

# Optimization of Adhesive Joints of Low Density Polyethylene (LDPE) Composite Laminates with Polyolefin Foam Using Corona Discharge Plasma

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**ABSTRACT:** In this work, surface modification of low density polyethylene (LDPE) film has been carried out to optimize adhesive joints with polyolefin foam for uses in technological applications. LDPE films were modified in a continuous way using corona discharge plasma with different powers, ranging from 200 to 600 W and several film advance rates in the 5–20 m min<sup>-1</sup> range. Changes in surface wettability have been studied with contact angle measurements and subsequent solid surface energy calculation. A polyurethane adhesive was used to join the LDPE film to a polyethylene foam. Mechanical performance of the adhesive joints has been determined by T-peel tests and also the aging effects of several hydrothermal conditions have been studied to evaluate the usefulness of these laminate composites in

technological applications. Results show that corona discharge powers between 400 and 600 W are suitable in terms of wettability improvement; on other hand, a slight decrease in surface wettability as the film advance rate increases is detected but the overall changes as a consequence of the film advance rate in the 5–20 m min<sup>-1</sup> range are small if compared to changes derived from working powers in the 200–600 W range. Adhesive joints offer excellent mechanical performance and good durability in hydrothermal conditions thus being appropriate for technical applications. © 2009 Wiley Periodicals, Inc. *J Appl Polym Sci* 114: 2971–2977, 2009

**Key words:** films; adhesion; ageing; surfaces; polyethylene (PE)

## INTRODUCTION

Composite laminates based on a polymer film and a polymer foam offer interesting possibilities from a technological point of view as each one of the individual components can contribute to optimize the overall laminate properties. These composite materials find some applications in automotive industry, aeronautics, packaging, etc.<sup>1–4</sup> The polymer film can contribute with good chemical barrier properties and the polymer foam can provide lightness and soft touch finishing thus obtaining a composite laminate easy to be adapted to complex shapes.

The main problem regarding these laminates is the poor adhesion between the individual substrates, mainly the polymer film, due to its relatively low wetting properties. This problem is even more pronounced when the polymer film is a non polar or low polar polymer such as polyolefins which are charac-

terized by very low surface energy values. In these cases it is necessary to carry out a surface treatment to increase surface energy and, subsequently, adhesive properties.<sup>5–9</sup> It is possible to modify surface properties of a polymer film without affecting the bulk material, by using different treatments. Many of these processes are based on the use of different chemicals which are capable to change surface activation; in some cases it is possible to attach some functional groups by using the appropriate monomer and UV radiation (photograft polymerization).<sup>7,10–16</sup> These surface treatments present some disadvantages: they are based on the use of aggressive chemicals such as acid or alkalis and generally, they could result in some environmental impact. Against these chemical processes, in the last decades research has focused on the use of physical processes through surface radiation to enhance surface activation in an environmental friendly process.<sup>6,17–23</sup> The use of low pressure plasmas represents interesting possibilities from the point of view of the process since it is possible to carry out a complete control of the different variables (working power, vacuum level, type of plasma gas and flow rate, exposure time. . .).<sup>17,24,25</sup> Nevertheless, from an industrial point of view, this process is useful for

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small pieces since it has to be carried out in a batch process. On other hand, corona discharge plasmas are interesting since they can run in a continuous way although it is not possible to control the same variables as in low pressure plasma. Corona discharge plasma is easy to be adapted in industrial production lines as an additional material pretreatment stage.<sup>26,27</sup>

Composite laminates fabrication requires the use of adhesives to enhance good adhesion joints. Among the wide variety of adhesives, the use of ethylene vinyl acetate copolymers and reactive polyurethanes is generalized as a consequence of their easy application and excellent balanced properties of the adhesion joints. Additionally, many technical applications of laminates require durability of adhesion joints in aggressive conditions; i.e., materials used in automotive industry are subjected to hydrothermal conditions which can promote a decrease in mechanical performance of adhesive joints. So, the use of a previous corona discharge plasma treatment could lead to an improvement on mechanical response of laminates together with durability of adhesive joints in hydrothermal or other aggressive conditions. On other hand we have to take into account that plasma effects are not permanent and this can induce some loss on mechanical performance.<sup>1,2,26–29</sup>

In this work, the usefulness of corona discharge plasma has been evaluated as a surface pretreatment on a low density polyethylene (LDPE) film for composite laminates with a polyethylene foam. The effects of different variables such as working power and film advance rate on wetting properties of LDPE film have been investigated. Furthermore, adhesive joints have been subjected to several hydrothermal aging conditions to determine the effect of temperature and relative humidity (RH) on final performance of adhesive joints of LDPE and a polyolefin foam with a reactive polyurethane adhesive.

## EXPERIMENTAL

### Materials

Composite laminates were prepared with a low-density polyethylene (LDPE) film and a polyolefin foam using a reactive polyurethane as adhesive. The film was a transparent LDPE commercial grade supplied by Logoplast (Logoplast S.L. Alicante, Spain) which is suitable for technical applications with a density of  $0.92 \text{ g cm}^{-3}$  and average thickness of  $50 \text{ }\mu\text{m}$  as described in the technical data sheet. The melting temperature was in the  $111\text{--}112^\circ\text{C}$  range, as obtained by DSC analysis.

The polymer foam was a crosslinked polyolefin foam Trocellen PE supplied by Trocellen Iberica (Trocellen Iberica S.A., Madrid, Spain) with a density of  $0.025\text{--}0.030 \text{ g cm}^{-3}$  and a melting temperature

between  $105^\circ\text{C}$  and  $110^\circ\text{C}$ . It is a closed cell foam which enhances low water and dust absorption and overall good impact behavior.

The adhesive was a polyurethane grade Supergrip 9238 supplied by Bostik Findley (Bostik Findley S.A., Barcelona, Spain) with a density of  $1.10 \text{ g cm}^{-3}$ . It is a polyurethane monocomponent solvent-free prepolymer. The appropriate temperature/RH range for activation is  $>25^\circ\text{C}/60\text{--}90\%$ , respectively. The adhesive viscosity (thermosel viscosity at 20 rpm and  $110^\circ\text{C}$ ) is in the  $10,000\text{--}15,000 \text{ MPa}\cdot\text{s}$  range and the appropriate dosage is  $2\text{--}60 \text{ g m}^{-2}$ . Before adhesive deposition, it is necessary a preheating process at  $100^\circ\text{C}$  for 45 min.

### Corona discharge plasma treatment and surface characterization

Before laminate processing, LDPE films were exposed to a continuous corona discharge plasma treatment with different film advance rates ranging from  $5$  to  $20 \text{ m min}^{-1}$ . The corona plasma equipment was supplied by FABRILEC S.L., mod. GF-100-BADIA (Fabrilec, S.L., Valencia, Spain). This corona discharge generator operates at  $50 \text{ Hz}$  with a maximum power of  $1 \text{ kW}$ . The distance between electrodes was fixed at  $1.5 \text{ mm}$  and the working power varied in the  $200\text{--}600 \text{ W}$  range.

To evaluate wettability changes, a KSV CAM 200 goniometer (KSV Instruments, Helsinki, Finland) was employed to measure contact angles. Contact angle measurements were carried out 5 min after the plasma treatment to obtain comparative results. The maximum error in the contact angle measurement did not exceed  $\pm 3\%$ . Four different test liquids were selected for contact angle measurements and surface energy calculation by the Owens-Wendt method.<sup>30</sup> These test liquids were selected to cover a wide range of polar ( $\gamma_l^p$ ) and dispersive ( $\gamma_l^d$ ) components of the total liquid surface energy ( $\gamma_l$ ).

Water:

$$\gamma_l^d = 22.0 \text{ mJ m}^{-2}, \gamma_l^p = 50.2 \text{ mJ m}^{-2}, \gamma_l = 72.2 \text{ mJ m}^{-2}$$

Glycerol:

$$\gamma_l^d = 34.0 \text{ mJ m}^{-2}, \gamma_l^p = 30.0 \text{ mJ m}^{-2}, \gamma_l = 64.0 \text{ mJ m}^{-2}$$

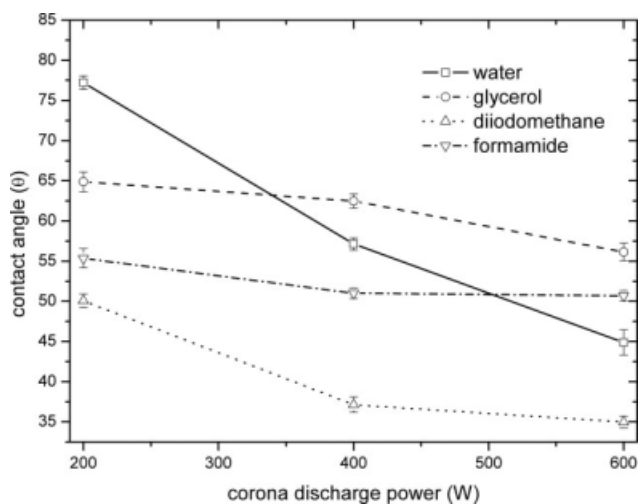
Diiodomethane:

$$\gamma_l^d = 48.5 \text{ mJ m}^{-2}, \gamma_l^p = 2.3 \text{ mJ m}^{-2}, \gamma_l = 50.8 \text{ mJ m}^{-2}$$

Formamide:

$$\gamma_l^d = 32.3 \text{ mJ m}^{-2}, \gamma_l^p = 26. \text{mJ m}^{-2}, \gamma_l = 58.3 \text{ mJ m}^{-2}$$

Weight changes as a consequence of the corona plasma modification were determined using a Mettler-Toledo AL-104 balance (Mettler-Toledo, Schwerzenbach, Switzerland). The films were weighed before and after exposure to corona plasma. At least,



**Figure 1** Variation of the static contact angle in terms of the corona discharge plasma power on a low density polyethylene (LDPE) in a continuous process with a film advance rate of  $10 \text{ m min}^{-1}$ .

five measurements were taken for each sample and average values were calculated.

### Laminates processing and characterization

The lamination process was performed in a laboratory scale hot-melt laminator supplied by Schaetti (Schaetti AG, Wallisellen, Switzerland). The processing conditions were as follows: cylinder temperature =  $120^\circ\text{C}$ , cylinder rate =  $6 \text{ m min}^{-1}$ , cylinder pressure = 2 bar.

Adhesive joints were subjected to an aging process in an aging chamber CTS mod. C-70/1500 (Climate Testing Systems, Warminster, United Kingdom). The selected storage conditions for the aging process were C1: temperature =  $38^\circ\text{C}$ , RH = 95% and C2: temperature =  $75^\circ\text{C}$ ; RH = 50%, since these conditions are widely used for material characterization in the automotive industry.

Mechanical characterization of the adhesive joints was carried out using an Instron Mod. 4501 (Instron, Barcelona, Spain). Five samples of  $50 \times 300 \text{ mm}^2$  in size with different corona discharge plasma conditions were subjected to the T-peel test ( $180^\circ$ ) at a peel rate of  $100 \text{ mm min}^{-1}$  using the guidelines of the standard UNE 40387, and the average values of T-peel strength were calculated. Before the test, a hand separation length of 70 mm was carried out and after that, tests were performed up to 150 mm separation length.

## RESULTS AND DISCUSSION

### Changes in LDPE surface wettability

Corona discharge plasma promotes a remarkable increase in wettability of LDPE film. This is due to the action of several plasma-acting mechanisms: sur-

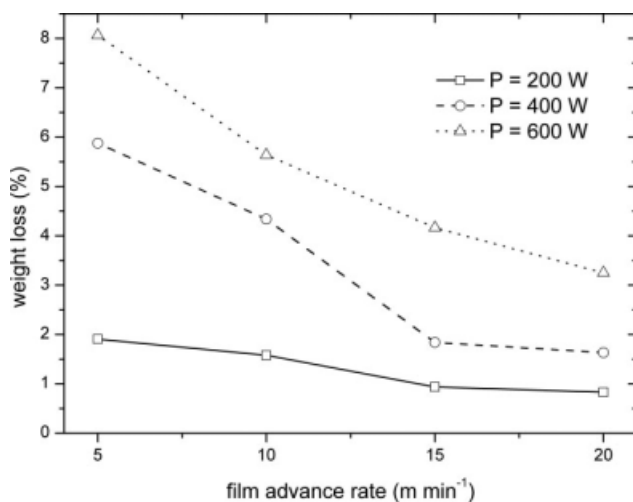
face functionalization by insertion of polar groups and changes in surface topography.<sup>26,28,30,31</sup> The overall effects of the corona discharge plasma treatment can be observed in a clear way in Figure 1 which shows the plot evolution of contact angles for different test liquids in terms of the corona discharge power. The initial contact angle of the film, located around  $93.5^\circ$ ,  $79.9^\circ$ ,  $65.4^\circ$  and  $70.1^\circ$  for water, glycerol, diiodomethane and formamide is considerably reduced for all working powers; nevertheless, as it can be observed, optimum results are obtained for working powers in the 400–600 W range.

The effects of surface functionalization by insertion of polar groups can be observed if we calculate surface free energy of plasma-treated films (Table I). If we take into account that this process can be carried out in a continuous way, an additional variable, the film advance rate, has been considered to evaluate the overall effects of the plasma treatment.

The initial surface energy of the LDPE film is close to  $27.6 \text{ mJ m}^{-2}$  with a polar component ( $\gamma_s^p$ ) of  $2.6 \text{ mJ m}^{-2}$  and a dispersive component ( $\gamma_s^d$ ) of  $25.0 \text{ mJ m}^{-2}$ . For a working power of 200 W, the polar component of the solid surface energy, shows a slight increase as the film advance rate increases from 5 to  $20 \text{ m min}^{-1}$  but it does not represent important changes (the polar component increases from  $6 \text{ mJ m}^{-2}$  up to values of  $7 \text{ mJ m}^{-2}$ ). Nevertheless, this working power is too low to promote a remarkable increase in surface energy which remains with values close to  $36 \text{ mJ m}^{-2}$  for all rates. The use of higher working powers, in the 400–600 W range, is suitable to promote a more pronounced increase in surface wettability in a similar way to that observed previously with contact angle changes. So

**TABLE I**  
Values of the Total Surface Free Energy ( $\gamma_s$ ) and its Polar ( $\gamma_s^p$ ) and Dispersive ( $\gamma_s^d$ ) Contributions of Untreated LDPE Film, and Plasma-Treated LDPE Film with Different Working Powers and Several Film Advance Rates

| Working power (W) | Film advance rate ( $\text{m min}^{-1}$ ) | $\gamma_s$ (mJ m <sup>-2</sup> ) |              |              |
|-------------------|---|----------------------------------|--------------|--------------|
|                   |   | $\gamma_s$                       | $\gamma_s^p$ | $\gamma_s^d$ |
| Untreated LDPE    | –   | 27.6                             | 2.6          | 25           |
| 200               | 5   | 37.3                             | 6.0          | 31.3         |
|                   | 10  | 36.7                             | 6.9          | 29.8         |
|                   | 15  | 36.6                             | 7.3          | 29.6         |
|                   | 20  | 36.3                             | 7.0          | 29.3         |
| 400               | 5   | 42.0                             | 18.4         | 23.6         |
|                   | 10  | 42.4                             | 16.2         | 26.2         |
|                   | 15  | 41.5                             | 14.7         | 26.8         |
|                   | 20  | 40.7                             | 12.7         | 28.0         |
| 600               | 5   | 48.8                             | 25.7         | 23.1         |
|                   | 10  | 47.1                             | 24.2         | 22.9         |
|                   | 15  | 45.4                             | 19.0         | 26.4         |
|                   | 20  | 45.7                             | 19.7         | 26.0         |



**Figure 2** Evolution of the weight loss of LDPE films treated with corona discharge plasma at different working powers in the 200–600 W range and several film advance rates.

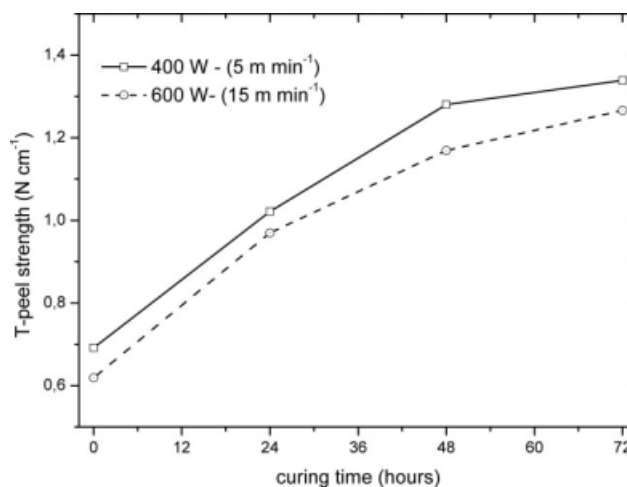
that, surface energy reaches values of 42 and 48 mJ m<sup>-2</sup> for 400 W and 600 W respectively. As we can observe in Table I, a slight decrease in surface energy as the film advance rate increases can be detected as expected; nevertheless, changes in wetting properties for film advance rates from 5 to 20 m min<sup>-1</sup> are small if compared to those derived from working power changes in the 200–600 W range. The use of film advance rates in the 5–20 m min<sup>-1</sup> range. Also, note the increase in the polar component of the solid surface energy; this is representative for surface functionalization as a consequence of surface interlock of some polar groups (mainly oxygen-based moieties).<sup>28,30,31</sup>

On the other hand, additionally to surface functionalization, corona discharge plasma promotes some surface abrasion that leads to material removing and, subsequently topography changes.<sup>32</sup> Figure 2 shows the plot evolution of the weight loss in terms of the working power and different film advance rates. For a working power of 200 W, corona discharge aggressiveness is low, thus we can observe slight variation on weight loss in the film advance rate range of 5–20 m min<sup>-1</sup> (from 62 μg cm<sup>-2</sup> [0.83%] up to 144 μg cm<sup>-2</sup> [1.91%] for film advance rates of 20 and 5 m min<sup>-1</sup> respectively). Regarding intermediate (400 W) and high (600 W) working powers, we can observe that corona discharge abrasion is much more aggressive and the weight loss reaches high values for low film advance rates of 5 m min<sup>-1</sup> (418 μg cm<sup>-2</sup> [5.87%] and 562 μg cm<sup>-2</sup> [8.07%] for working powers of 400 W and 600 W respectively). Even, for high film advance rates, the weight loss is important: 121 μg cm<sup>-2</sup> [1.63%] for 400 W and 237 μg cm<sup>-2</sup> [3.25%] for 600 W, thus showing high abrasion.

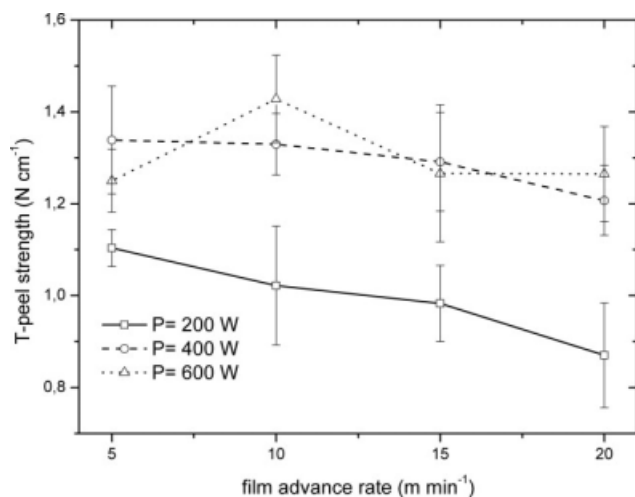
It is important to note that the overall effects of the corona discharge plasma treatment are not sensitive in a great extent to the film advance rate, but the abrasion mechanism, related to material removing, plays an important role. This fact could represent some restriction from an industrial point of view since abrasion is related together with substrate degradation so it would be preferable to use high film advance rates at intermediate-high working powers to avoid unnecessary degradation. As the working power increases, a remarkable increase in weight loss is detected. The action of some species present in the plasma gas promote chain scission and some low molecular weight species can be removed from surface.

### Characterization of LDPE-PE foam adhesive joints

Before mechanical characterization of LDPE-PE foam laminates, the optimum curing time for the reactive polyurethane adhesive has been studied to ensure optimum performance of adhesive joints. The curing time of the adhesive is a key factor to determine the appropriate processing conditions to obtain the optimum mechanical performance of adhesive joints. To quantify this, we have studied the evolution of the T-peel strength in terms of the curing time for two processing conditions: working power of 400 W and film advance rate of 5 m min<sup>-1</sup> and working power of 600 W and film advance rate of 15 m min<sup>-1</sup>, as two representative conditions of industrial procedure to achieve similar overall functionalization. It is possible to observe that the curing time is a decisive factor to obtain good mechanical response of adhesive joints. If we observe the evolution of the T-peel strength (Fig. 3), after 72 h of curing time, the overall



**Figure 3** Variation of the T-peel strength of LDPE-PE foam laminates in terms of the adhesive curing time for several previous corona discharge conditions ( $P = 400$  W;  $v = 5$  m min<sup>-1</sup>) and ( $P = 600$  W;  $v = 15$  m min<sup>-1</sup>).



**Figure 4** Variation of the T-peel strength of LDPE-PE foam laminates in terms of the film advance rate for several working powers.

T-peel strength is enough to ensure good adhesive properties.

Once the optimum curing time for the adhesive has been defined, we have proceeded to study the effect of the working power and film advance rate on overall performance of LDPE-PE foam adhesive joints. Figure 4 shows experimental results regarding changes in T-peel strength in terms of the film advance rate for several working powers. These results are in accordance with those described before regarding surface energy changes in terms of the working power and film advance rate. When corona discharge is applied under low working powers (200 W), the T-peel strength of laminates is quite low and slightly higher results can be obtained for low film advance rates. We have to take into account that surface energy values for a working power of 200 W are the low [36–37 mJ m<sup>-2</sup>] if compared to 400 [40–42 mJ m<sup>-2</sup>] or 600 W [45–48 mJ m<sup>-2</sup>]. Nevertheless, if we take into account that the T-peel strength of laminates, without previous surface treatment on LDPE film, is about 0.12 N cm<sup>-1</sup>, the relative increase in the T-peel strength value is remarkable, even for low working powers (between 1.1 N cm<sup>-1</sup> and 0.86 N cm<sup>-1</sup> for film advance rates of 5 and 20 m min<sup>-1</sup> respectively). The use of an intermediate power of 400 W is enough to obtain the appropriate performance on adhesive joints even for high film advance rates. The T-peel strength varies from 1.34 N cm<sup>-1</sup> and 1.2 N cm<sup>-1</sup> for film advance rates of 5 and 20 m min<sup>-1</sup> respectively. In these working conditions the decrease in T-peel strength as the film advance rate increases is relatively low, thus showing that it has not a noticeable effect on mechanical response. Otherwise, the increase in T-peel strength values is remarkable if compared to the use of a working power of 200 W. We have to

consider that this is a key factor from an industrial point of view since it allows high productivity. The T-peel strength is increased from 0.12 N cm<sup>-1</sup> for laminates without previous corona discharge treatment up to values around 1.33 N cm<sup>-1</sup> for a film advance rate of 10 m min<sup>-1</sup>. When LDPE films are exposed to a corona discharge of 600 W as working power, the maximum T-peel strength for adhesive joints is obtained, reaching values around 1.43 N cm<sup>-1</sup> for a film advance rate of 10 m min<sup>-1</sup>. As expected, this initial value is decreased up to values of 1.26 N cm<sup>-1</sup> (percentage loss of 11.9%) as the film advance rate increases up to values of 20 m min<sup>-1</sup>.

All these results are in good agreement with those described before regarding surface wettability and solid surface energy calculation. Changes in solid surface energy are directly related to changes in film wettability as a consequence of surface activation by insertion of polar groups and topography changes, both two mechanisms having a positive effect on adhesive properties of LDPE film.<sup>18</sup> The untreated LDPE film is characterized by high chemical inertness which involves low solid surface energy values (of about 27–28 mJ m<sup>-2</sup>) and this results in poor adhesion properties (T-peel strength of laminates is about 0.12 N cm<sup>-1</sup>). So that, the use of corona discharge plasma is an efficient method to increase surface wettability and adhesive properties of LDPE films for laminates with PE foam.

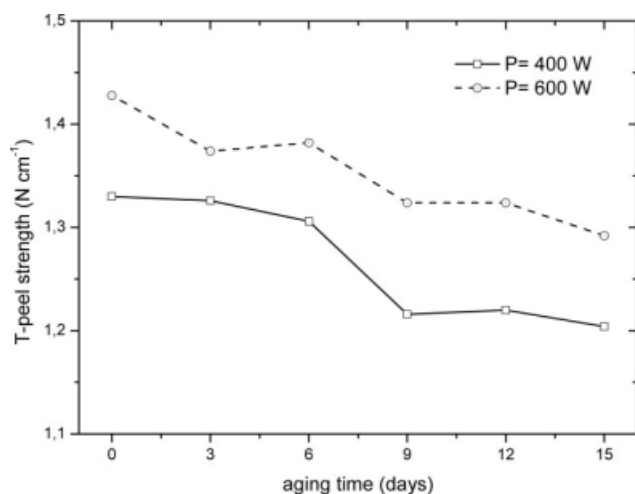
#### Aging of adhesion joints in hydrothermal conditions

The use of these composite laminates in technological applications requires, in many cases, durability of mechanical properties in aggressive conditions. Usually, hydrothermal conditions are typical conditions that lead to aging of materials; combination of temperature and RH is enough to produce a decrease in mechanical response of adhesive joints.<sup>1,2,33</sup> To determine the usefulness of LDPE-PE foam laminates, they have been subjected to the action of two hydrothermal conditions, one with high RH values (C1: 38°C–95% HR) and other characterized with high temperature (C2: 75°C–50% RH).

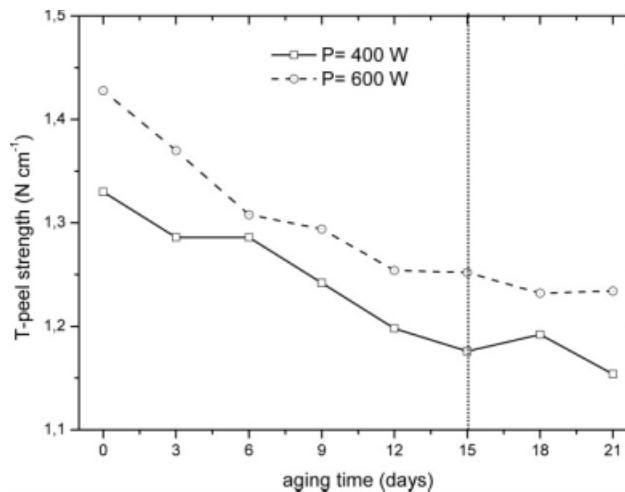
Figure 5 shows a plot evolution of the T-peel strength in terms of the storage time for aging conditions characterized by high RH (C1: 38°C–95% HR). The different data series correspond to different working powers (400 and 600 W) and film advance rate of 10 m min<sup>-1</sup> during the previous corona discharge plasma treatment. We can see in a clear way, a slight decrease in the T-peel strength as a consequence of the aging process. Despite this, the overall loss on mechanical performance is relatively low at the end of the cycle: less than 9.5% for both 400 W and 600 W after 15 days storage time, so we can

conclude that the combined effect of high RH and moderate temperatures results in a slight decrease on mechanical response of the adhesive joints and it does not restrict the use of these laminates in technological applications.

Regarding the combined effect of high temperature values with typical RH levels (C2: 75°C–50% HR), we can observe similar behavior (Fig. 6). We can see a slight decrease in mechanical performance as the storage time increases. Despite this, the percentage decrease in the T-peel force values is similar to that observed for C1 aging conditions. After 15 days of storage time, the T-peel strength value has been reduced by  $\sim 12\%$  for both working powers and at the end of the cycle, this reduction is less than 13.5%. These results indicate that even in aggressive hydrothermal conditions, the aging process occurs in a very low extent and does not restrict the use of LDPE-PE foam laminates in technological applications. Despite this, we can see that, in the range of temperatures and RH values examined in this study, the effect of temperature on mechanical performance (aging) of laminates is higher if compared to the overall effect of RH. Similar results are described in a previous article regarding use of low pressure glow discharge plasma (LPGD) as a method for improving mechanical performance of adhesive joints.<sup>18</sup> The use of LPGD plasma allows a complete control of the process parameters (gas, flow rate, vacuum level, . . .) but the main disadvantage is that the process can't be carried out in a continuous way so it is useful for small batches and/or individual parts. On other hand, the use of corona plasma in a continuous way, allows similar functionalization, durability and high productivity levels but the main problems are related to lack of absolute



**Figure 5** Variation of the T-peel strength of LDPE-PE foam laminates in terms of the storage time at aging conditions C1: 38°C/95% RH, for two working powers and a film advance rate of 10 m min<sup>-1</sup>.



**Figure 6** Variation of the T-peel strength of LDPE-PE foam laminates in terms of the storage time at aging conditions C2: 75°C/50% RH, for two working powers and a film advance rate of 10 m min<sup>-1</sup>.

uniformity (due to changes in environmental conditions). Despite this, the use of corona plasma is very useful from an industrial point of view due to high productivity and overall good surface modification.

## CONCLUSIONS

Corona discharge plasma treatment is appropriate to carry out surface modification of LDPE in a continuous way. Among the different variables to be considered as key factors for the process, the working power has resulted to be the most relevant while the effects of the film advance rate are not as remarkable. The use of a working power of 600 W at different film advance rates in the 5–20 m min<sup>-1</sup> range is enough to provide good surface wettability (the solid surface energy is increased from 27.6 mJ m<sup>-2</sup> up to values of 48 mJ m<sup>-2</sup>). We can observe a slight decreasing tendency of the solid surface energy as the film advance rate increases; nevertheless the effect of the film advance rate is not as significant as the effect of the working power in the ranges of film advance rates and working powers examined in this study.

The use of a previous corona discharge treatment on LDPE films ensures good adhesive properties on laminates with PE foam. Optimum results are obtained with working powers of 400 W and 600 W and film advance rates of about 10 m min<sup>-1</sup>, which are interesting from an industrial point of view of productivity. The initial (without corona plasma treatment) T-peel strength value is very low and it is located at 0.12 N cm<sup>-1</sup>. The use of the above mentioned corona discharge process conditions is enough to increase the T-peel strength up to values in the 1.30–1.4 N cm<sup>-1</sup>.

Regarding durability of adhesive properties in aggressive conditions (mainly hydrothermal conditions), we can conclude that the aging process promotes a slight decrease in the T-peel strength values. The combined effect of moderate temperatures (38°C) and high RH values (95%) results in a percentage decrease in T-peel strength of less than 9.5% at the end of the aging cycle (15 days). The use of high temperatures (75°C) and moderate RH values (50%) is responsible for a percentage decrease of about 12% after 15 days, thus showing that mechanical performance of adhesive joints is more sensitive to temperature than RH in the range of temperatures and RH examined in this study.

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