Analysis of Forces during UV Glue Curing for Micro-Assembly Applications

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***Abstract*—Positional drift resulted from the glue curing may result into serious challenges towards accuracy especially for micro-assembly processes. Studying forces and positional drifts resulted from the glue curing appears as a key objective towards reaching precise micro-assemblies. For this reason, works notably investigate the forces and displacements originated from the UV glue curing. Experimental investigations demonstrates that the force induced during the glue curing is in 160 μN range against a micro-object with cross section of 500 x 500 μm, and the corresponding positional drift in the 10 μm range was obtained. Works also show that these values depend on the system and strategy used for the assembly.**

***Index Terms*—Micro-assembly, UV Glue Curing, Micro-robotics, Accuracy**

I. Introduction

The importance of micro-assembly is continuously growing with research advancement in the micro world. Even with the availability of several micro-fabrication technologies, the robotized approach for precise micro-assembly is still a big need. In the recent years, there were several development in micro-assembly works, in context of different approaches such as using Laser die transfer technique [1], with microfluidic interconnection [2], and with Laser scanning confocal image alignment [3], whereas different strategies to handle complex task [4] and highly accurate assembly tasks [5]- [7] have also been demonstrated. For micro-assembly applications including MEMS devices, use of the glue is one of the widely used techniques in industries. Glue curing induces mechanical stress, which introduces positional drift as well. But there could be two possibilities in its use, the first with the use of thin film (typical thickness $< 1\mu$m) and the other with the use of thick film (typically $> 10\mu$m). With the use of thin film (surface functionalization), its possible to reach positional accuracy $<$ 1 μm. The dependency on many parameters makes it adopted to high product values (dedicated approach). Talking about thick film, it would result into a considerable problem towards positional accuracy primarily because high glue thickness and secondly challenges from considerable positional drifts, but this approach is flexible over the choice of materials to be used and also with the interaction surface. Many scientist and companies use this technique and develop highly complex gluing procedures to succeed in achieving positioning accuracy of some μm. To tackle this key, we aim at proposing an assembly strategy able to achieve gluing task with positional accuracy $< 1\mu$m despite of high glue thickness, drift during gluing and many other parameters. In order to address this challenge, force-position sensing and there accordingly use in development of control strategy is an important concerned. The importance of force position sensing is significant, specially because of very high dependency on the dynamic as well as the operational range. In [8], [9] force/position sensing was a common tool towards control strategy based solution against varying environment. The objective of this paper is to study the force and drift resulted from the glue curing. There are very less work done for the force/position behavior modeling and analysis, specially in the case of assembly with the glue. The force/position analysis with the glue curing thus appears a key towards assembly system design, choice of sensors integration and control strategy development. There are two sides of requirement, firstly the knowledge of force/position behavior, secondly making a decision for the release of micro-object at the end of glue curing. For this second requirement, keeping a track of glue stiffness based on force/position and stiffness around the glue, may be an interesting side to explore. With the objective of force/position analysis during the glue curing, the corresponding dependency of mechanical stiffness of gripping tool towards minimization of the positional drift resulted from glue curing and its influence over glue stiffness measurement is also discussed in the present work. In section (II), experimental works are presented, followed by the system modeling and behavior analysis discussion in section (III). Finally the conclusions and perspectives are presented in section (IV).

II. Experimental Works

In order to go ahead with the experimental analysis, there is requirement of an adequate experimental setup with which the different investigation could be done. Considering the tethered approach, the setup should include a microgripper to manipulate and hold the micro-object (or MEMS device), glue droplet placed over assembly platform where the micro-object need to assembled. To analyze the glue curing behavior with force/position analysis, a basic configuration is shown in Figure (1). It includes a passive beam holding the micro-object, the corresponding assembly platform comprised of substrate with a force sensor fixed on a fixation platform. With the use of position and force sensor in the presented configuration, the respective drift and force induced from the glue curing can be measured. In the situation of gluing operation, where the environment stiffness varying from almost zero (liquid phase) to very rigid (cured phase), the investigation of force/displacement study aims at analyzing the required gripping tool, sensors, their integration. The force sensing and accordingly the stiffness analysis in multiple direction is obviously an important need, but in the current study as shown in Figure (1) is done only about the z axis. As the placement of the micro-object is done in the plane orthogonal to z axis, the relative contact and the young modulus (higher compared to shear modulus) of glue can be considered to be high about this axis. Therefore the z axis was chosen for the analysis in the current study. From this study, we can analyze glue behavior and its impact towards the positional drift and force.

As shown in Figure (1), the point of interface between micro-object and UV glue is termed as A, and that between UV glue and assembly platform as B. The respective displacement at A and B are y_A and y_B, and the corresponding forces are denoted as F_A and F_B respectively.

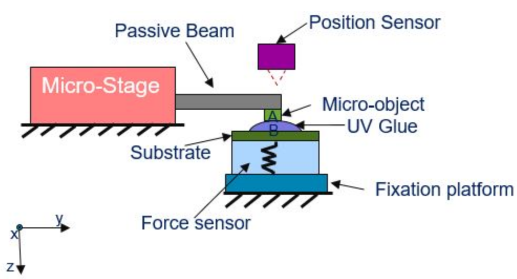

Fig. 1. Proposed configuration for force/displacement analysis during the glue curing

The choice of passive beam has dependency over the extent of positional drift induced by the glue curing. This can also be seen as the dependency over the choice of microgripper for micro-assembly using UV glue. Therefore in the presented work two different passive beams were used, one with low stiffness of 20 N/m and second with very high stiffness (> 10000 N/m), referred as Case: 1 and Case: 2 respectively in the following subsections.

A. Case: 1 (Experimentation with 20 N/m passive beam)

An experimental setup with 20 N/m passive beam to have the force/position study during the glue curing is shown in Figure (2). This setup includes a micro-stage for positioning of the micro-object against the glue. A passive beam attached with the micro-stage, and the second end of the passive beam is attached to the micro-object with the help of thermal glue as proposed in Figure (1). The cross section dimension of the micro-object was 500 μm x 500 μm. The force sensor used was TEI FSB100 with 0.5 N sensing range. The calculated stiffness of the force sensor was 2250 N/m. The employed UV glue for the experimentation was DYMAX 425. The similar testing could also be performed with the free object placement against the glue, but in that case the gluing force

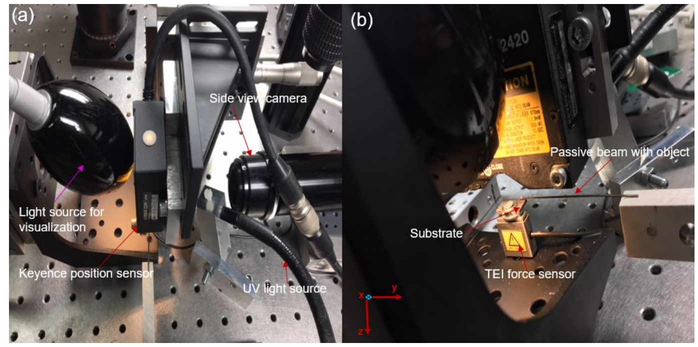

Fig. 2. Experimental setup for force/displacement analysis with 20 N/m passive beam (a) Top View (b) Side View

could only be sensed as an internal oscillatory force, and so the passive beam was used to transform this internal happening to external. For a better understanding, there could be two point

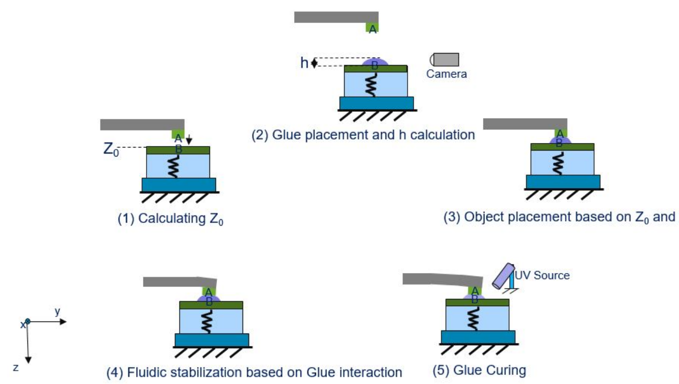

Fig. 3. Different procedures to follow with the experimentation

of interest, primarily the performance repeatability check and finally verification by means of stiffness change. The force to be measured in the case with any stiffness of the beam should be same, provided the glue contact, pressure and the other environmental conditions remain same. Usually the UV

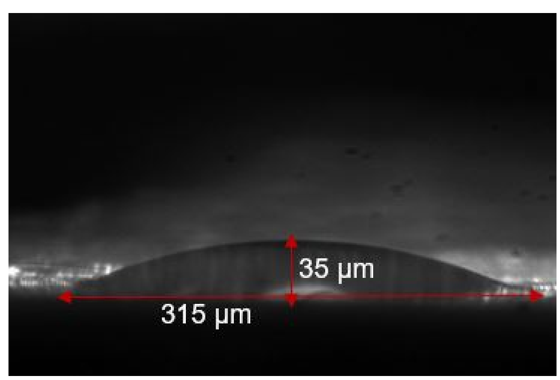

Fig. 4. UV glue drop, from side view camera

curing can be very fast, if the proper intensity is exposed for the curing, but just to monitor the happening from vision point of view (as UV filter was not used with camera), the UV light source was placed little far and so the intensity of UV light was kept low for the exposure.

In order to analyze the extent of displacement under the effect of the curing of the UV glue, KEYENCE (LC-2420) position sensor is used. Before starting the experimentation, there were several steps done, just to understand the possible happenings. These steps are shown in Figure (3), from (1) to (5), the point A position can be measured from position sensor. Primarily, its important to know the relative distance of the micro-object with respect to the platform of assembly (position Z_0 of B in (1)), so the micro-stage was moved towards the platform to calculate this position Z_0. Secondly, after the glue placement, from side view camera the glue droplet size was measured and accordingly quantity verified for other experimentation. The glue drop used as shown in Figure (4), was 315 μm wide and 35 μm in the height, assuming the equal density distribution throughout the shape. Based on the knowledge of glue droplet size and the relative distance between the micro-object and the assembly platform (as shown in Figure (2)), the micro-stage was moved to have contact of micro-object with the glue. As result of contact between the micro-object and the glue, the glue droplet starts spreading across the micro-object, as a result the passive beam bends towards the placed glue. The passive beam with micro-object was allowed to remain in contact with the glue, as long the fluidic redistribution of glue is going (monitored from the top KEYENCE sensor and side view camera). Once, it reached the equilibrium with this fluidic redistribution (no further displacement of passive beam), then the experiment with glue curing was started. So the important point concerning the methodology employed for the current analysis was the force and displacement resulted from the glue curing alone is taken into consideration. Different type of glues may show different behavior dependent on environmental conditions. In [10] the different glue and there variation in mechanical properties with temperature is presented.

There could be possibility of the force and minor displacement from the glue contact, or from the dynamic, but in the current measurement the obtained results correspond purely from the impact of curing alone, no any other inclusion. In order to have the adequate curing of the glue, the experimentation was done for little longer duration than the obtained exposure time from the past experimentation. For the first 2 minutes UV light source was OFF to analyze the stability of the object placement against the glue before start of the curing , then for the next 18 minutes UV light was turned ON, to start curing.

The result obtained from the Figure (5), shows that there is displacement of around 6 μm. The displacement analysis gives two important information for further complex analysis, firstly the stabilization of the object after the glue curing and secondly the typical drift is quantified from the glue curing based on the relative contact between glue with micro-object and stiffness. From Figure (5), glue is stiff enough to avoid further drift from glue curing and so the corresponding sensed

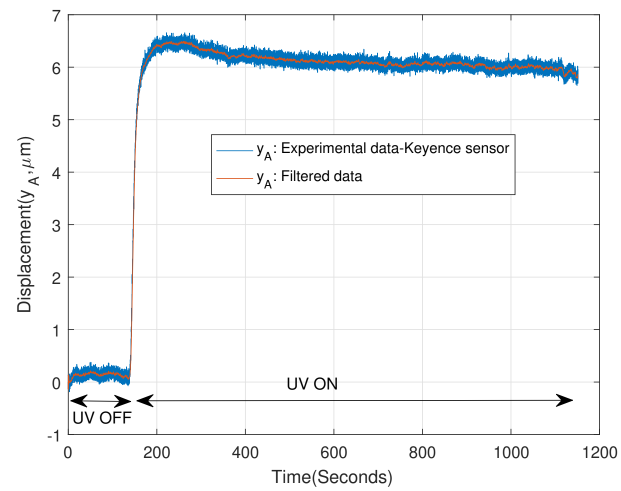

Fig. 5. Displacement of beam (point A) before and during glue curing

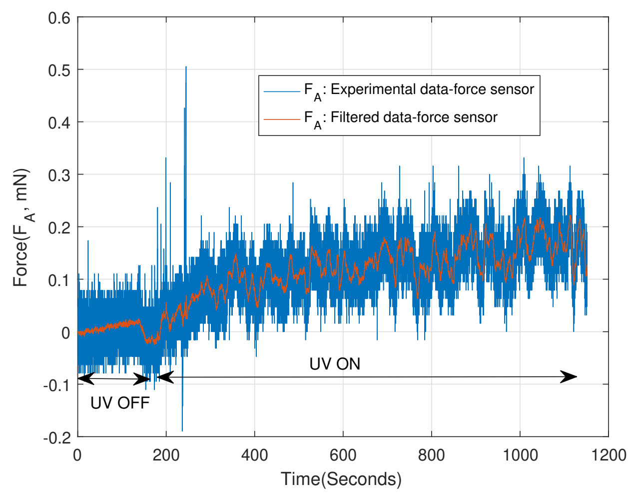

Fig. 6. Sensed force with 20 N/m beam

force is in the range of entire force resulted from the curing. The force measured is 0.16 mN as shown in Figure (6). This tells the requirement of force sensor which along with the gripping tool can measure this order of force during the micro-assembly using glue.

B. Case: 2 (Experimentation with Rigid passive beam)

In order to demonstrate the concluded remarks from the experiment with the 20 N/m passive beam. The question comes what if the 20 N/m beam would be replaced by a very rigid beam. So if the contact area between the glue and micro-object, and so the glue size remained same, the expectation is to have the same force measurement, even if we have a rigid support against the force sensor stiffness.

To study the concluded arguments, in the current part of the experiment with UV glue, the 20 N/m passive beam was replaced by a rigid beam ($>$ 10000 N/m). And the relative

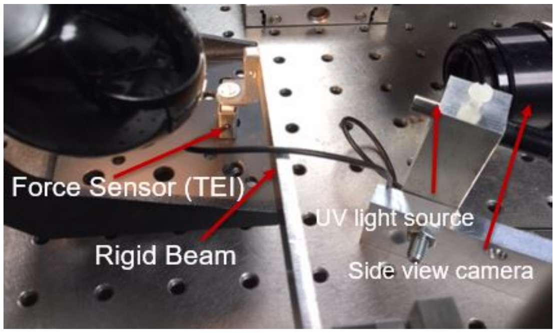

Fig. 7. Experimental setup with rigid beam

contact between the micro-object and UV glue was chosen approximately same, so as to see the same order of force measurement. Also as the beam was very stiff, there was

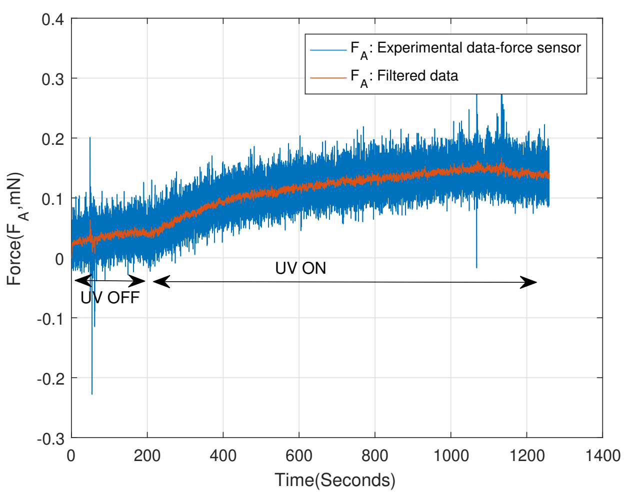

Fig. 8. Sensed force with rigid beam

no requirement of position sensing and so the KEYENCE position sensor was not used. The corresponding experimental setup is shown in Figure (7). For micro-assembly operation, it may be important to have the precise measurement of glue stiffness as with this knowledge it could be possible to make decision towards the release of the object. The placement of the passive beam against the glue drop was done using the feedback from the side view camera again. The sensed force by the force sensor is shown in Figure (8). The measured force is in the range of 0.15 mN, which is approximately same as that obtained in case of passive beam with 20 N/m stiffness.

III. Assembly System Modeling and Glue Curing Analysis

In order to study force/position during the experiment variation and accordingly glue stiffness measurement, the static mechanical modelling is addressed. In the static case the proposed system (Figure (1)) is modeled as spring equivalence as shown in Figure (9). In the spring equivalence system, k_b, k_g and k_f are respectively the beam stiffness, glue stiffness and force sensor stiffness. One important point of interest in the current analysis is the varying stiffness of the glue, which means k_g is not constant, and the respective variation range of the glue stiffness need to be considered.

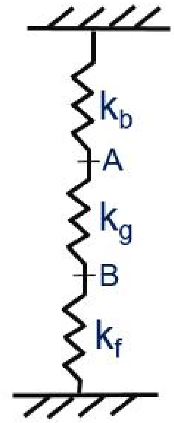

Fig. 9. Spring system equivalence for static case analysis

TABLE I
Different glue stiffness range of interest

Step: 1	$0 < k_g \leq k_b$ (1)
Step: 2	$k_b < k_g \leq \frac{k_b \times k_f}{k_f - k_b}$ (2)
Step: 3	$\frac{k_b \times k_f}{k_f - k_b} < k_g \leq k_f$ (3)
Step: 4	$k_g > k_f$ (4)

Glue curing from liquid phase to cured phased, can be splitted into four steps. For behavioral analysis, it is interesting to address the performance with these four steps (as shown in TABLE I). First one, the passive beam is allowed to bend up to the extent where the stiffness of the glue becomes equal to the stiffness of the passive beam, as defined in equation (1). Once the glue stiffness becomes higher than beam stiffness but less than the condition mentioned in equation (2), calculated from static equilibrium case, then there should be movement of beam (point A) but in opposite direction which is originated from the motion of point B. Provided the force at point B gets sufficiently strong enough to drive the point B against the force sensor stiffness, then there would be movement of B which result into measurement of force from the force sensor. There is only Step: 1 and Step: 2 resulted from glue curing alone, so in presence of no additional external force Step: 3 and Step: 4 correspond to the glue stiffness which may not be measured by the provided mechanism (measurement limitation from the choice of mechanical setup). So, apart from the force sensor measurement range, the measurable range of glue stiffness is also limited from the force sensor (or stiffness around) employed in the presented configuration. From the Figure (5), displacement curve has little bump down after the first raise and before reaching the stable value, this happening can be compared respectively with Step: 1 and Step: 2 (equation (1) and (2)) from little shifting of point B before point A becomes almost constant. This can be explained with the help of relative stiffness concept, where any relatively stiffer structure can compress the less stiffer structure provided there is sufficient force in between. Revisiting the equation (1) and (2), it can be said that the choice of k_b and k_f, would define the measurable glue stiffness for a given force. For the equations (1) and (2), it was written for $k_b < k_f$, but dependent on the other case k_b, k_f can be replace by each other with convenient sign convention. The glue stiffness for sure reach some higher stiff value if the UV exposure is still ON, but the force sensor is limited to sense the stiffness variation up to the stiffness surrounded (under static equilibrium). The current work included this limitation just as to verify the stiffness variation, force variation as per the desired theoretical analysis from the static case. k_b and k_f could be known from the stiffness calculation experimentation. Also the displacement of beam point A (y_A) is known from the position sensor data which corresponds to the beam displacement. The force acting at point B (F_B) is also known from the integrated force sensor. The displacement of point B can be calculated as:

$$y_B = \frac{F_B}{k_f} \tag{5}$$

from y_A, we can have the force acting at A so F_A can be given as:

$$F_A = k_b \times \; y_A \tag{6}$$

The glue stiffness can be calculated as:

$$k_g = \frac{F_A}{y_{AB}} \tag{7}$$

In equation (7), y_{AB} is the overall displacement of glue, which means the resultant displacement of segment AB in presented spring equivalence model. The force at A and B should be ideally same in static case, because of the single origin of the force starting from the glue curing and the connectivity. The glue curing allows the attached passive beam to go through some bending as per the allowed stiffness of the beam and the variation of glue drop size. In the currently proposed setup as shown in Figure (1), the support to glue is the force sensor and from the static analysis case we could only expect to have glue stiffness upto Step: 2, but in fact with the inclusion of dynamics it can go ahead (oscillation around). Moreover, the inclusion of force sensor at the base was another reason towards the measurement verification during the gluing process. From Figure (5) , bending of passive beam from glue curing can be until the stiffness of glue equal to stiffness of the beam. During this time, the force sensor measurement have only few oscillations (in absence of sufficient force to drive point B) as we can see from the force sensor data Figure (6). Once the stiffness of the glue reached Step: 2 (equation (2)), then force measured from beam bending and that from the sensor should be ideally same. In the Step: 2, the point B moves until the extent so that equivalent stiffness about the point A becomes equal. This should be the static equilibrium for the presented setup. This entire extent of displacement of the different points, along with the stiffness dependent solely on the external force acting on the system. Meaning that if the movement of the beam is ceased the force measurement from the type of sensor used in the presented setup should also be ceased. This could be defined by revisiting the spring system presented in Figure (9).

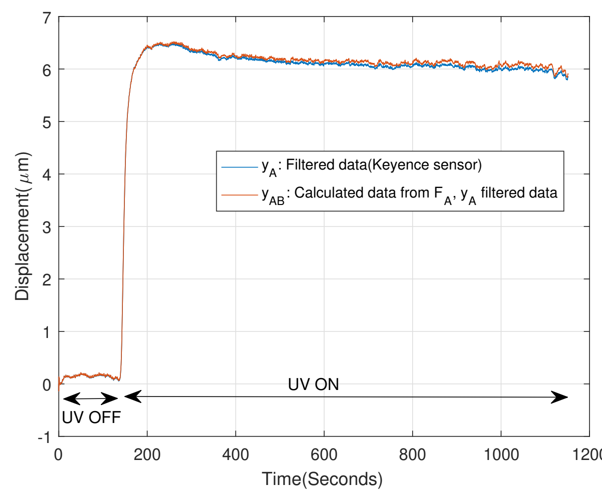

Fig. 10. Displacement of point A and overall displacement of glue (AB)

From y_A and equation (5), the overall displacement of the glue can be calculated. In Figure (10), the obtained filtered y_A and calculated y_{AB} is shown, it can be seen that the dynamic of the variation of point A and AB follows the same principle as explained with Step: 1 and Step: 2. The expected variation of y_{AB} was ideally supposed to be without the bump in the curve, the possible reason could be the error in stiffness calculation of the beams, and possible inclination from assembly substrate. Defined in equation (7), the glue stiffness could be calculated using the inclusion of displacement study of passive beam movement from the Figure (10). The limitation in glue stiffness measurement for defined Step: 3 and Step: 4 can be seen, with maximum calculated stiffness shown in Figure (11). For the Case: 2 with rigid beam, from equation (1) and (2), with $\lim\limits_{k_b \to \infty} k_g$ (and accordingly taking care of sign convention), then it can be said that glue stiffness can be measured up to the value of k_f. In the proposed configuration, with the known stiffness around the glue, the glue curing behavior can be monitored and verified in terms of glue stiffness variation and the possible limitation in the measurement (as can be seen from Step: 3 and Step: 4). So, it looks convenient to go for a rigid microgripper to minimize

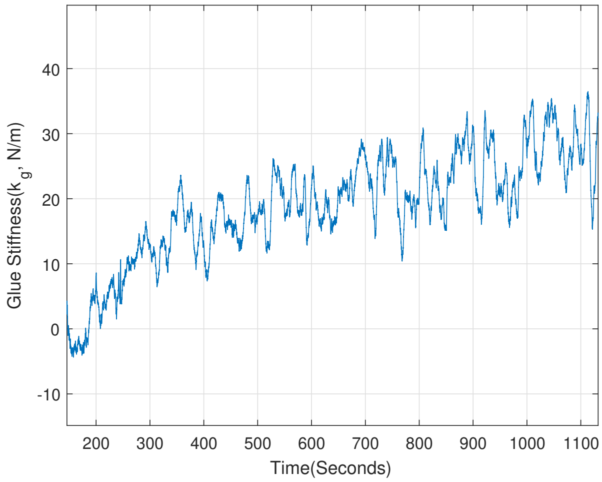

Fig. 11. Calculated glue stiffness with 20 N/m passive beam

the influence of positional drift from curing, but a very high stiffness of microgripper may not be good solution always specially from point of manipulation and handling. Secondly in terms of decision making towards release of the micro-object, the corresponding knowledge of the glue stiffness could be helpful. To monitor well the possible happenings during the micro-assembly, there is requirement of choice of appropriate stiffness and accordingly aware of the possible limitations.

IV. Conclusions and perspectives

The current work described the force and displacement analysis during the curing of UV glue. The limitations in precise measurement and its influence has also been discussed for the micro-assembly application, which could be interesting for integration of MEMS devices as well. The measured force, positional drift induced from glue curing and the corresponding stiffness variation of the glue were verified from the different arguments resulted from the proposed modeling. The 0.16 mN of force was measured from the glue curing against 500 μm x 500 μm micro-object cross section. The dependency of positional drift and glue stiffness over the choice of mechanical stiffness around the glue has been discussed and justified from the experimental observations. The chosen glue was taken as a case study for the assembly issue, the same analysis can be extended for other glues before getting into in depth treatment for the assembly process. With the current analysis we could have a better understanding of appropriate choice of sensing and gripping tool systems, also at the same time an adequate control strategy can also be accordingly employed. As a part of future work, with the help of current analysis proper sensing tool need to be integrated with a micro-assembly setup and with this knowledge adequate control strategy will be developed to insure an ultra precise assembly.

Acknowledgment

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