

# Using an Interlayer to Toughen Flexible Colorless Polyimide-Based Cover Windows

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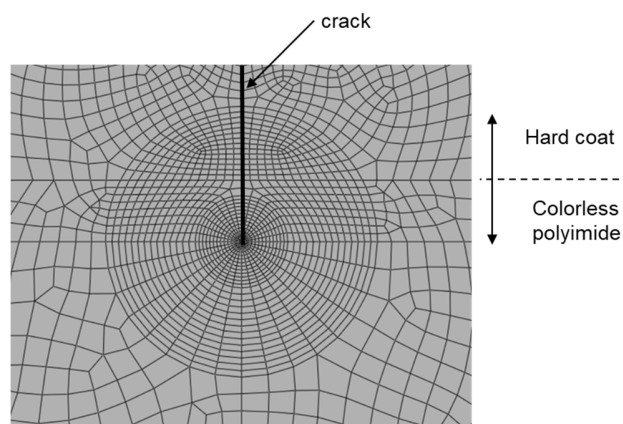
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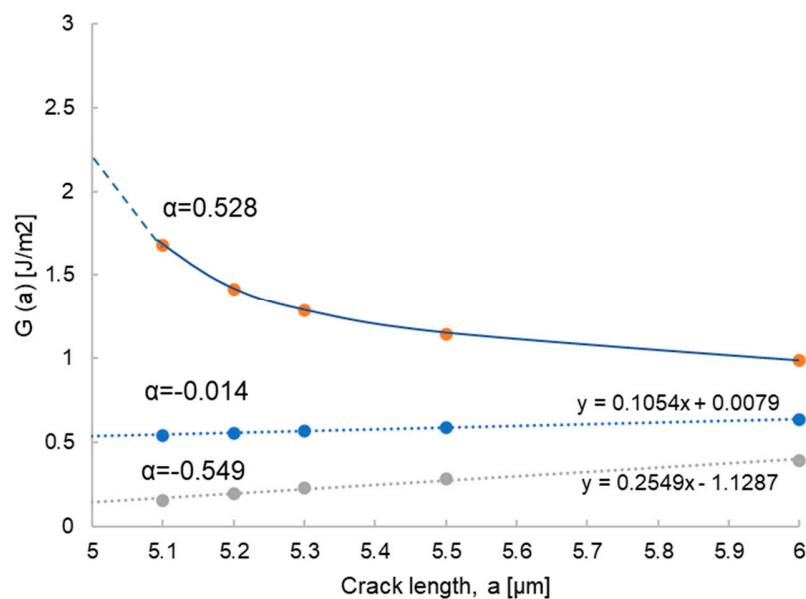
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The supplementary Video S1 shows the bending of a bilayer cover window composed of the hardcoat and the colorless polyimide (PI) films in Table 2 of the main article. By folding the cover window in the out-fold direction (the hard coat side is facing outward), the cover window fractured into two pieces. In contrast, the bending did not lead to the fracture of the bare colorless polyimide alone. It is noted also that the same cover window bent in the in-fold direction did not fracture neither.

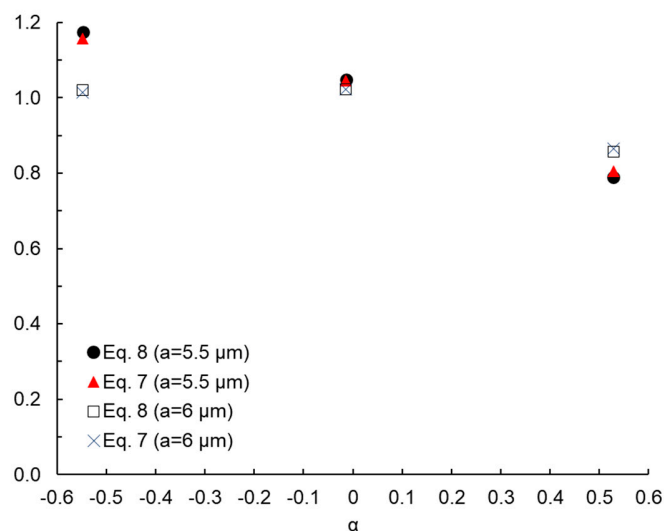
To validate the proposed method (Eq. 8) to characterize normalized critical strain,  $\epsilon_c$ , the first method using traditional J-integral and Eq. 7 was performed for case b1 with selected materials inputs. The J-contour integral geometry around the crack is shown in **Figure S1**. A finer circular mesh region was divided into 32 sections in the circumferential direction surrounded by a coarser transitory circular mesh region. Strain energy release rate for plane strain crack,  $G(a)$  was computed for the geometry with Dundur's parameter,  $\alpha = -0.549, 0.063$  and  $0.528$  as a function of crack length,  $a$  (**Figure S2**). The value of  $G(a=5 \mu\text{m})$  was estimated by a linear extrapolation for the negative  $\alpha$  values. For  $\alpha = 0.528$ ,  $G(5 \mu\text{m}) = 2.2 \text{ J/m}^2$  was assumed. The comparison of normalized  $\epsilon_c$  by the two methods for  $a = 5.5 \mu\text{m}$  and  $6 \mu\text{m}$  is shown in **Figure S3**. The computational results by the two methods generated almost identical results.



**Figure S1** FEA geometry for J-integral of a crack in bilayer cover window (case b1).



**Figure S2** Strain energy release rate for plane strain crack geometry,  $G(a')$  as a function of  $a$  for selected  $\alpha$  values.



**Figure S3** Comparison of normalized  $\varepsilon_C$  computed by the first method (Eq. 7 and J-integral) and the second method (Eq. 8).

The representative physical and functional properties of the colorless PI films are shown in **Table S1**. The polyimide film for cover windows must endure thousands of bend cycles and temperature cycling without creasing, crazing, or yellowing. Flex-life endurance measurements (Yuasa, Japan) over a 1 mm radius shows durability to 1 million cycles without visible damage.

**Table S1** Physical and functional properties of the colorless PI films

Mean Thickness	~ 50 $\mu\text{m}$
Total Transmittance (400-700 nm)	88.1%
Glass transition temperature, $T_g$	~380 $^{\circ}\text{C}$
Yellow Index, YIE313	2.7
$L^*$	94.5
$a^*$	0.05
$b^*$	1.38-1.41
Haze	~0.6 %
Haze (bulk haze)	0.38 %
Folding endurance	>1 million cycles* (1mm bending radius)

All the computation results of non-dimensional parameter  $Z$  for channel crack cases are listed in **Table S2** (bilayer cover windows), **Table S3** (trilayer cover windows with  $h_{\text{IL}} = 0.5 \mu\text{m}$ ), **Table S4** (trilayer cover windows with  $h_{\text{IL}} = 1 \mu\text{m}$ ), and **Table S5** (trilayer cover windows with  $h_{\text{IL}} = 5 \mu\text{m}$ ). Using these Tables and Eq.8, we calculated  $Z$  for channel crack of interlayer and colorless PI films under an already propagated channel crack (case t4 and case t5).

**Table S2**  $Z$  values for bilayer cover windows with varying elastic properties and crack length.

$\alpha$	$E_{\text{HC}}$	$E_{\text{PI}}$	Crack length, $a$ [ $\mu\text{m}$ ]			
			5	5.5	6	6.5
			$Z_{\text{bl}}$			
-0.549	3	10	1.37	1.53	1.83	2.20
-0.282	4.75	8.25	1.59	1.75	1.97	2.22
-0.014	6.5	6.5	1.89	2.08	2.26	2.45
0.063	5.6	4.8	2.00	2.20	2.37	2.54
0.256	8.25	4.75	2.33	2.57	2.72	2.85
0.528	10	3	3.04	3.39	3.51	3.57

**Table S3**  $Z$  values for trilayer cover windows ( $h_{\text{IL}} = 0.5 \mu\text{m}$ ) with varying elastic properties and crack length

$\alpha$	Modulus [GPa]	Crack length, $a$ [ $\mu\text{m}$ ]
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				5	5.5	6.5	10	10.5
	$E_{HC}$	$E_{PI}$	$E_{IL}$	$Z_{t1}$	$Z_{t2}$	$Z_{t3}$		
-0.549	3	10	0.46	1.92	1.96	2.17	5.26	5.73
-0.282	4.75	8.25	0.46	2.32	2.40	2.44	4.09	4.33
-0.014	6.5	6.5	0.46	2.72	2.85	2.79	3.68	3.81
0.256	8.25	4.75	0.46	3.18	3.39	3.24	3.60	3.64
0.528	10	3	0.46	3.79	4.13	3.91	3.74	3.71
-0.549	3	10	4.6	1.42	1.49	1.99	5.44	5.93
-0.282	4.75	8.25	4.6	1.66	1.75	2.12	4.14	4.40
-0.014	5.6	4.8	4.6	2.00	2.20	2.54	3.67	3.79
0.063	6.5	6.5	4.6	1.95	2.09	2.40	3.68	3.82
0.256	8.25	4.75	4.6	2.33	2.57	2.85	3.59	3.64
0.528	10	3	4.6	2.90	3.33	3.60	3.76	3.75
-0.549	3	10	10	1.37	1.53	2.21	5.85	6.35
-0.282	4.75	8.25	10	1.57	1.76	2.28	4.43	4.69
-0.014	6.5	6.5	10	1.83	2.09	2.55	3.91	4.06
0.256	8.25	4.75	10	2.17	2.55	3.00	3.79	3.85
0.528	10	3	10	2.67	3.29	3.77	3.97	3.95

**Table S4** Z values for trilayer cover windows ( $h_{IL} = 1 \mu m$ ) with varying elastic properties and crack length.

$\alpha$	Modulus [GPa]			Crack length, $a$ [ $\mu m$ ]			
	$E_{HC}$	$E_{PI}$	$E_{IL}$	5	5.5	6	6.5
	$E_{HC}$	$E_{PI}$	$E_{IL}$	$Z_{t1}$	$Z_{t2}$		$Z_{t3}$
-0.549	3	10	0.46	2.21	2.35	2.26	2.23
-0.282	4.75	8.25	0.46	2.68	2.89	2.76	2.67
-0.014	6.5	6.5	0.46	3.11	3.41	3.24	3.10
0.256	8.25	4.75	0.46	3.56	3.96	3.76	3.58
0.528	10	3	0.46	4.10	4.65	4.41	4.20
-0.549	3	10	4.6	1.45	1.55	1.65	1.86
-0.282	4.75	8.25	4.6	1.69	1.82	1.91	2.06
-0.014	5.6	4.8	4.6	2.01	2.20	2.37	2.54
0.063	6.5	6.5	4.6	1.97	2.15	2.26	2.38
0.256	8.25	4.75	4.6	2.33	2.57	2.73	2.85
0.528	10	3	4.6	2.85	3.20	3.46	3.61
-0.549	3	10	10	1.37	1.53	1.83	2.21
-0.282	4.75	8.25	10	1.56	1.74	2.03	2.33
-0.014	6.5	6.5	10	1.79	2.01	2.34	2.62
0.256	8.25	4.75	10	2.10	2.38	2.81	3.10
0.528	10	3	10	2.54	2.92	3.55	3.91

**Table S5** Z values for trilayer cover windows ( $h_{IL} = 5 \mu m$ ) with varying elastic properties and crack length

$\alpha$	Modulus [GPa]			Crack length, $a$ [ $\mu m$ ]				
	$E_{HC}$	$E_{PI}$	$E_{IL}$	5	5.5	6.5	10	10.5
	$E_{HC}$	$E_{PI}$	$E_{IL}$	$Z_{t1}$	$Z_{t2}$			$Z_{t3}$

-0.549	3	10	0.46	3.22	3.60	3.56	2.86	2.80
-0.282	4.75	8.25	0.46	3.83	4.37	4.22	3.23	3.13
-0.014	6.5	6.5	0.46	4.29	4.96	4.72	3.52	3.39
0.256	8.25	4.75	0.46	4.66	5.46	5.12	3.75	3.61
0.528	10	3	0.46	5.01	5.92	5.50	3.98	3.82
-0.549	3	10	4.6	1.62	1.77	2.19	3.41	3.59
-0.282	4.75	8.25	4.6	1.87	2.05	2.40	3.23	3.34
-0.014	5.6	4.8	4.6	2.07	2.29	2.66	3.64	3.75
0.063	6.5	6.5	4.6	2.12	2.34	2.66	3.32	3.40
0.256	8.25	4.75	4.6	2.40	2.66	2.98	3.58	3.64
0.528	10	3	4.6	2.74	3.06	3.40	4.03	4.08
-0.549	3	10	10	1.41	1.59	2.35	5.91	6.42
-0.282	4.75	8.25	10	1.58	1.75	2.36	5.00	5.35
-0.014	6.5	6.5	10	1.76	1.95	2.51	4.80	5.09
0.256	8.25	4.75	10	1.96	2.18	2.73	4.94	5.21
0.528	10	3	10	2.22	2.48	3.06	5.39	5.66