Polymeric Material Adhesion and Common Failure Mechanisms in the Assembly of Jettable Fluid Devices

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Abstract

The two most common methods of non-contact, jet printing technology in use today are piezo-electric crystal and thermal bubble. In operation, a piezo crystal flexes to push an ink or fluid drop out of the printhead nozzle while the thermal design uses a heating resistor to create a bubble that expands and exits the nozzle. In both designs there is intimate contact between the printhead and media being jetted. Jettable fluid delivery systems and other MEMS devices require reliable assembly of a variety of components. These components can be assembled through the use of molding materials, mechanical fasteners, and structural adhesives. Structural polymeric adhesives are most often the ideal choice because they mate the substrates to form a continuous surface. These bonding surfaces often consist of multi-layer silicon die, thin and thick wall engineered plastics, noble metals, and flexible substrates. The adhesives act as a barrier or seal, preventing the fluids from leaking while also protecting the device from potential environmental contaminates. This paper discusses polymeric material adhesion testing and common failure mechanisms associated with harsh environment fluid jetting. Some standard tests can be used to screen adhesives. One example of a widely used test is lap shear measurement, which can be developed for specific substrates. The test part can be evaluated at various temperatures as well as before and after exposure to a harsh chemical environment. If dissimilar substrates are to be bonded and a lap shear test is not practical, an alternative test can be developed. For example, a plastic and glass substrate bond may always fail with the glass fracturing. In this situation, the adhesive bond strength is not properly measured. Therefore, an alternative test, such as a shear strength push test, must be designed. In this test, a shear force is applied to an edge of a substrate bond, such as a die bonded to plastic. By altering the adhesive bond test, the failure mode will shift from a pull force to a peel force, thereby allowing for better representation of the actual bond strength for a given application.

Introduction

There are two types of non-contact, jet printing technology, piezoelectric crystal and thermal bubble. In operation a piezo crystal flexes to push an ink or fluid drop out of the printhead nozzle while the thermal design uses a heating resistor to create a fluid ink bubble that expands and exits the nozzle. In both designs there is intimate contact between the device and the harsh chemicals of the dispensing fluid. Piezo and thermal ink jet designs are under evaluation to dispense the harsh fluids used to build layer by layer of organic conducting and semi-conducting thin film transistors, organic light emitting diodes and dispensing fine multi-layers of reactive biological polymers to build the fine cell structure of bone and connective tissue.[1]

The manufacture of jettable fluid delivery and other microelectromechanical systems (MEMS) devices requires the assembly of a variety of components. The components can be assembled through the use of molding materials, mechanical fasteners or structural adhesives. Structural polymeric adhesives are most often the ideal choice because they mate the substrates to form a continuous surface. The bonding surfaces often consist of multi-layer silicon die, thin and thick wall engineered plastics, noble metals, and flexible substrates. Adhesives then become the barrier holding fluids within the device and also prevent the outside environmental contaminates from entering the device.

A schematic of a jettable device is shown in Figure 1. Typical devices will use a number of adhesives. For example, the electrical connections from the flexible circuitry connected to the silicon jetting device have to be protected from the chemical fluid inks within the device and from external contaminates. A uniform bead of a polymeric adhesive may be dispensed to surround these sensitive wires and encapsulate them. In addition to protecting the contacts from corrosion, the adhesive also cushions these wires from mechanical damage caused by equipment contact or dropping. This same material may also be used to fill the spaces or gaps created in the part design. Dielectric, thermally conductive or electrically conductive die attach adhesives fixture the silicon MEMS device in place orienting openings for fluid pathways from the ink reservoirs. Only adhesives offer the necessary flow control around and under components. These materials manage the coefficient of thermal expansion (CTE) mismatch of the various components and substrates.

Adhesive selection is influenced by many variables, but will primarily depend upon the bonding substrates, production processing options, and desired final finished product properties. There are some applications where the plastic substrates can not withstand high temperatures. In these cases, there are alternative curing methods for consideration. Additionally, there is a driving force to reduce the device size while increasing performance. Further, the aggressive fluid selected to dispense degrades the printhead assembly shortening the devices life.[2-6] This paper focuses on the adhesion testing criteria to help select adhesives for assembling a jettable device. The effect of jettable fluid on the adhesive performance is also discussed.

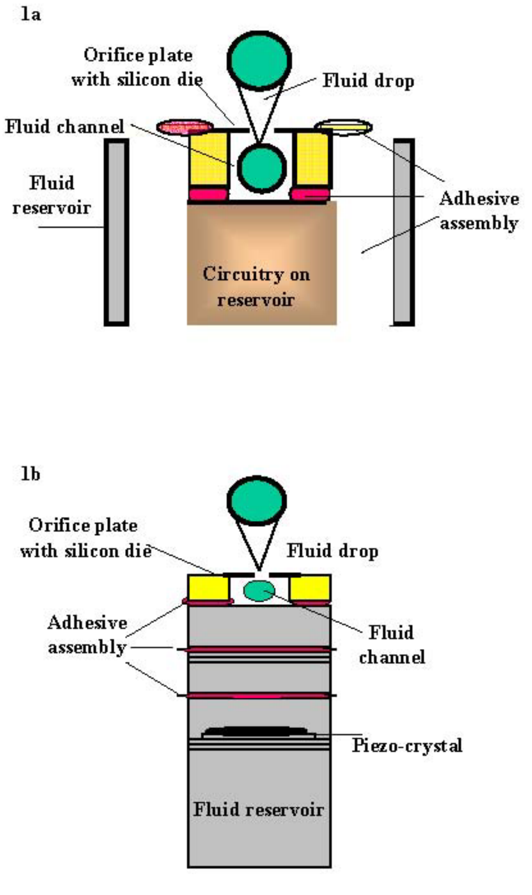

Figure 1. Schematic of ink jet devices (1a) thermal jet (1b) piezoelectric jet.[3,4,6]

Both thermal and piezoletrical jetting devices are complicated and require many adhesives for assembly.

Adhesive Design

Physical Property Considerations

The performance requirements of the device define the property targets for the adhesive. These adhesive targets may include:

Low Ionic Species

Adhesives with low ionic species such as halides may be desirable for wire bonds or lead encapsulation. Water from the ink media along with bias current during operation can extract anions such as chloride from low purity adhesive components. If the polymeric material, in conjunction with water, contacts the wire bond, corrosion will occur. Over time, the electrical contact may fail and cause a short making the device fail. Raw material selection for the adhesive can control the level of extractable species and extend device life. Thus, raw materials would be specially selected to have a low level of contaminates.

Coefficient of Thermal Expansion

When an assembly is thermal cycled, the various device components will expand and contract at different rates. The CTE mismatch among components and adhesive bond introduce residual stresses in the device. Theses stresses may generate small fractures and cause device failure. Failure may be adhesive to one of the substrates or cohesive where the adhesive tears leaving material on both bonding substrates. By selecting adhesives with a CTE closer to those of component and substrates, the component substrate's fatigue can be reduced by minimizing the movement of the device. Fillers are typically used in adhesive to reduce the CTE. As the filler loading increases, the CTE value decreases. An alternative path is to toughen the adhesive by including flexible compounds in the adhesive formulation. With this approach, the CTE of the adhesive will be greater but the adhesive will be more forgiving. The adhesive will move with the substrates without adhesion loss or fracture failure.

Modulus

Some assembly applications such as die attach and lead encapsulation require high modulus, or stiff support adhesives, for high strength. The adhesive must be toughened to resist impact damage. Conversely, a low modulus, flexible, rubber adhesive is used for potting and gap filling. The lower modulus allows the adhesive to move with the substrates. The adhesive absorbs and dissipates the stress so the assembly stays intact.

Thermal and Electrical Conductivity

Noble metals, such as silver, are compounded into adhesives to make an electrical connection between the die and substrate.

Thermally conductive adhesives are used to dissipate the heat from the device. Non-electrically conductive fillers such as boron nitride will simply conduct heat.

Compatibility with the Jetting Fluid

There are a variety of harsh chemicals that are jetted through the printhead nozzles and the assembly adhesives must not degrade with the contact.

Processing Consideration

Bonding and Curing

Adhesives may be thermoset or thermoplastic. Once a thermoset is cured it can not be reversed or easily re-worked. A thermoplastic can be applied from solvent or melted into place with a heated applicator. Typically, it is warmed until it is fluid and then poured into a casting. The higher the melt temperature, the lower the viscosity. The material can be applied to the substrate at room temperature or the substrate may be pre-heated to extend flow and open time until it is mated with another substrate. This process can be completed in seconds with the part attaining its full strength. Re-applying heat will soften and re-melt this adhesive for repair or re-positioning. Careful adhesive selection is required to assure the adhesive does not soften during normal device operating temperatures. An alternative to thermoplastics is thermosetting hot melt adhesives. Once applied, moisture post-cures the material to an irreversible solid. With either thermoplastic or thermoset hot melts, the assembly's substrates have limited temperature exposure. The hot melt solidifies immediately upon contact with the cooler assembly substrate. Flow can be enhanced by pre-warming the substrates.

Another type of fast, low temperature curing thermoset is acrylates. Ultraviolet light (UV) curable adhesives are cured very close to room temperature with a high intensity UV lamp. This type of adhesive requires a line of site exposure to the UV lamp. Some UV curable compounds contain additional curative to crosslink areas shielded from the UV source. These "shadowed areas" require a second curing step consisting of either heat or moisture. Most often UV curable materials are used in open areas and are applied as coatings, encapsulants and gap fillers.

Hot melt and UV curable adhesives are fastest processing with localized heat. UV curable material can cure so fast that the temperature exposure is very low. Products that have secondary cure require longer cure time and often have more operations steps in the curing process before the parts that are assembled are fully cured as is noted in Figure 2.

One and 2-part thermoset adhesives provide controlled curing options. In the case of 2-part chemistry, the cure is initiated with mixing. Work life can vary from minutes to days with these products. Materials with limited work life require quick assembly, but can be handled immediately. Full properties can be reached faster with an elevated temperature post-cure. One-part thermosets have a long open time and require a high temperature cure (typically above 100°C) to achieve maximum properties.

B-staged adhesive products are most often applied in liquid form to a carrier or substrate. Depending upon the composition, the B-staged product is then either dried by evaporating off lower molecular weight material or by partially curing or advancing the product into a dry form that can be handled for an extended period of time. If cast into sheets, parts can be cut into preform shapes for easier processing in a manufacturing environment. The part is positioned on the object to be assembled. Depending upon the product, clamps or mechanical fasteners are used to apply pressure to wet the bonding surfaces while the adhesive is heat cured.

Adhesive Performance

Ink Effect on Adhesion

Selecting an adhesive is a balance of

1. manufacturing ease in applying the product in the device assembly
2. curing it quickly at a temperature that will not harm the assembly
3. maximizing the chemical resistance to the harsh environment of the fluid to be jetted.

Figure 2 shows that adhesives choices can be narrowed by following the arrow to the target performance property of most importance. For example, 1-part adhesives will more likely have higher chemical resistance with a possible sacrifice of cure time and processing ease compared to a hot melt.

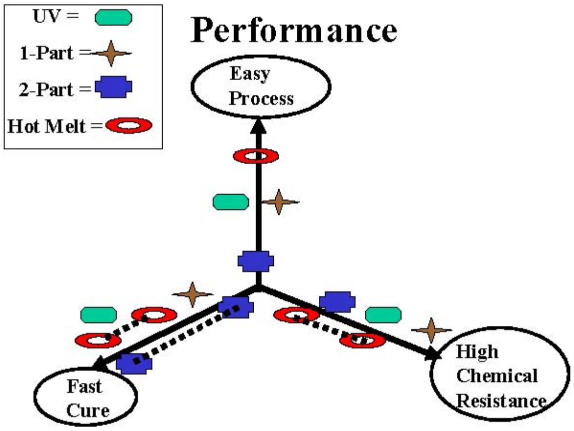

Figure 2. Illustrates the importance of balancing properties with manufacturability.

In this paper, a variety of adhesive chemistries, products, and substrates are examined by three different adhesion testing methods. The adhesives are denoted as follows:

Adhesive	EF	EG	EA	SM	SS	UO	ES	FF	EC
Chemistry	Epoxy	Epoxy	Epoxy	Silicone	Silicone hybrid	Acrylate	Epoxy	Epoxy	Epoxy
Package, # of part	1	1	2	1	1	1	1	1	1
Paste	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Film	Yes
Flexible	No	Yes	Yes	Yes	No	No	No	Yes	Yes
Conductive	No	No	No	No	No	No	Yes	No	No

The substrates are aluminum (Al), polycarbonate (PC), polyetherimide (PEI), polybutylene terephthalate (PBT). The chemical environments are none or dry, water and commercial dye and pigment aqueous inks. Adhesion tests often must be developed for a specific part design. Some standard tests can be used for screening various adhesives. One such test is a lap shear test, which can be developed for a specific grade of plastic or metal. The overlapped part can be tested at various temperatures or before and after exposure to the harsh chemical environment. Figure 3 demonstrates that adhesive strength will vary with both the substrate and with the adhesive selected. Dry lap shear strength is compared on Al, PBT and PC substrates. Dry adhesive strength on aluminum is much greater than on the plastics for the epoxy and silicone adhesives tested.

If dissimilar substrates are to be bonded and a lap shear test is not practical an alternative test needs to be developed. For example, a plastic and glass substrate bond may always fail with the glass fracturing. In this alternative test such as a shear strength push test could be developed. In this situation, the adhesive bond strength is not tested so an alternative test such as a shear strength push test could be developed. In this test, a shear force is applied to an edge of a substrate bond, such as a die bonded to plastic.

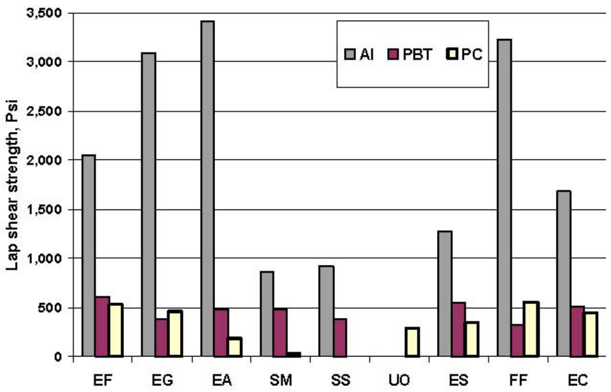

Figure 3. Adhesive lap shear on aluminum and plastic substrates before harsh environment exposure.

Changing to the die shear test from the lap shear test will change the failure mode of pull to peel force. This test may be better suited to studying the adhesive bond failure when the bonding assembly substrates are dissimilar. Figure 4 is a chart of silicon die adhesive strength to 3 plastics – PBT, PEI and PC before and after immersion at 40°C for 7 days. Each bar is a sum of the 3 substrates tested for each adhesive and environmental exposure. Adhesive strength most often decreases after chemical exposure. The exception is with silicone products. The adhesive strength varies very little with the environments which may be due to the hydrophobic properties of silicones.

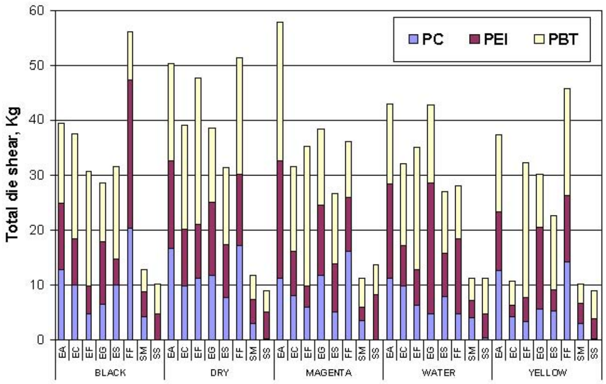

Figure 4. Die shear strength of 100 mm x 100 mm silicon die to plastic before and after exposure to chemical environments.

Another test method is the pad push test which exposes a large open surface of the adhesive to the chemical environment. Just as with the die shear test, the adhesive is removed in a peel mode. Figure 5 is an evaluation of the push strength of stencil printed 100 mm x 100 mm x 15 mil adhesive dots before and after environmental exposure at 40°C for 7 days. The trends observed with the stencil printed pad push test do not match the die shear results in all examples. The adhesive strength is influenced by the profile and height of the printed pad. Adhesives that maintained a very high pad profile during the cure sometimes had higher strength. An adhesive that flows during cure or wets the substrates too well had inconsistent results. Adhesive EG is an example. This may limit this test method to thixotropic paste adhesives.

Ink Effect on Physical Properties

Often times the best test is to actually assemble a "real" part and observe performance over the anticipated useful life, while exposing the part to expected environmental hazards. Upon failure, it is important that the failure mode be determined. The adhesive may fail or it may not adhere to one or both of the assembly substrates. In addition, the failure mode may be related to the chemical environment, mechanical or thermal stress, incomplete cure, or improper surface preparation. However, it is difficult to build a complete assemble. Therefore, analytical methods are often used to assess adhesive performance in harsh chemical fluids independently of substrate adhesion. Adhesives may be evaluated by analytical test methodology or mechanical tests on the assembly substrates. In addition, the same test suite may be run in the chemical media at ambient or operating temperatures. Most often a combination of tests is required to match the adhesive with the application, and the ideal test is to build a complete part and monitor its performance over time.

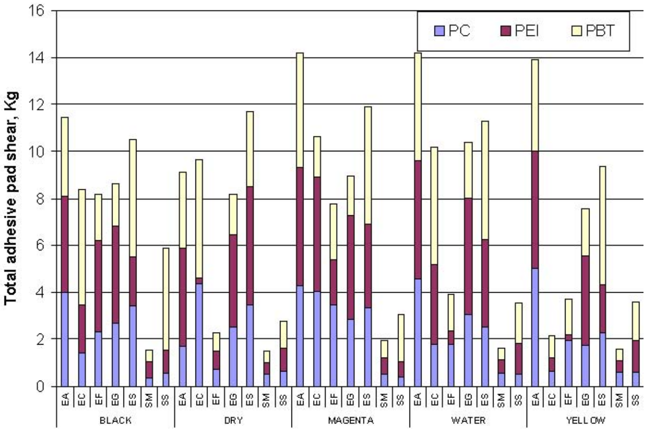

Figure 5. Printed pad push test on plastic substrates before and after exposure to chemical environments.

Dynamic mechanical analysis (DMA) is used to study the fluid exposure effect on physical properties with time and temperature. Adhesive EG is used in the DMA study. Figure 6 shows that there is a minor change in storage modulus (E') after 40°C chemical exposure. However, the E' change at 85°C chemical exposure is very noticeable; it is much lower than the control at DMA temperatures less than 70°C and levels off at higher temperatures. Glass transition temper-ature (Tg) as defined by the Tan δ peak shows even more pronounced effect than E' with the exposure temperature (Figure 7).

The change of E' and Tg is likely caused by the chemical fluid plasticizing the adhesive. The level of plasticization is temperature dependent. Higher exposure temperature leads to greater diffusion which in turn causes greater E' and Tg depression. The change of physical properties by plasticization may result in the reduction of adhesion strength. The Tg before exposure of the adhesive is also a factor that controls the diffusion process. Adhesives with a Tg higher than the chemical exposure temperature are expected to have slower fluid diffusion than low Tg adhesives. Therefore, the proper selection of an adhesive is dependent upon expected service temperatures, acceptable cure conditions, and exposure chemicals.

Conclusion

There are many adhesive options for assembling jettable devices. By balancing processing ease with device performance, the adhesive selection may focus on the effects of the harsh fluids. These fluids depress the glass transition and storage modulus of the adhesives with time and temperature conditioning. Balancing the harsh chemical environment, curing and adhesive properties maximize device performance.

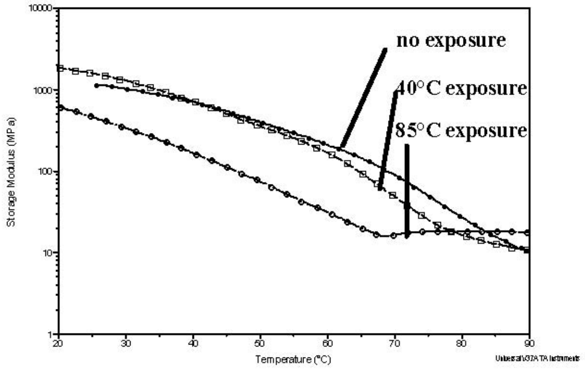

Figure 6. DMA storage modulus of adhesives EG before and after 1 week exposure to jettable fluids.

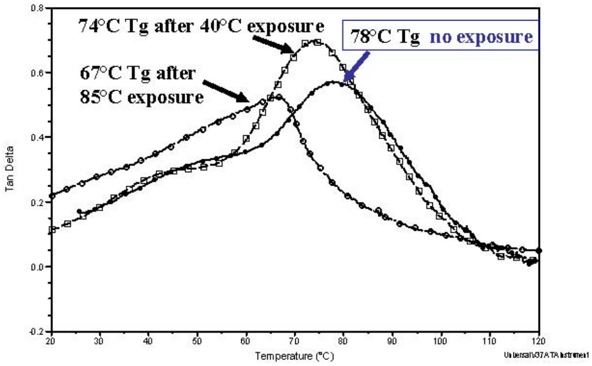

Figure 7. DMA tan δ storage modulus of adhesives before and after 1 week exposure to jettable fluids.

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