International Journal of ChemTech Research
CODEN (USA): IJCRGG, ISSN: 0974-4290, ISSN(Online):2455-9555
Vol.9, No.08 pp 519-531, 2016

Voice Coil Actuator as Adhesion Measurement Technique for Micro stereo lithography Components

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Abstract : Interfacial adhesion of UV curable polymers is important in Microstereolithography (MSL) due to the sticking problems during separation from their substrate and insuring adhesion between two dissimilar materials used in micro-fabrication. Therefore, standardizing quantitative ranking among different substrates helps to select the required substrate for fabrication of polymers according to their application. In this paper, a technique is proposed and used to perform experiment on interfacial adhesion of HDDA polymer over three different substrates: silicon, glass, and Teflon. A voice coil actuator with a pushing needle mechanism is modified to carry out experiments on interfacial adhesion of the polymer. The proposed technique has got additional advantage of removing micro-structures from their substrate without damaging the micro structure. Finally, interfacial adhesion of HDDA on Teflon, silicon, and glass is ranked according to the results obtained from the proposed technique.
Key Words : adhesion, curable polymers, micro stereo lithography, voice coil actuator.

1. Introduction

Voice coil actuator is a technique proposed to measure adhesion of micro-components fabricated by microstereolithogarphy. The actuator uses current carrying coil and permanent magnet to move a needle, installed at the end of the coil assembly, inward and outward. The inward and outward motion of the needle is directly used in pushing the polymer sample to delaminate. The actuation of the voice coil is due to electromagnetic attraction and repulsion. A coil is wrapped around a metal protrusion which is mounted within an assembly containing a permanent magnet. When current is fed to the coil, an electromagnetic field is generated that causes the metal to move inward or outward based on the attraction or repulsion force of the permanent magnet. The needle can be made move inward or outward, longer or shorter distance by changing the direction and magnitude of the electrical current.

A. Coefficient of friction at which delamination begins[1].

B. The interfacial energy of a coating-substrate system which is the energy needed to propagate a crack along the interface between the coating and the substrate per a unit area[2].

C. Force which can be described as the force needed to separate two bodies along their interface, and it is restricted therefore to the interfacial forces acting across the interface[3].

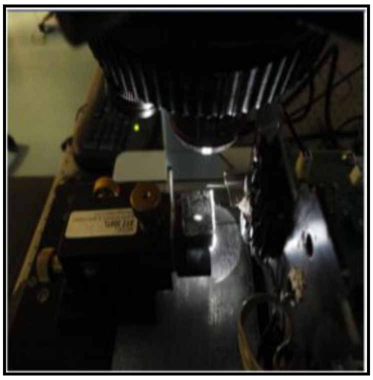


Fig.1 Voice coil actuator setup ready for experiment.

2. Current Carrying Coil

Even though every current carrying wire can induce magnetic field, a stronger magnetic field can be created by wrapping the wire into a coil shape with the same amount of electric current applied. The circling magnetic fields around the wire will join to create a larger field with a definite magnetic polarity i.e north Pole and south pole. Using left hand rule, when grasping the coil in your left hand with your fingers in the direction of the electron current flow, your thumb will point toward the north pole of the coil.

The amount of magnetic field force generated by a coiled wire is proportional to the current through the wire multiplied by the number of turns of wire in the coil. In general the strength or intensity of a coil's magnetic field depends on a number of factors.

The main factors are listed below:

- The number of turns of wire in the coil
- The amount of current flowing in the coil
- The ratio of the coil length to the coil width
- The type of material in the core

The force induced by a current carrying wire in a permanent magnetic field is given by Lorentz force law as:

$F= nl\ (I \times B)$ ----------- Eqn (1)

Where “n” the number of effective coil turns, “l” is effective length of coils, “I” is current applied to coils, and “B” is magnetic flux density.

3. Structure of Voice Coil Actuator

The voice coil in CD-Rom which is used as an optical pickup actuator is modified for adhesion testing by extending a needle on its lens holder. The actuator is then put in a comfortable position, on a vertical plate with the needle arranged in a horizontal plane as shown in Fig 1.

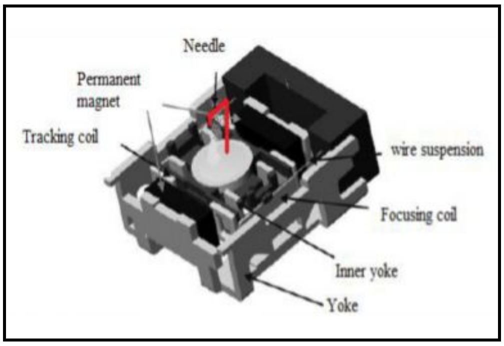


Fig. 2 Internal structure of the voice coil actuator .

The actuator has four suspension wires which supports the moving part (needle holder, and coils). In addition, the four wire springs have mechanical roles such deciding position of the moving part, inducing restoring force and suppressing tilt of the moving part, and they are also used as electrical path of the electrical current. The moving part is put into action by the voice coil motor in the focusing (inward and out ward) and tracking directions independently. Hence, the actuator system forms uncoupled two degree of freedom where the motion in the focusing direction is essential in this experiment. The inward and out ward motion of the needle is due to the force induced by the focusing coil (wounded in the needle holder) and the permanent magnet. Magnitude of the force induced on the needle holder can be analyzed by Lorentz force law given in Equation (1)

As Lorentz force law shows, magnitude of the force applied to the sample can be regulated by changing either the current in the coil or the magnetic flux density. In the setup, current flow on the coil is the only parameter that can be controlled by varying the voltage input to its terminals. The blister test has been used to measure the interfacial adhesion energy for a debond at the interface of a thin film and substrate[8,9].

4. Calibration of Voice Coil Actuator

There are many ways of measuring the force generated by the needle of the voice coil actuator subjected to an electric current. One of the common techniques used to measure the induced force is microbalance which is available in the laboratory. Microbalance with suitable setup for the measurement is used to measure the force induced by various voltage differences at the terminals of the voice coil actuator. The amount of voltage given to the terminals is controlled from a d-space which is the power source for the coil. For different voltage inputs, the corresponding force induced in the micro-balance is measured and the multiplication factor is analyzed. Hence, the force of adhesion can be easily calculated from the critical voltage input by multiplying with a constant factor obtained from the calibration.

The setup used to calibrate force induced on the needle of the voice coil actuator is shown in Fig.3, with a known mass of C-cross-section gripped by a needle whose pushing force is measured from the increasing reading on the microbalance.

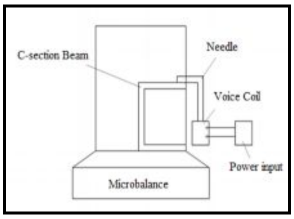


Fig. 3 Microbalance for measuring the force induced by the needle of the voice coil actuator

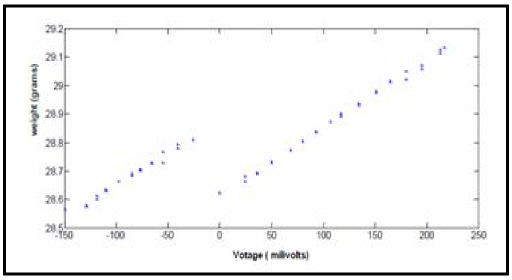


Fig. 4 weight sensed on the microbalance versus the voltage supplied to the voice coil

The slope for the graph in Fig.4 is the same for the negative and positive voltages which is linear as shown in the graph. The discontinuity at zero voltage is due separate experiment is done for the negative and positive voltages. The average force induced by the needle of the voice coil actuator per unit voltage is calculated to be ***0.023068422.*** Consequently, the constant number can be used as a conversion factor for the change in voltage into the corresponding force during adhesion test by the actuator. Blister test uses a sample which needs complicated fabrication process; which is not suggested when qualitative or semi quantitative data are required[14].

5. Advantage and Constraints of Voice Coil Actuator Adhesion Test

When compared to the modified scratch testing, the voice coil actuator has advantages and shortcomings during experimentations and in the total setup development. The main advantages of the newly developed voice coil actuator are easy setup development using locally available equipments, and low cost almost negligible when compared to the modified scratch testing. The only processes required are winding, and preparing suitable arrangement on the setup with the stage and microscope.

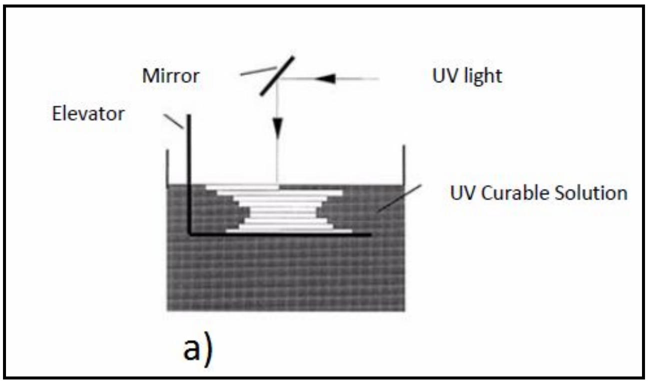
The results of the experiment are dependent on the voltage given to the terminals of the voice coil. Therefore, the data taken during delaminating of the sample are free from vibration. The independence of our adhesion force on vibrations, sources of error in experiments, is helpful in getting good results.

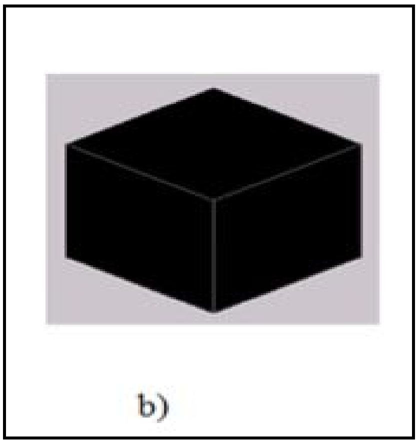
The drawback of voice coil actuator is the manual operated supplying of voltage until delaminating of the sample takes place. Delaminating of the sample is recognized by the help of microscope which leads to human error in recording the voltage during delaminating.

6. Sample preparation and Experimental Procedure

(a)Microstereolithography for Sample Preparation

Microstereolithography is used in fabricating square HDDA sample (0.5 x 0.5 mm) on different substrates: glass, silicon, and Teflon. The basic principle of microstereolithography is schematically shown in Fig.4.1. A 3D solid model designed with CAD software is sliced into a series of 2D layers with uniform thickness. The code generated from each sliced 2D file is then implemented to control a motorized x–y stage carrying a container of UV curable solution. The focused scanning UV beam is absorbed by an UV curable solution consisting of monomer called HDDA and photo-initiator BEE, leading to polymerization. As a result, the HDDA layer is formed according to each sliced 2D file. After one layer is solidified, the elevator moves downward and a new layer of liquid resin can be solidified as the next layer. With the synchronized x–y scanning and the *Z*-axis motion, the complicated 3D micro part is built in a layer by layer fashion. The laser wavelength used in the experiment is 351 nm from an Ar+ laser.





c)

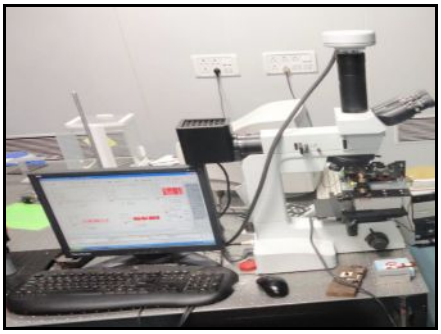
Fig.5 a) The principle of microstereolithography[13], b) HDAA sample CAD model, c) Optical microscope picture of the sample (0.5 X 0.5 X 0.7 mms).

After 7 layers HDDA samples are fabricated with 7μm line spacing and 0.8 mm/s scanning speed, they are taken for development with acetone. Finally, after giving enough time for drying; optical- microscope is used to take picture of the samples.

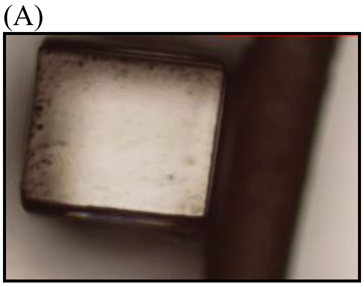
(b) Experimental Procedure

The assembly experimental setup for interfacial adhesion force measurement includes: stage (X, Y, and Z), optical microscope, d-space, and a voice coil actuator bolted to a vertical plate with a needle in a horizontal plane to push the MSL-component. Initially, the sample is kept in touch to the needle, with the help of the stage and microscope. Furthermore, delaminating of the component from its substrate is visualized with the help the microscope.

After the sample is put in touch with the needle, the initial voltage recorded from the control desk of the d-space. The input voltage is in between -1volt to 1volt which is prepared in a simulink on Matlab. At the time voltage is supplied, from the d-space, to the terminals of the coil, the needle will start pushing the sample which is observed through the microscope. Subsequently, when the pushing force exceeds a critical value, the sample is observed to be detached from its substrate, and the corresponding voltage is recorded. Therefore, the interfacial adhesion force can be calculated by multiplying the change in voltage from the experiment with the conversion factor.



(A)



(B)

Fig.6(A)Voice coil actuator assembled with its all accessories (B) the needle kept in touch with the sample initially

HDDA samples are prepared on different substrates, silicon, glass, and Teflon cleaned using acetone. The samples prepared on silicon are fabricated on different laser powers i.e 80 and 150 . As a result, the effect of laser power in strength of the adhesion of MSL components with their substrates is studied. In general, the experiments are concerned in how the strength of adhesion behaves by changing substrates and fabrication laser power of the samples.

7. Results and discussion

7.1 Adhesion of HDDA on Different Substrates

The results from the experiments performed on the three different substrates: silicon, glass, and Teflon are acquired after completing all required procedures. At the time the electrical voltage supplied to the terminals of the voice coil actuator reaches a critical value; the samples are observed to be delaminated from their substrate.

The results for adhesion of HDDA fabricated at a laser power of 150µw, on the three substrates mention above, are given in the following tables.

Table 1: Adhesion of HDDA fabricated at a laser power of 150µw on Teflon substrate

Sample number	Initial voltage on the voice coil actuator terminals (volts)	Final voltage on the voice coil actuator terminals (volts)	Change in voltage	interfacial adhesion force in milinewton (mN)
1	-0.55	0.22	0.77	17.71
2	-0.53	0.16	0.69	15.89
3	-0.51	0.22	0.73	16.79
4	-0.56	0.18	0.74	17.02

The experiments on HDDA-Teflon interface shows consistent results with an average adhesion force of **16.85 mN**.

Table 2: Adhesion of HDDA fabricated at a laser power of 150µw on silicon substrate.

Sample number	Initial voltage on the voice coil actuator terminals (volts)	Final voltage on the voice coil actuator terminals (volts)	Change in voltage	interfacial adhesion force in milinewton (mN)
1	-0.78	0.12	0.9	20.70
2	-0.81	0.20	1.01	23.23
3	-0.83	0.11	0.94	21.62
4	-0.75	0.13	0.88	20.24

From the results in the above table .2, the average adhesion force of the HDDA-Silicon interface at the given laser power is calculated to be **21.45 mN**. Four-point bend test has been used largely by researchers & scholars in obtaining fully quantitative information on the adhesion strength of coatings[10-12].

Table 3: Adhesion of HDDA fabricated at a laser power of 150µw on glass substrate.

Sample number	Initial voltage on the voice coil actuator terminals (volts)	Final voltage on the voice coil actuator terminals (volts)	Change in voltage	interfacial adhesion force in milinewton (mN)
1	-0.94	0.35	1.29	29.67
2	-0.95	0.28	1.23	28.29
3	-0.93	0.38	1.31	30.13
4	-0.89	0.36	1.25	28.75

From the results in the above table 3, the average adhesion force of the HDDA-Glass interface is **29.21 mN**.

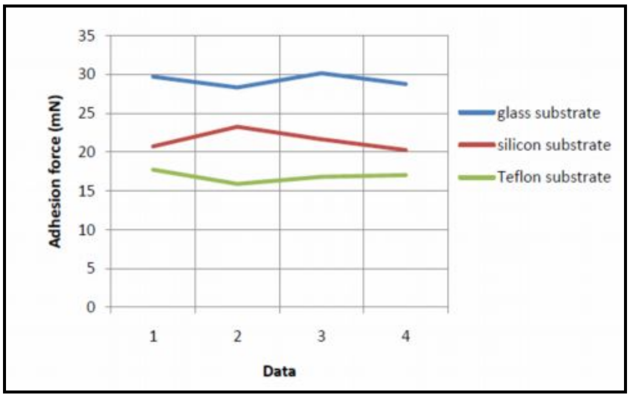


Fig 7. Interfacial adhesion force of HDDA on three different substrates

The results shows, HDDA has higher interfacial adhesion with glass than with silicon and Teflon. Furthermore, the adhesion of HDDA on silicon is examined to be stronger than Teflon. An experiment has been carried out on the surface roughness of glass, silicon, and Teflon with white light interferometer. As a result, glass is found to be rougher than silicon and Teflon. And Teflon is observed to be the smoothest of both the substrates as shown in Fig.8, Fig.9, and Fig. 10. The rougher the substrate surface, the more contact area will be available between the polymer and the substrate; which results in strong interfacial adhesion. Therefore, since the experimental rank on the surface roughness of the substrates is matching with the rank on their interfacial adhesion with HDDA; then, the adhesion results of HDDA on the three substrates are feasible.

The strength of the bond between the atoms that made the substrate also affects their reaction with the external atoms from the HDDA polymer. The stronger inter-atomic bond of the substrate the weaker is the chemical bond between atoms of the substrate and the polymer. Teflon is very non-reactive; partly because of the strength of carbon–fluorine.

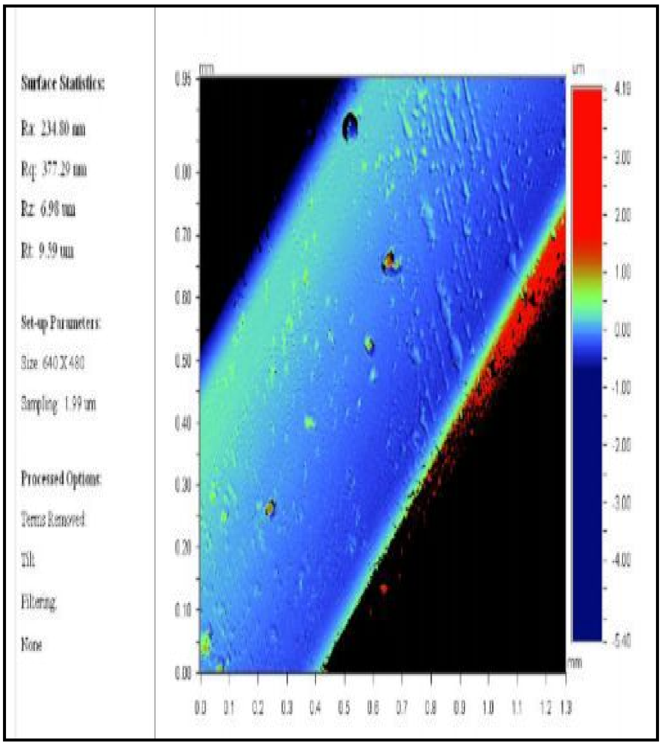


Fig. 8 Surface roughness of glass

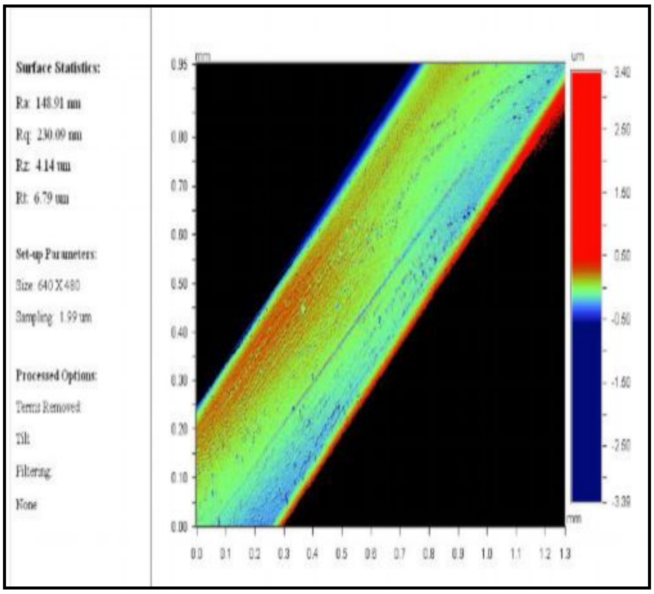


Fig.9. Surface roughness of silicon

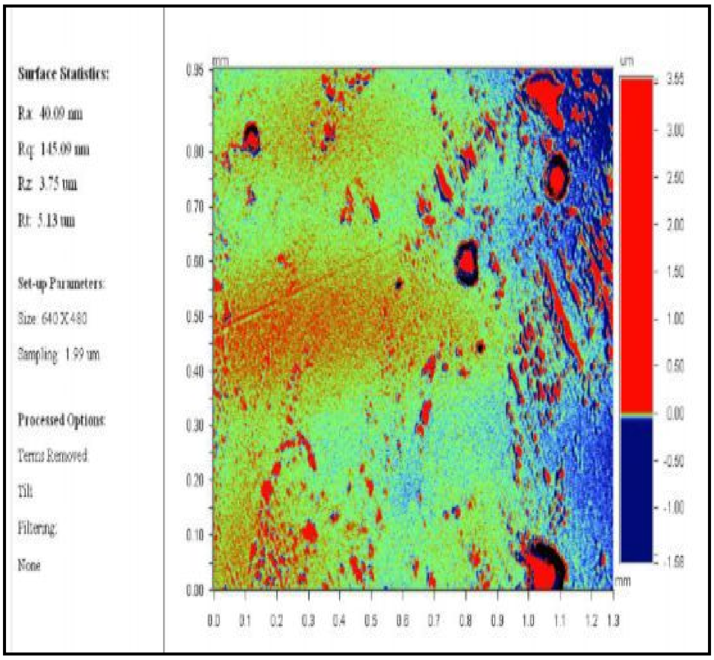


Fig. 10. Surface roughness of Teflon

8. Adhesion of HDDA on Silicon with varying Fabrication Laser Power

The effect of laser power on the adhesion strength of HDDA with silicon substrate is studied using the voice coil actuator setup. Hence, HDDA fabricated on silicon substrate with 150µw and 80µw laser powers of the MSL are examined for their adhesion strength. The adhesion force of HDDA-silicon interface fabricated at 150µw laser power is previously given in table 2.

Furthermore, the experimental adhesion force on HDDA-silicon interface fabricated at 80µw laser power is given in the following table 4.

Table 4: Adhesion of HDDA fabricated at a laser power of 80µw on silicon substrate.

Sample number	Initial voltage on the voice coil actuator terminals (volts)	Final voltage on the voice coil actuator terminals (volts)	Change in voltage	interfacial adhesion force in mili newton (mN)
1	-0.56	0.25	0.81	18.63
2	-0.45	0.31	0.76	17.5
3	-0.53	0.20	0.73	16.80
4	-0.49	0.33	0.82	18.86

From the results given in the table 4, the average adhesion force of HDDA-silicon interface built at a laser power of 80µw is calculated to be **17.95 mN**.

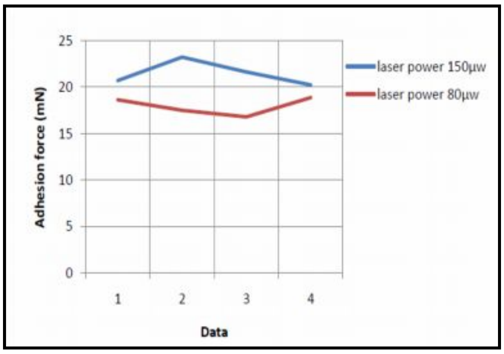
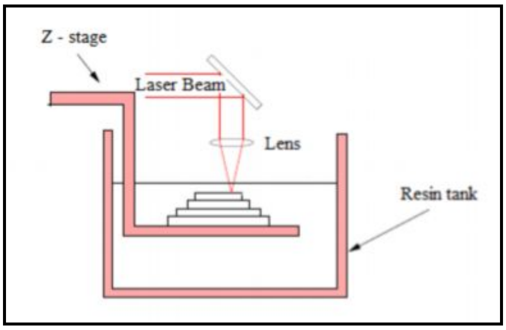


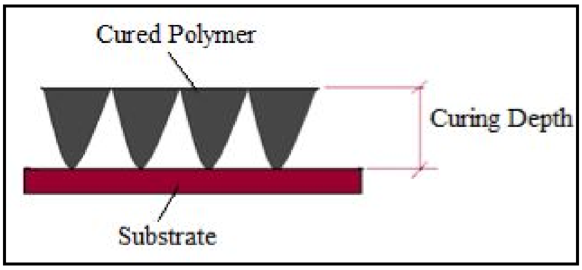
Fig.11 Adhesion force of HDDA on silicon in two different fabrication laser powers

As it is shown in Fig.10, when the laser power of MSL for fabrication of HDDA on silicon substrate is increased from 80 µw to 150 µw, the adhesion force is also observed to increase by an average of 3.5 mN. Peel test is a destructive adhesion measuring methods which is mostly used for flexible coating[7].

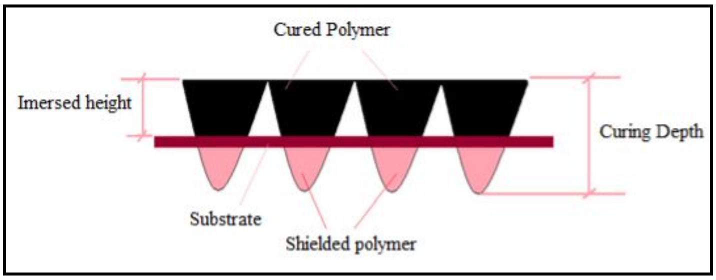
If laser power of the MSL increases, the curing depth of the laser beam into a given photopolymer also increases. This enables us to control curing depth of the laser beam into the photopolymer by changing laser power



(a)



(b)



(c)

Fig.12 a) Microstereolithography b) cured polymer at low laser power c) cured polymer at high laser power.

When the initial height deepened to the resin, Fig 12 (a), is equal to the curing depth of the laser on the photopolymer, then the initial layer will have small contact area with the substrate as shown in Fig 12b. The shape of the cured polymer is due the Gaussian distribution of the laser beam as discussed.

Furthermore, once the power of the laser beam increase without changing the initial height deepened to the resin in the upper case, the curing depth of the laser into the photopolymer will increase. However, since the laser beam is shielded by the substrate, the depth of the actual cured photopolymer will remain the same. Shielding of the laser beam at its wider width improves the contact area between the polymer and its substrate. As shown in Fig 12b and 12c, keeping the immersed height in z-stage unchanged, the contact area between the substrate and the cured polymer is larger at higher fabrication laser power than at lower fabrication laser power.

In Fig.12c, it is clearly shown how the substrate is shielding the laser beam and how it affects the contact area between the polymer and its substrate. As previously discussed, the higher the contact area the higher is the mechanical retention, secondary forces, and chemical bonding of the polymer with its substrate.

Thus, as fabrication laser power increases the interfacial adhesion also increases; which supports our experimental results.

On other hand, increasing fabrication laser power of MSL enlarges the curing width of the laser beam in the polymer, which makes difficult to fabricate thin micro-components. Therefore, while increasing laser power, it is important to compromise the reduction in resolution of the MSL with the improvement of the interfacial adhesion between the substrate and the polymer.

Moreover, the initial height given from the z-stage can affect the strength of interfacial adhesion of polymer. The smaller immersed height of z-stage the higher is the interfacial adhesion when the power remains unchanged.

9. Conclusions and Future Works

9.1 Conclusions

Based on the results on adhesion of HDDA with glass, silicon and Teflon, glass is the preferable substrate to fabricate HDDA polymers which are required to stay stuck with their substrate. And Teflon is the best choice to use it as a substrate for polymers which are going to be detached and assembled with other components.

In constrained layer MSL, the sample is required to stay stuck to the substrate rather than to the constraining window of the laser beam. Therefore, Teflon is the preferable material for the constraining window and glass as substrate so that the sample will remain stuck to the glass substrate due to the larger adhesion of HDDA-glass than HDDA-Teflon interfaces.

Power of the laser beam has been observed to affect strength of interfacial adhesion of HDDA polymer over silicon substrate. As a result, although the effect of laser power on quality of the curing polymer during polymerization need to be studied, laser power can be used as an alternative way of regulating interfacial adhesion of UV-curable polymers according to their application. An increase in fabrication laser power of polymers leads to a larger curing width of the laser beam in the polymer which makes difficult to fabricate thin components. Therefore, it is necessary to compromise the reduction in resolution of MSL with the high adhesion achieved at the time high laser power is used.

9.2 Future works

1. Study of change in adhesion strength of UV curable polymers due to their phase change from liquid state to solid state during photo-polymerization.
2. Automation of the voice coil actuator and increasing its loading capacity.
3. Optimization of MSL laser power for strength of adhesion, resolution, and quality of the component to be fabricated.
4. Identification of the failed surface near the interface in beam bending test.
5. Development of constrained surface MSL to increase resolution of the current available MSL in Mashruwala Micro-Engineering Laboratory.

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