Analysis of Mechanical Stresses on Foldable Devices

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ABSTRACT

Knowledge of mechanical stresses on foldable devices is the key factor to develop them. When you study stresses, you should control motion profile then study dynamic stress. In our study, we reproduce some motions on our folding tester, compare a result of simulation and real mechanical stress.

1. Introduction

Recently, we find many kinds of flexible devices in trade shows and markets. 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 evaluate flexible devices during mechanical deformation.

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 use non-stretchable specimens but bendable thin film which length and thickness never change during mechanical deformation. For evaluation equipment, we use our own “Clamshell-type folding tester” to put desirable mechanical stresses (fig.1). The equipment has two axes (hinges) to make folding motion, it is called “double hinges clamshell structure.” It keeps moving in constant condition whenever a specimen is attached on the equipment or not. Thus, it is easy to simulate what happens on a specimen. For our evaluations, we tested four deformation profile (equipment mechanical structure), 1) hinges on each edges, 2) hinges on each center of round, 3) Outer offset hinges, 4) Inner offset hinges.

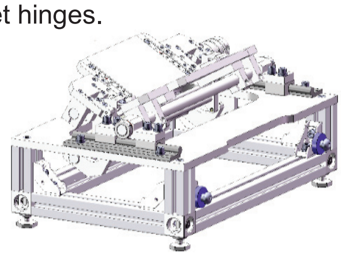


Fig.1 Clamshell-type folding tester

3.1 Simulating conditions

1) Decide a specimen specification and its target folding radius, so on. (for example, thin film: width 40mm, length 40mm, thickness 0.05mm, folding radius 3mm, and reciprocating speed 1Hz)

2) Simulate holding–plates motion profile at every 20 degrees without specimens.

3) Simulate status of the specimen on each simulated holding-plates profile.

3.2 Simulation, case 1: Hinges on each edges

For standard configuration of our clamshell-type folding tester, the hinges are put on each edge of holding-plate of specimen (fig.2). When that starts folding motion, the specimen will be bended little by little, and then it will be fully folded in U-shape (fig.3). The specimen will be never bended in smaller radius than a target radius during folding motion.

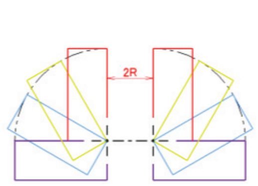


Fig.2 Plates motion

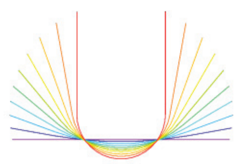


Fig.3 Specimen motion

3.3 Simulation, case 2: Hinges on each center of round

In structure of "Hinges on each center of round", hinges are located on outside of a folded specimen, and the round of the specimen holding plate are designed its center of round will be coaxial to hinge (fig.4). When the evaluation equipment start folding motion, the specimen will be changed suddenly, thereafter its bending radius will almost unchanged, and then the specimen will be folded in teardrop-shape (fig.5).

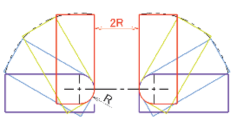


Fig.4 Plates motion

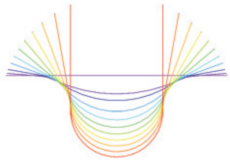


Fig.5 Specimen motion

3.4 Simulation, case 3: Outer offset hinges

In structure of "Outer offset hinges", hinges are located on outside of a folded specimen same as "Hinges on each center of round", but each plate are longer than case 2 in order to have better support a specimen (fig.6). When the evaluation equipment start folding motion, the specimen will be suddenly changed in small radius, then folding radius will be large to the target radius, and then the specimen will be folded in U-shape (fig.7)

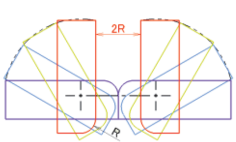


Fig.6 Plates motion

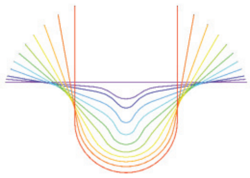


Fig.7 Specimen motion

3.5 Simulation case 4: Inner offset hinges

In structure of "Inner offset hinges", hinges are located on inside of a folded specimen (fig.8). With this structure, it is easy to produce not only cases but also evaluation equipment. But, when the evaluation equipment start folding motion, a specimen will be stretched by the evaluation equipment (fig.9). This phenomenon can be also found on uniaxial folding testers.

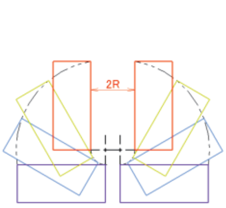


Fig.8 Plates motion

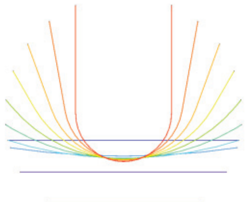


Fig.9 Specimen motion

It is difficult to control the stretching force, but it is easy to verify a stretching length by the "Pythagorean theorem." (fig.10)

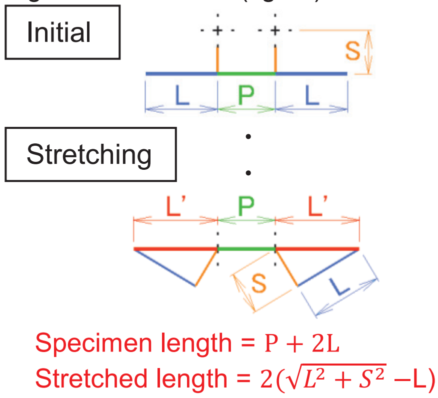


Fig.10 Formula to verify the stretched length

In this simulation, P=2mm, L=18mm, S=2mm, thus the specimen will be stretched 0.22mm ($e=5.5x10^{-3}$).

4. Verification

In order to see mechanical stresses on specimen for those four evaluations, we use "mechanoluminescent (ML) materials" In order to compare a specimen motion simulation and stress, we observed each specimen motion on each testing conditions with ML sensor sheet that has ML material on PVC (Polyvinyl chloride) sheet. In these evaluations, specimen size is width 40mm, length 40 mm, thickness 0.05mm, and the folding radius 3mm, and reciprocating speed is 10 reciprocation/min.

4.1 Mechanoluminescent materials

Mechanoluminescent (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.11). Currently, ML sensors have been used in practical applications such as structural health monitoring for bridge or welding points, and sophistication of computer aided engineering (CAE).[1]

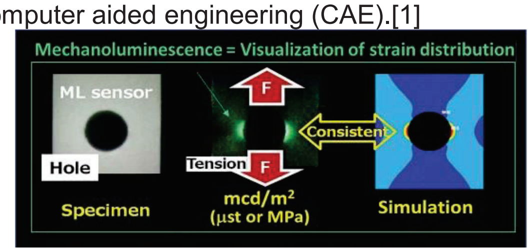
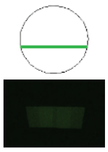
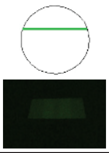
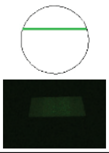
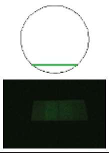
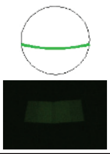
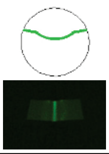
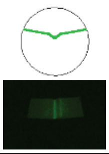
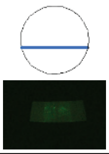


Fig.11 Mechanoluminescence on stretching

5. Result

Mechanoluminescence for each case was observed as shown on the table 1, below.

Table 1 Comparison: Simulation and ML

	Case1, Hinges on each edges	Case 2, Hinges on each center of round	Case 3, Outer offset hinges	Case 4, Inner offset hinges
0 deg. <Initial>				
20 deg.				Tension 
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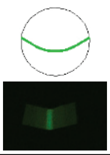
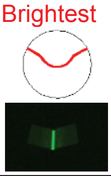
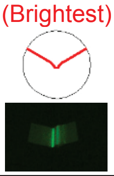
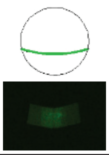
60 deg.		Brightest 	(Brightest) 	
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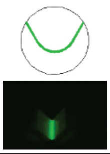
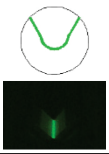
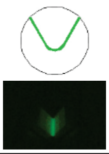
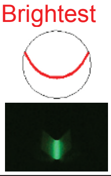
120 deg.				Brightest 
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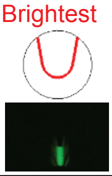
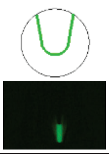
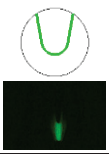
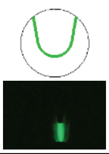
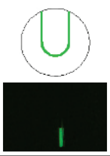
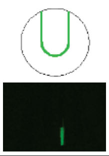
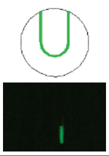
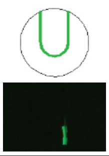
160 deg.	Brightest 			
180 deg. <Target>				

In case 1, the specimen deformed as like simulation. Luminescence could be observed at only center of the specimen (bended area): Luminescence became strong little by little, and then brightest luminescence occurred when the specimen bended in 160 degrees (right before stop the motion).

In case 2, the specimen deformed as almost like simulation. The specimen looked be momentarily off from holding plates at right after starting testing motion, that is different from simulation. And, various luminescence was observed at not only center of the specimen (bended area) but also held points. At center of the specimen, three narrow strip luminescence was observed: These luminescence happened suddenly then became dark little by little. Each held points lit only when the specimen looked be momentarily off from holding plates.

In case 3, the specimen did not deform same as simulation, it had deformed to unnatural form. And then, after evaluation, the specimen had got plastic deformation.

In case 4, interesting luminescence was observed on the specimen right after starting folding motion: Even though the specimen was still straight, all over the specimen lit slightly, and some strong light like stars were observed. And then, when the specimen began deforming, luminescence was observed at center of the specimen, and it became strong little by little as like the standard “Hinges on each edge” structure, but it was stronger than the standard structure.

6. Discussion

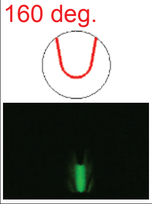
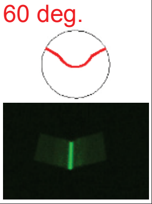
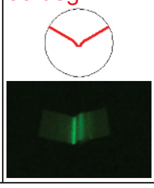
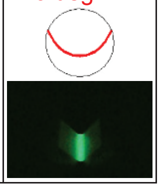
These results show that different structure apply different stresses on a specimen even if reciprocating speed and some conditions are same. Each specimen initial shape and its fully folded shape looks similar. However motion profiles (shape during deformation) are definitely different. Only by luminescence observation, it is impossible to figure out the causes of stresses, but simulation help to figure them out.

If clamshell hinges are ‘offset outside’, deformation (compression stress) suddenly occurred on a specimen. As you know, the compression stress (parallel direction to surface) would be a serious cause of delamination. If a specimen is a layered object as like a flexible display, delamination may be occurred on it immediately because these compression stress will be happen in short period of time.

If clamshell hinges are ‘offset inside’, a specimen will be stretched. In the market, we can find some products (bendable/ foldable display) have “Inner offset hinges” structure. For these products, the display can slide over the case, so that it is never stretched by the case. If that is the final design, it is necessary to reproduce the slide motion by an evaluation equipment.

For us, “hinges on each edge” structure is ideal structure as ideal folding tests, because it looks given smallest stress on specimen (its luminescence looked most dark as shown on the table 2). However, in order to evaluate more precisely, we have to compare each luminescence brightness by objectively reliable amount.

Table 2 Comparison: Each brightest luminescence

Hinges on each edges	Hinges on each center of round	Outer offset hinges	Inner offset hinges
160 deg. 	60 deg. 	60 deg. 	120 deg. 

We can control motion profile 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.

7. Acknowledgment

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8. Reference

[1] 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).