Analysis and Design of Mechanical Stresses on Foldable Devices

Nao Ando[1], Kei Hyodo[1], Hisao Sasaki[1], Yoshihito Ota[1],
Tomoki Sasayama[2], Yoshihiko Iwao[2], Tomoya Tsuda[2], Nao Terasaki[3]

[1]YUASA SYSTEM, 2292-1, Kibitsu, Kita-ku, Okayama-shi, Okayama 701-1341, Japan
[2]Shimadzu Co., 1, Nishinokyo Kuwahara-cho, Nakagyo-ku, Kyoto 604-8511 Japan
[3]AIST, 807-1, Shuku-machi, Tosu, Saga 841-0052, Japan

Keywords: Mechanical stresses, Foldable devices, Endurance test, Mechanoluminescent material

ABSTRACT

Knowledge of mechanical stresses on foldable devices is important to develop them. When you study stresses, you should control motion profile then study dynamic strain energy. In our study, we slightly adjusted each testing conditions to figure out effect from these difference and sensitivity of the analyzing method.

1. Introduction

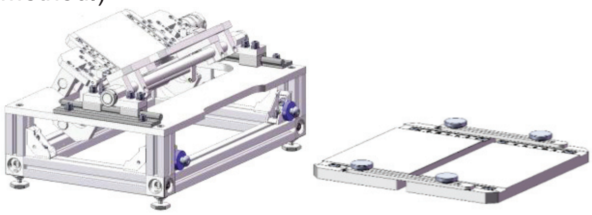
Recently, we can find many kinds of flexible devices in trade shows and market. For example, cell phones are used be mechanically rigid, but many venders exhibit flexible cell phone prototypes during such trade shows. When you develop such flexible devices, it is necessary to study those stresses will change by not only initial form and final form but also motion profile during mechanical deformation. In order to see the effect of those stresses, it is necessary to know how effect each mechanical structure and deforming speed and something.

2. Objectives

Needless to say, it is important to do an evaluation following standardized methods. Although an evaluation equipment follows said standardized methods, since evaluation equipment may have different mechanical structure, it may give different mechanical stresses on a specimen. For example, most folding testers fold a specimen from straight (0 degrees) to 180 degrees with target radius. In some cases, an evaluation equipment may give suddenly huge compression on a specimen, and another evaluation equipment may stretch a specimen without noticing. Therefore, not only product designers but also all of suppliers should share not only the final shape of mechanical deformation but also mechanical deformation profile to compare results of mechanical deformation in order to develop reliable products. At same time, evaluation equipment vender should prepare a specifications of deformation profile which users can understand what happen during mechanical deformation.

3. Our experiment and simulation

In this paper, we used non-stretchable bendable thin film which length and thickness never change during mechanical deformation. And, we painted mechanoluminescent (ML) material on one side of specimens. For evaluation equipment, we use our own “Clamshell-type folding tester” to put desirable mechanical stresses (fig.1a). The equipment has two axes (hinges) to make folding motion, it is called “double hinges clamshell structure.” It keeps moving in constant conditions whenever a specimen is attached on the equipment or not. Thus, it is easy to simulate what happens on a specimen. And it can be changed holding-plates (fig.1b) to make different mechanical stresses. For our evaluations, we slightly changed mechanical conditions (holding-plates thickness and bonding method.)



a) Overview b) Holding-plates

Fig.1 Clamshell-type folding tester

3.1 Mechanoluminescent materials

ML materials emits intense light under mechanical stress induced by deformation, friction, or impact, even in elastic deformation region. When dispersedly coated onto a structure, each particle acts as a sensitive mechanical sensor, while the emission pattern reflects dynamical stress distribution (fig. 2). [2]

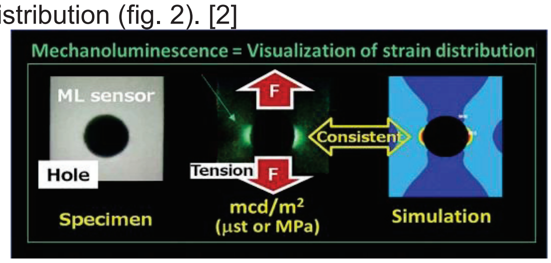


Fig. 2 Mechanoluminescence on stretching

3.2 Simulation, case 1: Plate thickness

In standard configuration of our clamshell-type folding tester, the hinges are put on each edge of holding-plate of specimen (fig.3). When that starts folding motion, the specimen will be bended little by little, and then it will be fully folded in U-shape (fig.4). The specimen will be never bended in smaller radius than a target radius during folding motion. But, holding-plates stretch a specimen if their thickness are 2 mm thinner than the standard, and other holding-plates compress a specimen if their thickness are 2 mm thicker than the standard even if folding radius and reciprocation speed are same [1]. For most of flexible display researchers, 2 mm difference is too huge. So, in this study, we adjusted holding plate thickness every 0.1 mm. The above phenomenon should occur even when their difference is only 0.1 mm.

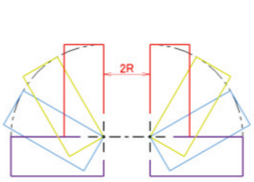


Fig.3 Plates motion

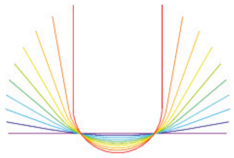
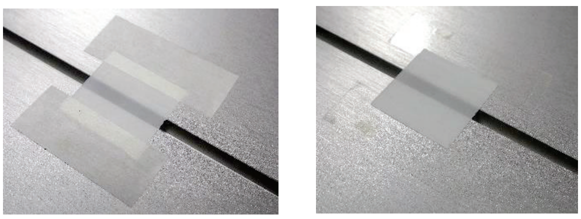


Fig.4 Specimen motion

3.2 Simulation, case 2: Bonding method

You can find many bonding methods to hold a specimen to holding-plates. For example, a tape, a double-sided-tape, adhesion and something. A tape covers and holds a specimen to holding plates, so specimen touches holding plates (fig.5a). But, a double-sided-tape and adhesion are used between a specimen and holding-plates (fig.5b).



a) Tape b) Double-sided-tape

Fig. 5: Holding method

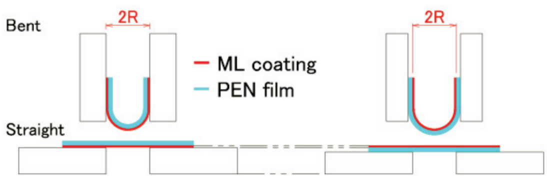
A specimen, held on thick holding-plates with a tape (fig.6a), and a specimen held on standard holding-plates with double-sided-tape (fig.6b) should be deform in almost same profile.

a) Tape b) Double-sided-tape

Fig. 6: Simulation case 2 conditions

3.3 Simulation, case 3: Inward / Outward

Needless to say but, if a specimen is single material, a neutral plane is in center of its thickness. When it is bent, compression stress occur inward of neutral plane, and tensile stress occur outward of a neutral plane. And then, strain on both of surface become same if a neutral plain is in center of a specimen. We adjusted some condition to compare an outward surface (fig. 7a) and an inward surface which has same deforming profile as an outward surface, above (fig. 7b).



a) Outside b) Inside

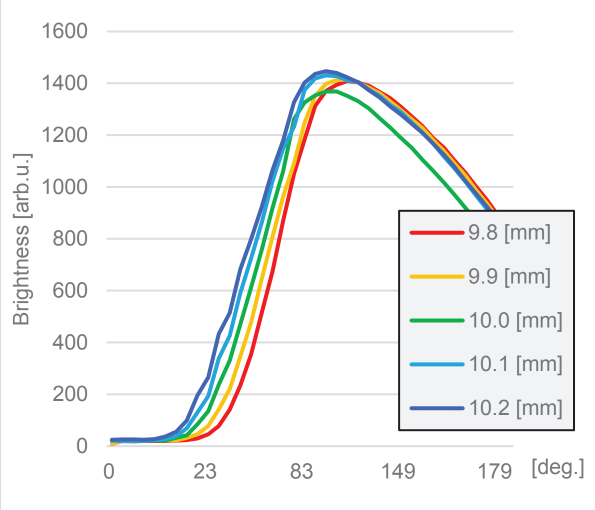
Fig. 7: Simulation case 3 conditions

4. Verification

In order to see mechanical stresses on specimen for these evaluations, we painted Epoxy based ML ink on one side of PEN (polyethylene naphthalate) sheet. In these evaluations, specimen size is width 30 mm, length 30 mm, thickness 0.1 mm, coating thickness 0.01 mm. And, we tape a specimen by 6 mm area from each edge to fold them in radius 5 mm in 30 reciprocation/min. In usually, a specimen is held with masking-tape (easily removable tape.)

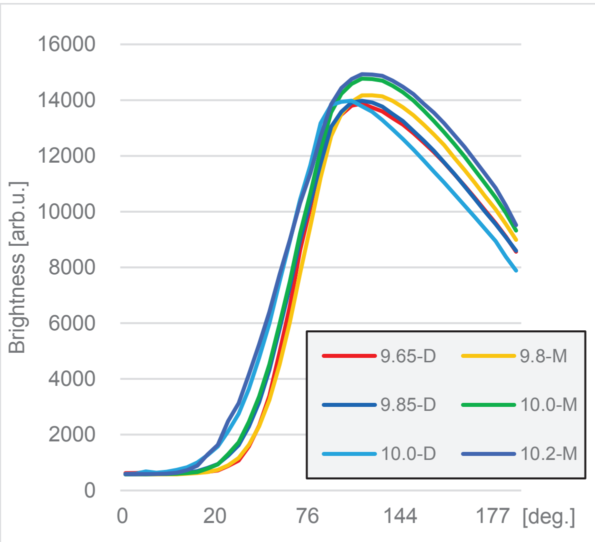
5. Result

First, ML emission showed 0.1 mm holding-plates thickness difference as shown on graph 1. ML emission become bight faster if holding-plates are thicker. On 9.9 mm holding plates, peak of ML emission was weakest.



Graph 1: Result by various thickness plates

ML showed 0.1 mm thickness difference. So, we prepared 0.15 mm thickness double-sided-tape to compare to a tape holding. We also adjusted cartridge thickness 0.15 mm thinner only when using double-sided-tape to align specimen states to a specimen held by masking-tape. Graph 2 shows double-sided-tape thickness affect test result as like changing holding-plate thickness.

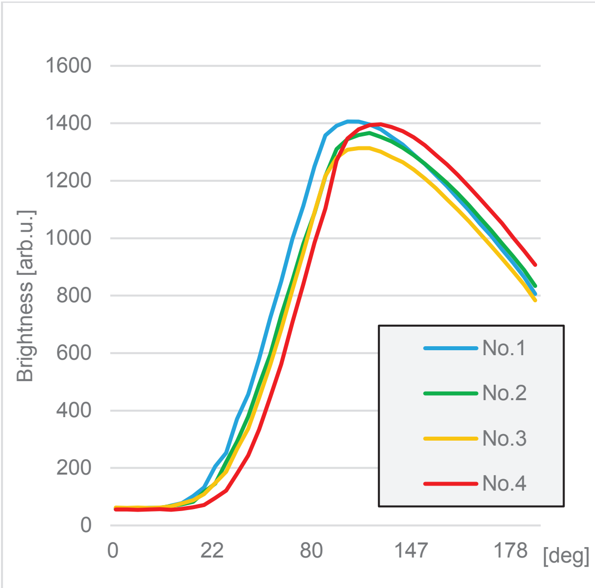


Graph 2: Masking-tape vs Double-sided-tape

ML painted film has front and back. We set specimen painted side up (bent ML coating inward) first, and then other one set up side down (bent ML coating outward). Then, we change test conditions shown on table 1. In these cases, ML coating on specimen No.2 and No.3 were bent in same bending radius, and it is shown on graph 3, ML emission from specimen No.2 and No.3 are almost same.

Table 1: Test conditions

Specimen No.	1	2	3	4
Direction — ML coating — PEN film	Inward	Outward	Inward	Outward
Cartridge	10.0 mm	10.0 mm	9.9 mm	9.9 mm
Target radius (outside of specimen)	5.0 mm	5.0 mm	5.1 mm	5.1 mm
Target radius (ML coating)	4.9 mm	5.0 mm	5.0 mm	5.1 mm
Simulated strain	-0.0101	0.0101	-0.0099	0.0099



Graph 3: Inward vs Outward

6. Discussion

It is extremely difficult to find any differences when we observed bending specimen with different thickness holding plate if the difference is just only 0.1 mm. Even if you use ML, their difference are too small to find by naked eyes. It is necessary to observe ML emission with a measurement system to compare them. Although, we don't know if these differences shown on this paper are serious or not, but 0.1 mm difference make definitely different stresses. These differences are made not only from mechanical structure (equipment specifications) but also from holding method and something test conditions (human factor.)

In this study, we compared inward surface and outward surface. It shows that two conditions had emitted almost same ML emission. Theoretically, suppose to a neutral plane of specimen is center of

PEN film, calculated strain on inward surface and outward surface are same. So, specimen No.1 and No.2 should deformed in same strain, and also specimen No.3 and No.4 should deform in same strain. But results shew, specimen No.2 and No.4 emitted almost same ML emission even though No.2 got tensile stress and No.4 got compression stress. We can explain this phenomenon by evaluation equipment mechanical structure. Our standard structure deform a specimen little by little, without unnecessary stresses. But it was designed without considering a specimen thickness. In this tester, the neutral “tension-free” plane is on surface of standard holding plates. In this case, specimen No.2 and No.4 are on the neutral “tension-free” plane. That means, it is important to know not only a specimen’s neutral plane but also a mechanical neutral plane (fig. 8).

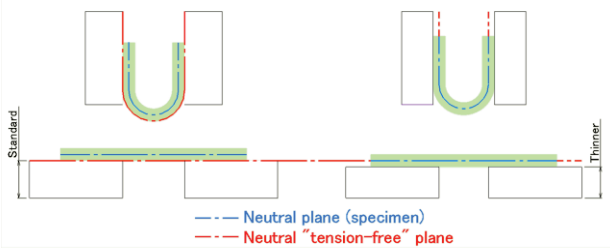


Fig.8 Neutral plane and tension-free plane

Peak of ML emission become bright when ML coating is gotten far from the tester’s neutral plane. If a specimen is inside of the neutral plane, it get compression stress. If a specimen is outside of the neutral plane, it get tensile stress. But, ML emission never shows their cause. It is necessary to simulate strain on ML emitted point to understand that. We think, it is better to simulate strain on a specimen first because sometimes ML emission emitted from not simulated point. You will not find these point if you do not simulate strain before. ML emission have a lot of information.

Concerning about folding mechanism, our double-hinges-clamshell-type folding tester can be adjust thickness of holding-plates to align a specimen to the neutral “tension-free” plane, but a specimen must not leave from the neutral “tension-free” plane.

Our double-hinges-clamshell-type folding tester never touch curved area of a specimen, the curved area is free. We think that it is necessary to support its curved area if a tester should control specimen’s neutral plane as like it reproduce phenomenon will occur on end devices, the tester make definitely different stresses from our standard equipment. We can design mechanical stresses with mechanical structure as shown on this report. In other words, we have to know what happen on each evaluation equipment, and what phenomenon is a purpose of an evaluation, and what profile is best to an evaluation. Researchers and equipment venders should share not only initial and final specimen form but also motion profile to reproduce desirable motions on evaluation equipment.

Reference

[1] Nao Ando, Kei Hyodo, Hisao Sasaki, Yoshihito Ota and Nao Terasaki, “Analysis of Mechanical Stresses on Foldable Devices”, P-130, SID Display Week (2018).

[2] Nao Terasaki, Yuki Fujio, Yoshitaro Sakata, Shin Horiuchi and Haruhisa Akiyama, “Visualization of crack propagation for assisting double cantilever beam test through mechanoluminescence,” The Journal of Adhesion (2018).