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From Surface Energy to Delamination: A multi-faceted mechanical approach for predicting Failure in EB-Printed Corona Treated PET - PE Laminates in flexible packaging

Carolina Suárez Vallejo, M. Sc. Chem. Eng.

From Surface Energy to Delamination: A multi-faceted mechanical approach for predicting Failure in EB-Printed Corona Treated PET - PE Laminates in flexible packaging

TECHNISCHE UNIVERSITÄT DARMSTADT

SunChemical
a member of the DIC group
DIC Color & Comfort

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2026
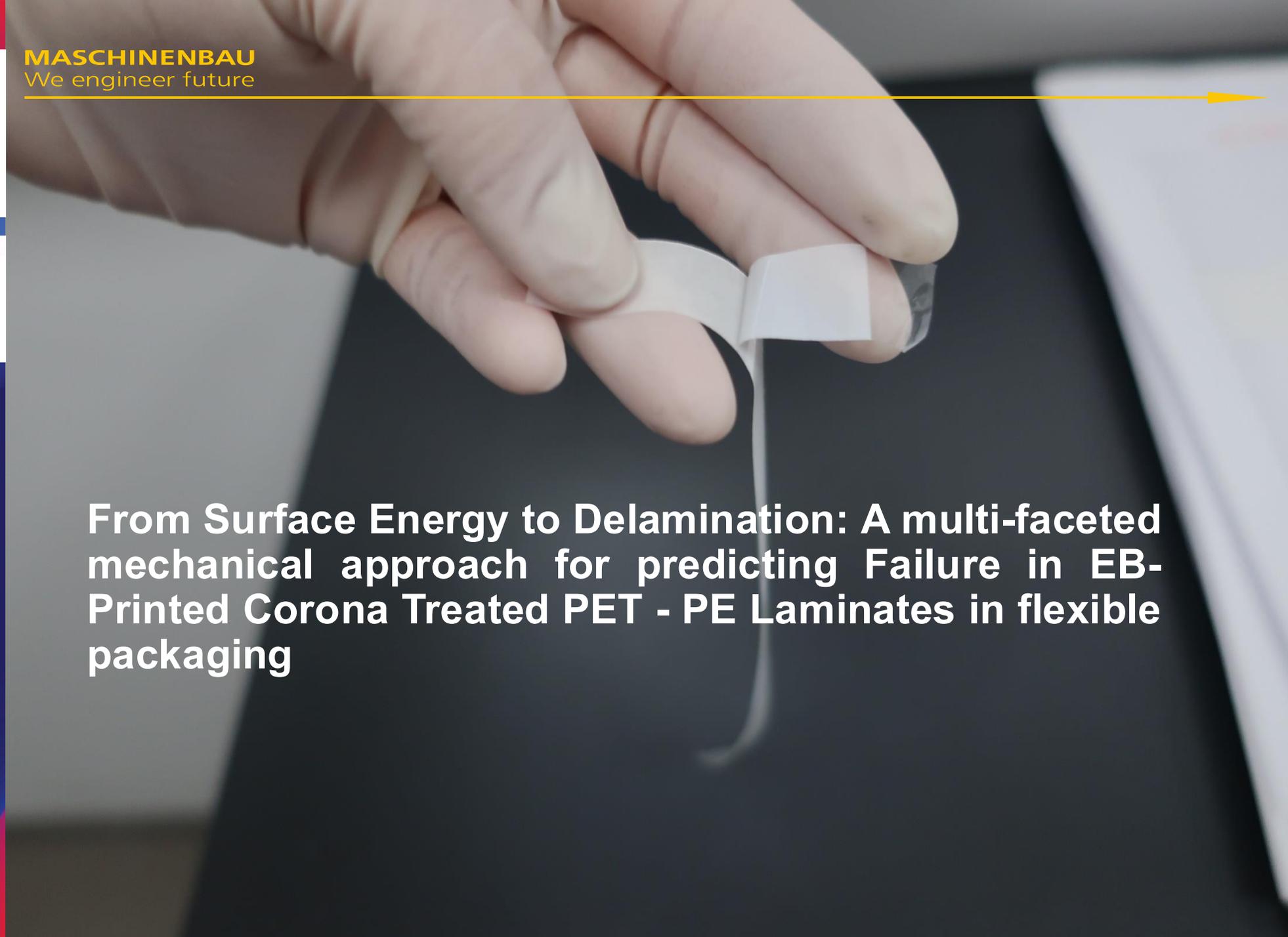
Introduction And Background:
# Why is Lamination Important in The Packaging Industry?

As the demand for plastic materials in packaging increased, so did the desired **requirements**. In many cases, these cannot be met by any single material. One way to address this issue is to **combine two or more materials together** to act as one *providing benefits of all the materials*.

↓

LAMINATION

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Carolina Suárez Vallejo, M. Sc. Chem. Eng.   01/19

Introduction And Background:
Materials and Market Trends
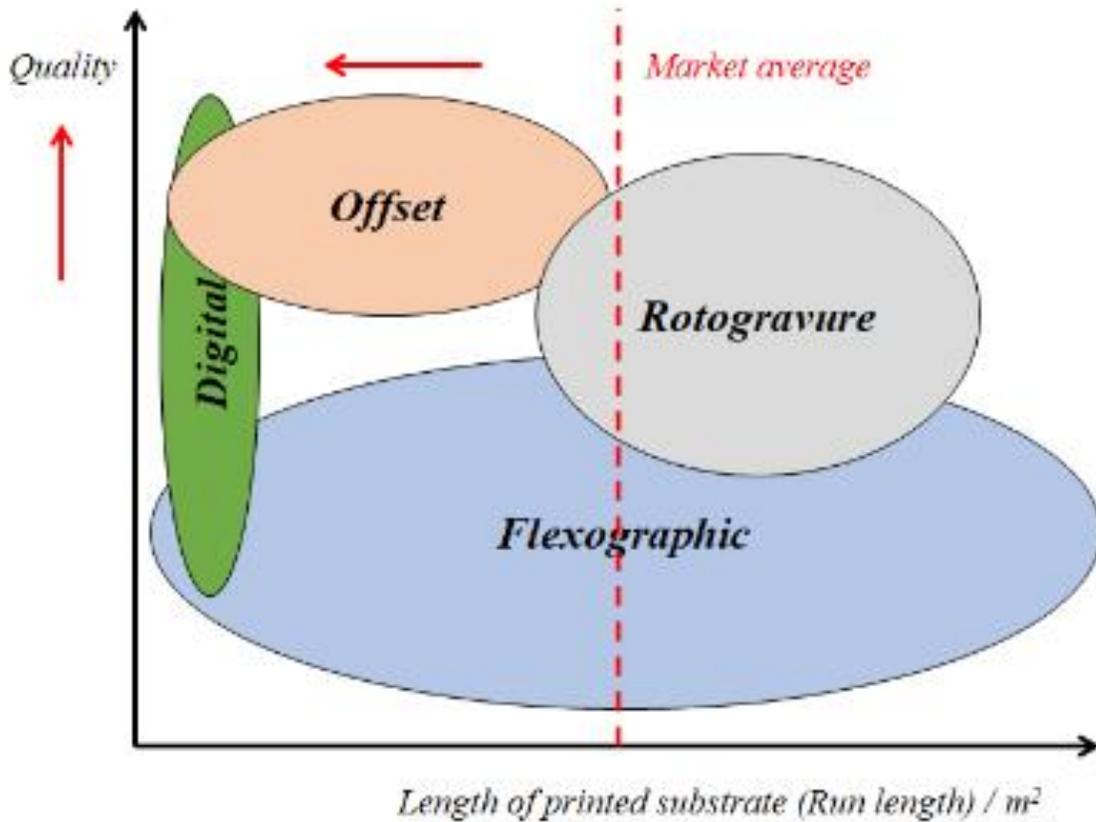
**Flexible packaging market trends
(Based on COMEXI, 2016)**
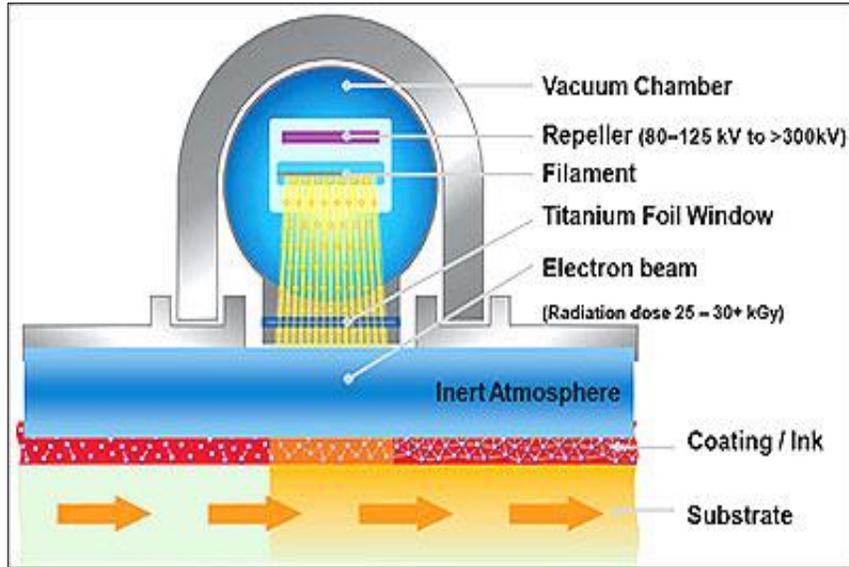
**Corona Treated
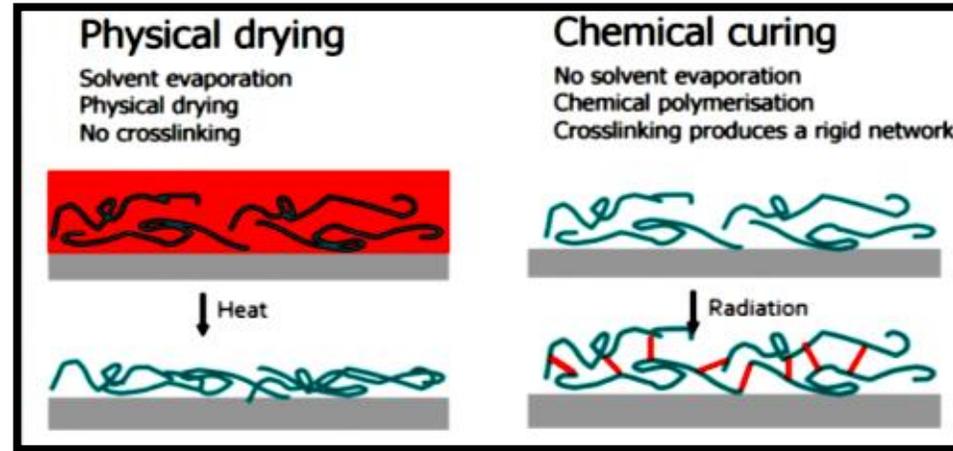PET**

**Corona Treated
BOPP**

**Chemical Treated
PET**

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EB Printing Technology

EB Offset Ink Curing Equipment

Vacuum Chamber
Repeller (80–125 kV to >300kV)
Filament
Titanium Foil Window
Electron beam
(Radiation dose 25 – 30+ kGy)
Inert Atmosphere
Coating / Ink
Substrate

Electron beam curing uses the high energy of accelerated electrons to directly cause the cross-linking of inks and coatings

Physical drying
Solvent evaporation
Physical drying
No crosslinking

Heat

Chemical curing
No solvent evaporation
Chemical polymerisation
Crosslinking produces a rigid network

Radiation

The high energy of this curing process ensures that a high degree of conversion from oligomer to polymer takes place

Main dis-advantages

✓ Limited adhesion to FP films.

✓ Radiation equipment handling.

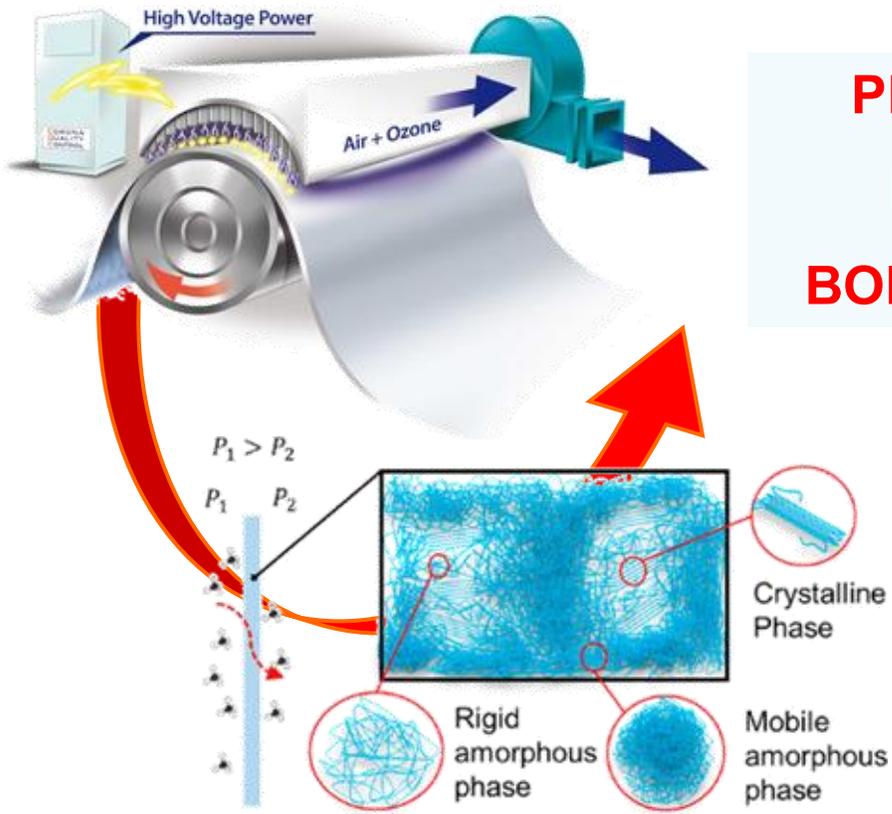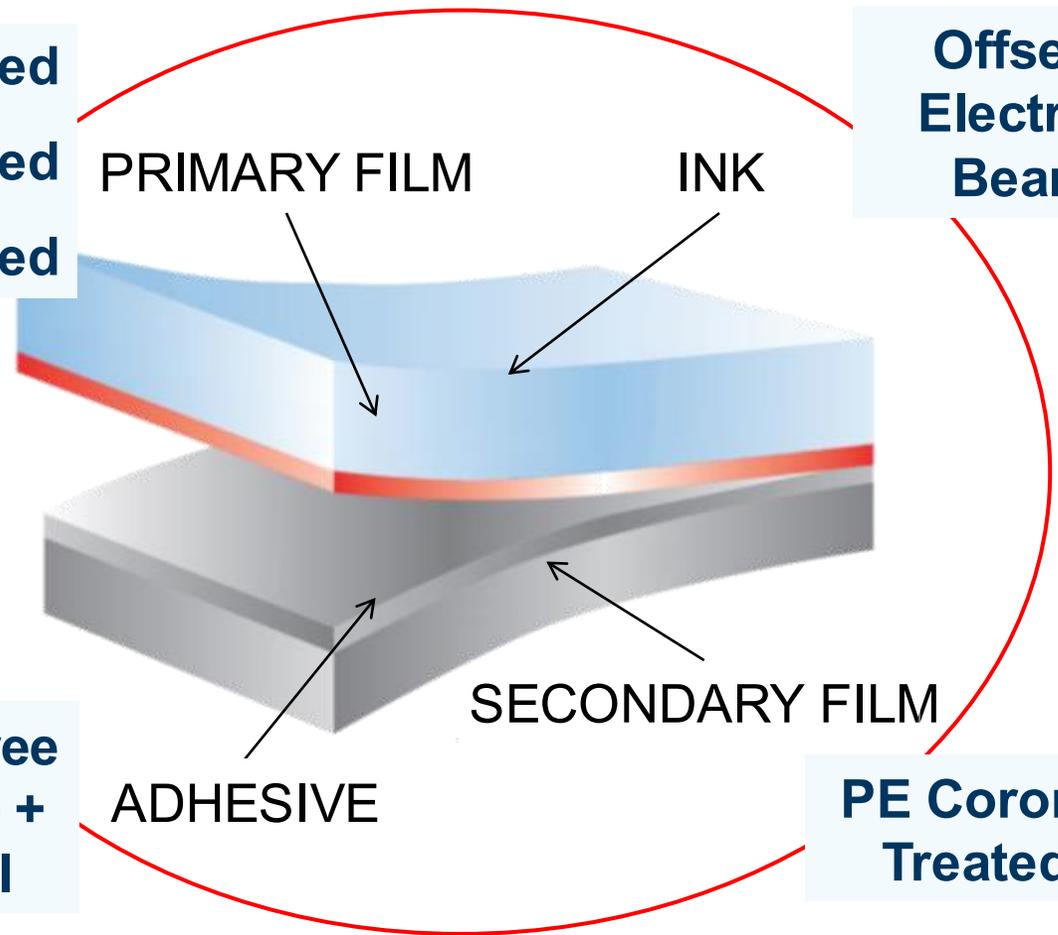✓ High investment + N_2 consumption.

✓ FP film structures modification.

Main advantages

✓ No solvents.

✓ No photo initiators.

✓ Solvents resistance when cured.

✓ Low temperature impact.

✓ Less migration risk.

✓ Higher conversion of acrylates.

✓ EB radiation is not affected by pigment.

Biro. D "Advances in Electron Beam Curing in Wide Web Flexible Package Printing". UV+EB Technology. August 2016.<https://uvebtech.com/articles/2016/advances-in-electron-beam-curing-in-wide-web-flexible-package-printing>

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Lamination in The Flexible Packaging Industry

High Voltage Power

Air + Ozone

$P_1 > P_2$

P_1 P_2

Crystalline Phase

Rigid amorphous phase

Mobile amorphous phase

PET Corona Treated

PET Chem Treated

BOPP Corona Treated

PRIMARY FILM

INK

Offset / Electron Beam

SECONDARY FILM

ADHESIVE

Solvent Free Isocynate + Hydroxyl

PE Corona Treated

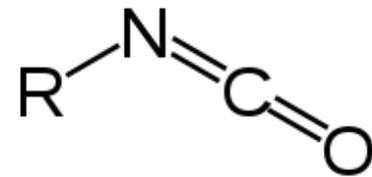S.Zekriardehani, etal. Effect of Chain Dynamics, Crystallinity, and Free Volume on the Barrier Properties of BOPP Films. Macromolecules 2017, 50, 7, 2845–2855

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Affinity Between Adhesive and Secondary Substrate

Main Resin

$$OCN - R_1 - NCO$$

Isocyanate Group

Hardener

$$OH - R_2 - HO$$

Hydroxyl Group

$$HO^-$$

Time & Heat
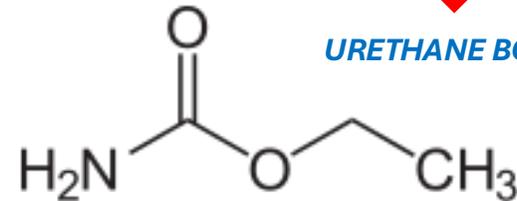
URETHANE BOND

Cured polymer, containing urethane and urea bonds
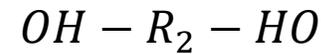
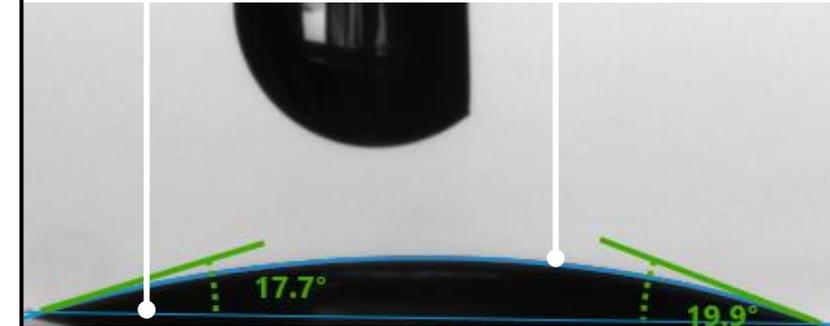PE **Virgin**   Adhesive

39.0°   39.5°
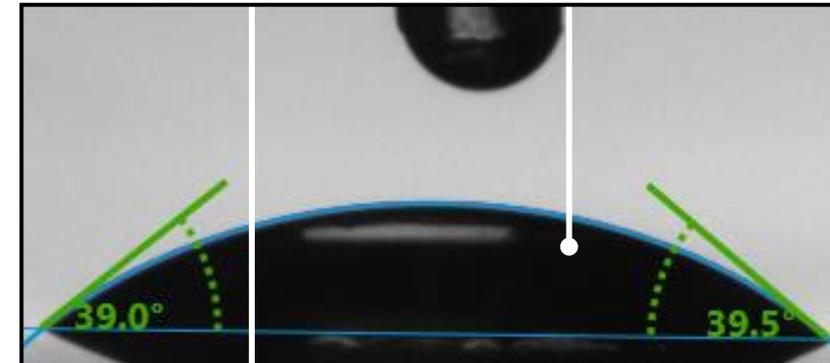
PE **Corona**   Adhesive

17.7°   19.9°

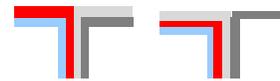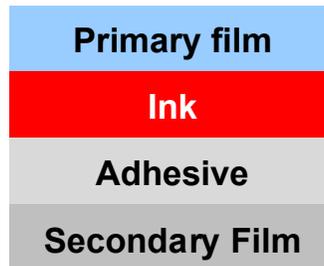S. Patil. Safer adhesives via thiol-ene chemistry. Toxics Use Reduction Institute (TURI). Massachusetts, (2012).

M. Pandini. Chemistry of lamination adhesives for flexible packaging. Sun Chemical Italy, (2023), Internal presentation.

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Measurement of Adhesion

Lamination Bond Strength (LBS)
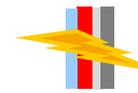

Failure mode

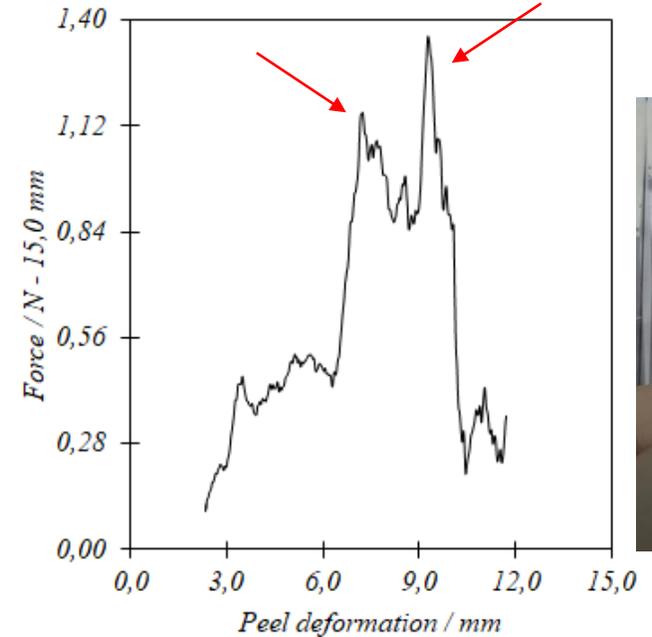| Primary film |
| Ink |
| Adhesive |
| Secondary Film |

1) Adhesive failure
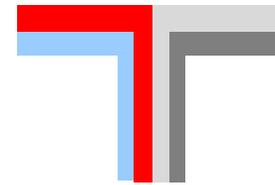
2) Partially ink split

3) Ink split

4) Tear

Tape test of adhesion

Inside the film

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The Lamination Problems on PET Corona Composites
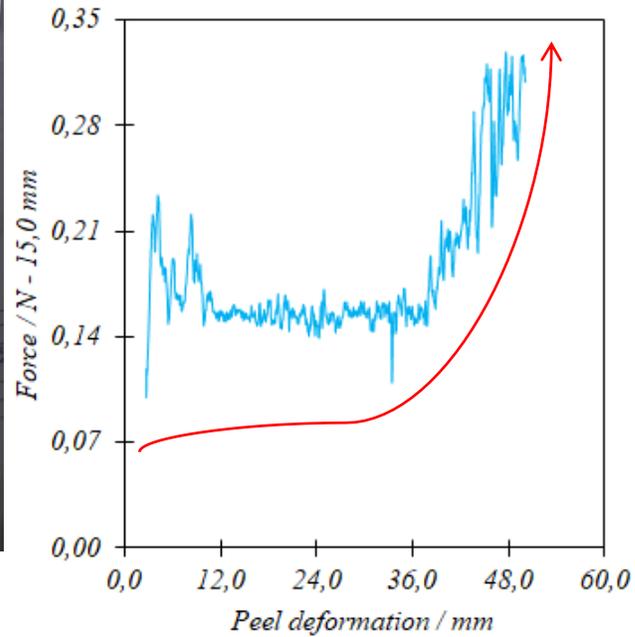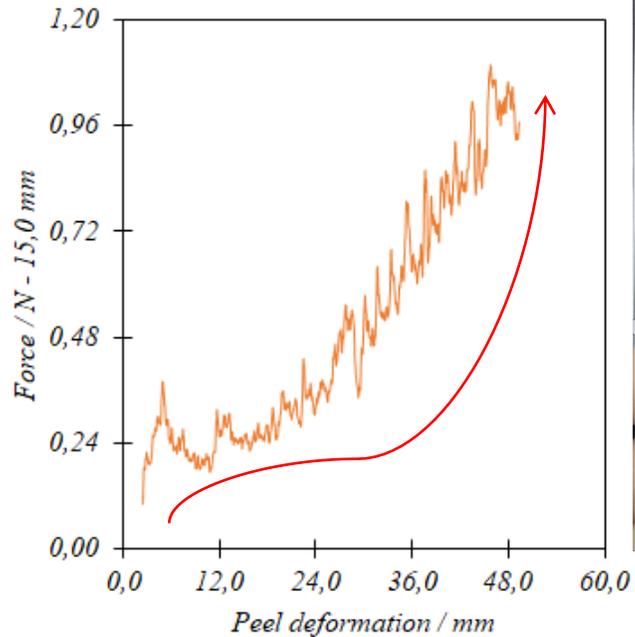
Several modes of total delamination

Non - homogeneous tear

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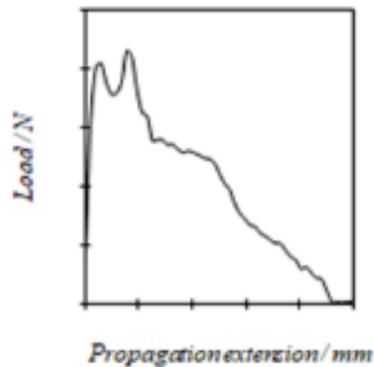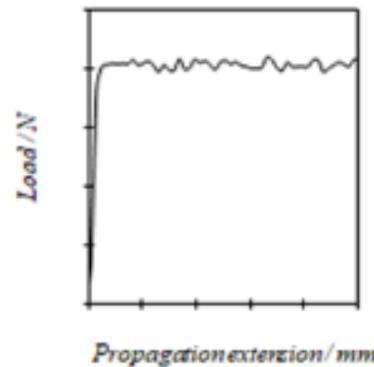# The Problem of Lamination Bond Strength
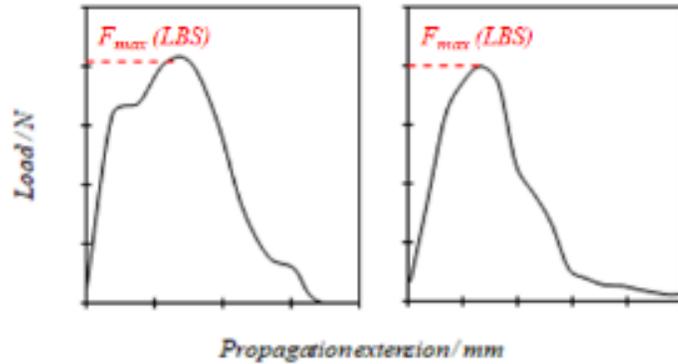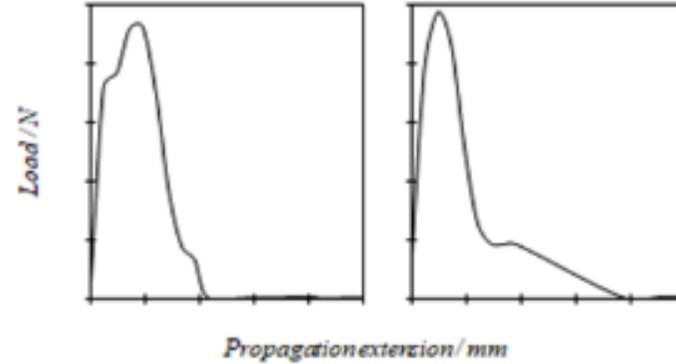

Types of load curves obtained during delamination tests.

(a) Different delamination tests with similar maximum loads.

(b) Similar delamination tests with similar maximum loads.

(c) Delamination test with multiple local load maxima.

(d) Delamination test without a well-defined maximum load.

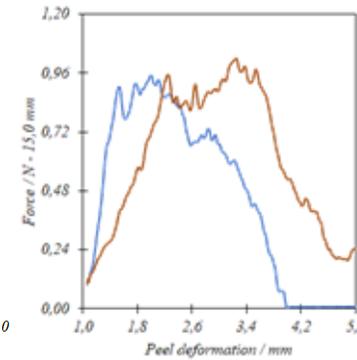# Solution to the Problem of Lamination Bond Strength: Work of adhesion
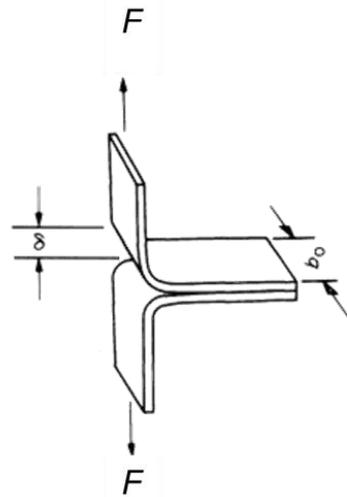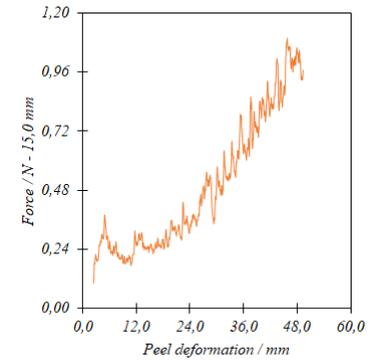

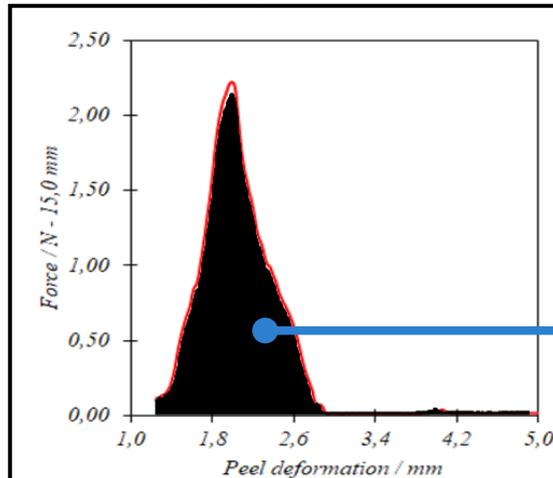Auto Tensil Tester (INSTRON)

Double cantilever beam test (DCB)
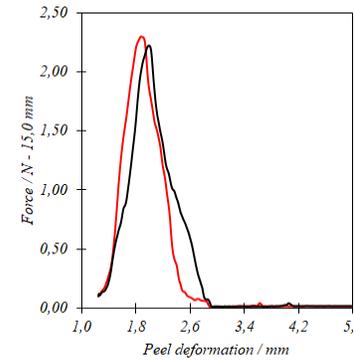
Similar LBS
Similar behavior
Which is the best?

Similar LBS
Different behavior
Which is the best?

PET Corona problems
How to be compared?

Work of adhesion [J/m^2]
The area under the Force vs. Peel deformation curve

$$W_a = \frac{1}{A} \int F \, d\delta$$
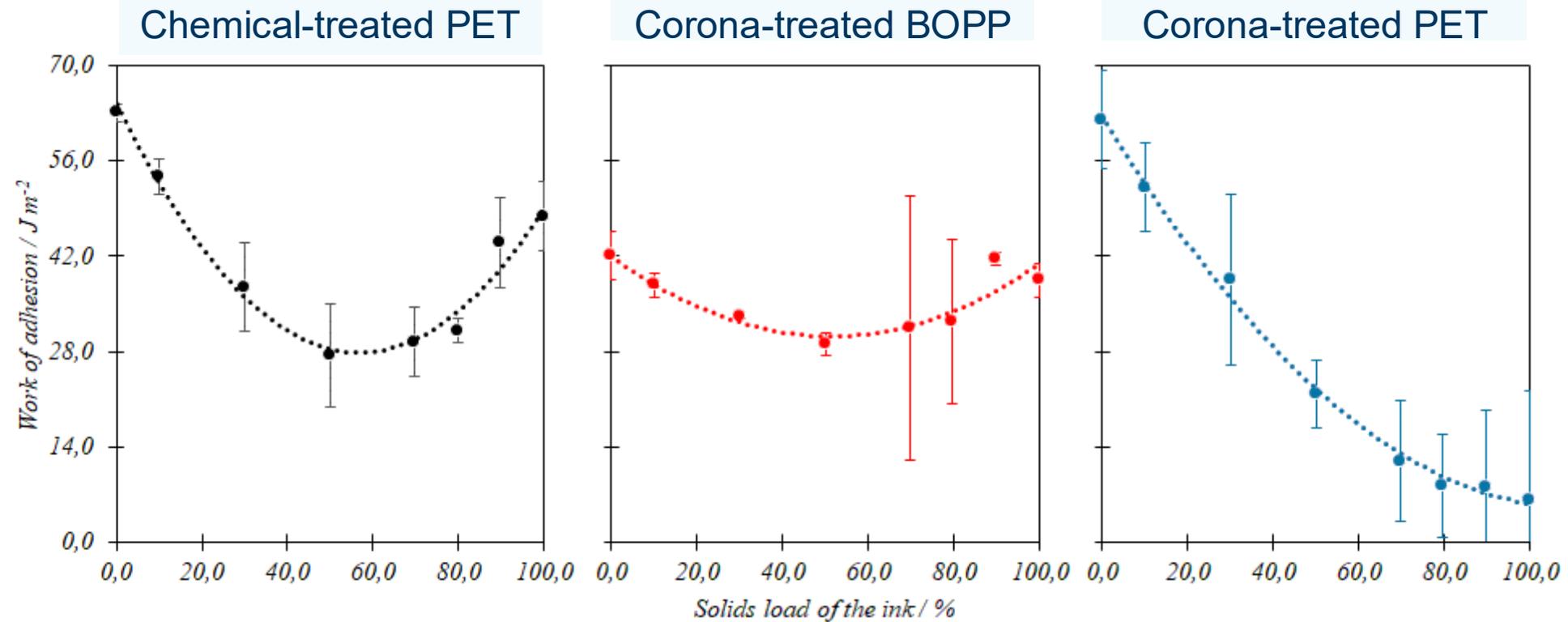
Strain Energy Release Rate

$$G_I$$

[Energy/Area]
as parameter of
delamination's physics

$$G_I = f(geometry, F, \boldsymbol{E_{ii}})$$

K. Kendall. The adhesion and surface energy of elastic solids. J. Phys. D: Appl. Phys. 4 (1971) 1186. doi.org/10.1088/0022-3727/4/8/320.

K. L. Johnson, K. Kendall, A. D. Roberts. Surface energy and the contact of elastic solids. Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences. 324 (1971) 301. doi.org/10.1098/rspa.1971.0141

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An Example of Using Work of Adhesion as an Assessment Parameter

Trials with solids load of the ink between 10,0 and 50,0 % were completed.
Work of adhesion is now used as a new parameter for the comparison.

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There is a way beyond the LBS

Ratio Vs. Work of Adhesion

$$Ratio = \frac{Amplitude\ Peaks - Valleys}{Average\ Force}$$

Load Curve: BOPP + Adhesive 3 + PE

2,32 N − 15mm

Lamination Bond Strength BOPP + Adh + PE / N − 15 mm

Work of adhesion / J m⁻²

10,4 J m⁻²

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Main Experimental Setup:
Massive Trials on Sun Chemical "SoA" Laminator

PRIMARY FILM   INK

ADHESIVE   SECONDARY FILM

2nd Subst. PE 50 μm
SFAD
EB Inks
Primary Substrate

Mixed Ink Area   CMYKW
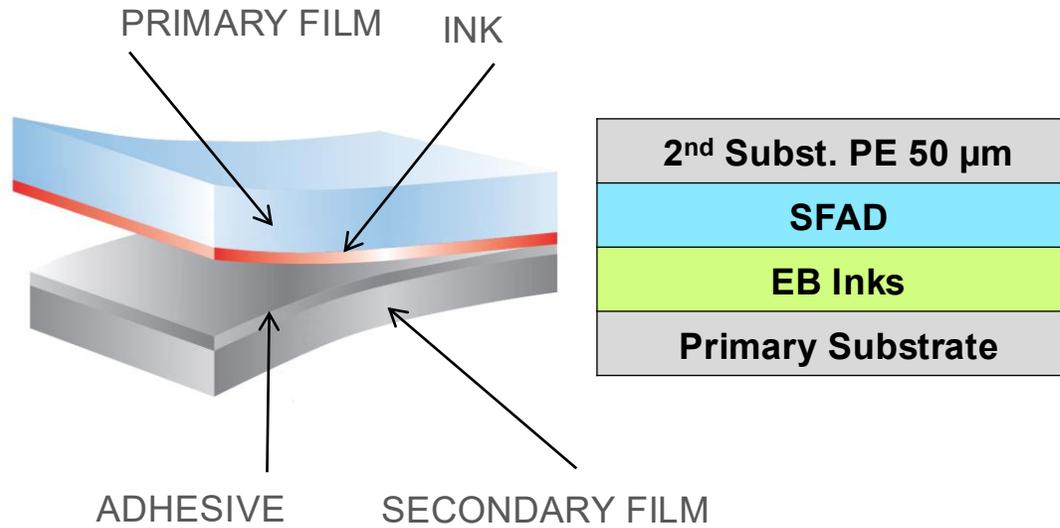
**SFAD:** 4 different adhesives
EB Inks: 6 different colours
Primary Substrates: BOPP
Corona-treated PET
Chemical-treated PET

135 trials

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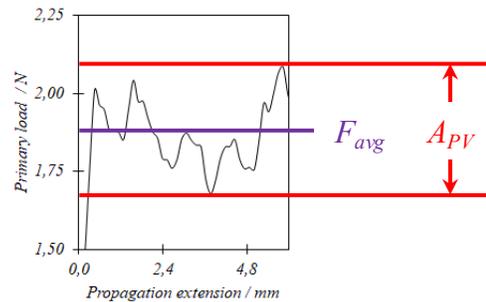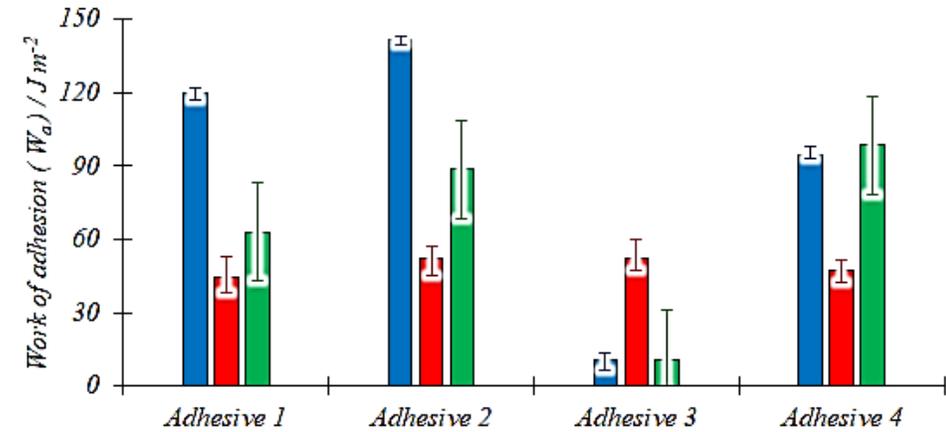
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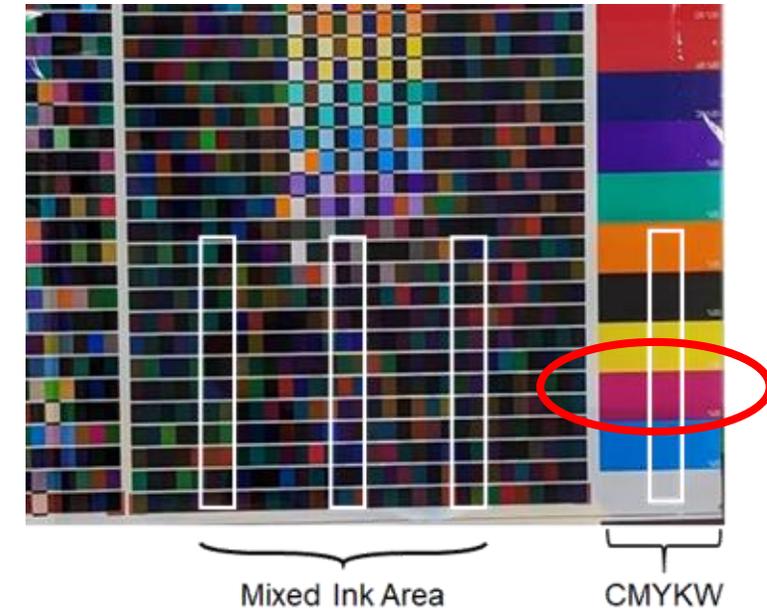
Experimental Results and Discussion

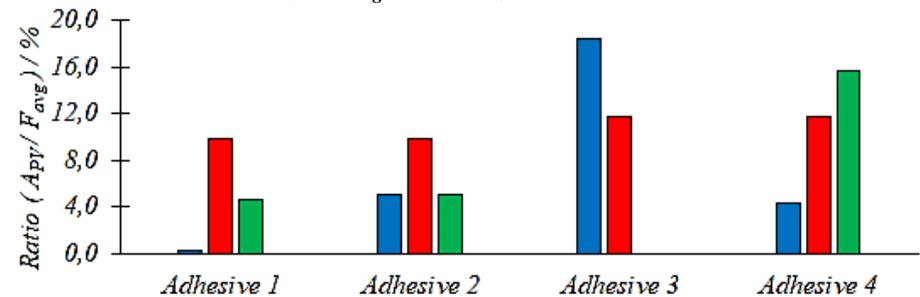Lamination Bond Strength: Primary Film + Adhesive + PE / N – 15 mm
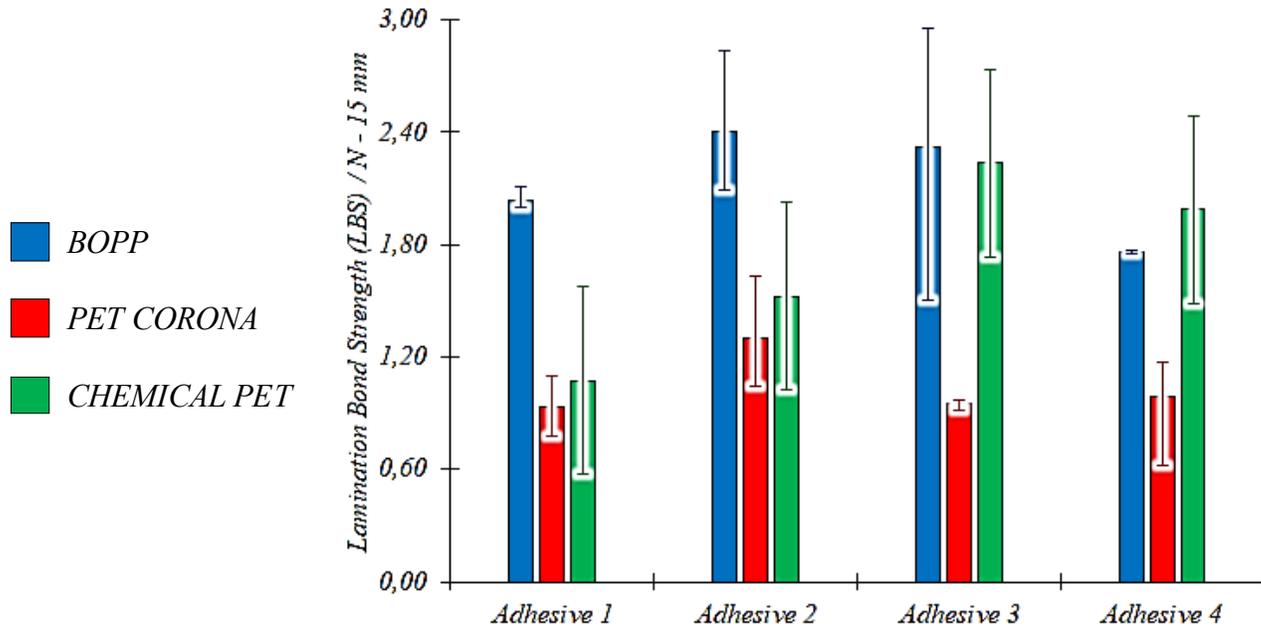
Work of adhesion: Primary Film + Adhesive + PE / J m⁻²

Ratio (A_{PV} / F_{avg}): Primary Film + Adhesive + PE / N – 15 mm
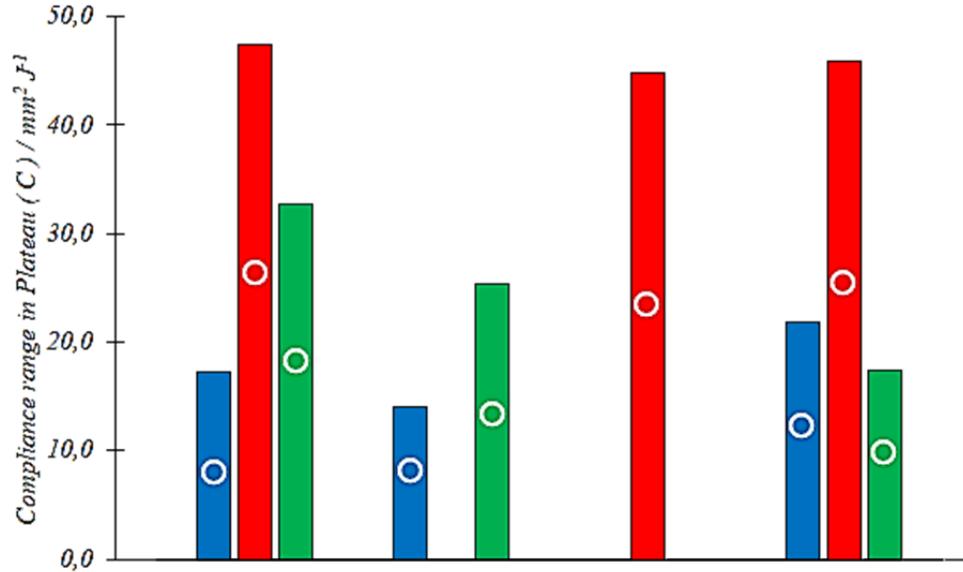
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Compliance in Plateau:
Primary Film + Adhesive + PE
$mm^2 J^{-1}$

$$\left\langle C = \frac{F}{\delta} \right\rangle$$

Compliance Slope (dC/da) in Plateau:
Primary Film + Adhesive + PE
N^{-1}

dC/da form lineal behavior

$$\frac{dC}{da} = m$$

BOPP

PET CORONA

CHEMICAL PET

Average Value

A. Kaveh. Determining the crack propagation in DCB composite specimens by fiber bridging modeling. Rev. Téc. Ing. Univ. Zulia. 37 2 (2014) 1.

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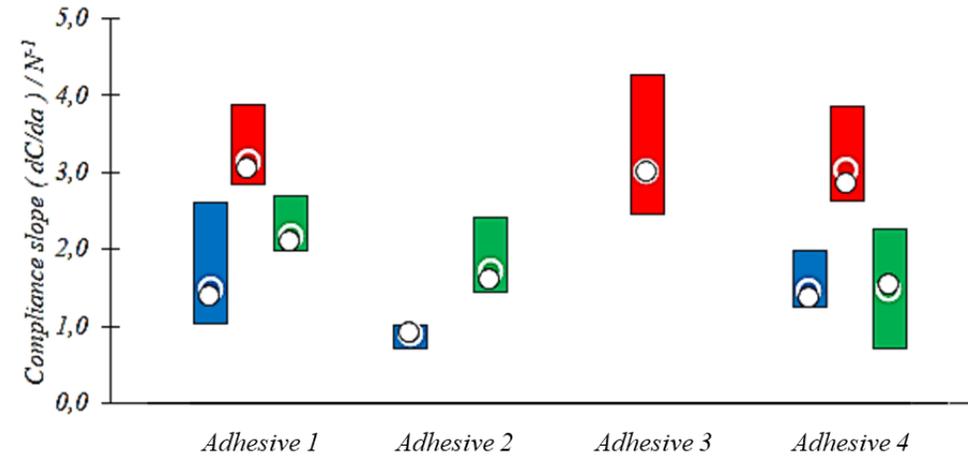
Energy Release Rate:
Primary Film + Adhesive + PE
$mm^2\ J^{-1}$

Ideal Value

C – Based Value

$$G = \frac{2 \cdot F}{b}$$

$$G = \frac{F^2}{2 \cdot b}\frac{dC}{da}$$
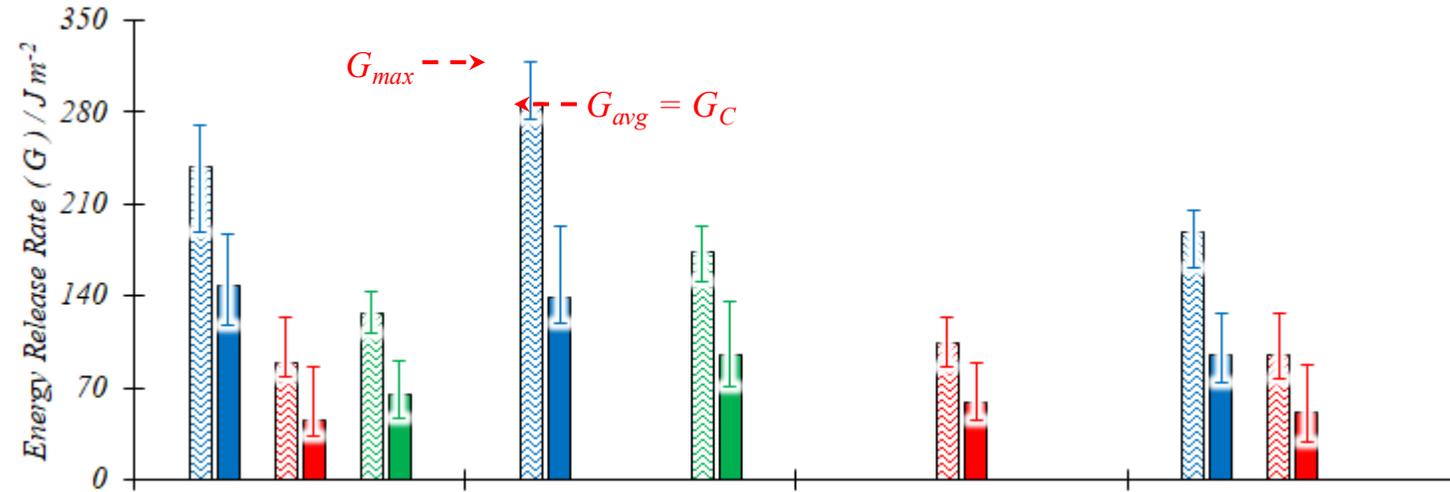
Brittleness index:
Primary Film + Adhesive + PE

$$bi = \frac{G_{max}}{G_C}$$

J. J. Bikerman. The fundamentals of tackiness and adhesion. Journal of Colloid Science. 2 1 February (1947) 163. doi.org/10.1016/0095-8522(47)90017-2.

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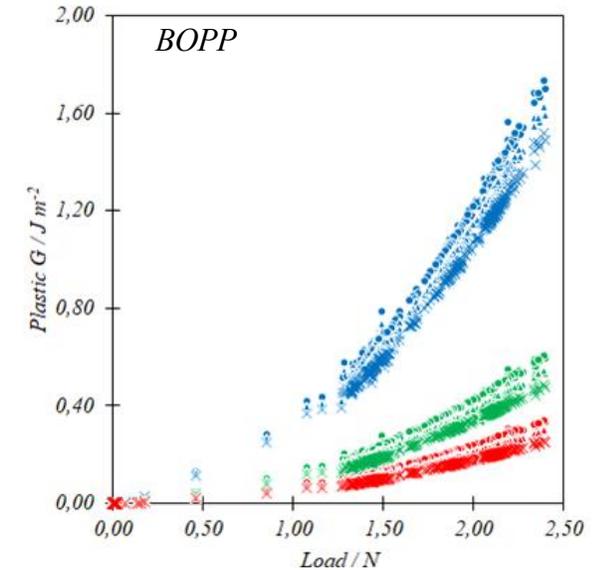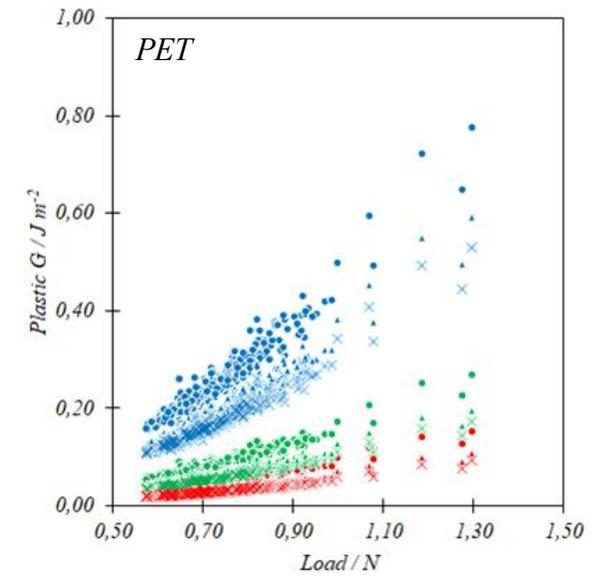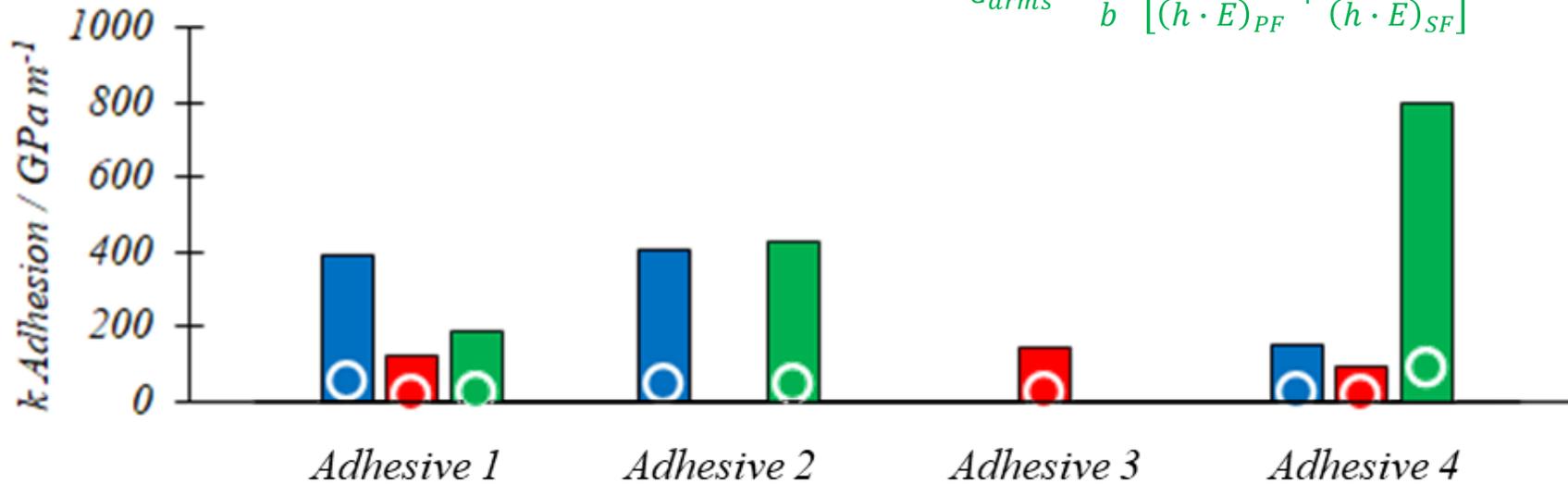
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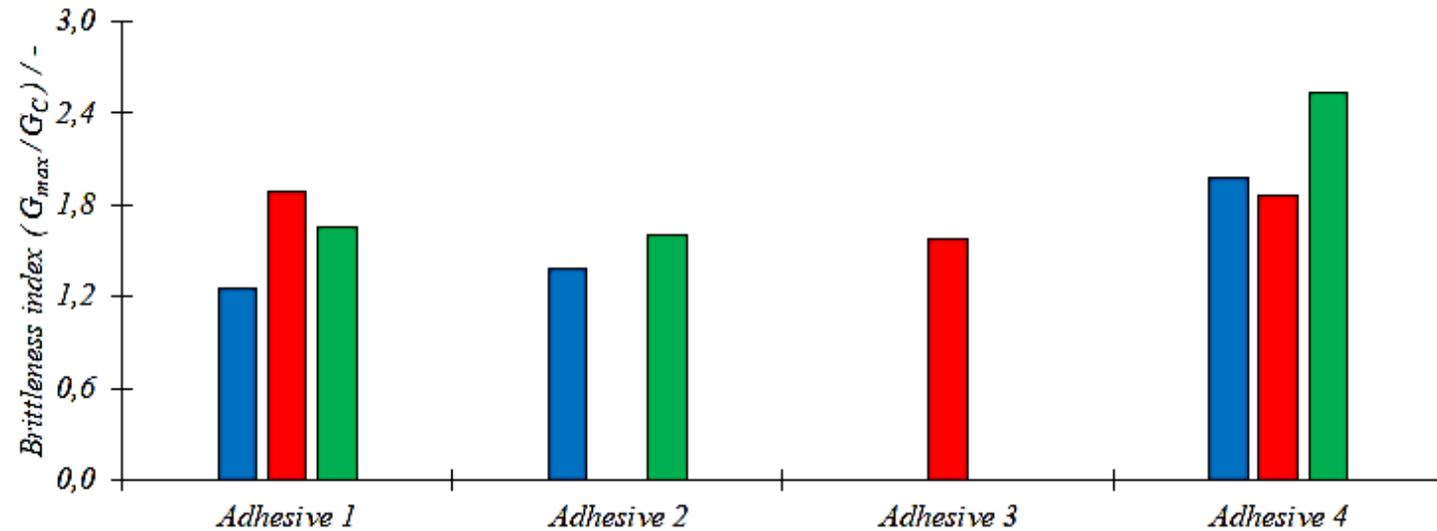
BOPP

PET CORONA

CHEMICAL PET

◎ Average Value

$$k = \frac{4 \cdot (E \cdot I)_{eq}}{b} \cdot \left[C_{interfase} \cdot b \cdot (E \cdot I)_{eq} \right]^{-4/3}$$

$$C_{interfase} = C - C_{arms}$$

$$\frac{1}{(E \cdot I)_{eq}} = \frac{1}{(E \cdot I)_{PF}} + \frac{1}{(E \cdot I)_{SF}}$$

$$C_{arms} = \frac{a}{b} \cdot \left[\frac{1}{(h \cdot E)_{PF}} + \frac{1}{(h \cdot E)_{SF}} \right]$$
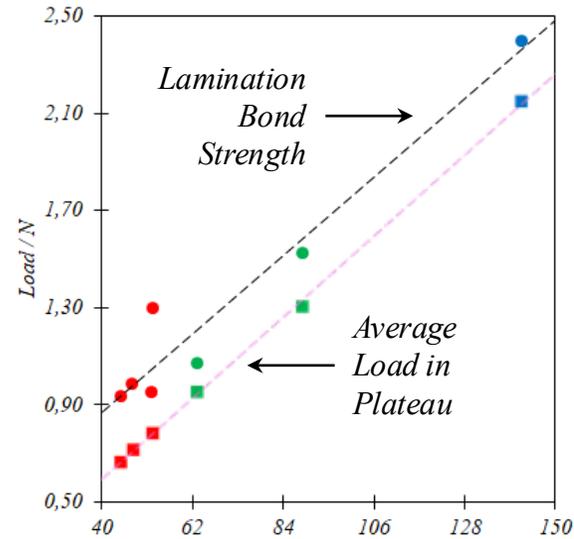
A. Kaveh. Determining the crack propagation in DCB composite specimens by fiber bridging modeling. Rev. Téc. Ing. Univ. Zulia. 37 2 (2014) 1.
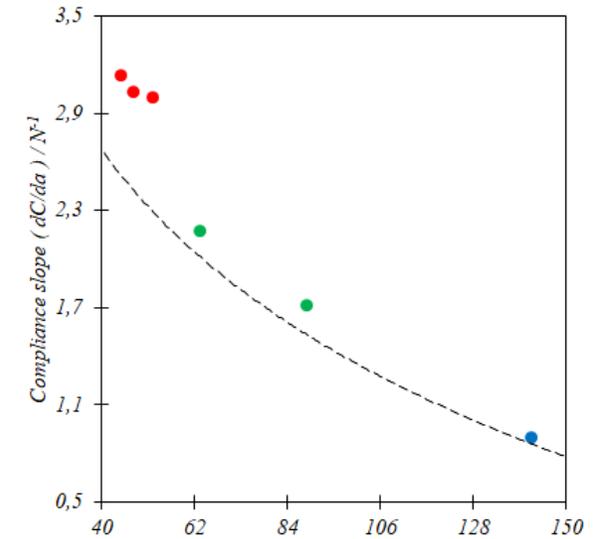
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Experimental Results and Discussion

Load
Vs.
Work of adhesion

Lamination Bond Strength

Average Load in Plateau

- BOPP
- PET CORONA
- CHEMICAL PET

Compliance slope
Vs.
Work of adhesion

Ratio (A_{PV} / F_{avg})
Vs.
Work of adhesion
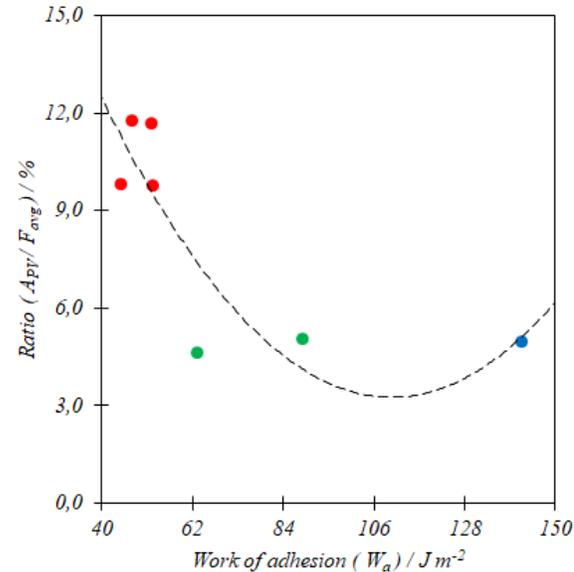
Energy Release Rate
Vs.
Work of adhesion

Ideal

C – based

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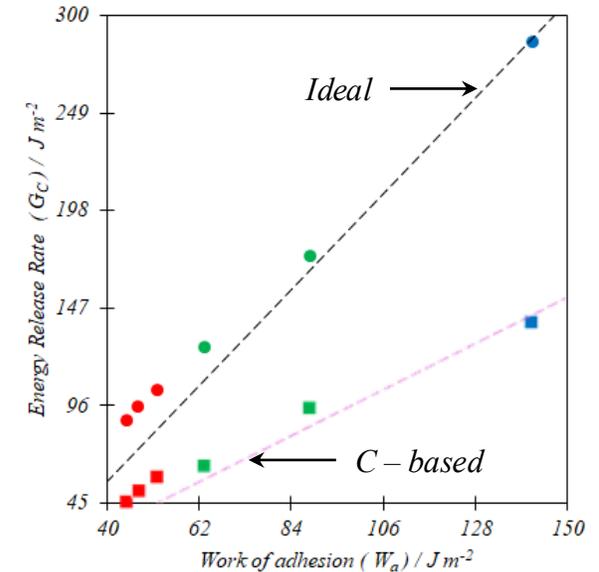
Experimental Results and Discussion

k Adhesion
Vs.
Work of adhesion

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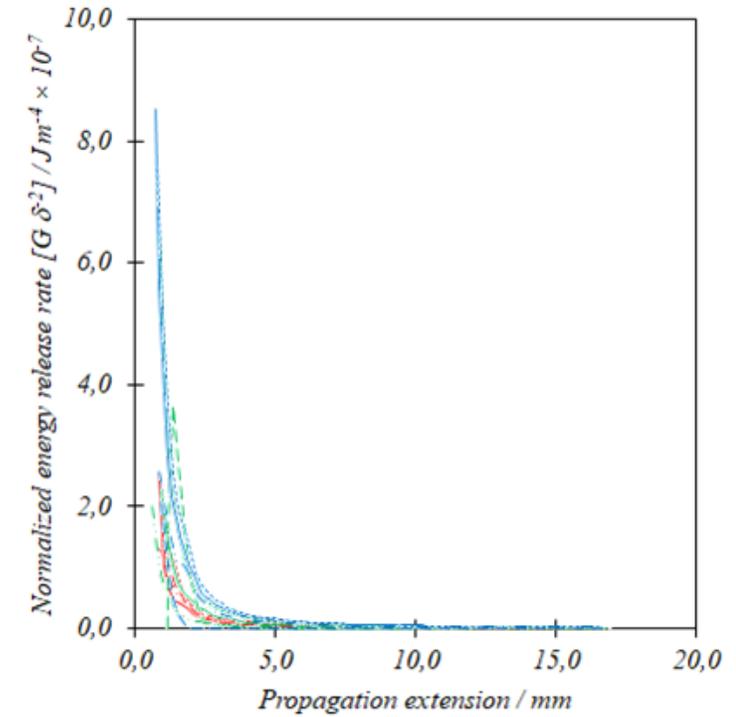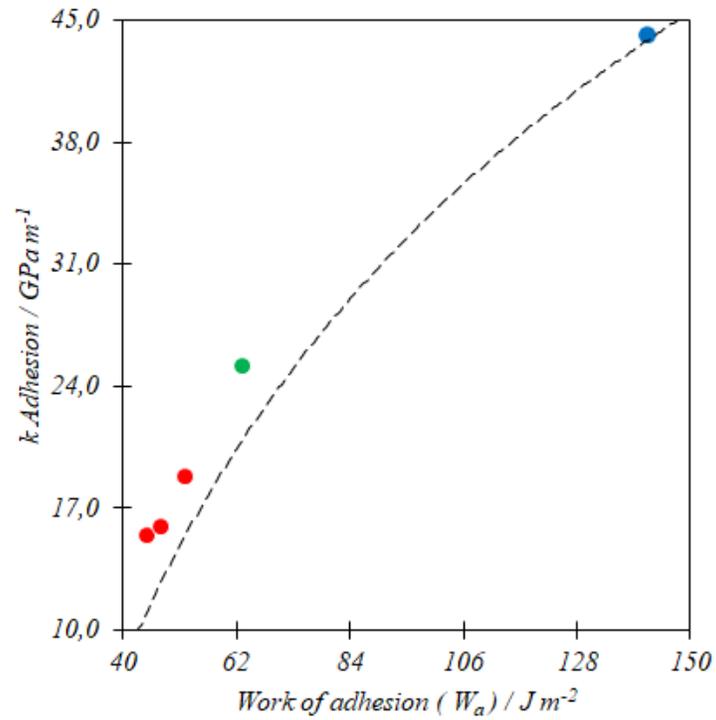
Conclusions and Further Remarks

- ✓ A method beyond Lamination Bond Strength (LBS) is presented.

    - ✓ Systematic approach to evaluate and predict the quality of laminates made of thin polymer films.

    - ✓ The effect of several parameters on the adhesion issues.

    - ✓ Work of Adhesion and Strain Energy Release Rate as key parameters in the delamination physics.

    - ✓ The relationship between LBS and Work of Adhesion.

    - ✓ Adhesive characteristics obtained from delamination tests.

- ✓ Physical explanation of the problem of PET film lamination and its comparison with other materials.

    - ✓ Further than chemical affinity, mechanical characteristics.

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Thank you very much for your attention

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From Surface Energy to Delamination: A multi-faceted mechanical approach for predicting Failure in EB-Printed Corona Treated PET - PE Laminates in flexible packaging.
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