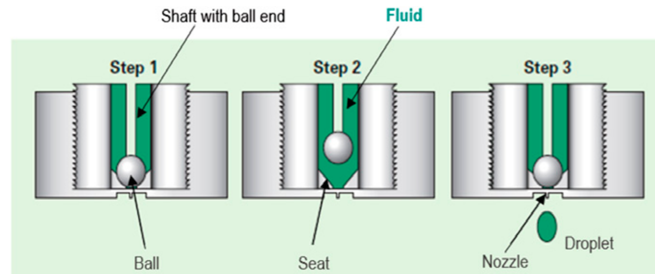

Fig. 3. Jetting technology [20]. Step 1: ball on the seat. Step 2: ball retract and fluid fill. Step 3: ball returns and fluid shears ejecting a droplet.

valve moves from one dispense location to another, droplets are fired simultaneously to have them land at the commanded position. Jetting technology creates droplets of more precise volume due to the action of the piston striking the seat, releasing the droplet from the nozzle [1, 19].

Jetting, as shown in Fig. 3, uses the "ball and seat" mechanism to supply the fluid to the ball seat area with the application of pressure. For this method, as the ball moves in the downward direction to strike the seat, it dispenses the fluid in the form of a droplet onto the substrate [4, 7]. The ball is always seated on the seat to close the fluid path eliminating any drooling or stringing from the nozzle tip.

Considering the requirements of the electronic packaging industry, numerous studies have been performed in the past. To achieve optimal performance, maintaining the distance between the nozzle and the substrate and ensuring precise position control and increased cycle time are essential.

Related Work

To address the limitations of contact-type dispensers, a new jetting dispenser, which ejects fluid from the nozzle using the kinetic energy of the needle movement, has been developed [13, 14]. Wang et al. developed a jetting dispenser that incorporates two piezo stack actuators and a displacement amplification mechanism [16]. Luo and Deng developed a dynamic model of a piezoelectric jetting dispenser and assessed the jetting performance using computer simulation, considering parameters, such as temperature, backpressure, and frequency [15]. Ning et al. [8] proposed a flexible hinge displacement amplifier for micro displacement amplification of a piezo-actuator to realize high-frequency jetting dispensing with the use of silver conductive inks. Borghetti et al. [9] demonstrated the influence of printing parameters on the performance of the Nordson PICO Jetting system mounted on the Neotech PJ15X machine by depositing an extremely low-viscosity silver ink, typically used for the fabrication of sensors and interconnections. Improper setting of the printing setup caused undesired spots and irregular lines therefore optimal settings for the printing setup were found for each silver ink. Kolbe et al. [10] demonstrate the feasibility of an inkjettable, isotropically silver-filled conductive adhesive applied successfully by piezo-ink jet technology. Lu et al. [11] highlight how the effect of spring compression along with the impact stroke influences the dot diameter of the dispensed adhesive. Cheng et al. [12] focus on the high- and low-voltage driving methods of piezoelectric spray jet dispensing valves. This technique measures the droplet volume of 900 centipoise viscosity UV glue at different high- and low-voltage drives. Borghetti et al. [17] demonstrate the use of an aerosol jet printer to dispense a silver conductive ink with a viscosity of 500 centipoise at 25°C for printing of silver conductive tracks for a low-cost bioelectronic device. Gugliandolo et al. [18] display an inkjet printing technology dispensing a silver-based conductive ink on a conventional 1.6-mm-thick FR4 substrate. All earlier work highlights more on the low viscosity adhesives within the range of 3-10 centipoise with the inkjet piezo printing technology which is very slow and not suitable for medium viscosity adhesives. With inkjet piezo technology, it is hard to set up and optimize the process parameters for better dispensing quality along with good dot placement accuracy. Medium-viscosity epoxy adhesives ranging from 6,000 to 20,000 centipoise viscosity are difficult to jet due to their thixotropic nature. Thixotropic fluids tend to lower down in viscosity with the application of constant shear but are not attainable to viscosity levels close to conductive silver inks. This article proposes an approach to dispensing smaller dispense deposits with good weight repeatability at much higher actuation speed and dot placement accuracy required for medium viscosity thixotropic epoxy adhesives required in microelectronics packaging.

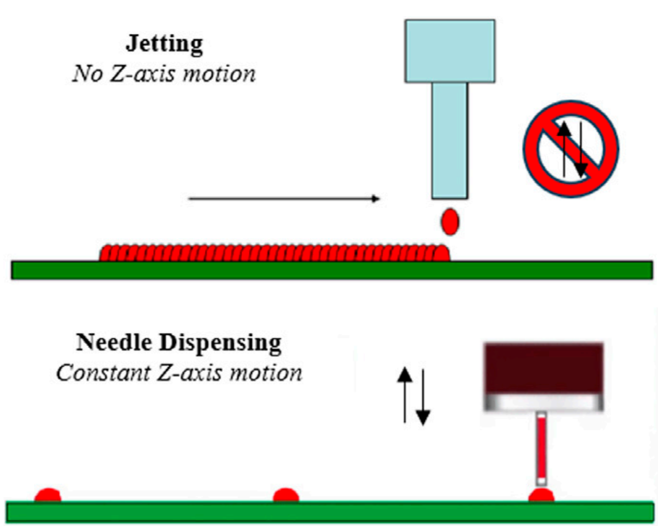

Fig. 2. Jetting vs Needle Dispensing [3].

Dispensing Theory of Operation

The piezo-driven dispense valve as shown in Fig. 4 is a piezoelectric actuated jet to deliver high throughput with exceptional

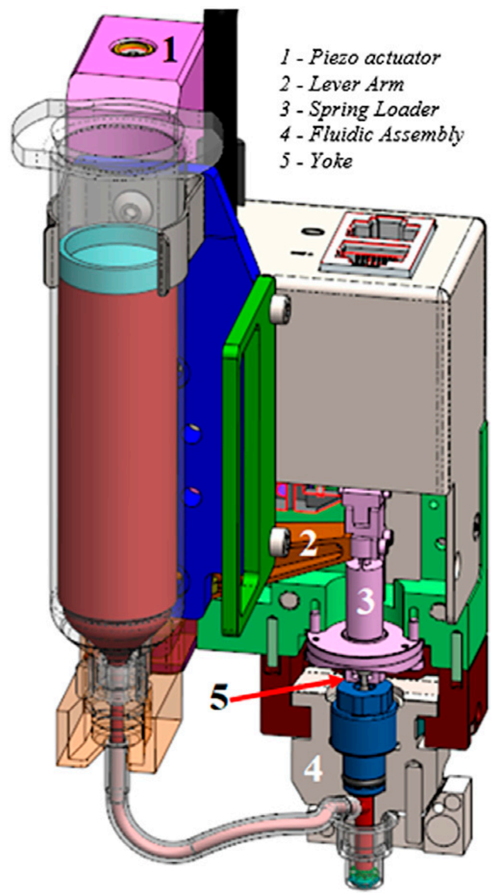

Fig. 4. Schematic diagram of a piezo-driven valve.

droplet deposition accuracy and superior process control. There are several piezoelectric jets available commercially for dispensing purposes, but these are limited to low-viscosity materials. A more refined way is to control the drive mechanism to open and close the orifice rapidly to dispense fluids through a ball-seat striking mechanism [2].

Fluid is fed at high pressure to the system therefore when an orifice is opened a droplet of fluid gets filled in section in front of the piston and gets detached from the orifice when the ball piston strikes the seat. The rapid shut-off motion of the piston provides momentum to the droplet carrying the fluid away from the nozzle which converts into a droplet propagating toward the substrate at a velocity several times the contact velocity of the piston striking the seat as up to 12.0 m/s. A high-speed camera for droplet visualization at a higher frame rate is used to observe the trajectory of the droplet along with measuring the distance traveled in a given time frame to measure the velocity of the ejected droplet. A spring above the piston head located in the yoke helps in decoupling the mass of the higher mass actuator along with the lever arm from the lower mass piston while approaching the down stroke motion. The maximum charge of 0.52 mm required to dispense various droplet sizes at desired frequencies is produced by amplifying the piezoelectric motion through a lever mechanism. The quantity of fluid, i.e., jetted out of the orifice in a single stroke can also be controlled with a fast and repeatable valve actuation made possible by piezo actuators only. Easy and quick changeover of parts reduces the operator's intervention to provide a stable configuration over a period in the production environment.

To dispense small droplets, small nozzles are required along with high pressure onto the fluid, temperature to lower down the viscosity, and precisely controlled valve actuation. To deliver the fluidic pressure wave needed to eject a droplet from the orifice, an electric drive signal between 0 and 150 V is applied to the piezoelectric material. The advantages of this technology are the droplet size, actuation speed, higher droplet placement accuracy, and better droplet characteristics with good circularity.

Fluid is pressurized in the syringe using air to maintain the continuous flow of fluid across the fluid path in the dispensing system. The chamber at the end of the fluid path is surrounded by a nozzle nut over which the heater is mounted to control the desired temperature. Temperature helps to lower down the viscosity so the fluid can be jetted with more ease. Fluid begins to flow toward the nozzle as the piston begins its upstroke. As the piston begins its down stroke, fluid velocity at the nozzle increases, ultimately resulting in the release of a droplet as the piston strikes the seat. The advantages of a piezo-driven valve are indicated below

1. increased throughput;
2. automatic calibration; and
3. volume control.

A. Increased Throughput

The most crucial factor in meeting the UPH requirements set mostly by the electronic packaging assemblers and manufacturers to meet customer demand has been increased throughput in the manufacturing assembly environment. The number of units of the final product produced per hour (UPH) is the unit of measurement used in industrial production processes. Better vision capture and imaging systems, conveyor mechanisms, strong software-controlled architecture, and laser height sensing—all of which are placed on a more accurate and swifter platform to produce consistent dispensing results—are some of the main components boosting throughput.

Fig. 5 shows a 65% reduction in cycle time at 500 Hz compared with 50 Hz, with a 10-fold increase in actuation speed. A piezo-driven valve offers an 186% UPH advantage at 500 Hz compared with 50 Hz. UPH is a measurement of manufacturing

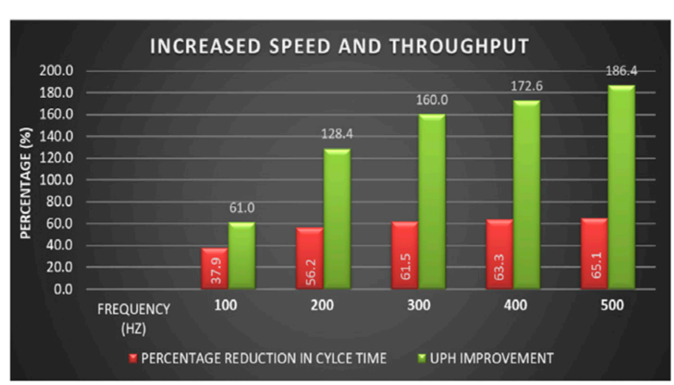

Fig. 5. UPH Improvement.

or assembly production capacity, i.e., how many units of a final product can be produced per hour. A programmed test which consists of lines and dot commands from the process program is executed in a manufacturing environment similar to the manufacturer's facility. This test helps to determine the UPH improvement and cycle time reduction percentage numbers.

A frequency of 500 Hz implies that the valve can dispense 500 shots per second on the substrate. The cycle time and UPH calculation for different frequencies during the dispensing operation of one carrier containing four panels with four boards each which in total includes 16 PCBs of the product along with the clean needle operation. Each PCB is like a handheld consumer device board. The time intervals for board transfers through the conveyor system, board clamping, capturing board reference points via machine vision, and height sensing commands are not factored into the cycle time computation.

B. *Automatic Calibration*

Automatic calibration characterizes the valve to determine the droplet size (weight per dot) as a function of the charge value as shown in Fig. 6. Charge is defined as the distance the piston moves from the starting position during the upstroke [3]. The charge value is settable in the programming software system. A piezo-driven valve is initially characterized within a charge range to target the desired droplet size depending upon the hardware used. The feedback control on the charge value allows the automation of this droplet size adjustment.

A piezo-driven valve hardware configuration and characteristics of the dispensed fluid can have a profound effect on the PISTON UPSTROKE versus DROPLET SIZE function. Droplet size is mostly affected by piston upstroke, i.e., charge, nozzle orifice size. Other factors that would come into play would be the nozzle temperature through an external nozzle heater which is used to lower the fluid viscosity to jet a droplet. Higher nozzle temperature will help to increase the droplet size. As the temperature increases, the molecules move more rapidly and their kinetic energies are better able to overcome the forces that hold them together; thus, the viscosity of the liquid decreases. Nozzle temperature is mostly recommended by the adhesive manufacturer. Referring to the piezo-driven valve characterization, the automatic calibration function runs a convergence algorithm to estimate a starting charge value that satisfies the droplet size requirement. The valve output is measured, and the results are compared with the target droplet size. If the droplet size is within the allowable process tolerance, the "tuning" is done. If not, a second estimate is made, and the output is measured with a new charge value. Again, the droplet size is compared with the target. This process will iterate until the measured droplet size is within tolerance or the maximum number of iterations are exceeded. This automated process helps to target the desired droplet size over an extended period of time without any operator intervention.

C. *Volume Control: Good Performance and Stability*

Repetitive droplet formation requires precise control of the volume being dispensed from the valve to deliver consistent droplets through reliable hardware and software control settings. The armature yoke holds the piston in place during the upstroke and downstroke motion, and the piston is tracked by a piezo-driven valve using two sensors and a closed-loop control architecture. To maintain the necessary charge, an adaptive feed-forward control operates in the background, driving the piston's next stroke based on its previous strokes. Here charge is the piston opening during the upstroke motion and closing during the downstroke at a determined starting position when the ball piston strikes the seat to restrict any further motion of piston in the downward direction. A piezo-driven valve charting tool provides the user with the capability to track each complete stroke of the piston as shown in Fig. 7. The black, red, and green line indicates the reference, armature (yoke) and piston position, respectively. A little bit of rebound was observed in the piston profile because of the piston hitting the contact seat. This rebound occurs within less than 0.5 ms going up and down. Rebound does not allow the piston to open the outlet to feed little material in front of the piston during the down stroke motion to dispense another droplet therefore not affecting the final droplet quality. The armature is overdriven to a position below the seat contact to dampen the effect of vibration at higher speed of operation to make sure the piston contacts and seals against the seat with minimum bounce.

Droplet Analysis

Quality tests were formed to check the droplet characteristics in terms of droplet weight repeatability, droplet placement accuracy, droplet diameter repeatability, and visual inspection of droplets to account for any contamination due to satellites. These are some initial findings on the droplet characteristics after the valve is evaluated for performance stability in terms

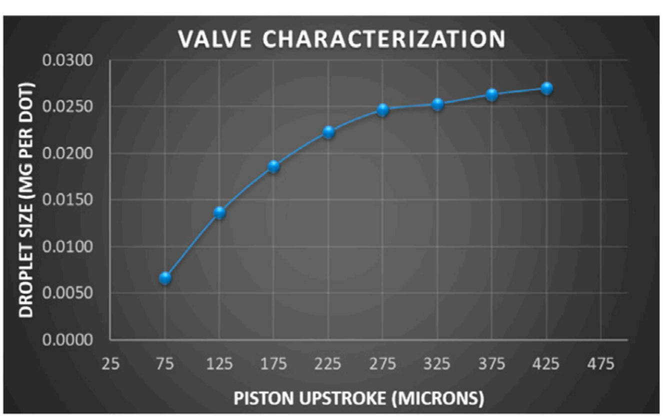

Fig. 6. Piezo-driven Valve Characterization.

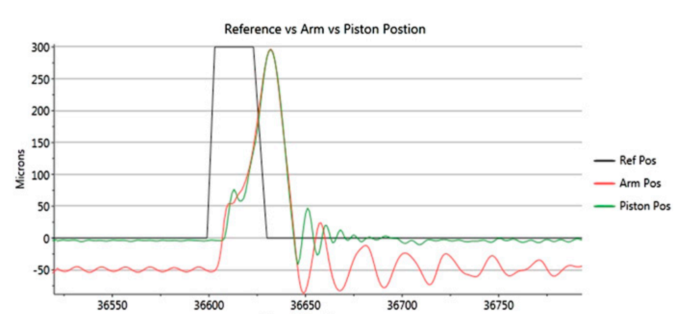

Fig. 7. Piezo-driven Valve Charting Tool.

of droplet weight repeatability. An important aspect is whether the process is capable of meeting requirements which are stated as specification limits in the electronic packaging industry. Process capability is used to analyze the performance of the valve in terms of total weight variability.

A. Valve Performance: Weight Repeatability

Valve performance is defined in terms of long-run weight stability in the production environment to lay out a robust set-up to determine good yield. A practical way to evaluate the performance is to determine the variation of the dispensed weight from the target weight. If the jet dispenses less material from the desired target, then there is insufficient coverage over the components and more material tends to overflow onto the adjacent components therefore contaminating the board in both cases. Commonly most of the jets have a problem of dispensing materials without causing a drift in volume from the desired target weight over time which affects the yield.

Piezo-driven valve jetting has shown good results in dispensing epoxy adhesives for electronic encapsulation during trial applications. Fig. 8 displays the weight repeatability data for both 2 and 5 mg of epoxy adhesive dispense material.

Table I shows the process capability calculated at different target total weights for a tolerance level of ±5% assumed during trial evaluations.

B. Droplet Placement Accuracy

An array of droplets is dispensed on a glass substrate at a commanded location and the difference between each droplet's actual dispensed position and its commanded position is used to calculate the droplet placement accuracy. This difference is marked as a deviation in the *X* and *Y* direction. An OGP Metrology system is used for the measurement of *X* and *Y* location of each droplet along with droplet diameter. Droplet placement accuracy depends upon the distance traveled by the droplet while propagating in the downward direction from the orifice tip toward the substrate which is termed as dispense height. Placement accuracy differs with the increase in dispense height which lowers down the impact velocity as the droplet needs to travel a larger distance while moving vertically downward [5]. Less impact velocity can cause the droplet to deviate slightly from the vertical path therefore affecting the placement accuracy. When the fluid gets detached from the nozzle, it converts into a droplet which sometimes gets deflected through the orifice tip and lands away from the commanded location on the substrate therefore affecting the placement accuracy. The difference between each droplet's measured or actual dispense location and its nominal or commanded position is the measured deviation. Deviation in *X* and *Y* direction results is within ±25 μm for epoxy adhesive for different dispense heights varying from 2 to 4 mm is shown in Fig. 9. Such good accuracy even at higher dispense height provides an advantage to dispense within tighter pitches between components.

Table I
WEIGHT REPEATABILITY DATA

TOLERANCE LEVEL	5.0%	5.0%
TARGET WEIGHT PER DOT, *mg/dot*	**0.0250**	**0.0250**
TARGET TOTAL WT, *mg*	**2.00**	**5.00**
Cpk	**2.41**	**2.24**
Cp	**2.44**	**2.31**
AVERAGE TOTAL WEIGHT, *mg*	2.001	4.993
STD DEVIATION	0.014	0.036
UPPER SPECIFICATION LIMIT, *mg*	2.100	5.250
LOWER SPECIFICATION LIMIT, *mg*	1.900	4.750
MAX. WT, *mg*	2.038	5.080
MIN. WT, *mg*	1.972	4.905
RANGE	0.066	0.175

C. Droplet Quality and Circularity

Droplet quality defines how the droplet gets placed onto the substrate with good droplet diameter accuracy and no contamination of the adjacent components. Visual inspection is the process of visually inspecting droplets under a microscope with a human eye to detect any satellite contamination or formation that may occur during the dispensing cycle. Visual examination is yet another useful tool for determining whether the droplets are misaligned or not [5]. To jet small droplets, smaller nozzles are required with smaller charges which can be achieved through the piezo-driven valve. Visual inspection shows good droplet quality with good placement accuracy even with smaller diameter droplets close to 300 μm with no satellite formation. Fig. 10 shows the droplet quality along with circularity with an epoxy adhesive material from a dispense height of 2.0 mm from the substrate.

Fig. 8. Weight Repeatability for a piezo-driven valve.

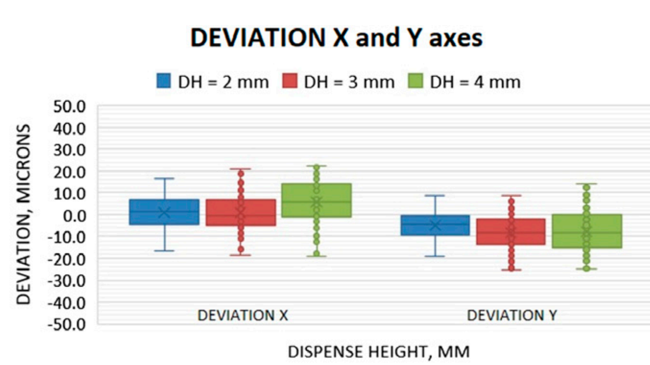

Fig. 9. Deviation in X and Y axes at varying dispense height.

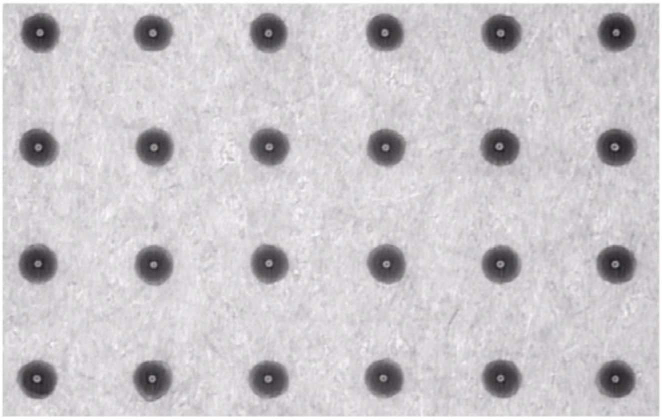

Fig. 10. Droplet quality and circularity.

Droplet sizes can vary from as small as 200 μm to large sizes like 4,000 μm. Larger dots can either be dispensed as a combination of smaller individual droplets stacked on top of each other at the same *XY* dispense location or large individual droplets from a bigger nozzle orifice. The former approach is used more widely given the challenge to dispense into very tight spaces.

Molecules in a fluid attract each other equally in all directions, but surface molecules feel attraction from fewer surrounding molecules, causing the fluid to minimize surface area; thus, small droplets adopt a spherical shape for optimal volume-to-surface area ratio, whereas larger droplets become less spherical due to external influences like gravity and air resistance. Smaller droplet sizes are difficult to dispense given the material viscosity, percentage of filler content present, and orifice hole size limitations. They are easy to get deflected from a vertical trajectory path given their smaller volume as compared with larger droplets. Droplet circularity is very much dependent on dispensed fluid characteristics, the surface finish of the substrate on which the droplet will be dispensed, and how it adheres to the dispensed substrate. But both smaller and large droplets hold a round shape once they land on the substrate.

Good circularity is defined through the droplet diameter measurement. Fig. 11 shows the droplet diameter within ± 10 μm for an epoxy adhesive material for the desired droplet diameter of 350 μm.

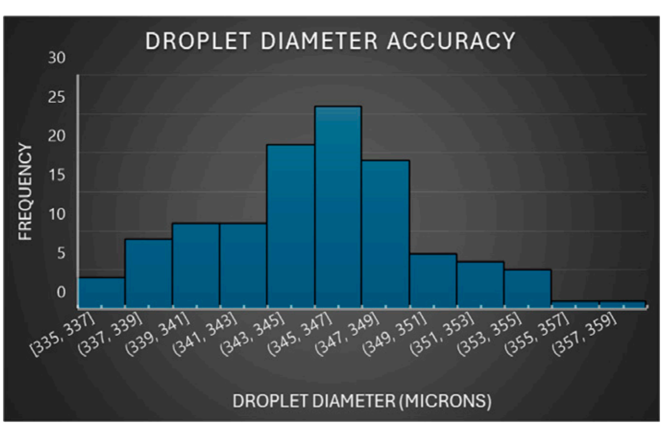

Fig. 11. Droplet diameter accuracy for epoxy adhesive.

D. Droplet Impact

Any size droplet can cause contamination due to satellite formation during the fluid separation from the nozzle tip. That is where proper process parameters, such as piston ball size, nozzle orifice size, air feed pressure, and nozzle temperature are essential to set up a good process with no contamination. Splashing is a phenomenon that occurs when fluid is dispensed into a cavity or trench present on the substrate already filled with fluid. These fluids have very low viscosity in nature.

Jetting frequency is defined as the number of piston strokes per second which is equivalent to the number of droplets dispensed per second. Jetting frequency is driven by how fast the piston will be lifted, fluid filled into the chamber, and piston stroke down to hit the seat to eject a droplet. Because of the piston movement onto the seat with a very high velocity, the fluid is pushed with high pressure through the nozzle. The transferred momentum from the piston to the fluid works as an additional acceleration force. Higher jetting frequency leads to higher droplet velocity but that does not reflect a good droplet formation every time. If there is not sufficient tact time between piston strokes, then piston rebound can result in tiny droplet formation on the nozzle orifice tip which could cause contamination for the successive droplet. To avoid either epoxy splash or contamination after each stroke at higher frequencies, the jetting frequency must be lowered down to avoid splashing or contamination.

E. Line Dispense Quality

Droplet characteristics, as previously defined in terms of droplet placement accuracy and circularity, have a significant impact online dispense quality. Individual droplets fired at a specific point through the line width in the process program make up a line command. The number of droplets dispensed per millimeter in a line command that contains a series of droplets spaced correctly to align and form a straight, non-scalloped line is known as the line width [5]. The fluid follows the shortest path to the deepest scallop to form a perfectly straight line. Once the droplets touch, the boundary is scalloped but the droplets compress further to form straight edges as shown in Fig. 12.

Customers are becoming more concerned these days with the consistency and straightness of the lines that are dispensed in jetting operations, rather than just from dot-to-dot command

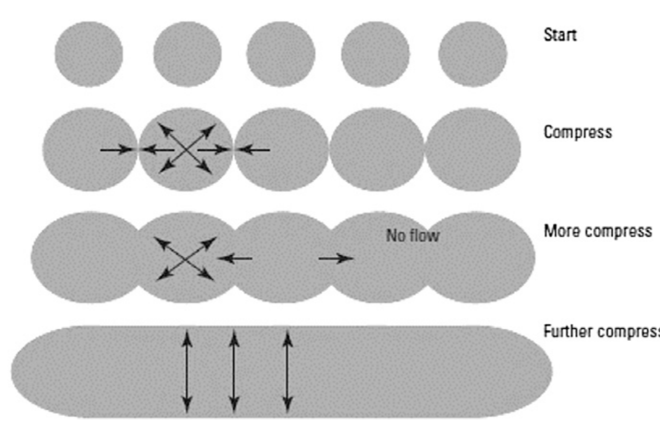

Fig. 12. Jetting droplets within line command [6].

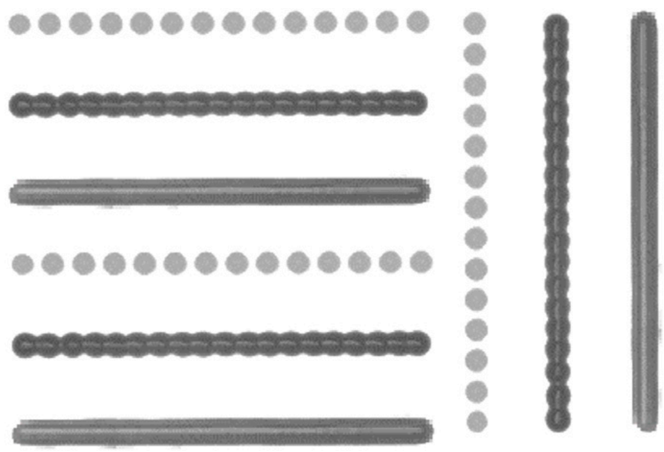

Fig. 13. Line Quality at different line widths.

motion to shorten the cycle time of their applications and boost UPH. Fig. 13 shows the line quality in the *X* and *Y* direction with the epoxy adhesive dispensed for line width ranging from 1 to 3 droplets per millimeter at a dispense gap of 3 mm from the substrate. The line formation becomes denser with more droplets dispensed per millimeter, resulting in a straight, non-scalloped line. The line quality improves with decreasing distance between the dispense valve and substrate.

Conclusions

Jetting has become a standard method in the assembly production environment because of the advantages over needle contact dispensing. Jetting operation can be used over a variety of fluids for a range of applications in the PCB assembly, advanced semiconductor packaging, LED assembly, flat panel display assembly, electromechanical devices and products that support alternative energy resources. A piezo-driven valve makes jetting faster and more repeatable with closed-loop controls and real-time piston tracking which enables more consistent valve performance. The ability to produce small droplets of thixotropic adhesives with good volume control, precise droplet placement accuracy and droplet diameter within tighter tolerances from higher dispense heights over the substrate at higher speeds are all significant advantages that differentiate and places the piezo-driven valve much ahead of other available jets in the marketplace.

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