Out-Foldable Smartphone Will Be Real?: Challenges for Developing Glass-like Cover Plastic Films

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Abstract

An out-foldable smartphone is more favorable for consumers' convenience but technologically more difficult than an in-foldable one. Particularly, for the out-foldable one, a large elongation of cover window film induced by tensile stress outside display module is required. However, it is difficult to realize the large elongation in the hard coating on the cover film. This invited paper deals with the issues of hard coating and proposes newly developed solution with high scratch-resistance for out-foldable smartphone.

Author Keywords

Out-foldable smartphone; Cover plastic film; Hard coating; Elongation; Low friction coefficient; Scratch resistance; Flex9H

1. Objective and Background

In last few years, major display panel companies have unveiled prototypes of the foldable displays to be used in real foldable smartphone. Finally, after endless leaks and rumors, Samsung will launch commercial foldable smartphone "Galaxy Fold" with a flexible display called the 'Infinity Flex Display'. The phone itself has a tablet-sized screen that can be inside folded up to fit into a pocket. The device includes two displays: a cover display that acts as a phone, and a main 7.3-inch tablet display. This in-foldable smartphone is disadvantageous in terms of price, battery capacity, thickness and form factor design. Thus, out-foldable smartphone that uses a single display for both a phone cover and a main tablet display is more favorable than in-foldable one. Royole introduced the world's first out-foldable smartphone "FlexPai" in last year and Huawei will release "Mate X" out-foldable smartphone with an 8-inch single display screen in later this year. However, since the out-foldable smartphone always exposes the display screen to the outside, it must be protected from external impacts or scratches. Thus, the out-foldable smartphone is very concerned about reliability of protection against external damage in addition to folding in order to come out to the market.

The biggest challenge in implementing a foldable smartphone is replacing the glass used as the cover and display substrate with a plastic film. Display substrate films have already been replaced by yellow PI (polyimide) films with high thermal stability to enable plastic OLEDs. Cover plastic film that replace chemically reinforced (Gorilla®) glass must be mechanically durable enough to withstand a smaller folding radius when folded hundreds of thousands of times. In addition, additional hard coating on the surface are required to protect against scratches. In respect of the reliability of the smartphone, it must have excellent mechanical properties to withstand the various stresses and strains that occur when the device is folded. Especially, contrary to the in-folding smartphone in which the cover plastic film is folded inward to be hidden, the hard coating on cover plastic film which is the outermost layer of the module structure should provide more reliable protection and simultaneously endure the highest level of tensile strain during out-folding condition. Therefore, it is no exaggeration to say that the success of out-foldable smartphone highly depends on the performance of the hard coating.

Usually, the hard coating materials with high strength are brittle not to be flexible. Also, we need thick hard coating to obtain high hardness on the soft plastic substrate. Thus, we have developed epoxy siloxane based flexible hard coating material (Flex9H®) exhibiting glass-like strength and plastic-like modulus to be applicable to foldable smartphone cover film [1]. Its coating with over 35μm thickness demonstrated 9H pencil hardness and perfect foldability with less than 1mm in-folding radius [2]. However, the hard coating for out-folding cover application requires additional large elastic elongation in addition to high strength and low modulus. When the device is folded, compression and tension are applied internally and externally, respectively. The tension in the outside of the module makes positive strain. Thus, the hard coating layer that is the outermost of the device should be elongated during out-folding. The larger elastic deformation is required for the hard coating material used in out-foldable smartphone cover. However, elastic strain of the hard coating material is limited to be applicable to out-foldable smartphone.

The tensile stress created maximum strain value (ε) at the outside surface during folding is

$$\varepsilon = \frac{z}{R} \tag{1}$$

z is the distance from the stress neutral plane and R is the radius of curvature at the stress neutral plane. For the hard coating to have better out-foldability; obtain smaller folding radius, there are two options: Increase in elastic elongation, *i.e.*, yield strain (ε_y) and decrease in thickness of the device module including hard coating thickness. The former can be expressed in terms of yield strength (σ_y), elastic modulus (E) and hardness (H) with the aid of linear elasticity and Tabor's relationship as follows.

$$\varepsilon_y = \frac{\sigma_y}{E} \propto \frac{H}{E} \tag{2}$$

It means that materials with high hardness or strength to modulus ratio can result in large elastic elongation prior to failure. Our flexible hard coating (Flex9H®) also exhibits rubber-like elasticity of outstanding elongation of *ca*. 4% in micrometer length scale. In bulk scale for the actual application, yield elongation of Flex9H® was about 2%. Nevertheless, for acceptable folding performance of out-foldable smartphone, the hard coating materials with high elongation should be developed. It is noted that it is a challenging work because materials with high yield elongation exhibit low level of hardness as a regular rule.

Table 1. The specification of Flex9H® coating films for out-folding application

Characteristics	Grade			Method
	S1	S2	S3	
Film thickness	80 μm	50 μm/80 μm	50 μm	ISO 2808
Coating thickness	1 μm	15 μm	20 μm	
Pencil hardness	4H	6H	8H	ISO 15184, 1kgf, Speed of 180mm/min,
Water contact angle	≥110°	≥110°	≥110°	ASTM D 7490
Scratch resistance	≥5,000 cycles pass Water contact angle ≥ 100°	≥5,000 cycles pass Water contact angle ≥ 100°	≥5,000 cycles pass Water contact angle ≥ 100°	Steel-wool #0000, 1kgf/2x2cm^2, Speed of 40cycles/min, Migration length of 4cm
Out-folding test	5R, ≥200K pass	5R, ≥200K Pass	5R, ≥200K pass	IEC 62715, Speed of 60cycles/min

Furthermore, in case of the latter approach, *i.e.*, the thinner coating certainly contributes to reduction of the required elastic strain but similarly leads to degradation of hardness due to hardness dependence on coating thickness. We are newly developing the elastic hard coating material with elongation of higher than 3% by hybridization of siloxane with elastomer to demonstrate out-foldable module with hard coating cover film.

When the out-foldable smartphone will be used in real life, the scratch resistance will be more critical than surface hardness for cover window. Because the cover window of the smartphone that is directly exposed to the consumer will be scratched by several damage. In fact, scratch resistance of coating is influenced not only by surface hardness but also by a type of abrasive material, surface roughness, modulus and elasticity, friction coefficient, environments, etc. Above all, the most effective way to increase scratch resistance is to reduce friction during contact between hard coating and abrasive material so that they easily move relative to one another. The most common way to reduce friction is to impart hydrophobicity to the hard coating [3]. This will give the glass-like smooth touch feel to cover window.

Based on these background understanding, here, we provide newly designed hard coating solution for the cover film of the out-foldable smartphone. A good extensible hard coating with hydrophobicity function will represent excellent folding and excellent scratch resistance for the cover film of the out-foldable smartphone.

Figure 1. Procedure of steel-wool scratch test (left) and excellent scratch resistance of Flex9H® (right).

2. Results

We have developed new design of hard coating (Flex9H®) having high elasticity and low friction by hybridization and composite of siloxane material with elastomer and hydrophobic chemicals. The optimized hard coating solution was determined for out-foldable cover film. We fabricated three types of out-foldable cover plastic films, by varying the Flex9H® coating thickness on a 50μm or 80μm thick colorless polyimide (CPI) film substrate in order to meet the required specifications of various out-foldable display module designs. As shown in Table 1, each film provides different pencil hardness of 4H, 6H, and 8H depending on Flex9H® coating thickness as discussed earlier.

The hydrophobic surface of the Flex9H® coating resulted in low kinetic friction coefficient of 0.035 and high water contact angle of >110° This can also give the anti-finger (AF) and glass-like smooth touch feel that are required in the cover window of the smartphone.

Figure 1 shows operation process of steel-wool test to confirm the scratch resistance. Interestingly, regardless of pencil hardness, all specimens showed no visual scratch line on the coating surface maintaining water contact angle of >95° after 5,000 cycles. This is because in the case of steel-wool test, since the normal pressure is considerably less than that of pencil hardness test even though normal load is same as 1kgf, the surface property plays a more important role than coating thickness and substrate effect.

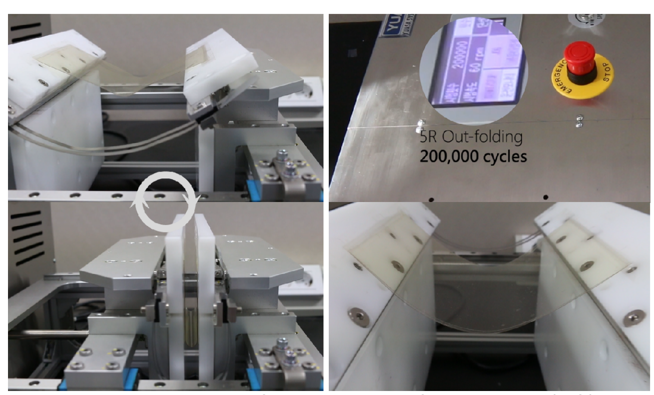

Figure 2. Procedure of dynamic out-folding test (left) and outstanding flexibility of Flex9H® (right)

To confirm the out-folding characteristics of three types of cover plastic films, U-shape folding tester was used as described in Figure 2. After 200,000 cycles with folding radius of 5mm, there was no change in appearance including crack and permanent deformation in all specimens. We will also demonstrate the out-folding performance of simulated module of up to 300μm thick film stack including cover film. This can represent its feasibility of hard coating cover film for out-foldable smartphone.

3. Impact

For commercialization of reliable out-foldable smartphone, the development of hard coating on cover window film with large elongation, high hardness and superior scratch resistance is recognized as a very important task. In this work, we demonstrate that the satisfactory solution can be achieved by making the surface of Flex9H® coating, which is our patented hard coating technology, to be more hydrophobic and have less surface friction. We believe that our findings can implement the out-foldable smartphone with better foldability and reliability.

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