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Article

Designing an Evaluation Method for the *in-situ* Impact Strength of Rollable Devices

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Abstract

In this study, a methodology for evaluating impact strength in rollable devices was developed, focusing on measuring impact strength and evaluating rolling and unrolling durability simultaneously, with findings reported from tests on a real demonstration unit. The study utilized a flexible and rollable polyimide (PI) substrate for the evaluations. The chosen parameters for this methodology were a flat-type impactor, weights of 300 g, 500 g, and 1000 g, a rolling shaft ranging from 30 R to 5 R, and the positioning of the impactor. The results revealed that the difference in defect rates when comparing the 300 g and 500 g weights was minimal. However, the adoption of a 1000 g weight markedly increased the defect count due to damage to the PI film's surface. Furthermore, an uptick in rolling and unrolling cycles led to more pronounced surface scratches on the PI film. These methods and findings are poised to make a substantial contribution towards refining reliability testing for a wide array of rollable device applications, including smartphones, watches, pads, and wearable technology.

Keywords: *Rollable devices, Impact strength, Evaluation method, Reliability, Form factor free*

1. Introduction

Displays are increasingly recognized as key to the future of information presentation devices, prompting extensive research into their innovation and sustainability[1-2]. With technological advancements, there is an increase in the amount of information and mobility, leading to innovations in form factors for enhanced convenience according to user environments[3]. Such innovations play a important role in opening new market segments, attracting consumer interest, and strengthening competitiveness in existing markets[4].

Furthermore, changes in device form factors are expected to radically alter our lifestyles and work environments, influencing a range of industries through device integration[5-7]. The current pursuit of form factor changes is moving towards shapes that can easily be bent, folded, and unfolded to represent screens larger than the device size itself, emphasizing portability and the increasing amount of information that needs to be displayed[8-11]. Foldable mobile devices that can be folded in two parts have already been commercialized, attracting a lot of consumer attention, and research is actively being conducted to commercialize even more advanced form factors, such as rollable displays [12-13]. Rollable displays, which can be rolled and unrolled like a scroll, are expected to revolutionize not only design but also storage, portability, and space-saving[14].

For the commercialization of these products, the evaluating the effect of impact strength and durability test according to the user environment is very important, but for rollable devices, there is still a lack of standardized evaluation methods[15-16]. Especially since rollable displays can undergo various innovations depending on the curvature radius, and although smaller radii are advantageous in terms of design, the stress on the panel can increase several times, making the durability evaluation according to the curvature radius also important [17-18]. Thus, this study sought to create and establish a combined method for evaluating both impact strength and durability for rollable products. This approach entailed performing extensive rolling/unrolling cycles and impact strength evaluation, tailored to the user environment. It involved choosing flexible materials that could accommodate a wide range of curvatures, from 30 R to 5 R, to ensure the method's applicability across different device designs. By proposing a new reliability evaluation method, it is expected to contribute significantly to the development of reliability test methods for various form factor free products, such as smart phones, watches, pads, and wearable devices.

2. Experimental

2.1. Material selection for rollable substrates

Ultra-thin glass (UTG), thermoplastic polyurethane (TPU), and polyimide (PI) are three materials commonly used as substrates in flexible and rollable electronics, each offering distinct characteristics and advantages for specific applications[19-21]. UTG boasts exceptional optical clarity and surface smoothness, along with high chemical stability and resistance to scratches and thermal expansion[19]. It is also highly

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Table 1. The Physical Properties for PI Substrates

Property (@23 °C)	PI (125 μm)
Ultimate Tensile Strength (psi)	33500
Ultimate Elongation (%)	82
Tear Strength (N)	46.9
Yield Point at 3% (psi)	69

impermeable to gases, which is beneficial for OLED displays and electronics where moisture and oxygen penetration can degrade performance[22]. Despite its ultra-thin designation, UTG is still more rigid and fragile compared to polymeric substrates. Its flexibility is limited, making it less suitable for applications requiring extreme bending or rolling [23]. Additionally, UTG can be more expensive to produce due to the precision required in manufacturing processes[24].

TPU stands out for its elasticity and flexibility, allowing for significant bending and stretching without damage[20]. This makes it especially suitable for wearable devices[25]. TPU also has good resistance to oils, greases, and various chemicals[26]. On the other hand, TPU's optical properties might not be as good as those of UTG, with potential for yellowing over time when exposed to UV light[27]. Its thermal stability is lower than PI, making it less suitable for applications involving high processing temperatures[28].

Polyimide is renowned for its excellent thermal stability, able to withstand high temperatures without degrading. This makes it suitable for applications requiring high-temperature processing[29]. PI films are also flexible and can be made very thin, making them ideal for rollable and foldable applications[21]. However, PI can have lower optical transparency compared to UTG, limiting its use in applications where clarity is critical[30]. It can also absorb moisture, which might affect its electrical properties and dimensional stability[31]. Among these, in this study, considering flexibility and other factors for rollable devices, we have selected polyimide (PI) film[21,29]. The characteristics of the physical properties data for the PI substrate, including Ultimate Tensile Strength, Ultimate Elongation, Tear Strength, and Yield Point at 3%, are shown in Table 1[32].

3. Results and discussion

3.1. Design an impact strength evaluation methods for rollable substrates

To design an impact strength evaluation method for flexible and thin polyimide (PI) films, we have first investigated previous several international standards (ASTM) for impact strength evaluation methods. Among them, as shown in Figure 1, the most representative one is the Charpy and Izod Impact Strength tests (ASTM D6110-04 and ASTM D256-10)[33,34]. These methods require the specimen to be vertically mounted and have a thickness of at least 3 mm. However, The PI film specimens used in this experiment have a thickness in micrometers (μm) and are very flexible, making them unsuitable for these traditional evaluation methods. Therefore, as shown in Figure 2, we devised an impact strength evaluation method by laying the thin and flexible substrate on a flat stage and dropping a weight onto it.

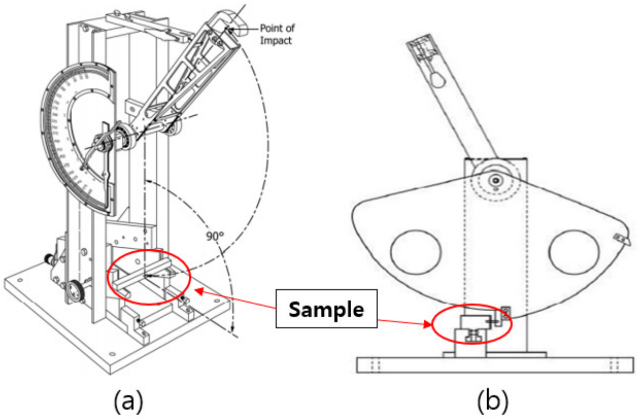


Figure 1. The typical durability evaluation methods. The Charpy (a) and Izod (b).

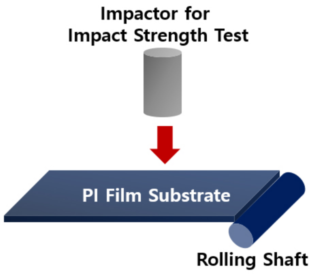


Figure 2. A concept for the impact strength test and durability evaluation method of rollable devices.

This concept includes attaching the test sample (PI film) to a rolling shaft for a rolling/unrolling test and incorporating an impactor for simultaneously evaluating the impact strength. To verify a variety of experimental measurements, we introduced rolling shafts of 30 R, 20 R, 10 R, 5 R, and impactor types of flat, pointed, round, with weights of 300 g, 500 g, 1000 g, as shown in Figure 3(a).

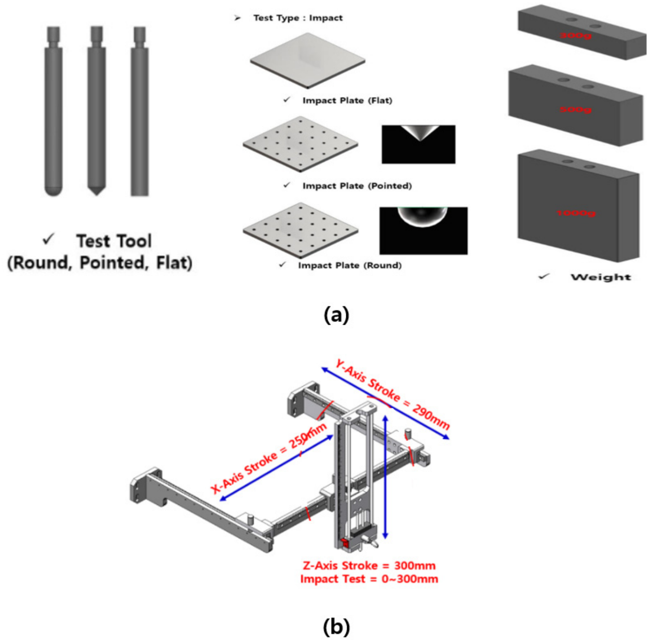
Furthermore, to investigate the various impacts that actual flexible products might experience during use, we expanded the range of evaluation to allow impacts from any positioning on the substrate. As shown in Figure 3(b), the impactor was designed to move along the X, Y, and Z axes, with a range of motion of 250 mm in the X-axis, 290 mm in the Y-axis, and 300 mm in the Z-axis.

3.2. Configuration of impact strength test equipment for rollable substrates

Based on this design, the actual rolling and impact strength test equipment was built, which is presented in Figure 4. Figure 4(a) shows the actual equipment manufactured by FlexiGo, Inc. with the rolling shafts of 30 R, 20 R, 10 R, 5 R and Figure 4(b) is actual impact strength evaluation system with the weights of 300 g, 500 g, 1000 g.

3.3. Selection of evaluation factors

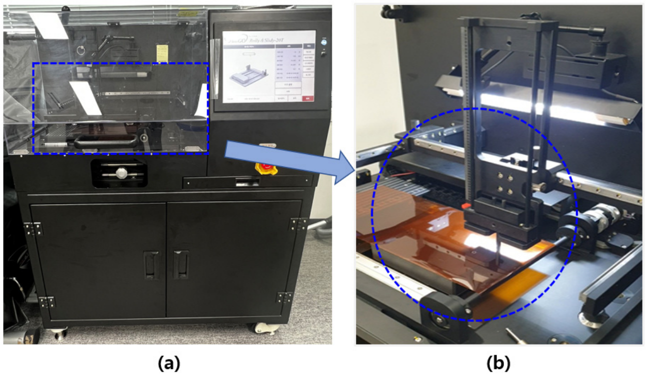
Before conducting tests and evaluations using PI film, it was hypothesized that the impact of the overlaps, which vary depending on



(a)

(b)

Figure 3. A design for the impact strength for rollable devices. (a) Various impactor shape and weight. (b) Design of impact strength evaluation system.



(a) (b)

Figure 4. An actual reliability test equipment with in-situ impact strength evaluation system for rollable devices. (a) Reliability test equipment. (b) Impact strength evaluation system.

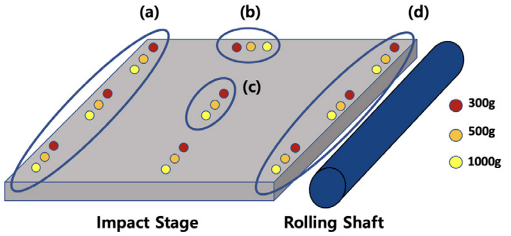


Figure 5. A schematic drawing for the consideration of evaluation factors selections for rollable devices.

Table 2. The Potential Energy Applied to the PI Film

m (kg)	g (m/s^2)	h (m)	P (N · cm)
0.3	9.8	0.291	86
0.5	9.8	0.291	143
1.0	9.8	0.291	285

the position on the substrate (with more overlaps occurring closer to the rolling shaft), would affect the rollable devices differently. This led to an investigation into how the number of overlaps affects the impact strength, evaluating the impact of center and edge positions on the substrate on impact strength as well.

This method of evaluating impact strength is depicted in Figure 5. Figures 5(a) to 5(d) represent areas with the least number of overlaps, the edge, the center, and the area with the most overlaps, respectively. The parameters used in this evaluation method include the impactor, weight, and impactor position. The impactor was a flat type, weights were 300 g, 500 g, and 1000 g, and the impactor position was set to 291 mm.

3.4. Development of impact strength evaluation method

We conducted an impact strength evaluation with reliability test of PI film using the built-Rollable and Impact Strength Test equipment. The sample size of the PI film was 150 × 330 mm, with a thickness of 125 μm. The rolling shaft radius was set at 10R, the rolling length at 121 mm, and the reciprocating (rolling/unrolling) time at 3 seconds. The impactor type was flat, with weights of 300 g, 500 g, and 1000 g. The total number of rolling was 50000, and the Impact Strength Test was repeated every 10000 rolling from 0 to 40000 for a total of 5 cumulative sessions. The potential energy applied to the PI film by the three different weights is presented in Table 2.

High-Resolution SEM analysis for impacted area with difference weight was shown in Figure 6. As indicated in Figure 6, there is no significant difference in the occurrence of defects between the 300 g and 500 g weights. However, when a 1000 g weight is used, it can be observed that the occurrence of defects is significant due to damage on the surface of the PI film. Additionally, an increase in defects can be observed at the boundary areas of the circular traces formed by the impact of the impactor (flat type), as shown in Figures 6(d) and 6(e).

3.5. The *in-situ* impact strength evaluation method with durability test

The experimental conditions are almost identical to those described in section 3.4. The sample size, thickness of the PI Film, and the type of impactor remain the same. In this experiment, the rolling shaft was set to 5R, and the rolling length was increased to 180 mm, allowing for approximately 5.7 times more overlap. The total number of reciprocations (rolling/unrolling) was conducted 300000 times, and the Impact Strength Test was repeated every 50000 cycles for a cumulative total of 6 times. Considering that the durability tests for currently commercialized foldable smart-phones are based on around 200000 cycles over a 5-year period at 100 cycles/day[35], this experiment chose a more stringent condition of 300000 cycles. Furthermore, the Impact Strength Test was conducted following the experimental method established in section 3.3 and 3.4.

After completing 300000 cycles of rolling and unrolling a PI film

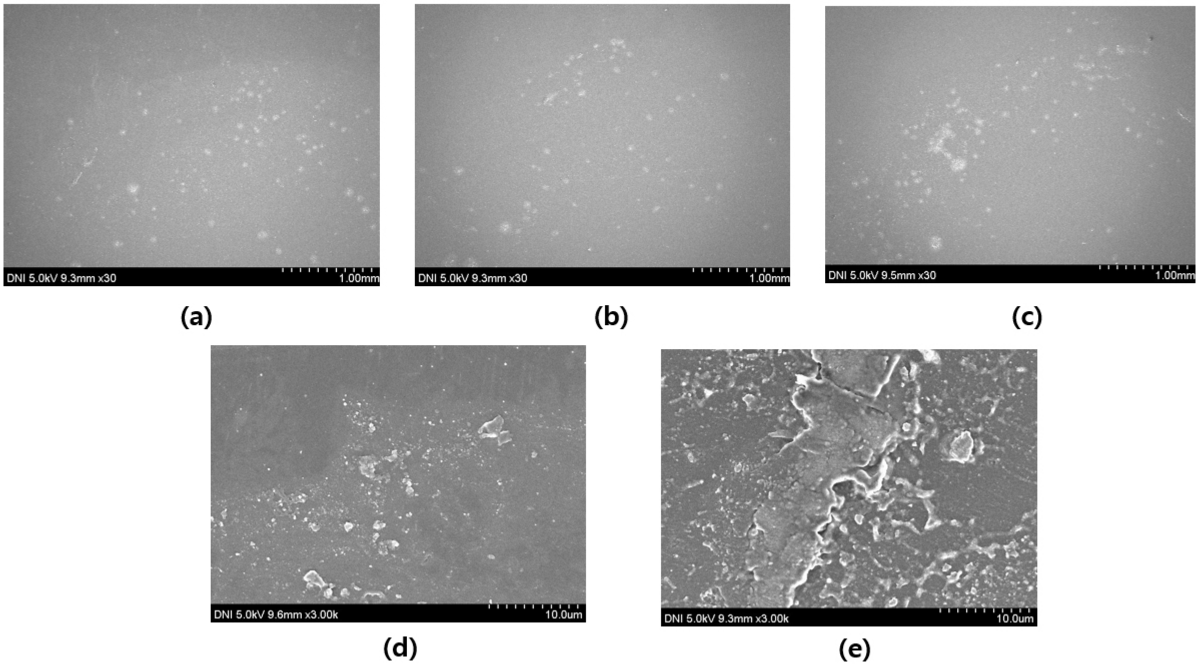


Figure 6. High-resolution SEM analysis for impacted area with difference weight (x: resolution). (a) 300 g, x30, (b) 500 g, x30, (c) 1000 g, x30, (d) 300 g, x3000, (e) 1000 g, x3000.

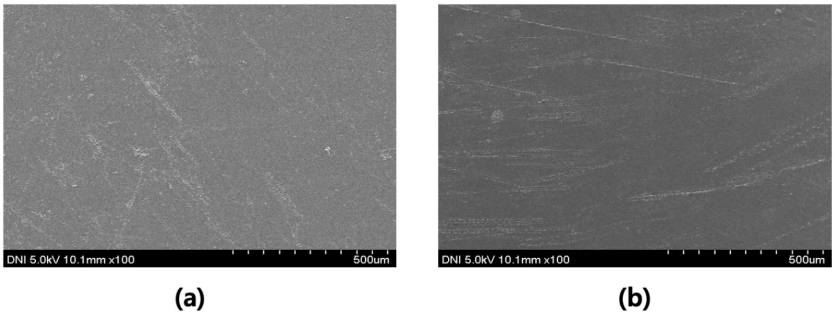


Figure 7. High-resolution SEM analysis for impacted area with difference overlaps. (a) 3 overlaps. (b) 5 overlaps.

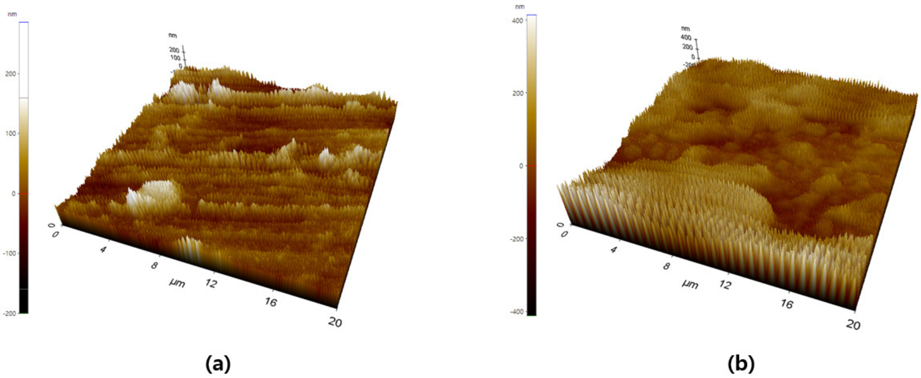


Figure 8. AFM Images for the difference overlap area. (a) 3 overlaps, (b) 5 overlaps.

over an area with 5 overlaps, high-resolution SEM analysis depicted in Figure 7 revealed a significantly higher increase in scratches compared to areas with only 3 overlaps. To quantify the observations mentioned, further analysis was carried out using Atomic Force Microscopy (AFM), as illustrated in Figure 8. In this figure, 8(a) shows the area with 3 overlaps, while 8(b) depicts the area with 5 overlaps. As indicated, the area with 5 overlaps exhibited more severe scratching, a result quantitatively corroborated by RMS roughness measurements: 40

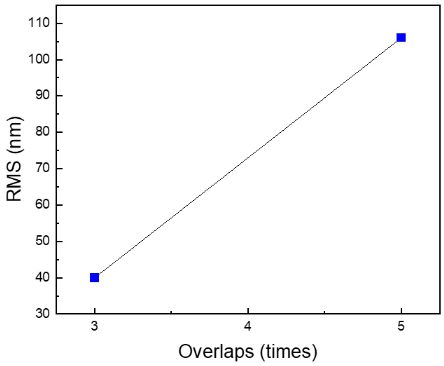


Figure 9. An RMS roughness according to difference overlaps.

nm for areas with 3 overlaps and 106 nm for areas with 5 overlaps, as presented in Figure 9. Additionally, the impact strength's effect remained consistent across both the center and the edge of the sample, showing no significant variance.

4. Conclusion

In this study, a method for evaluating impact strength was developed to examine the influence of impact strength and the rolling/unrolling durability simultaneously, using a actually built-demo unit for evaluation. The evaluation method chose parameters like the flat type of the impactor, weights of 300 g, 500 g, and 1000 g, a rolling shaft ranging from 30 R to 5 R, and the position of the impactor. Utilizing this design, we performed an evaluation on the durability and impact strength of PI film with the custom-built Rollable and Impact Strength Test apparatus. The occurrence of defects shows little difference when comparing the effects of using weights of 300 g and 500 g. However, the use of a 1000 g weight significantly raises the defect count, mainly due to the damage caused to the surface of the PI film. Moreover, an increase in the number of rolling/unrolling cycles leads to more pronounced scratching on the PI film's surface. The methodologies and results of this evaluation are expected to play a important role in enhancing the reliability testing techniques for various flexible and rollable products, including smartphones, watches, pads, and wearable technology.

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